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EXTENDED ABSTRACTS

URANIUM DEPOSIT TYPES, EXPLORATION METHODS AND CORPORATE SOCIAL RESPONSIBILITY PROGRAMS: CASE OF LERE (CHAD)

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1. INTRODUCTION

The Lere uranium deposit is one of numerous uranium showings in Chad. It was highlighted in the Mayo-Kebbi West area, close to the border with Cameroon. This deposit is best known because it has been the subject of previous studies by UNDP (United Nations Development Program) and the IAEA (International Atomic Energy Agency) between 1970 and 1980. Recently, these studies were supplemented by exploration Signet Mining Services Ltd (SMS), a European-based mining company, known in Chad as Chad Mining Services. Furthermore, the consulting company SRK was requested by Signet to generate a mineral resource estimate of the Lere deposit as part of the initial exploration program.

2. DESCRIPTION: METHODS AND RESULTS

Located in southwestern of Chad, the Lere deposit has uranium hosted in near vertical shear zones and secondary foliation in albitized and silicified granite in a mixed terrain of Precambrian units.

It occurs within the Zabili granitoids, proximal to the contact with the schist and amphibolites of the Mayo Kebbi series. The ore-body is a weathered, iron-stained (haematized), fractured and sheared, feldspar-rich (albite), low-quartz granite. Within the orebody desilicified as well as silica impregnated zones are recognized.

Signet Mining Services Ltd had six concessions comprising 841 km² that include the Lere Project in southwestern Chad near the towns of Lere and Pala. Exploration activities included an airborne geophysical survey, a geological survey and a surface radiometric survey. Uranium anomalies and potentially significant structures have been identified. Anomalies A and B have been drilled by percussion drilling (18 541 m) and core drilling (2 676 m), enabling the development of a geological model and providing sufficient data for resource estimation. Chad Mining Services Company has completed over 170 vertical drillholes, 22 trenches and a dozen inclined drillholes. Uranium concentrations vary between drillholes, with the greatest value is in the order of 4000 ppm in drillholes and 50 to 100 ppm on the surface during the mapping. The deposit is estimated at 8 000 000 t of ore [1].

Resources compliant with the South African Mineral Resource Committee Code for the reporting of exploration results, mineral resources and minerals reserves have been evaluated to amount to 3 190 tU, at an average grade of 200 ppm U (0.020% U). At a uranium price of less than USD 50/lb U₃O₈, the identified deposit is considered uneconomic. Further uranium occurrences will need to be identified to increase the resources in order to move the project to a development stage [2].

Corporate Social Responsibility initiatives of Chad Mining Services included various aspects, namely: Employment, infrastructure, supplies, compensation, transfer of competences, safety, environmental protection, information and communication, other community programs.

3. DISCUSSION AND CONCLUSION

In general, the subsoil of Chad has an abundance of important mining resource particularly an important potential in uranium ore that it exploitation would contribute to the national economy. It is important to note

that Chad is still very under explored compared with other African countries. For that reason, as prospecting or mining research is the first step in the development of the mining sector, Chad Mining Services made uranium exploration in the Mayo Kebbi Province (Lere). Studies conducted by Chad Mining Services have outlined several areas that are highly prospective for uranium.

However, exploration, mining and processing operations can have both positive and negative environmental, economic and social impacts on communities. They can provide employment and business opportunities to local communities such as exploration activities of Corporate Social Responsibility. In addition, a rational exploitation coupled with the modernization of techniques for extracting and processing minerals will increase employment nationally and regionally.

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EXPLORATION AND RESOURCE DEVELOPMENT OF URANIUM MINERALIZATION IN CENTRAL JORDAN

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1. INTRODUCTION

Uranium mineralization has been known within the central areas of Jordan for a long time [1], although uranium resources were only estimated in 2014 [2]. The exploration success has become possible because of detailed geological studies that have allowed a better understanding of the geological control of uranium mineralization in central Jordan. On the basis of these studies, the exploration model was revised and implemented by the Jordanian Uranium Mining Company for delineating mineralization and estimating resources.

2. REGIONAL GEOLOGICAL CONTROL

Most of Jordan's territory is covered by platform sedimentary rocks of Cretaceous and Palaeogene age. Uranium mineralization was discovered within the platform cover where it is confined mainly to the Upper Cretaceous rocks, in particular the Muwaqqar Chalk Marl (MCM) Formation. Uranium minerals, found in the weakly lithified friable sediments of the MCM Formation are represented mainly by uranium vanadates colloquially termed carnotite [2]. Uranium mineralization is distributed as fine-grained disseminations forming areas of variable size and shape that have impregnated the host sedimentary rocks and also coated the surfaces of joints and fractures.

Faults also possibly played a role in the distribution of the uranium mineralization in central Jordan, where higher grade mineralization and associated gamma anomalies are broadly coincident with the location of regional faults, mainly the E–W and NW–SE striking splays of the Dead Sea Transform fault.

3. PYROMETAMORPHISM

A unique feature of the surficial uranium mineralization in central Jordan is its close spatial relationship with pyrometamorphic marbles that are hosted by unmetamorphosed marls, chalks and limestones. The marbles are varicoloured, commonly brown, greenish, reddish, white and, locally, black. They are cut by hydrothermal veins and have experienced different degrees of low temperature alteration. A unique feature of these rocks is the widespread distribution of high and ultra-high temperature (up to 1500°C) low pressure metamorphic mineral assemblages, including spurrite, wollastonite, ellastadite, diopside and garnet [3–5]. The contacts of marble with the unmetamorphosed host sequence are sharp, although contact outlines are often irregular.

The formation of marbles in central Jordan is commonly explained by pyrometamorphism, either caused by the burning of bituminous marls [5] or, alternatively, by the combustion of deep reservoirs of hydrocarbon gases relating to mud volcanoes [3, 4].

Another unique geological feature of the uranium deposits in Jordan is the occurrence of exotic paramagmatic dykes that cut pyrometamorphic marbles. These dykes were identified in exploration trenches and marble quarries in central Jordan. These are similar to the dykes found in the adjacent territories, where they are also associated with high temperature metamorphic rocks [3]. The dykes are interpreted as paralavas that have been formed as a result of the host rocks melting during high temperature combustion metamorphism [2–4].

Dating of these pyrometamorphic rocks has identified several episodes of combustion metamorphism that have occurred in Miocene (\sim 16 Ma), Pliocene (\sim 3 Ma) and Pleistocene (1.7–1.0 Ma) periods [6]. These ages broadly coincide with the age of mafic magmatism that occurred in Jordan during the Miocene (23.8–21.1 Ma and 12.05–8.08 Ma) and Pleistocene (3.2–1.5 Ma) [7, 8], suggesting that this basaltic magmatism could have triggered the rapid combustion of hydrocarbons, or at least that these processes are part of the same tectono-magmatic event.

4. SUPERGENE PROCESSES

Within the MCM Formation, the uranium mineralization is hosted by near surface weathered chalks and marls and concentrated in a narrow layer, approximately 4.5 m thick, distributed close to the topographic surface. The vertical profile of uranium distribution in central Jordan has been studied in great detail using 2188 trenches and 5691 drill holes [2]. It was noted [2] that the degree of weathering varies from complete alteration, when rocks have been converted to saprolite, to mildly weathered sedimentary rocks. The highest uranium concentrations were found along the contact between saprolite and mildly weathered/fresh rocks.

The near surface distribution of uranium mineralization, which is characterized by a highly variable degree of isotopic disequilibrium, has required the digging of exploration trenches in order to obtain representative samples and for estimating uranium resources [9]. Mapping of the trench walls has shown that uranium mineralization is not controlled by phosphorite layers.

5. SUMMARY AND CONCLUSIONS

In general, the uranium mineralization that is hosted by the weathered chalk and marl of the MCM Formation in central Jordan has many characteristics in common with the conventional surficial type uranium mineralization [10]. However, the close spatial relationship of uranium in central Jordan with pyrometamorphic rocks suggests that this is a special type of surficial uranium mineralization which has resulted from the interplay of different processes, where combustion metamorphism has played a very important role in facilitating leaching of uranium from the host rocks. The liberated uranium was eventually redistributed by supergene processes towards the surface, where uranium mineralization should not be confused with synsedimentary accumulations of uranium in the phosphorite beds which are also present in Jordan [2].

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GEOCHEMICAL SIGNATURES OF U-BEARING METASOMATIC DEPOSITS OF THE CENTRAL MINERAL BELT, LABRADOR, CANADA

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1. INTRODUCTION

The Central Mineral Belt (CMB) of Labrador hosts multiple $U \pm Cu \pm Mo \pm V$ prospects and deposits, including some with affinities to albitite hosted uranium deposits and others with iron oxide–copper–gold (IOCG) deposits [1–3]. Extensive exploration campaigns during the mid-2000s generated a large amount of industry geophysical and geochemical data.

Worldwide, IOCG deposits host significant polymetallic resources, with the Olympic Dam deposit being the largest uranium deposit in the world. Over the past decade, the demonstration of a diagnostic evolution of alteration facies within IOCG systems has led to the development of geochemical tools useful for detecting prospective areas [4]. In the CMB, geological and mineralogical characteristics analogous to those of IOCG systems include pervasive regional sodic alteration prior to brecciation and iron oxide \pm K-feldspar alteration and subsequent mineralization. Thus, it is worthwhile to investigate potential links between IOCG systems and the CMB uranium mineralization as means to advance exploration models.

The CMB uranium geochemistry database (CMBUG [5]) consists of over 40 000 data entries compiled from Geological Survey of Newfoundland and Labrador data files and drill core geochemistry submitted in mineral assessment reports for the period 2002–2011. In this paper, the authors provide a general characterization of the CMBUG data in terms of their alteration types, along with a preliminary principal component analysis done on a smaller suite of data from the CMBUG.

2. GENERAL GEOLOGY

The regional geology of the CMB described herein is summarized from Refs [1, 6–13]. The Archaean Nain Province gneisses are the basement to the variably deformed tonalite, granodiorite and granite intrusions of the Kanairiktok Intrusive Suite, both of which are transected by 2.23 Ga Kikkertavak dykes.

The Palaeoproterozoic (younger than 2.2 Ga) metavolcanic and metasedimentary packages of the Moran Lake and Post Hill groups unconformably overly the Archaean gneisses and Kanairiktok Intrusive Suite intrusions. The Post Hill Group (north-eastern CMB) is overlaid by mixed sedimentary and bimodal volcanic rocks of the Aillik Group. The Moran Lake Group (south-western CMB) is unconformably overlain by the Bruce River Group, which consists of conglomeratic arkose and sandstone covered by a thick sequence of 1.7 Ga felsic volcanic rocks. The youngest supracrustal sequences in the CMB are the Letitia Lake and Seal Lake Groups. The ~1.3 Ga Letitia Lake Group is dominated by alkaline volcanic rocks that are overlain by sedimentary and mafic volcanic rocks of the Seal Lake Group.

The Archaean intrusions and Palaeoproterozoic sequences are metamorphosed (up to amphibolite facies) and variably deformed by at least three orogenic episodes (Makkovikian: \sim 1.8–1.7 Ga, Labradorian: 1.7–1.6 Ga and Grenvillian: \sim 1.0 Ga).

The CMB U±Th±Cu±Pb±Zn mineralization occurs within all the Archaean to Palaeoproterozoic to Mesoproterozoic intrusive (e.g. Two Time prospect), volcanic (e.g. Moran Lake Upper C and Michelin deposits) and sedimentary (e.g. Anna Lake prospect) rocks. Mineralization styles include breccia (e.g. Two Time and Moran Lake Upper C zone) and fracture hosted (e.g. Anomaly No. 17 prospect) plus disseminated (e.g. Anna Lake prospect) mineralization. However, in most cases, ore-bearing events are preceded by moderate to pervasive sodic metasomatism (e.g. Michelin deposit) and iron oxide replacements or breccia infill (mainly haematite).

3. ANALYTICAL METHODS

The major and trace element analyses compiled in the CMBUG were obtained from various laboratories mainly using 'total digestion' techniques. The total digestion techniques rely on a mixture of three to four different acids to attempt to fully dissolve samples followed by inductively couple mass spectrometry analysis to provide relatively complete geochemical results. Although total digestion techniques are typically effective, incomplete digestion of the sample is still possible due to the presence of highly resistive minerals. Thus, total digestion (e.g. As, Se, Te and U) may be under-represented in the analyses. Less commonly, samples in the CMBUG were analysed by a mixture of lithium metaborate/tetraborate fusion, instrumental neutron activation analysis and X ray fluorescence techniques. The combination of these techniques allows for improved quantification of major and trace elements contained in resistive minerals (e.g. magnetite and rare earth-bearing minerals).

4. DATA DISTRIBUTION

The CMBUG encompasses over 40 000 data points from multiple locations within the CMB. However, over 95% of the data are from six main areas: Moran, Jacques Lake, Snegamook, Michelin, Anna Lake, Kitts–Post Hill and Kanairiktok (see Figs 1 and 2 in Ref. [5]). These areas may represent one or many prospects and/or deposits. For example, the Moran dataset includes the Moran Lake Upper C Zone deposit and Moran Lake B and Armstrong prospects. On the other hand, the Jacques Lake dataset only comprises samples from the Jacques Lake deposit. In this report, data characterization is restricted to the aforementioned main locations and no additional geographical distinction was considered.

5. ALTERATION CHARACTERIZATION

The alteration facies hosting uranium mineralization in the CMB were evaluated through an alteration discrimination plot [4]. For this purpose, only samples having non-zero Al, Na, K, Ca, Mg and Fe concentrations are selected. To better illustrate the data description below, reference should be made to Figs 1, 5 and 6 in Ref. [14].

In general, the CMBUG samples present significant scatter, with most samples plotting in the least altered and Na and Fe-(Mg) alteration fields. In the Snegamook and Jacques Lake areas, most samples are Na altered and a lower portion of these data plot mainly within the unaltered and K alteration fields. In the Anna Lake, Kanairiktok and Michelin areas, most samples plot within the least altered and Na alteration fields, with less significant clusters consistent with K, Ca–K–Fe and K–Fe altered rocks. The Moran Lake data account for the greatest portion of the CMBUG database and show the largest scatter. Similar to other CMB locations, most samples are contained in the least altered, Na and Fe–(Mg) alteration fields, with a relatively minor portion plotting within the K, Ca–K–Fe, K–Fe, Fe-rich Ca–K–Fe and Ca–Fe alteration fields.

Notably, it is observed that distribution of high uranium contents is not associated to a particular type of alteration. Instead, uranium mineralization is found in almost all fields on the alteration plot, including that representing least altered rocks.

In IOCG deposits, sodic alteration is commonly associated with deeper and higher temperature parts of the hydrothermal system that evolve over time and over distance to Ca–Fe and K–Fe alteration assemblages [2–4, 15, 16]. Generally, rocks contained in the K–Fe field are considered as geochemically 'mature' and economically fertile in terms of base, precious and specialized metals. In the CMB, the data suite as a whole does follow the prograde path of IOCG evolution; rather, it either evolves from the Na to Fe–(Mg) alteration or from the Na to K alteration which is typical of telescoping of alteration facies. Such telescoping leads to significant overprints that result in a shift of major elements contents into the least altered field. However, it is possible that mineralization hosted in veinlets, fracture coatings and/or disseminated in relatively unaltered rocks could also account for the high uranium content of rocks in the least altered field.

In summary, the preliminary interpretations of the data distribution in the alteration plot are that: (i) Na alteration is the most common alkali alteration in the CMB, (ii) emplacement of iron oxide minerals is generally decoupled from potassium (few samples located in the K–Fe alteration field) and (iii) the mineralization is not necessarily strictly associated with alkali or iron oxide altered rocks. However, the latter may result from alteration overlaps that shift the major element composition of mineralized rocks to the least altered field. Furthermore, as the CBUG relies on industry data submitted for analysis (i.e. targeting a specific style of mineralization such as the uranium-bearing Na \pm Fe style observed at the Michelin deposit), there is potential for sampling bias in the data. As such, it is possible that certain alteration facies are under-represented in the database.

6. PRINCIPAL COMPONENT ANALYSIS

The statistical characterization of whole-rock geochemistry requires data treatment prior to analysis. The centered log-ratio transformation overcomes the closure constraint inherent to geochemical data [17], which allows the use of multivariate statistical tools (e.g. principal component analysis) to identify geochemical processes. A suite of ~5000 whole rock analyses obtained from total digestion were transformed using the centered log-ratio technique prior to principal component analysis.

As a whole, base metals tend to exhibit co-variation together with cobalt, vanadium and iron which forms a sub-group distinct from cadmium, chromium, zinc, copper and nickel. The association of the iron, cobalt and vanadium is likely related to the incorporation of the latter two elements in iron oxides such as magnetite and haematite. From the principal component analysis view, it is also remarkable that alkali alteration related elements (e.g. potassium and sodium) do not correlate directly with uranium, as is also suggested by the alteration plot. However, this lack of association, especially with sodium, might be masked by the fact that, proportionally, the sodium alteration in the CMB is more common and regionally widespread in comparison to the local occurrences of uranium mineralization. In addition, uranium might have been remobilized and concentrated along structural traps (e.g. unconformity, shear zones) even though it was first precipitated within the iron oxide alkali–calcic alteration systems.

7. CONCLUSIONS

Evaluation of the data in the alteration plot indicates that: (i) sodic alteration is the most common alkali alteration in the CMB, (ii) the emplacement of iron oxide minerals is generally decoupled from potassium and (iii) uranium mineralization is not necessarily associated with alkali or iron oxide altered rocks. Nevertheless, alteration type overlaps may shift the major element composition of mineralized rocks to the least altered field. The absence of an association of uranium and other base metals with alkali elements is also recorded by principal component analysis. However, further statistical analysis based on the individual alteration types and by geographical location of the CMBUG is necessary to fully characterize the mobility

of uranium and base metal elements and their association with alteration facies.

This paper is a contribution to NRCan's Targeted Geoscience Initiative programme under the metal pathways and traps in polymetallic ($U \pm Fe$, Cu, Au, REE) metasomatic ore systems activity.

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URANIUM DEPOSITS OF THE KARELIAN-KOLA PROVINCE (RUSSIAN FEDERATION)

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1. INTRODUCTION

The Karelian-Kola uranium ore province is situated within the East European Platform and covers the eastern Baltic Shield and the northern Russian Plate. The area of study includes Kola-Belomorian, Laplandian-Karelian, Svecofennian megablocks and dividing suture fold–overthrust zones: The East Karelian and Raakhe-Ladoga zones. These old structures are composed of Archean and Proterozoic volcanogenic and sedimentary–volcanogenic formations of various lithologies which have been subjected to repeated structural transformations under the impact of tectonic, hydrothermal–metasomatic and exogenic processes of various ages. This history is reflected in the geochemistry of the geological formations and the specific conditions of ore genesis.

In the Precambrian geology of the Baltic Shield, several tectono-magmatic cycles (TMC) and corresponding metallogenic epochs can be distinguished: The Early Archean (>3.15 Ga), the Late Archean (3.15–2.6 Ga), the Early Karelian (2.6–2.4 Ga), the Late Karelian (2.4–1.95 Ga), the Svecofennian (1.95–1.65 Ga), the Riphean (1.65–0.65 Ga), and the Vendian–Paleozoic (0.65–0.34 Ga). Each of them is characterized by a specific type of sedimentation, volcanism, metasomatism and the origin and concentration of ore. Of all these uranium ore epochs, the Svecofennian TMC epoch is the most productive for uranium. The complexity of uranium mineralization is reflected in the variety of ore deposit types. This is caused by the complexity of ore forming systems and the superposition of ore associations through time.

2. URANIUM TARGETS OF VARIOUS ORE FORMATION TYPES

Comprehensive metallogenic and prospecting studies conducted in the Russian part of the Baltic Shield led to the discovery of uranium deposits of different types, including unconformities, sandstone, quartz-pebble conglomerates, veins, metasomatic, etc. [1–4]. Their resource potential is in excess of 2 million tU [3]. Zones of structural–stratigraphic unconformity (SSU) are widespread in the Baltic Shield. Uranium mineralization within the uranium-bearing SSU zones have different grades: high grade ore in pre-Riphean zones, low grade ore but with significant reserves in the pre-Vendian SSU zones, low grade ore in pre-Early Proterozoic SSU zones.

The pre-Riphean SSU zone is characterized by the greatest potential because the Pasha-Ladoga through hosts the Karku unconformity-type uranium deposit. The structural–stratigraphic unconformity corresponds to the deposition of Riphean sedimentary deposits on intensively tectonized Archean and Proterozoic rocks. Riphean sediments and basement rocks are intensely kaolinized and carbonatized. Sulphide and bitumen are abundant. The uranium mineralization is confined to the cement of the sandstone and is represented by pitchblende and coffinite. Elevated grades of Zn, Ag and Pb also occur. The uranium mineralization is also recorded in the basement rocks. Uranium grades range from 0.03% U to 0.2–0.5% U, and locally up to 19% U. The age of the mineralization varies from 1400 Ma to 200–190 Ma. Prognosticated resources of the Karku deposit are 6700 tU (category P₁) and 50 000 tU (category P₁ + P₂) [5]. Riphean troughs also occur in the Belomorian block, which hosts the Tersky Bereg uranium ore district. Speculative resources in the district are 63 900 tU (category P₃) and 9387 tU (category P₂) [3].

The position of the targets of the pre-Vendian unconformity ore type is regionally related to the junction of the Russian Plate complex with the structures of the Baltic Shield and the Baltic-Mezen fault-block zone.

The sandstone and gritstone of the Vendian basal horizon overlie Early Proterozoic schist and gneiss intruded by a uraniferous leucogranite. Anomalous uranium concentrations have been recorded both in the sandstone and gritstone of the basal horizon and in the rocks of the weathering crust. The uranium occurs as pitchblende and uranium oxide, with occasional coffinite. The uranium mineralization is accompanied by pyrite, galena and molybdenite. Uranium grades range from 0.03% U to 0.1% U for a thickness of 0.5–3.5 m. The age of the main uranium mineralization is 350–420 Ma. Younger ages (300–5 Ma) evidence uranium redistribution up until recent times. This ore type is represented by the Ratnitskoe, Ryabinovskoe and Slavyanka deposits.

The metasomatic ore type in black shale occurs in the Onega Depression (Onega uranium ore district). Carbon-bearing terrigenous rocks host the ore. The complex uranium–gold–platinum–palladium–vanadium deposits are controlled by linear fold–fault zones. Eleven zones have been recognized within the Onega Depression. These are systems of narrow anticlines of NW strike and having lengths of 30–100 km and a width of 2–4 km. The ore-bearing intervals that host these complex deposits are 2–2.5 km long and 500–600 m wide. In the fold–fault zones, the rocks are intensively albitized, carbonatized and biotitized. Several significant deposits (Srednyaya Padma, Kosmozero, Tsarevka and other deposits) and nine ore-showings of this type were discovered in the Onega Depression. The uranium mineralization is represented by brannerite, coffinite and pitchblende. Average ore grades are 0.15-0.25% U (and up to several percent for 1–3 m), and 2.5-3.5% V₂O₅. Speculative resources (category P₃) total 110 000 tU [3].

Metasomatic pegmatite ore type includes numerous ore targets located in the Archaean basement complex, mainly in the Ladoga–Barents Sea longitudinal faulted block zone. Minor showings were also identified in granite–gneiss domes of the Svecofennian megablock.

The zones of fault blocks are characterized by granite formation, silica–alkali and siliceous metasomatism. Ore-hosting metasomatite is dominated by quartz-microcline, quartz-albitite, and quartz-microcline-albitite metasomatite, microclinite, albitite pegmatite that form veins concordant with the host gneiss. These vary from several tens of metres to several hundreds of metres long and from several metres to 30 m wide. Ore minerals are dominated by uraninite, thorite and uranothorite. The age of the mineralization ranges from 2700–2200 Ma to 1800–1700 Ma. In the Karelian megablock, this ore type, is represented by the Gimoly, Khukkaly and other ore showings. Speculative resources (category P₂) of the Khukkaly uranium clusters total 60 000 tU [5]. In the Svecofennian megablock, this ore type is represented by the Khirsimyaki, Khotinoya and Mursula ore showings.

The initiation and evolution of Early Proterozoic proto-riftogenic and proto-platform depressions was accompanied by the formation of basal horizons represented by conglomerate-gritstone strata with a weathered horizon at its base. The quartz-pebble conglomerate ore type is closely associated with these rocks. The location of ore targets is controlled by deep fault zones, where basement rocks are chloritized and carbonatized; gritstone and conglomerate are carbonatized, sericitized and silicified. The ore mineralization is represented by uraninite and uranium titanite. Gold occurs as nuggets. Uranium grades vary from 0.017% U to 0.05% U. This ore type is represented by the Rigovaraka, Pjajavara, Jangozero and other ore showings.

The metasomatic (vein) type groups uranium targets located in micaceous and aluminous gneiss, within the zone of the leucocratic granite and granodiorite of the Litsa–Araguba Complex. Chloritization, hydromicatization and albitization of host rocks is intensive in the contact zone with the granite, where NE trending faults also occur. The uranium mineralization is represented by pitchblende, coffinite and uraninite. Uranium grades range from 0.073–0.0138% U to 1.74% U. The absolute age of the uranium mineralization is 400 Ma and 1750–1650 Ma. The Litsevskoe, Beregovoe, Koshkajavr and other ore showing belong to this ore type.

The ore targets of the phosphorous–uranium (phosphorous) type are concentrated in the fold–fault Raahe–Ladoga zone of the Svecofennian megablock. Skarns and intensively brecciated Jatulian dolomite and dolomitized limestone host the ore. They are characterized by elevated phosphorus and organic matter contents. The ore mineralization is represented by uraninite, fluorapatite, abundant sulphides and carbonaceous matter. Average uranium grades range from 0.02-0.05% U to 0.044% U (the maximum grade is 0.098% U). The phosphorous grade is 6% P. The age of the mineralization is 2300 ± 50 Ma and 1720-1960 Ma. This ore type is represented by the Mramornaya Gora, Ruskeala and Kharlu ore showings.

An interest in gold–uranium mineralization located in Early Proterozoic structures has increased with the discovery of the Rompas group deposits in Finland. Gold–uranium deposits are located in the Perapohja schist belt with widespread mafic volcanic rocks, and black and mica schists, intrusive magmatism occurring as late orogenic (1.84–1.80 Ga) and post-orogenic (1.79–1.76 Ga) granitoids and abundant quartz-carbonate veins with anomalous gold grades (up to 617 ppm Au) [6]. Gold mineralization has a clear relationship with uranium mineralization. Gold minerals (native gold, hunchunite, maldonite) fill in cracks in uraninite and form fine disseminations in carbonates in the immediate vicinity of uraninite [6]. Gold mineralization, identified in the Ozernoe ore occurrence (Pana-Kuolayarvi structure, North Karelia), has a similar location to the Rompas group deposits. Uraninite grains identified in albite-carbonate metasomatite in ore zones of the Ozernoe ore occurrence are finely fractured. Veinlets consisting of intergrowths of native gold and altaite occur in the fractures of uraninite [7].

The intrusive carbonatite (uranium-thorium-rare metals hosted in carbonatite) type is related to the Kovdor, Vuorijarvi, Sokli and other carbonatite massifs. The mineralization is represented by tantalum-niobium and thorium-uranium ores. Principal uranium-bearing phases are baddeleyite, perovskite and uranothorite. Uranium grades vary from 0.025% U to 0.31% U. The age of the deposit varies from 360 Ma to 420 Ma. The Kovdor deposit, and the Afrikanda, Vuorijarvi and other ore showings are among the ore targets of this type.

The lignite (black shale) type is related to the Cambrian–Ordovician black Dictyonema oil shale widespread in the southern slope of the Baltic Shield. The orebodies here are stratabound. The uranium mineralization is represented by pitchblende and uraninite. Uranium grade varies from 0.02% U to 0.046% U. The ore targets of this type are the Krasnoe Selo, Kotlovskoe and Kingiseppskoe deposits. The deposit types associated with the pre-Riphean SSU (Karku) and the metasomatites in black shale (Srednyaya Padma and others) are of economic significance.

The main distinctive geological, petrographicl-ithological, epigenetic, radio-geochemical, geophysical and other typical features of the ore-bearing areas have been identified, based on the analysis of the location of the uranium deposits and ore showings. Tectonic structures control the location of the ore targets in spatially. These are deep faults, zones of schistosity, fissuring and brecciation, which are characterized by elevated permeability and which promote migration of ore-bearing fluids, including those from deep crustal zones into upper horizons. Zones of regional SSUs are the most important of them in this region. Petrographiclithological controls are uraniferous sedimentary and magmatic rocks, including leucogranite, alkaline intrusive rocks, carbonatite, carbon-bearing shale, phosphate-bearing sand, bauxite-bearing rocks, etc. These rocks provide, to a great degree, the geochemical resource during the epigenetic stage of ore formation. Epigenetic processes include ore genesis and transport mechanisms and ore-hosting epigenetic rock transformations. Hydrothermal-metasomatic conditions favourable for ore formation include quartzfeldspathic pegmatite and metasomatite which concentrate uranium, thorium and other elements in the orebodies; greisens, which promote uranium migration; albite-carbonate-micaceous metasomatite which generate an environment favourable for ore formation; and chlorite-carbonate and albite-hydromicas and other metasomatites which form near-ore and ore-hosting zones. A group of indicators evidencing the processes of ore concentration, located at some distance from the ore occurrence, are defined as indirect features. Indicators occurring within the vicinity of a favourable mineral occurrence are defined as direct features.

Uranium metallogenic zoning of the Karelian-Kola area has been defined on the analysis of geological features and prospecting indicators for uranium mineralization. The following metallogenic taxa were identified, depending on the degree of uranium ore enrichment and the importance of ore controlling factors: uraniferous and potentially uraniferous structural–metallogenic zones (SMZ) or regions that correspond to large structural zones or their parts; uraniferous and potentially uraniferous districts corresponding to local structures; uraniferous clusters and potentially uraniferous clusters or areas characterized by high ore enrichment and the most intensive manifestation of all controlling factors.

The most industrially significant of metallogenic taxa are the following:

- 1) Onega uranium ore district, which covers the Onega Depression and the Preonega Depression, has speculative resources of 110 000 tU [3];
- 2) North Ladoga SMZ, which covers the Raahe–Ladoga structural–formational zone and the activated margin of the Karelian megablock. The Karkulampi uranium ore cluster is established in the northern part of the North Ladoga SMZ and hosts the Karku uranium deposit and a group of mineralized occurrences confined to the pre-Mid-Riphean unconformity surface in the NE Pasha–Ladoga graben. Speculative resources (category P₁+P₂) of the Karkulampi uranium cluster are 50 000 tU and prognosticated resources (category P₁) total 6700 tU [5];
- 3) The South Ladoga SMZ is situated in the contact zone between the East European platform basement and the Vendian–Paleozoic plate complex. The uranium potential of the zone consists of deposits and ore showings located in the basal layers of the Gdov horizon and the extensive uranium reserves hosted in the Ordovician Dictyonema shale. The Neva-Volkhov and Baltic uranium ore districts are established in the South Ladoga SMZ. The Neva-Volkhov district hosts the Slavyanka, Ryabinovskoe and Ratnitskoe uranium deposits. Speculative resources of the Neva-Volkhov uranium district are 500 000–520 000 tU [3, 8];
- 4) The Dictyonema Shale of the Lower Ordovician Pakeror horizon is the host rock in the Baltic uranium ore district. The ores are low grade, 0.01–0.03% U (up to 0.07% U). In addition to uranium, the shale is enriched in molybdenum, vanadium and other elements. Speculative resources (category P₃) are 600 000 tU [3].

3. CONCLUSIONS

The zones of the SSUs and fold-fault zones have the greatest potential for hosting both uranium and complex with uranium deposits. The Pasha–Ladoga graben (pre-Riphean unconformity type deposits) and the Onega Depression (fold-fault zones) show considerable promise for uranium mineralization Archean–Early Proterozoic basement zones represented by superimposed low temperature alterations also have significant potential for hosting uranium deposits (Litsa and other areas). Early Proterozoic structures are promising for gold–uranium deposits.

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STOCHASTIC MODELLING OF URANIUM ROLL-FRONT DEPOSITS BASED ON STREAMLINE SIMULATION

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1. INTRODUCTION

Roll-front deposits are an accumulation of minerals in reduced permeable sandstones or other sediments between mostly reduced and pervasively oxidized environments [1]. Roll-fronts are classified as epigenetic mineral deposits, i.e. their genesis occurred after host environment was created, and that can often be found in arid areas and trapped within permeable sedimentary environments. Deposits of the roll-front type are crucial to the uranium industry. As much as 60% of worldwide production deriving from uranium resources hosted in sandstone environments can be attributed to roll-fronts [2]. Roll-fronts can be found in various sandstone provinces, including the Colorado Plateau, Crow Butte, Smith Ranch, Wyoming, Texas Coastal Plain (USA), Mali–Nigeria, Czech Republic, Chu-Sarysu, Syr-Daria, Kyzylkum, Moynkum, Inkai and Mynkuduk (Kazakhstan) and Bukinay, Sugraly and Uchkuduk (Uzbekistan) [3, 4]. Uranium can be extracted from many roll-front deposits in a safe and convenient manner with in situ leaching (ISL) method. Of all uranium produced globally in 2016, Kazakhstan accounted for 39%, where almost all uranium deposits are being developed with ISL [2]. Kazakhstan has the world's second largest uranium reserves with almost a million tonnes of recoverable uranium (2013), of which almost 70% can be recovered using ISL [2].

One of the main difficulties in the exploration of uranium roll-front type deposits lies in the limited number of available exploration techniques that, on a small scale, are generally limited to the drilling of numerous wells in prospective areas [4], which is a long and costly process.

Two basic approaches to modelling exist at the moment: the traditional interpretation of geophysical data with the subsequent connection of ore contours and geostatistical 3-D modelling [5]. Currently, there are a number of stochastic methods for modelling roll-front uranium deposits [5–7]. Renard and Beucher developed the technology of three dimensional modelling of such deposits based on the pluri-Gaussian simulation model [6].

Unfortunately, current modelling techniques rarely account for the hydrodynamic and geochemical processes involved in the genesis of roll-front uranium deposits. The authors propose to supplement existing stochastic models with additional methods of computational hydrodynamics.

2. METHODS AND RESULTS

Roll-front deposits formed as the result of dissolution of minerals from source rocks, their subsequent migration along porous channels and deposition along so-called geochemical barriers between oxidized and reduced media. The formation of roll-front uranium deposits can be divided into three stages: leaching of uranium by oxygen rich meteoritic water, downstream migration of the dissolved chemical uranium components and precipitation of uranium in reduced environments. Upon reaching reduced environments, the dissolved uranium precipitates as uranium minerals (such as pitchblende or coffinite), together with other elements such as iron and sulphur, thereby forming a roll-front type deposit. It is important to note that the redeposition of minerals is a dynamic process sustained by a continuous flow of oxygenated meteoritic water which push minerals further downstream. In other words, in active deposits, minerals continuously dissolve from the upstream side of the mineralization zone and precipitate at the front. When no more oxygen is available in the water flow, often because it has been consumed previously by the oxidation of organic matter prior to reaching the mineralized zone, the roll-front deposits stabilize.

It is clear that the genesis of roll-front deposits is intimately linked to the infiltration process of dissolved uranium compounds. Therefore, consideration of the hydrodynamics of infiltration processes can further increase the precision of any geostatistical approach that is used in modelling roll-front deposits.

Well log information is usually used as input data for geostatistical modelling of roll-front uranium deposits. In addition to uranium concentration, such data commonly include details on the filtration properties of the stratum.

Application of various estimation methods such as inverse distance weighting or kriging are based on weight assignment to well data in order to determine values at any specific node on a computational grid. The weight assignment technique is a determining factor that differentiates one estimation algorithm from another. For instance, while in kriging based methods the variogram is used for weight computation, in inverse distance based methods (as the name suggests) the distance between nodes is the most influential factor. In many implementations of the aforementioned methods, the search ellipsoid is used to gather input information from well log data. The form of this ellipsoid is usually dictated by anisotropy of a particular geological formation.

In current work, based on filtration properties gathered from well data and natural head difference, the streamlines of solution flow through strata under consideration were determined. These streamlines were further used as an aid for distance based methods, while variograms were calculated along the streamline by substituting the distance variable with 'time of flight' (a property specific to streamline simulation methods).

To verify the stochastic approach to modelling uranium roll-front deposits based on streamline simulation, well log data from Kazakhstan deposits were used. In each verification iteration, one or more well data were excluded from the modelling input for later comparison between numerical and hard data. For further verification purposes, hypothetical deposits were simulated, based on reactive transport models by reproducing uranium roll-front deposit information.

3. DISCUSSION AND CONCLUSIONS

Results show that, in terms of error, when compared with conventional estimation algorithms, stochastic modelling of uranium roll-front deposits based on streamline simulation provided a clearer understanding, both qualitatively and quantitively, of these deposits. In most of cases, stochastic modelling based on streamline simulation provided a lower average error for every node in the computational grid, as well as slightly more accurate resource estimation. The modelling approach was further investigated for various well placement patterns in order to identify optimal distances between exploration wells.

Overall, the aim of this work was to stochastically model roll-front deposits by consideration of the hydrodynamic properties of the stratum by constructing variograms along streamlines of groundwater flow to provide additional information on variability, as well as to redefine the procedure of assigning weight to hard data. In several cases, stochastic modelling of uranium roll-front deposits based on streamline simulation provided results with higher accuracy when compared with conventional methods based on kriging or gaussian simulation.

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THE MIDWEST PROJECT, EAST ATHABASCA BASIN, NORTHERN CANADA: REVIVING OLD DEPOSITS TO PREPARE FOR THE FUTURE

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1. INTRODUCTION

The Midwest property, which hosts the Midwest Main and Midwest A deposits, is located within the eastern part of the Athabasca Basin in northern Saskatchewan. The Midwest Project is a joint venture between Orano Canada Inc. (Orano; 69.16%), Denison Mines Corp. (25.17%), and OURD (Canada) Co., Ltd. (5.67%) with Orano as the active project operator.

The Midwest Main uranium deposit was initially discovered in 1977 by Esso Resources with the initial discovery of sandstone mineralization immediately above the sub-Athabasca unconformity drilled from the follow-up of initial airborne and ground geophysical surveys, ground geochemical sampling, and boulder surveys. The Midwest A uranium deposit was later discovered along trend in 2005 by Orano following up on historical mineralized intercepts from the Esso Resources' property wide drill program between 1977 and 1981 [1, 2].

2. DESCRIPTION

Located 840 km northeast of Saskatoon in northern Saskatchewan on the east margin of the prolific Athabasca Basin, the Midwest Project was recently updated with new mineral resource estimates as of November 2017. The project is estimated to comprise 1.060 Mt of Indicated mineralization at an average grade of 2.19% U_3O_8 (1.85% U) with a contained uranium metal content of 51.1 Mlbs U_3O_8 (19,650 tU) as well as 0.830 Mt of Inferred mineralization at an average grade of 0.99% U_3O_8 (0.84% U) with a contained uranium metal content of 18.2 Mlbs U_3O_8 (6,980 tU) [1, 2].

The Midwest Project contains two separate deposits, Midwest Main and Midwest A, which feature high grade uranium mineralization mainly situated along the regional unconformity between the Athabasca Group sandstones and basement rocks of the Wollaston-Mudjatik Transition Zone comprising Paleoproterozoic Wollaston Group metasediments and Archean orthogneisses [3]. Midwest Main is interpreted to consist of a large unconformity lens with a basement mineralized root and 19 perched sandstone lenses. Midwest A consists of a large unconformity low grade lens that encompasses an interior high grade lens with a small basement root.

3. PURPOSE OF THE WORK

In response to the envisaged forecast of increased growth in electricity demand, and in turn the growth of nuclear power worldwide, medium to long term uranium prices are expected to reflect this increase in uranium demand [4]. In an effort to prepare and better plan for the next phase of the uranium market, mineral resources will need to be brought up to modern resource estimation standards to be readily available when their need arises.

The Midwest Main and Midwest A deposits have seen several resource estimations since their discoveries, however none were considered readily available to be used for the next levels of assessment prior to mining. Over the course of 2017, intensive work was completed to bring the dataset and estimates up to a more modern and rigorous standard. This resulted in the completion of separate resource estimates for both

deposits in accordance with CIM Definition Standards (2014) in National Instrument 43-101 – Standards of Disclosure for Mineral Projects ("NI 43-101"), which not only represented an increase in contained resources, but also an upgrade in the confidence level.

4. METHODS AND RESULTS

To modernize the mineral resource estimates at both deposits a comprehensive review of project data was undertaken prior to resource estimation. Concerns were identified at both deposits that needed to be addressed to increase both the confidence and the accuracy of the final estimate.

Given the historic nature of the data at Midwest Main a limited amount of data was readily available digitally; downhole gamma probe ("probe") data existed only as paper logs making it previously unavailable to be used, no comprehensive 3D geological model was available, perched mineralization was not fully modeled, as well as further data QAQC was needed. Midwest A has a much more modern data set, however no dry bulk density measurements were available, the latest drilling was not taken into account in the previous estimate, and the High Grade Zone was assigned an average uranium grade rather than performing grade estimation. Additionally, both deposits required new probe to chemical uranium assay grade ("grade") correlations for the calculation of equivalent uranium (eU), combination of probe and grade data based on core recovery and probing/drilling parameters to be available for estimation, updated lithology and structural models (geological model), and updated resource model.

Work began with verifying the grade data against assay certificates and a historical nine track database from ESSO. Some discrepancies were noted in the sample locations as well as some of the grades due to typographical errors. After comparison to the original drill logs and probe logs, these were rectified.

The Midwest deposits often have core loss associated with the mineralization, due to the high amount of clay alteration and quartz dissolution which makes core recovery while drilling difficult. This results in gaps in the grade dataset that are typically addressed by using probe equivalent uranium (eU) data. Digital probe data was available for Midwest A, however for Midwest Main most of probe data was never digitized and remained only available on paper logs. The paper logs for 218 holes were digitized and added to the Midwest data set. This was followed up by ensuring the probe data was depth matched with grade data, as well as the creation of grade correlations for both deposits.

Midwest Main had a robust density to grade correlation however, Midwest A did not have any dry bulk density measurements taken. The only density data at Midwest A was in the form of specific gravity measurements which do not take into account porosity and therefore tend to overestimate the density. Due to the high density of uranium, density is a vital reference for the expected tonnage of high-grade uranium deposits which has a direct effect on the amount of uranium estimated. Given this uncertainty at Midwest A, previous resource estimations were forced to use a very conservative grade to density regression formula to avoid overestimation of resources. During a 2017 site visit 25 dry bulk density measurements were taken from the remaining Midwest A drill core and sent for dry bulk density and geochemical analyses. A new grade to density regression formula was established showing an increase to the correlation by approximately 10%. This corresponded to a similar increase in mineral resources.

At Midwest Main, uncertainty of basement lithologies' foliation trends existed, which have a control on the basement and unconformity mineralization. More data is needed to improve the understanding of the structural setting, as few oriented structural measurements are available leaving some uncertainty on fault orientations. A geological model, which provided additional information on the controls and constraints on the mineralization, was created. For Midwest Main, this included digitization and generalization of drill log descriptions to make them available for cross-sectional 2D and 3D interpretation. To aid in this interpretation, the geophysical surveys (electromagnetic, magnetic, and resistivity) were re-interpreted to confirm orientation of some structures and basement lithologies.

Based on this work, a complex structural setting appears to control the mineralization location at Midwest Main. Several reactivation stages occurred within the north-northeast-trending belt of graphitic metasediments which was a key-element for Egress-style hydrothermal fluid circulation along the unconformity and into the Athabasca sandstone. These NNE faults are interpreted extending into the sandstone, off-setting certain lithological markers. A series of N80° "EW" small-scale structural features (probable faults) appear to cross-cut the unconformity mineralization, locally off-setting and extending the mineralization. Additionally, these "EW" structures appear to be limiting the extensions of certain perched mineralized lenses. North-south trending "Tabbernor"-style faults cross-cut the deposit and appear to control some extents of the high-grade mineralization at the unconformity. Additionally, the main mineralized basement root seems to follow this fault in the northern part of the deposit. High-grade mineralization at Midwest Main is interpreted to be located in certain triple-point zones where the reactivated northeast-trending graphitic belt is intersected by cross-cutting EW and NS trending fault systems. The dominant control for perched mineralization in the sandstone appears to be the stratigraphic bedding planes. Mineralizing fluids are believed to have circulated through localized fault zones precipitating uraninite/pitchblende along bedding planes.

The updated geological model at Midwest A showed that the uranium mineralization follows the northeastsouthwest structures with some broader areas where interpreted north-south structures cross-cut the mineralization. These north-south structures also appear to limit the extent of the high-grade mineralization along strike, with the unconformity limiting its down-dip extents. Mineralization was also modelled to reflect the control by the basement graphitic lithologies, and the unconformity on the mineralization. The higher-grade material is generally interpreted to be associated with the graphitic packages and NE-SW structures. Some mineralization control is also provided by the unconformity. A relatively minor basement mineralized root was modelled and is interpreted to follow the steeply-dipping graphitic packages.

At Midwest Main the mineralization is interpreted to consist of a larger Unconformity Zone, a small Basement Zone, and 19 Perched Zones. The Unconformity Zone is relatively flat lying and approximately 920 metres long, 10 to 140 metres wide, and up to 33 metres in thickness, not including the basement roots which have been modeled to extend approximately an additional 90 metres into the basement. The bulk of the mineralization occurs in the Unconformity Zone at depths ranging between 170 and 205 metres below surface

Midwest A mineralization is interpreted to consist of a larger Low Grade Zone encompassing an interior High Grade Zone. The deposit is approximately 450 metres long, 10 to 60 metres wide, and ranges up to 70 metres in thickness. It occurs at depths ranging between 150 and 235 metres below surface. Based on the geological model, the interior High Grade Zone was interpreted to reflect the orientation of the steeply dipping basement graphitic lithologies while being limited down dip by the unconformity and along strike by the cross-cutting north-south structures. The relatively minor basement mineralized root was modelled and is interpreted to follow the steeply-dipping graphitic packages.

Block models were created for both deposits, constrained by the re-interpreted mineralization models which utilized the geological models. A two to three-run ordinary kriging analysis was conducted for the unconformity mineralization at both deposits estimating DG (density x grade in %U) and density. The majority of the blocks were estimated with the first run. The remaining run(s) were used to fill in any unestimated blocks. Hard boundaries were used to prevent the use of composites between the unconformity, perched, and basement zones. A single run inverse distance estimate was completed for the Basement and Perched lenses. In order to manage the influence of high grades within the unconformity zones, the influence of high grade samples were restricted to prevent smearing into lower grade areas. No restrictions were placed on the High Grade Zone at Midwest A, as it was able to be domained and estimated separate from the surrounding lower grade mineralization.

5. CONCLUSION

Data mining and QAQC as well as a detailed evaluation of lithology and structures that control the mineralization are vital to the construction of a robust resource model. Many of the previous outstanding issues were addressed, readying the Midwest Project deposits to become a new source of uranium supply to help meet global uranium market demands when the price recovers.

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GENESIS OF SANDSTONE TYPE URANIUM DEPOSIT IN DHOK PATHAN FORMATION, SIWALIK GROUP OF TRANS-INDUS SALT RANGE (SURGHAR RANGE), PAKISTAN

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Abstract

The Surghar Range (Trans-Indus Salt Range) is a part of Himalayan Fold and Thrust Belt of Pakistan. The 5300m thick Siwalik rocks represent molasse type clastic freshwater sediments. The Siwalik Group in Pakistan is divided into three subgroups, Upper, Middle and Lower, according to their lithological characteristics. The Middle Siwaliks Dhok Pathan Formation varies in thickness from 807 m to 1540m and typically represents cyclic alternation of a fluvial fining upwards sequence. Detailed petrographic and geochemical studies of surface and sub-surface core samples led to the characterization of the formation of the uranium ore body and allowed a metallogenic model to be proposed. Scanning electron microscope observations evidenced that a significant amount of uranium is precipitated in interstitial spaces, on and along grain boundaries in the reduced zone mainly as micro-to- nano-crystals of UO₂ and USiO₄, as well as adsorbed onto clay minerals in amorphous form. The uranium mineralization corresponds to synsedimentary/diagenetic concentrations which have been redistributed and remobilized due to successive phases of Himalayan tectonic activity. The ore body has attained the present horizontal position, 15-25m below the current water table. The sandstone depositional model and geochemical data suggest that the source of uranium mineralization was contained within the sediments.

1. INTRODUCTION

The NW Himalayan foreland Fold and Thrust Belt formed by the progressive south directed folding and over-thrusting of crustal slices of the Indian Plate during the ongoing collision between India and Eurasia [1]. Following the onset of collision along the Main Mantle Thrust and its lateral equivalents during the Late Cretaceous to Early Tertiary [2], thrusting generally progressed southwards over time. Most of the youngest thrusting has occurred along the frontal thrust system in the Salt Range in the east and the Trans-Indus Ranges in the west. The Surghar-Shingar Range (SSR) of the outer Himalayas represents the eastern end of the Trans-Indus Salt ranges of north Pakistan [3]. The range exhibits an East-West structural trend along the southern margin of the Kohat Plateau and changes to North-South trend along the eastern flank of the Bannu Basin. The SSR forms an asymmetrical, overfolded anticlinal structure plunging to the south near the Kurram River, with Permian strata exposed in the core, overlain by Mesozoic and Palaeogene rocks [4]. The western limb of the range is well exposed (present study area), while its eastern limb is deeply eroded, exposing older formations. The end of marine sedimentation in the SSR is marked by the deposition of fluvial rock units of the Siwalik Group. The Neogene-Quaternary Siwalik Group preserved in the Himalayan foreland basin have been extensively documented along the Himalayan arc from Pakistan to Nepal, providing valuable information on mountain building in space and time, and past organization of drainage networks and palaeoclimate [5].

Geologically, the Siwaliks represent molasse type clastic freshwater sediments. These sediments accumulated in a foreland basin of the Himalaya during the third and most intense phase of deformation during the Mid Miocene-Pleistocene. The Siwalik Group sediments are one of the most comprehensively studied fluvial sequences in the world. They comprise mudstones, sandstones and coarsely bedded
conglomerates deposited at times when the region was an extensive basin. Rivers flowing southwards from the Greater Himalayas, resulting in extensive multi-ordered drainage systems, deposited these sediments. Following this deposition, the sediments were uplifted through intense tectonic regimes (commencing in Upper Miocene times), subsequently resulting in a unique topographical entity-the Siwalik Hills or the Siwaliks [6].

The Siwalik Group in Pakistan can be clearly divided, according to its lithological characteristics into three subgroups, Lower, Middle and Upper, and further into their formation scale lithostratigraphic units. The Lower Siwaliks (Kamlial and Chinji Formations) consist of a sequence of sandstone-mudstone couplets with a marked dominance of the mudstones over the sandstones. The Middle Siwaliks (Nagri and Dhok Pathan Formations) are dominantly arenaceous, consisting of multiple sequences of coarse-to fine-grained (generally medium-grained), light grey, bluish-grey massive sandstones with subordinate representation of siltstones, mudstones and clays. The Upper Siwalik (Soan Formation) is mainly conglomeratic in nature. These sedimentary deposits are 5300m thick in this area. The thickness of the Dhok Pathan Formation varies from 807m to 1540m and represents alternating fining upward sedimentary sequences of shale, siltstone and sandstone units [7]. The Dhok Pathan Formation of this area has been assigned an age of 7.5-2.5 Ma based on the magnetostratigraphic studies [8]. The Dhok Pathan Formation hosts a small scale tabular sandstone type uranium deposit known as Qubul Khel which is located in the southern part of SSR.

The present contribution is aimed at gaining an understanding of the genesis of this uranium deposit and to propose a metallogenic model.

2. METHODS AND RESULTS

The methods used and results obtained can be summarized as follows:

- 1) A comprehensive geological map has been prepared with the help of high resolution satellite data, selective traversing of the area and ArcGIS 10.2 software;
- 2) Detailed sedimentological and lithofacies analyses of different sandstone and mudstone units of the Dhok Pathan Formation has enabled the identification of seven distinct lithofacies (Gt, St, Sh, Ss, Sl, Fm and Fl) which had been deposited under traction current, low and upper flow regime conditions by sand moved in a large river. Palaeocurrent studies indicated a 210° direction of palaeoflow within a braided stream pattern;
- 3) XRD and SEM analyses of different sandstone and mudstone units (38 samples) reveal that kaolinite, smectite (montmorillonite and saponite), illite, vermiculite and chlorite (clinochlore and chamosite) are the main clay mineral suites present in the Dhok Pathan Formation. The morphology of clay mineral suites is indicative of weathering products or a contribution from source areas. The sandstones units are classified as lithic arkose to feldspathic lithic arenite based on petrographic studies;
- 4) Organic-rich samples were analysed for carbon isotopes that characterized a type III kerogen, mainly derived from terrestrial plants;
- 5) The analyses in (iii) and (iv) were carried out at a State owned key laboratory in the East China University of Technology (ECUT) in Nanchang;
- 6) To understand the geochemical variations, 28 surface and sub-surface drill core samples were analysed for 42 elemental analyses on XRF and LA-ICP-MS at the Beijing Research Institute of Uranium Geology. The analytical range for various chemical species were as follows: SiO2: 55.2-68.35%, Al2O3: 12.54-14.59%, Fe2O3(total): 3.07-6.03%, MgO: 1.8-4.03%, CaO: 5.08-7.86, Na2O: 2.35-2.61%, K2O: 1.51-2.91%, MnO: 0.06-0.96%, TiO2: 0.36-0.67%, P2O5: 0.078-0.159%, U: 0.0001-0.16%, Th: 0.0007-0.0012%, Pb: 0.001-0.002%, V: 0.006-0.015%.

3. DISCUSSION AND CONCLUSIONS

The Qubul Khel uranium deposit developed in the basal part of a sandstone belonging to the upper part of Dhok Pathan Formation of the Middle Siwalik Group. The host sandstone is about 100-400m thick with occasional grit and calcification, with concordant sandstone lenses of various sizes. The host sandstone dips 21-38° SW with the strike varying from N26°W-EW. The sandstone is friable to weakly cemented, generally medium-grained and light grey to bluish-grey on a fresh surface. The mineral assemblage includes quartz 26-30%, feldspar 14-16%, igneous-metamorphic rock fragments 12-21%, micas 6-7%, amphibole 2%, clay minerals 2-18%, calcite 8-12% and magnetite, haematite/limonite, monazite, zircon, and tourmaline as accessories. The ore body is of irregular tape-like configuration, trending NW-SE and has a length of some 200 m, a thickness 2-15 m (averaging 6.5 m), a grade averaging 0.053% U and persists over a depth interval 68-118 m[9].

The study of the Qubul Khel uranium deposit evidenced that a significant amount of uranium is precipitated in interstitial spaces, on and along grain boundaries in the reduced zone below the present-day water table mainly as micro- to nano-crystals of pitchblende (UO₂), which also occur as cluster of micro-fine globules. Minor amounts of coffinite (USiO₄) occur as pore fillings and coatings along grain boundaries and a considerable amount is still present adsorbed on clay minerals and earthy iron oxide/hydroxide in amorphous form. Uranium mineralization does not show any preferred affinity for any sedimentary, textural or structural feature of the host sandstone, although adsorption onto clay minerals, organic matter and iron oxide are common. Detrital uraninite (identified through micro-analysis on SEM and EPMA) and its alteration products such as schoepite, metaschoepite, carnotite and uranophane are typical uranium mineralization phases for oxidized environments.

Studies of the nature and evolution of organic matter indicate that a type III kerogen is inherited from land plants as coaly phytoclasts, thermally immature and devoid of any free hydrocarbon. Two different morphological types of pyrite are characterized: (i) framboidal pyrite as replacement of organic matter and (ii) idiomorphic pyrite which may have been crystallized during diagenesis.

The Qubul Khel uranium deposit is thought to have evolved through multiple reworking by infiltration. Continual leaching and migration of uranium to its present location occurred during successive tectonic activity and is related to fluctuations in the water table in response to Himalayan tectonism. Uranium precipitation was caused by permeability barriers combined with upwards migrating hydrocarbons, which are considered to have provided the required reductants [9].

The careful investigations led to an understanding of the possible uranium concentration processes. Uranium was first concentrated in the basin at a synsedimentary stage, which may have been reduced directly or shortly after the first step of adsorption onto clay mineral surfaces and organic matter as UO_2 micro-tonano-crystals disseminated in the host sandstone. Uranium reduction probably happened during early diagenetic processes within the reduced depositional environment. The initial uranium concentrations gradually increased within the depositional environment or in the host sediment which was interacting with the surface water involved in the ongoing sedimentation. At the diagenetic stage, uranium may have been liberated from organic matter during its replacement by pyrite or by desorption from clay minerals. The presence of framboidal pyrite in replacement of organic matter and the occurrence of phosphorous-rich uranium minerals most likely reflect the metabolic activity of sulphate reducing bacteria [10]. Microorganism activity may have occurred during the diagenetic evolution of the host sediments and is most likely responsible for iron sulphidization and, possibly, uranium reduction, the H₂S produced by bacteria being a strong reductant [11]. After burial of the host sediments, Himalayan tectonic events may have caused groundwater movement and thereby in situ and local redistribution and remobilization of uranium characterized by recrystallization of pitchblende and coffinite. The Qubul Khel uranium deposit has experienced three main stages of uranium concentration processes: (i) a synsedimentary/early diagenetic stage concentrating uranium in a reduced environment, possibly most if not all of the uranium stock present in the deposit has been brought in, (ii) a late diagenetic stage with formation of different morphologies of pyrite followed by almost in situ uranium mineralization and (iii) in the final phase of uranium mineralization of the Qubul Khel uranium deposit, uranium was redistributed and remobilized during the successive upheaval of Himalayan tectonics and the ore body assumed its position, 15-25m below the present-day water table. The organic matter, framboidal and idiomorphic pyrite, are the main reductants involved in the uranium concentration processes. The system is devoid of any free hydrocarbon, in contrast to the previously considered view that permeability barriers combined with upward migrating hydrocarbons provided the required reductants [9].

The presence of detrital uraninite and its alteration products are evidence that the source of uranium mineralization came from within the sediments. The contribution of other uranium-bearing detrital minerals such as zircon, monazite and uranothorite is limited as these behave as refractory minerals and have not released their uranium.

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URANIUM LEACHING FROM PHOSPHATE ORES PRIOR TO PROCESSING FOR PRODUCTION OF PHOSPHATIC FERTILIZERS (AND PHOSPHORIC ACID)

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A leaching reagent (LR) has been successfully used (for environmental importance) to leach uranium from phosphate ores prior to processing for production of phosphatic fertilizers (and phosphoric acid), without dissolution of any amount from the phosphate mineral. In (traditional) phosphate industry, rock phosphate is digested with sulfuric acid leading to the formation of phosphoric acid which is then used to produce phosphatic fertilizers. Thereupon, uranium present in rock phosphate is transferred to the products, phosphoric acid and derived phosphatic fertilizers and, and by-product (phosphogypsum). The uranium contaminations could enter the environment and possibly pose radiation exposure concerns through several pathways: From using fertilizers in cultivation of the agricultural lands from using phosphogypsum as agricultural gypsum, and from using phosphogypsum as a building material. Phosphate rocks, superphosphate fertilizer contain uranium and phosphogypsum contains the highly radioactive uranium series radionucleides as a host of environmentally hazardous chemical element, and they contaminate the agricultural soils through the use in cultivation. Uranium apart from its radioactivity is chemo-toxic (its biochemical toxicity is estimated to be six orders of magnitude higher than the radiological toxicity), and because of these properties, it is considered as a disease-causing element. Due to the extensive usage of these contaminated fertilizers, the danger posed to human health is very large. The geochemical pathways lead this toxic element (U) into food crops, soil, water, air and ultimately human body tissues via the food chain.

Therefore, removal of U from input phosphate ores prior to processing for production of phosphatic fertilizers, is considered a very important operation in order to prevent disease in humans (through healthy environments) on one hand, and obtaining the valuable U element as a source of energy on the other hand. On the other hand, in case of processing rock phosphate for phosphoric acid production (wet phosphoric acid process) without uranium removal – by our (LR) – prior to processing, practically most of the uranium present in phosphate rock ends up in solution. Present commercial recovery of uranium from phosphoric acid is based on solvent extraction methods that have the following disadvantages, namely: 1) solvent extraction methods are expensive, especially because of the required prepurification of the phosphoric acid in order to assist phase separation, and the subsequent treatment of the acid to prevent attack of the rubber lining of phosphoric acid evaporation equipment. These previous acid conditioning stages are associated with large investment and operation costs; 2) the treated phosphoric acid may be contaminated with organic solvents; 3) the economy of the process is strongly affected by the uranium concentration, because the investment and operating costs depend on the acid throughput; and 4) recovery of uranium from phosphoric acid in combination with direct production of concentrated (>45-52% P2O5) acid, i.e., the so-called hemihydrate process (>45% P2O5) is not possible on a commercial scale using solvent extraction techniques.

ENVIRONMENTAL FACTORS CONTROL AT SIERRA PINTADA, ARGENTINA: WATER QUALITY

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1. INTRODUCTION

The Sierra Pintada uranium mine is located in Mendoza Province, Argentina, 38 km west of San Rafael and 240 km south of Mendoza. The mine was in production from 1975 to 1995, when the operations were stopped owing to economic reasons. Under the open pit extraction system, 1600 t of uranium ore were extracted and treated by acid leaching and ion exchange columns, which had a nominal capacity of 120 tU/year. More than 6000 t of uranium mineralization remain to be extracted. Over a 22-year period, the CMFSR (San Rafael manufacturing and mining complex) satisfied the country's demand for uranium for nuclear power production, research reactors and production of radioisotopes.

Currently, the activities carried out at the site comprise maintenance, monitoring and environmental management. At this moment, the treatment of pit water and the management of solid waste disposed of in the complex is at the environmental impact assessment stage. It is expected that activities will soon be started with the object of defining the closure of the El Gaucho open pit, one of the four pits in which the mining operation was completed and which still remains open, pending the restoration.

The area where most of the facilities of the CMFSR are located is in the basin of the El Tigre stream, which crosses the mineralized zone and flows into the Diamante River, the main water course that feeds the irrigation network of the San Rafael Department (administrative division). Owing to the El Tigre stream originally passing directly over the mineralized zone, a diversion of its natural course was made prior to the mining operation stage, thereby preventing the water from entering one of the open pits which recorded a high uranium content.

The importance of the Diamante River as a water resource in the south of Mendoza Province is underscored by it being the main water supply for irrigation in the city of San Rafael and its surroundings, where economic activities related to agriculture are carried out, with special emphasis on fruit and viticulture production [1]. This area is characterized climatically by being a semi-desert zone, which, owing to the irrigation supplied by this river, has been transformed into a productive agricultural area.

CNEA (National Atomic Energy Commission) is committed to maintaining and constantly improving the environment, according its environmental policy, by ensuring that environmental factors, especially water courses, are not adversely affected by the activities undertaken in the mining complex. This has led to the development of an extensive monitoring plan to evaluate the quality of the water resource.

In a similar manner, the concern of the population living near the site turns is reflected by strict controls of the water by the control organizations: The General Department of Irrigation and the Nuclear Regulatory Authority (ARN), the former provincial and the latter national.

2. MONITORING PLANS

From the very beginning of the activities developed at the Sierra Pintada uranium deposit, the controls of the different environmental variables were carried out with special emphasis on the water resource. CNEA has a wide network of water monitoring instrumentation, internal and external to the mining complex. The quality of this resource is verified in the environmental laboratory located in the CMFSR, which is certified

by the Argentinian Accreditation Organization for uranium determination in samples of surface and underground water.

The main objective of the water monitoring plan is to analyse the temporal and spatial evolution of the parameters and to have data available to detect possible anomalies or incidents and, where appropriate, evaluate them and make evolutionary predictions.

The current network includes 45 points for groundwater, of which 29 are internal wells, located within the deposit area, and 32 points for surface water, of which 17 are internal. The remainder lie outside the boundaries of the mine complex, in areas of interest for nearby populations.

The regularity of sampling at each of these points, (monthly, bimonthly, quarterly or biannually) according to the needs of the site, was defined from the analysis of the seasonal variation, or if not, of the normal behaviour, after more than 40 years of compilation of data and experience.

On average, about fifty different samples are analysed monthly, which are studied for determination of physicochemical parameters (electrical conductivity, total dissolved solids, acidity, temperature), anions (chloride, nitrate, sulphate, carbonate, bicarbonate, hydroxide), cations (ammonium, sodium, potassium, calcium, magnesium, lead, chromium, arsenic, mercury) and radiological parameters (uranium and radium-222).

Special emphasis is placed on eight control points measured monthly, comprising four of surface water and four of groundwater, which can give an environmental diagnosis of the situation of water quality in the area. These points are strategically located upstream and downstream of the mining complex and allow correlation of the contribution of the deposit to the values of uranium, since the water courses pass through a highly mineralized zone.

Regarding surface water, the most significant control points are upstream and downstream of the CMFSR and are located in both the El Tigre stream and the Diamante River. This allows estimation of the variation in uranium values, if any exists, attributable to the mineralized zone which contributes to the modification of water quality.

Both the Mining Code (National Law 24.585) and the Provincial Law 5961, Decree 820/2006 establish a limit of 100 μ gU/L as the permitted limit in water for human consumption. The same maximum limit is allowed for the discharge of liquids to receiving bodies according to Resolution Number 647/00 of the General Department of Irrigation.

In the case of the El Tigre stream, which has an average flow of 0.16 m³/s before entering the mineralized zone, stream water enters with, on average, 3.94 μ gU/L and leaves with an average of 12.31 μ gU/L, indicating an increase in uranium level of more than 200%.

As for the Diamante River, which has an average flow of 28.25 m³/s upstream of the mouth of the El Tigre stream, the average concentration is 1.57 μ gU/L and downstream an average of 2.028 μ gU/L, indicating an increase of 30%, which is contributed by the stream.

Regarding groundwater, the most significant control points are two up gradient and two down gradient of the CMFSR, strategically located according to the direction of groundwater flow. The average values are around 15 µgU/L with no appreciable difference between up and down gradients.

The analyses are carried out in the environmental laboratory of the complex, since it has the technology to undertake such studies. It is equipped with an atomic absorption spectrophotometer for the determination of metallic elements and an ion chromatograph for the determination of anions. The laboratory can provide

an analytical service for environmental samples, not only of groundwater and surface water, but also of sediments.

In 2014, the laboratory was able to gain accreditation, through the Argentine Accreditation Organization, for the laser fluorimetric technique for determination of uranium in water. The laboratory meets high quality standards; there are no other laboratories with a comparable degree of quality nearby, including the laboratories of the control organizations.

With respect to the air quality, radon levels are monitored periodically in both the CMFSR area and in nearby populations. A study is currently under way to model the transport of particulate matter in the atmosphere to implement a new air quality monitoring plan.

3. CONTROL ORGANIZATIONS

Owing to the concerns of the population living in the area adjacent to the mining complex, and the importance of the Diamante River for the area of influence of the CNEA facilities, the control authorities carry out periodic checks on the activities developed in the facilities and their impact on the environment.

On the one hand, the General Department of Irrigation, through the Sub-Delegation of the Diamante River, takes water samples which are analysed by the National University of Cuyo.

The General Department of Irrigation takes the samples at the exit of the industrialized zone for the El Tigre stream and downstream from the mouth of the same in the Diamante River. The average values of uranium content are 16.62 μ gU/L and 1.74 μ gU/L, respectively, which are concordant with those measured by CNEA. In all the measurements made by this control body, the measured values are lower than the limits allowed by Resolution Number 647/00.

At a national level, control is carried out by ARN, which takes samples of both air (to control the levels of radon gas) and surface water on an annual basis. ARN has approved the water and sediment monitoring plans and analyses both the results of its monitoring and those reported monthly by CNEA, submitting quarterly reports that have concluded, until now, that the levels of uranium in the water courses surrounding the deposit are at normal levels and below the prescribed limits. This corroborates CNEA's commitment to the environmental policy on the site.

The results of the analyses implemented by ARN on the El Tigre stream give average values of 3.9 μ gU/L for waters taken upstream of the mineralized zone and 13.3 μ gU/L for samples taken downstream of the same, with registered maximum values of 6.3 \pm 0.3 μ gU/L and 29.0 \pm 3.5 μ gU/L, respectively. Average values in the Diamante River measured by the control organization are 1.2 μ gU/L upstream from the mouth of the El Tigre stream and 1.4 μ gU/L downstream, with historical maxima of 3.0 \pm 0.7 μ gU/L and 2.9 \pm 0.5 μ gU/L, respectively [2].

ARN concludes in its reports that the concentrations reported by CNEA are compatible with the results of the routine monitoring carried out by the control organization and that, in addition, they are lower than the guideline established by the World Health Organization for drinking water of 30 μ gU/L.

4. CONCLUSIONS

During mine production and the subsequent stages, no concentrations were recorded above those allowed in the water courses of the El Tigre stream and the Diamante River, demonstrated not only by its own monitoring, but also confirmed by those measurements carried out by the General Department of Irrigation and ARN.

After more than 40 years of CNEA activity in the area, with almost 20 years using sulphuric acid for mineral treatment, there has been no alteration in the quality of the surface or underground water, since the beginning of production activities of uranium concentrates in 1979, suitable methodologies have been used for handling of acid solutions and for the management of process effluents.

In all this time, CNEA has maintained its commitment to the care of the environment, through the implementation of its environmental policy and putting into practice the concept of continuous improvement to ensure sustainable environmental management.

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NEW STUDIES OF URANIUM DEPOSITS RELATED TO GRANITES IN ARGENTINA

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1. INTRODUCTION

At present, the Comisión Nacional de Energía Atómica, in cooperation with the National University of Córdoba, is carrying out the project entitled Melallogenesis of Granite-Related Uranium Deposits in Argentina within the framework of an IAEA coordinated research project which is Geochemical and Mineralogical Characterization of Uranium and Thorium Deposits. This paper briefly describes the specific objectives and activities in progress as part of this research project, which has been underway since 2015 [1].

This project aims to focus on the characterization of the Devonian–Lower Carboniferous magmatic and hydrothermal systems related to granitoids of the Pampean Ranges and to relate these processes to uranium metallogeny. Therefore, several metallogenetic studies have been carried out in order to improve the geological, structural, geochemical and mineralogical characterization of uranium deposits related to granites. To this end, efforts have been made to define those felsic igneous rocks that have played the most relevant role as uranium sources, including successive fractionation in the different magmatic complexes and characterize the relationship between magmatic uranium enrichment and hydrothermal deposits, and alteration and uranium mobility.

2. DESCRIPTION AND RESULTS

The scientific scope of this paper specifically covers four areas of uranium mineralization where graniterelated (endogranitic) hosts have been described: Sala Grande, Don Alberto and Los Riojanos are enclosed in the Achala Batholith, and La Estela is located in the Cerro Áspero–Alpa Corral Batholith [2, 3].

Petrographic data were obtained from observations of polished thin sections using conventional transmitted and reflected light microscopy. Appropriate unaltered mineral areas suitable for laser ablation analysis were selected using a CAMECA SX100 electron microprobe (EMP). Major and trace elements (U, Pb, Th, Ca,Si, Al, Ti, Fe, Mn, V, Na, Nb, La and Y) were obtained by the EMP method, while rare earth element (REE) and a series of trace element contents of uranium oxides were determined using laser ablation inductively coupled plasma mass spectrometry (LAICPMS). These studies were carried out at the facilities of the University of Lorraine's Geo Ressources Laboratory-CREGU [4, 5].

The Don Alberto, Sala Grande and Los Riojanos sites are located in the peraluminous S-type Achala Batholith (area of~2500 km²) and belong to the Córdoba Pampean Ranges. This batholith is composed of several magmatic suites and numerous facies, where two-mica monzogranites are by far the most widely exposed lithologies and muscovite leuco-monzogranite is the most evolved rock that occurs as marginal plutons or facies [6, 7].

In the Don Alberto site, uranium mineralization is hosted in dark grey, coarse-grained biotite gneiss, weakly foliated, intruded by a porphyritic two-mica granite. The microtexture is predominantly granoblastic, with few biotite–sillimanite domains. It exhibits polygonal aggregates of quartz, plagioclase and cordierite (pinnite replacing cordierite). Accessories minerals are apatite, zircon and opaque minerals (uraninite, ilmenite and rutile).

The cordierite shows two textural varieties: (i) idioblastic poikilitic, and (ii) xenoblastic highly poikilitic with biotite, zircon, apatite and euhedral uraninite crystal inclusions. The uraninite shows concentric radioactive disintegration halos of yellowish and brown tones and marked radial fracture.

Uranium oxides from the two samples analysed of Don Alberto material are present as euhedral uraninite grains with significant Th content (about 1 wt% ThO₂) which indicates a high temperature origin. They have between 2.7 and 3.8 wt% PbO, corresponding to chemical ages between 255 and 325 Ma. Their yttrium contents are moderate (0.07–1 wt% Y₂O₃) and the highest value corresponds to an altered uranium oxide (characterized by the lowest UO₂: 86.2 wt% and PbO: 0.1 wt% contents, and the highest SiO₂: 7.58 wt% and CaO: 3.18 wt% contents, compared with the other analytical points).

The global fractionation of the REE patterns and the high REE contents of the U-oxides from the two samples of Don Alberto rock are identical. Only one analysis has slightly lower REE contents. These patterns are similar to those found for magmatic uraninite at the Rössing deposit in Namibia, but with lower total REE contents [8]. The other trace element patterns of these U-oxides are also similar, with significant enrichment in W, Zr and Mn and more limited enrichments in B, As and W, except for two samples which are not enriched in Mo, W or Ti. They are both very poor in Nb.

At the Sala Grande site, the uraniferous mineralization is located in a subhorizontal contact between the biotitic (\pm sillimanitic) gneiss and the intrusive granitic surface. The metamorphic rock lies as a roof pendant affected by contact metamorphic processes, developing a compact hornfels rock in the hornblende facies [9].

The intrusive facies at this site is a porphyritic, two-mica, coarse-grained granite. The microstructure shows a well-defined foliation; the foliation being defined mainly by biotite and sillimanite and separates microlithons composed of quartz, relict andalusite, cordierite and scarce plagioclase. Secondary andalusite blastesis is poikilitic with inclusions of biotite, apatite and fibrolite. It presents hexagonal shaped uraninite inclusions with marked radiohalos that may be partially altered to oxidized uranium minerals, probably corresponding to uranophane. Other accessory minerals are monazite, zircon, fluorite and manganese-rich ilmenite.

Uranium oxides from Sala Grande are similar to those from Don Alberto, with a ThO_2 content of about 1%, indicating high temperature uraninite. Their REE patterns are also identical to the non-altered uranium oxides from the Don Alberto mineralization, suggesting a similar origin for the two occurrences. The trace element pattern is also very similar to that of Don Alberto, indicating similar environment and formation processes.

At Los Riojanos, the main lithologies at this site are an equigranular reddish fine-grained muscovite leucogranite and fine-grained porphyritic granite. The first facies has monzogranitic modal composition with albitic plagioclase (An05–10) and shows intergrowths of quartz and antiperthitic textures. Biotite has

been totally muscovitized. Accessory minerals are apatite, zircon, monazite and rutile. The porphyritic granite is a monzogranite, but its composition may be locally modified by post-magmatic hydrothermal processes. The accessory minerals are apatite, zircon, rutile, titanomagnetite, fluorite and tourmaline.

The main uranium mineralization is hosted in a cataclastic belt affecting the equigranular granite. These cataclasites are formed by a recrystallized fine-grained granitic matrix and also low temperature hydrothermal quartz [10].

The sample has been selected in a drill core from a depth of 44 m. The uranium mineralization is located in a 0.5 mm thick vein, associated with pyrite and quartz. This vein presents a 'mortar' texture formed by crushed and recrystallized quartz grains. Both the vein and small cavities are filled with pyrite and sooty pitchblende.

Uranium oxides from Los Riojanos have no detectable thorium content but register significant yttrium $(0.47-1.01 \text{ wt}\% \text{ Y}_2\text{O}_3)$ and calcium (3.49-4.46 wt% CaO) with low to moderate silica contents (1.7-3.21 wt%), indicating a low temperature hydrothermal origin.

La Estela mine, with estimated resources of 1500 tU at 0.07%U, is located in the calc-alkaline high-K Cerro Áspero–Alpa Corral Batholith (~440 km²) which belongs to the Comechingones Range [11]. The main internal facies is represented by coarse-grained biotite monzogranites. The border facies is made of two-mica or muscovite leucogranites whose compositions range from monzogranites to alkali feldspar granites [12]. In this deposit, fluorite is spatially associated with pitchblende and other hexavalent uranium minerals (uranophane, meta-autunite). This granite has a primary magmatic foliation which has controlled the percolation of younger hydrothermal fluids generating intense E–W brecciation of surrounding granitic rocks. The breccia is poly-episodic, showing fractures filled with black fluorite (antozonite) associated with pitchblende and pyrite [13].

Uranium mineralization has a completely different composition compared with that at Don Alberto and Sala Grande. The La Estela deposit does not have detectable thorium or yttrium contents and shows relatively high Si (14.82 and 15.47 wt% SiO₂, respectively) and Ca concentrations (6.91 and 6.67 wt% Ca, respectively), corresponding to a coffinite type composition. Their REE patterns are similar to deposits associated with granites, but with an important positive Ce anomaly and a very high abundance in total REE. Their trace element patterns are characterized by a very high abundance of elements associated with hydrothermal granite related deposits, such as B, As, Mo, W and Mn, as well as less mobile elements, such as Ti, Nb and Zr.

3. DISCUSION AND CONCLUSION

The interpretation of different REE and other element patterns in uranium oxides from uranium deposits [14] improved the metallogenetic knowledge of the uranium mineralization related to granites, which could in turn aid in the exploration guides to be applied. Finally, it can be pointed out that granites play an important role both as a uranium source and hosts of diverse types of uranium mineralization. Additionally, it is thought that, at the existing level of knowledge, there are prospects to develop new uranium resources related to granites in Argentina.

This contribution is a summary of several studies that were conducted by the National Atomic Energy Commission (Argentina), the University of Lorraine-Geo Ressources Laboratory-CREGU Nancy (France), the IAEA and the National University of Córdoba. The authors are grateful to several institutions for allowing the information to be assessed and presented here.

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DEVELOPMENT OF ALKALI LEACHING TECHNOLOGY: KEY TO SELF-SUFFICIENCY IN URANIUM PRODUCTION IN INDIA

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1. INTRODUCTION

Geological investigations for uranium deposits initiated in India during 1949–1950 have led to the discovery of a number of favourable geological basins in the country. The first uranium deposit located at Jaduguda in the Singhbhum Shear Zone in the eastern state of Jharkhand has continued to attract investment in terms of exploration for, and mining of, uranium for over five decades. However, extensive exploration in other parts of the country has brought to light more uranium deposits/occurrences in South Cuddapah Basin (Andhra Pradesh), North Cuddapah Basin (Telangana), Mahadek Basin (Meghalaya), Bhima Basin (Karnataka) and Delhi Supergroup strata (Rajasthan) in addition to those of the Singhbhum Shear Zone (Jharkhand).

Uranium mining in India, the front-end activity of India's nuclear power programme, has always been challenging, considering the uranium deposit characteristics in the country. India's uranium deposits in general are of medium tonnage and low grade. Detailed studies of the geological characteristics of these deposits are undertaken for selection of the proper mining method and technology. Ore processing technology is subject to the mineralogical and metallurgical characteristics of the ore and hence determination of suitable extraction technology and process parameters is crucial for successful operation of these deposits. Of all the above areas, the South Cuddapah Basin in Andhra Pradesh accounts for about 49% of India's uranium resources and occurs in carbonate hosted rock which necessitates development of an alkali leaching process route. Part of this resource, a section extending over a strike length of 6.6 km, is under development at Tummalapalle. An underground mine with a capacity to produce 3000 t of ore per day with a plant of matching capacity based on alkali leaching has been established.

2. ALKALI LEACHING TECHNOLOGY AT TUMMALAPALLE

The ore zones at Tummalapalle are confined to thin distinct bands occurring within a thick pile of predominantly carbonate rocks comprising massive limestone, intra-formational conglomerate, dolostone, shale and cherty limestone. The mined ore, after conventional crushing and grinding (80% passing 74 µm) are thickened, re-pulped and subjected to alkali leaching by sodium carbonate and sodium bicarbonate solutions. Leaching is carried out under high pressure and high temperature conditions in autoclaves arranged in series, and with a nominal residence time of 6.5 h. The leached slurry is then filtered in a horizontal belt filter and the desired concentration of leached liquor is achieved through repeated recirculation and washing. The washed cake, in the form of slurry, is disposed of in a tailings impoundment facility. The leached filtrate, after clarification and pre-coat filtration, is subjected to precipitation with the addition of sodium hydroxide. The final product, at pH12 or above, is precipitated as sodium diuranate. Extensive laboratory and pilot plant studies have been undertaken to develop these process parameters and flowsheet. The process has undergone several improvements in different areas to enhance both leaching and precipitation efficiency. A major breakthrough was recently achieved for the settling and complete recovery of precipitated product by commissioning the re-dissolution system facility in which part of the product is sent to precipitation tanks. Regeneration of sodium carbonate and sodium hydroxide treated barren liquor prior to recycling has been implemented. The plant will also produce sodium sulphate as a by-product.

Uranium tailings management is an integral part of the uranium mining industry. In view of the effective utilization of available and acquired land and the ease of handling and monitoring of tailings, Uranium Corporation of India has recently proposed the concept of near surface trench disposal of uranium tailings, which consists of an earthen construction combined with the use of impervious and geo-synthetic liners along with arrangements for withdrawal of excess water and for temporary coverage of the top surface during heavy rain. This method will lower the transportation costs as well as increase the stability and life of the structure. Successful implementation of this concept will benefit new uranium mining projects in the country in terms of both time and cost. A further detailed study on the concept and its implementation is currently being undertaken.

3. CONCLUSION

India has had a long commitment to nuclear energy since the establishment of the Atomic Energy Commission in 1948 and the Department of Atomic Energy in 1954. Nuclear energy plays a critical role in addressing energy challenges, meeting increasing energy demand, mitigating carbon emissions and enhancing energy security. The three-stage nuclear power programme being pursued to develop nuclear power in India is consistent with India's unique resource position of having limited uranium but correspondingly large thorium reserves and, hence, uranium production will play a vital role in this growing indigenous nuclear power programme. The alkali leaching technology adopted for processing the low-grade ore at Tummalapalle is the result of extensive research work by the Department of Atomic Energy. Carbonate hosted uranium mineralization accounts for the majority of India's uranium inventory and therefore successful operation and extraction of uranium at Tummalapalle will enable the development of more uranium deposits in this area (South Cuddapah Basin, Andhra Pradesh). Newer areas in other geological basins amenable to acid leaching have also been considered for development in order to satisfy domestic requirements for uranium in the coming decades.

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REMOTE SENSING IDENTIFICATION OF URANIUM EXPLORATION TARGETS – LAGUNA SIRVEN PROJECT, SANTA CRUZ, ARGENTINA

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1. INTRODUCTION

The Laguna Sirven uranium-vanadium deposit belongs to the surficial geological type. The presence of uranium minerals, mainly carnotite, has been detected between 0.5 to 3 m depths, within the calcrete level which serves as cement to a polimictic matrix.

Uranium target areas were identified by means of the processing and interpretation of multispectral satellite imagery and SRTM data. LandSat 7 ETM+ and ASTER generated products indicated mainly two types of non-pedogenic mineral patterns related to the precipitation of uranium and vanadium minerals, showing two different depositional pathways, one related to carbonate minerals and another to sulfate minerals.

The present contribution briefly describes the methodology and results of the application of remote sensing techniques for the identification of uranium exploration targets in this type of geological model.

Laguna Sirven corresponds to a surficial deposit formed by rich uranium precipitations at the water table interface, creating calcretes of a large extent and typically tabular form. In most of these deposits, uranium comes from the weathering of volcanic rocks and sandstones. Uranium solubility is closely linked to oxidation potential, whereby under oxidizing conditions uranium is found as U^{6+} cation in the uranyl ions, highly soluble and therefore very mobile. However, in a reducing environment, the U^{6+} ion is converted to the insoluble form U^{4+} . Thus, the uranium in solution flows through permeable strata until it meets conditions to precipitate, such as the sediments of the Deseado River [1]. As previously studied, soils are important fixing materials due to the content of clay minerals, organic matter, iron hydroxides, manganese or aluminum hydroxides [2].

2. METHODOLOGY & RESULTS

The rationale behind the application of this technology in the identification of uranium exploration is that the migration of U as soluble species or colloids can occur to the subsurface and thereby can generate local anomalous areas, which are characterized by reduction conditions that facilitate the development of a variety of chemical and mineralogical changes that can be detected through remote sensing techniques. Possible alterations include bleaching, the development of iron and clay minerals, and the formation of carbonates, among others. Geo-botanical anomalies could be associated to those processes.

Thus, the analysis of the presence and abundance of such minerals and soil chemical anomalies combined with a comprehensive study of the structural geology and geomorphology of the area facilitates the identification of uranium mineralized potential target areas.

The remote sensing study comprised different phases. Prospective areas are identified after the careful selection of imagery data during the acquisition phase and the later effective preparation, processing and interpretation of such spectral data.

First, LandSat-7 ETM+ and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) multispectral imagery and SRTM data was acquired, with the following spatial and spectral resolutions:

LandSat 7 ETM+:

Spatial resolution: Spectral resolution:	15, 30, 60 meters; Seven (7) bands, ranging from 0.45 to 12.50 nm, (Visible, Near Infrared, Short Waye IR and Thermal IR)
ASTER:	
Spatial resolution:	15, 30, 90 meters;
Spectral resolution:	Fourteen (14) bands, ranging from 0.50 to 11.40 nm, (Visible, Near Infrared, Short Wave IR and Thermal IR).
SRTM:	
Spatial resolution:	90 meters;
Frequency:	5.3-9.3 GHz.

Atmospheric, radiometric and geometric corrections were applied to this data in a preliminary processing stage. Upon such corrections, imagery was georeferenced according to the POSGAR 1994, Zone 2 System. In this stage, ASTER's thermal IR data was converted to superficial emissivity values by means of the normalization values taken from global maps with surface properties generated by various international research programs.

Later data processing included spectral enhancements through the application of a series of digital filters and the application of band ratioing and statistical analysis procedures, such as principal components. Band ratioing is a very fast and effective method to obtain information about the Earth's surface components from LandSat ETM+ and ASTER multispectral imagery. These ratios are simple mathematical relationships between values of two specific selected bands. The principal component analysis or rotation is a mathematical process originally designed to evaluate the spectral correlation between bands. By means of this process, the highly correlated data present in LandSat-7 ETM+ or ASTER bands is comprised into fewer bands using statistical algorithms. In the resulting set, the bands are non-correlated, and its reduced dimensionality allows the extraction of more information from it.

A suite of abundance mineral maps was created through the combination of several ratios that enhanced the presence of Al-OH and Mg-OH associated with clays and other hydroxyl minerals as well as other ratios that showed the presence of carbonates and iron oxide and hydroxide rich sediments. These mineral indexes have the advantage of normalizing spectral data, reducing the effect on the ground variations and the illumination differences [3].

The interpretation stage showed that both the Gypsum and the Carbonate Indexes proved to be the most useful tools within the generated products in the identification of uranium targets in the project.

The analysis of such mineral indexes indicated that the NW sector of the project is characterized by a suite of carbonate minerals while the SE section showed a large abundance of sulfate minerals. It is understood that this difference in exploration indicators was essentially due to the difference of the chemistry of the fluids from which mineralization was formed. Both high non-pedogenic carbonate and sulfate areas have a wide superficial extension and correlate with the known uranium anomalies found in the Laguna Sirven plateau. Such preliminary model was validated by means of ground gamma-ray spectrometry and soil geochemistry surveys recently performed [1].

3. CONCLUSIONS

Two prospective uranium exploration targets were identified within the project after the careful selection of remote sensing data during the acquisition phase and the later preparation, processing and interpretation of such spectral data.

The analysis of the presence and abundance of sulfate and carbonate related minerals indicated by both the Gypsum and the Carbonate Indexes proved to be a very useful tool to identify uranium targets in this calcrete-type deposit.

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BIOGEOCHEMICAL ORIENTATION SURVEY FOR SURFICIAL URANIUM DEPOSITS, LAGUNA SIRVEN, SANTA CRUZ, ARGENTINA

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1. DESCRIPTION

In Argentina, mineral ores are abundant but few studies of the chemical analysis of native vegetation growing in such areas have been reported. Uranium related activities begun in the 1950s. The Laguna Sirven project, located in Santa Cruz, Argentina has been identified by remote sensing to contain potential deposits of uranium.

A study in Nov. 2014 resulted in the collection of soils and plant species, along with radiometric field data, from sites associated with a possible U-deposit.

This study hopes to provide an insight into the potential of using remote sensing for mineral exploration of uranium and other minerals using the identification and chemical analysis of possible indicator plant species (based on specific components – roots or leaves) and soil profiles.

2. METHODS AND RESULTS

Based on remote sensing data a sampling site was selected at Laguna Sirven, Santa Cruz, Argentina. Radar data obtained from the Endeavour Space Shuttle Radar Topography Mission (SRTM) provided a coarse digital elevation model. Various mineral index maps were generated based mostly on SWIR band data. These maps agree with the geology described for this area as a possible uranium deposit. This was used to confirm the sampling site investigated in this study.

The region is extremely arid and the plant life of this site is comprised of low level scrub-like species varying in density over the sampling area. The site was selected based on the satellite information. After an initial inspection using the Radiation Solutions RS-230 BGO Super-SPEC handheld gamma-ray spectrometer, surface soil (top 5 cm) and soil profiles (to a depth of approx. 90 cm) were collected. Approximately 500 g of soil were placed into labelled plastic bags and sealed.

At the locations with the highest radiometric levels there was a scarcity of plants, with only the presence of small shrubs and low-level surface grasses and moss-type species. Plant samples were selected where possible to represent the sampling site. Soil material was carefully removed from the roots and all of the plant sample(s) placed in separate paper bags, sealed and labelled.

All samples were stored in a large plastic storage bin for transport back to the accommodation at Las Heras. Plant samples were dried (>20 °C) before packing in large plastic sealed bags for transport to the UK.

At the University of Surrey, it was deemed necessary to evaluate the analytical procedures, including sample preparation and instrumental analysis for uranium and other trace elements (Th, As, V, Fe, etc) by inductively coupled plasma mass spectrometry (ICP-MS), which have been found to be present in acidic volcanic rocks [1].

The techniques most suitable for routine analysis are laser-ablation ICP-MS or traditional solution nebulisation ICP-MS [3]. Furthermore, ICP-MS has the further advantage of determining the isotopic composition and ratio of the sample (²³⁴U, ²³⁵U, ²³⁶U and ²³⁸U) [2]. In this research traditional solution nebulisation ICP-MS was used with a collision cell due to the need to determine other trace elements besides uranium and thorium in the samples. This is because it may be possible to obtain further mineralisation information be evaluating the composition of the sample, for other elements 'geochemically-associated' with uranium, namely, Fe, Mn, V, As, Se, Zr, rare earths, etc.) [4, 5].

The preferred digestion method was found to be dry ashing using a subsequent acid dissolution of the 'ash' with aqua regia for plants and aqua regia/hydrofluoric acid for soils before elemental analysis. Therefore, all uranium analyses were undertaken using aqua regia digestion of media due to the possible stability of uranyl (V) chloride species [6]. Furthermore, multi-element analysis by ICP-MS uses a set of standards from 1 to 750 μ g/l. In order to enhance the accuracy for selected elements, especially U and Th which are found at low levels in digested plant and soil samples (0.05 to 30 μ g/l), it was found to be necessary to use an appropriate linear dynamic range of standards that reflected the levels found in the digested sample solutions. This provided good quality control (QC) calibration data for certified reference material (CRM) analysis with good levels of accuracy (agreement between calculated mean values and the certified reference values) and precision levels of < 10% relative standard deviation.

The uranium values for plant samples in this study, based on the radiometric field measurements can be divided into 'background or low mineralised' areas and 'mineralised'. Therefore, the 'background or low mineralised' uranium levels ranged over 0.01 to 0.47 mg/kg (dry weight), with a median of 0.05 mg/kg (d.w.). Similarly, the 'mineralised' values cover 0.01 to 2.05 mg/kg (d.w.) with a median of 0.32 mg/kg (d.w.). These values are in agreement with the limited number of reliable values available in the literature. Several studies have also reported the uranium concentrations in plants and plant components (roots, stems, leaves) as a function of different soil levels [7].

Uranium levels in plant parts clearly confirm the findings of Singh *et al.* (2005) with the highest uranium levels in roots > stems~leaves > flowers. The plant component levels do not show any accumulation of uranium as the values are typical of those reported by others as control sites after growth in soil with moderate levels (< 20 mg/kg) [7, 8].

Several studies have reported uranium levels for soils. Kabata-Pendias & Pendias (2000) provided a review of uranium levels in soils for various countries which ranged from 0.79 to 11 mg/kg (dry weight). The data for 'background or low mineralised' areas are in good agreement with the natural uranium levels in soils reported, ranging over 0.81 to 1.34 mg/kg (dry weight), with a median of 1.09 mg/kg (d.w.). Similarly, the 'mineralised' values cover 1.21 to 741.87 mg/kg (d.w.) with a median of 6.91 mg/kg (d.w.).

Interestingly, Kabata-Pendias & Pendias (2000) also reported thorium levels for soils ranging from 3.4 to 10.5 mg/kg (dry weight). Therefore, the data for 'mineralised' areas are in general agreement with these typical thorium values for soils. Similarly, these sites have interesting levels of arsenic and vanadium which are for 'mineralised' areas above the range of normal values reported for soils; arsenic <1 to 95 mg/kg (dry weight) with a typical mean of 2.2 mg/kg As (d.w.); and vanadium <7 to 300 mg/kg V (d.w.) with a typical average of 90 mg/kg V (d.w.) [1].

3. DISCUSSION AND CONCLUSION

A Pearson correlation analysis of the plant data confirmed the existence of statistically significant correlations between uranium and arsenic ($t_{cal} = 7.11 > t_{crit} = 2.68$, p < 0.01) or uranium and vanadium ($t_{cal} = 5.97 > t_{crit} = 2.68$, p < 0.01). The same pattern was observed for As and V but not for Th and Fe. The data is in good agreement with published uranium values for soils by Kabata-Pendias & Pendias (2000) and Gavrilescu *et al.* (2000). Based on the multi-element values it is possible to evaluate what is the possible mineralisation of these sites, namely, carnotite.

Radiometric data collected during the field trip is in good agreement with the uranium values for plants and soils at Laguna Sirven. This confirms that the use of gamma radiation measurements for U, Th and K in the field are of use for identifying sampling sites for subsequent U/Th analysis. Moreover, this will aid in the identification of specific plant species for biogeochemical prospecting.

In summary, this data is in good agreement with the limited published values by Bowen (1979), Dilabio *et al.* (1980), Kaur *et al.* (1988), Vargas *et al.* (1997), Singh *et al.* (2005) and Favas *et al.* (2014). Remarkably, the highest uranium levels were found in plant roots, with the U, As and V results confirming that the site around Laguna Sirven is of interest for future uranium and associated elemental research.

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ALTERATION FINGERPRINT OF THE EARLY YANSHANIAN GRANITE-RELATED HIGH TEMPERATURE HYDROTHERMAL URANIUM MINERALIZATION IN THE NANLING METALLOGENIC BELT, SOUTHEAST CHINA

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Abstract

In the Xiazhuang and Zhuguang uranium orefields of the Nanling Metallogenic Belt in southeast China, graniterelated hydrothermal uranium deposits formed in two major mineralization stages: (i) an early Yanshanian high temperature stage (175–145 Ma) concomitant with the early Yanshanian magmatic event, and (ii) a late Yanshanian low temperature stage (110–50 Ma) that occurred during the Cretaceous–Early Cenozoic crustal extension in eastern Asia. To date, the Baishuizhai occurrence (175 \pm 16 Ma) and the Shituling and Zhushanxia deposits (162 \pm 27 and 165–146 Ma, respectively) represent the early Yanshanian uranium mineralization in the belt. The Zr–Th–Ta-bearing disseminated to vein type uranium mineralization is cogenetic, with a hydrothermal alteration assemblage of epidote, chlorite, muscovite, adularia, illite, calcite, apatite, aluminium phosphate–sulphate minerals and titanite. The ore trace element signature and the propylitic and potassic alteration are both in agreement with relatively high temperatures (>250°C), corroborated by temperatures of 316–455°C estimated from chlorite. This early mineralization stage appears to be related to the intrusion of the early Yanshanian granites where the mineralizing fluids could partly to totally derive from the granites in a high temperature hydrothermal system. This would be, to date, the first description and known occurrence of a new type of hydrothermal uranium deposit associated with granites worldwide.

1. INTRODUCTION AND GEOLOGICAL SETTING

The South China Uranium Province accounts for the largest amount of explored uranium deposits and resources in China (\sim 50% of identified uranium resources [1–4]). It includes three major types of uranium deposit, from the most to the least economic: (i) granite-related vein type deposits, (ii) volcanic-related vein type deposits, and (iii) black shale-related deposits (i.e. C–Si–pelite type [1, 5, 6]). Some small sandstone type uranium deposits are also hosted in several Mesozoic–Cenozoic basins in the province. In addition to uranium, the province is also renowned for W, Sn, Bi, Sb, Mo, Au, Ag, Cu, Pb and Zn deposits [2, 3, 6], some of which belong to the world class category in terms of grade and tonnage.

Granite-related hydrothermal uranium deposits from the Xiazhuang (eastern part of the Guidong batholith) and Zhuguang orefields within the Nanling Metallogenic Belt (NMB) formed in two major mineralization stages [5]: (i) an early Yanshanian high temperature stage (175–145 Ma) concomitant with the early Yanshanian magmatic event that occurred in South China during the Jurassic and (ii) a late Yanshanian low temperature stage (110–50 Ma) that occurred during the Cretaceous–Early Cenozoic crustal extension in eastern Asia. To date, the early Yanshanian stage is only represented by the Baishuizhai occurrence (175 \pm 16 Ma) and the Shituling (162 \pm 27 Ma) and Zhushanxia (165–146 Ma [7]) deposits located in the Xiazhuang orefield [5]. These early Yanshanian deposits are mainly hosted in Triassic granites (e.g. Baishuizhai and Maofeng plutons) emplaced during the Indosinian orogeny, among which peraluminous S- and L-type leucogranites and highly fractionated high K calc-alkaline A2-type granites constitute the most favourable U sources [5]. The primary uranium mineralization mainly occurs as Zr–Th–Ta-bearing uraninite and pitchblende disseminated in the host granite or as vein filling fractures. Large amounts of secondary uranium

mineralization are also characteristics of these deposits. Preliminary description of the alteration mineral assemblage, including hydrothermal epidote, chlorite, muscovite, K-feldspar, apatite, etc., presented in Ref. [5] and ore forming fluid temperatures in the range 290–338°C at the Shituling deposit [8] were strong evidence for a high temperature hydrothermal system. This paper summarizes work aimed at a better characterization of the genetic conditions of the early Yanshanian uranium stage through detailed petrographic and mineralogical studies carried out on the alteration minerals associated with the uranium mineralization.

2. MATERIAL AND METHODS

Six mineralized samples were collected from the Baishuizhai occurrence (XB1) and the Shituling (XS1, XS2) and Zhushanxia (ZSX1, ZSX2, ZSX3) deposits in the Xiazhuang orefield. The textural and paragenetic relationships of the alteration minerals associated with the early Yanshanian uranium mineralization were determined through detailed petrographic studies by optical reflected light microscope and scanning electron microscope (SEM). The chemical composition of the alteration minerals was analysed by electron microprobe (EMP) and their trace element concentrations were measured by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

3. RESULTS

3.1. Petrography and mineral assemblage of the alteration

The hydrothermal alteration of the host granites associated with the early Yanshanian uranium mineralization can be pervasive (e.g. Baishuizhai) or confined to the vicinity of fractures (e.g. Shituling and Zhushanxia). The alteration mineral assemblage identified in the studied deposits includes epidote, chlorite, calcite, adularia, muscovite, illite, quartz, apatite, titanite, aluminium phosphate–sulphate (APS) minerals, albite and iron oxide. Sulphide minerals such as pyrite, chalcopyrite, galena, molybdenite, sphalerite, bismuthinite and greenockite are also frequently observed. These alteration minerals either occur disseminated in the altered host granite (e.g. Baishuizhai) or along the mineralized veins (e.g. Shituling). This typical mineralogy characterizes extensive propylitic (epidote–chlorite–calcite ± albite) and potassic (adularia–muscovite–illite) alterations and silicification (quartz). In the Baishuizhai occurrence, the magmatic feldspars are completely replaced by muscovite, illite and quartz, which is characteristic of greisenization.

3.2. Chemical signatures of the alteration minerals

Among the alteration minerals that were identified, epidote, chlorite and muscovite occur in the three studied deposits and show specific major, minor and trace element compositions, although chlorite is rare in samples from the Shituling deposit. Epidote from Baishuizhai is characterized by its high Mn content (16.3-17.5 wt%) whereas epidote from Shituling and Zhushanxia presents similar compositions ranging from 22.9-36.4 wt% CaO, 11.4–25.9 wt% Al₂O₃ and 5.7–13.4 wt% FeO. All epidotes are characterized by variable concentrations of Ti (27–1215 ppm), V (10–819 ppm), Zn (6–309 ppm), Y (0.1–99 ppm), Sn (5–89 ppm) and Zr (limit of determination (LOD)-8 ppm). It can be noted that only epidote from Baishuizhai returned heavy REE concentrations up to 7 ppm Lu, 11 ppm Er and 33 ppm Yb. Epidote from Shituling and Zhushanxia also has additional concentrations of Sr (5-287 ppm), W (3-56 ppm) and Nb (9-42 ppm). Chlorite from Baishuizhai and Zhushanxia is Fe-dominant (18.9-31.4 wt% FeO, 9.0-16.9 wt% MgO) giving a chamosite composition. Trace elements of petrogenetic interest are Ti (70-1559 ppm), Zn (473-1450 ppm), Li (441–1024 ppm), V (25–425 ppm), Rb (4–170 ppm), Sn (2–58 ppm), Cs (9–51 ppm), Nb (LOD– 31 ppm) and Zr (LOD-12 ppm). The calculated temperatures from the chlorite compositions (Al^{IV} thermometer, after Ref. [9]) range from 316 to 455° C (n=19). Muscovite from the three studied deposits shows a relatively homogeneous composition with 46.2-53.2 wt% SiO₂, 27.4-33.8 wt% Al₂O₃ and 3.1-11.5 wt% K₂O contents. It has variable Rb (120–2856 ppm), Ti (37–2319 ppm), Cs (29–1667 ppm), Li (43–

1084 ppm), Sn (LOD–628 ppm), Sr (LOD–252 ppm), Nb (LOD–451 ppm), W (LOD–111 ppm), Zr (LOD– 57 ppm) and Ta (LOD–31 ppm) concentrations. Titanite from the Zhushanxia deposit (average of 34.4 wt% TiO₂, 30.9 wt% SiO₂ and 29.4 wt% CaO) shows minor Al₂O₃ (0.9–1.4 wt%) and FeO (0.1–0.8 wt%) contents and has variable W (160–2010 ppm), Zr (42–878 ppm), Y (81–352 ppm), Sn (47–248 ppm), Nb (100–190 ppm) and Ta (4–12 ppm) concentrations. Finally, apatite from the Shituling and Zhushanxia deposits presents a fluorapatite composition with 52.2–58.5 wt% CaO, 38.0–43.3 wt% P₂O₅ and 1.6–2.2 wt% F contents. Trace elements with significant concentrations are Sr (615–3640 ppm), Y (69–777 ppm), Rb (2–151 ppm), Th (1–130 ppm), W (3–70 ppm) and Sn (2–19 ppm).

4. DISCUSSION AND CONCLUSIONS

The alteration mineral assemblage from Baishuizhai, Shituling and Zhushanxia including epidote, chlorite, K-bearing silicate, titanite and apatite associated with Zr-Th-Ta-bearing uranium oxides characterize an extensive propylitic and potassic alteration strongly suggesting high temperature conditions. The high temperature of the hydrothermal system was thus confirmed by temperature estimates in the range 316-455°C calculated with the Al^{IV} thermometer in chlorite [9], which is also corroborated by homogenization temperatures of 290–338°C determined from fluid inclusions for the ore forming fluid of the Shituling deposit [8]. The chemical signatures of the alteration minerals showing characteristic concentrations of incompatible elements (K, Cs, Li, Rb, Sr, Y, Zr), rare metals (Sn, W, Nb, Ta) and occasionally heavy REE indicate highly differentiated crustal source rocks [10, 11], such as peraluminous leucogranite or highly fractionated, highly potassic calc-alkaline granite [5], widely represented in the Nanling Metallogenic Belt, which also suggests the contribution of magmatic derived fluids. For instance, hydrothermal titanite largely occurs in alteration zones associated with the intrusion of igneous rocks. It is a common alteration product highlighting late magmatic to post-crystallization hydrothermal alteration in porphyry Cu and Fe–Cu–Au– W–Mo skarn mineralizing systems [12, 13]. Moreover, the Zr content in titanite, up to 878 ppm in the case of titanite from Zhushanxia, also reflects the magmatic contribution as a source of fluid for the hydrothermal system [13]. The greisenization characterized in Baishuizhai constitutes another strong piece of evidence for the contribution of magmatic derived fluids to the hydrothermal system. It is indicative of the late magmatic alteration of the host granite that most likely occurred during the cooling stage of emplacement of the early Yanshanian granite in the district. As they are generated during the final stage of granite crystallization, the late magmatic fluids responsible for the greisenization tend to be enriched in incompatible elements [10, 11], and also known to be at the origin of W-Sn-Mo-(U) mineralization in the province [2, 3, 6, 14]. Then, the significant and systematic record of this suite of elements in the studied alteration minerals would be the marker of the contribution of such fluids. In the Xiazhuang orefield, the early Yanshanian uranium mineralization is also associated with minor tungsten occurrences such as wolframite in the Shituling deposit [15] and scheelite in the Zhushanxia deposit (up to 0.3% W [7]), indicating possible genetic relations between uranium and tungsten mineralization. Finally, the occurrence of fluorapatite (up to 2.2 wt% F) in the Shituling and Zhushanxia deposits, together with calcite in the three studied deposits, suggests that the hydrothermal solutions were enriched in fluoride and carbonate ions which have the capability to form complexes able to transport metals, including uranium [5].

Therefore, the early Yanshanian uranium stage appears to be strongly related to the intrusion of the early Yanshanian granites providing: (i) the heat source for the high temperature hydrothermal system, (ii) magmatic derived fluids that can mix with hydrothermal fluids already present in the basement, and (iii) major sources of incompatible elements and rare metals that are concentrated in the alteration minerals and the uranium mineralization. This model is new for hydrothermal uranium deposits related to granites and seems to represent the only occurrence of this type in the world.

On the scale of the Nanling Metallogenic Belt, the alteration fingerprint that was characterized in this study for the early Yanshanian uranium event presents numerous similarities to the genetic model proposed for the giant W–Sn event in south China [5, 6, 14], which is also related to the intrusion of the early Yanshanian

granites (peak at 160–150 Ma). Further studies will be conducted in order to characterize the spatial-temporal relations between the U and W–Sn mineralizing systems in the Nanling Metallogenic Belt.

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SUSTAINABLE DEVELOPMENT OF URANIUM PRODUCTION: STATUS, PROSPECTS, CHALLENGES

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Recent WNA [1] and UxC [2] reports demonstrate similar approaches for uranium supply demand forecasts until 2035 in the reference case scenario. Both reports show uranium oversupply at least until 2023. About 10% of global requirements will be provided during this period from secondary sources. The share of the secondary sources will gradually decrease in time. Primary uranium has no alternatives in a long term perspective. According to the WNA report, uranium production is expected to increase in about 40% by 2035. Primary uranium production from existing mines will decrease by 30% in 2035 due to resources depletion and mines closure, while new planned mines will only compensate exhausted mines capacities. Both reports show, that during 2023-2026 uranium demand may exceed supply and new prospective mines from so-called supply pipeline, which development is not yet confirmed by companies plans, must start production during the next 10 years to fill the gap and ramp up to 30 ktU/y by 2035. Are uranium resources and mining capacities sufficient to meet future long-term NPP requirements?

Despite depressed market, uranium production continued to grow steadily during the last decade and reached 62 ktU in 2016, which was a historical maximum since 1983. However, in 2017 it dropped back to 59 ktU. Kazakhstan provided the major historical input, increased uranium production six times during the last decade and keeps the world leadership since 2009. Its share comprised 40% of the world total in 2017, followed by Canada with 22% share. Kazatomprom keeps leadership in companies ranking with 21% share, followed by Orano, Cameco (both 16%) and Rosatom (Uranium One + ARMZ) with 14% share.

In Situ Leach is the main uranium mining method. Its share in the world total production has increased from 20% in 2005 to 50% in 2016 and 2017. Kazakhstan contributed 40%, while five other ISL producing counties (Uzbekistan, Russia, USA, Australia, China) - 10% of the world total. ISL mining capacities will start to decline after 2028 and production from low cost ISL mines will sharply decline starting from 2022 due to resources depletion, while higher cost ISL production may partly replace it and only until 2028 [3]. Thus, uranium companies may face economic and technical challenges in new ISR projects development due to higher costs and resources availability.

Statistics in ranking operating mines by costs and mining capacities show that 95% of mines with full cost below current spot price are located in Kazakhstan [3]. While keeping only 27% of total existing production capacities, they produce 40% of world total. All six Uranium One mines in Kazakhstan are in top 20 of low cost mines and five of them are in top 5. Today is the era of Kazakhstan, however in the new mines supply pipeline there are only seven small new ISL mines, and only one of them in Kazakhstan.

Only 40% of 43 currently operating mines produce U at a cost below spot market price. That means than only companies with low cost production or favorable long term contracts may survive in current challenging uranium market. Low uranium prices do not boost production and force companies to stop, revise or defer their exploration and development projects. In addition to low U prices, companies face technical constraints, political, social and environmental factors. These risks hamper development of several world class uranium projects in Canada, Australia, Africa, Russia and other countries. Kazakhstan has recently announced that production will be about 20% below 2018 contracts requirements, Cameco announced that mining at the McArthur River mine will cease in 2018. This may

result in further decrease in uranium production in 2018 by at least 10%. However, the companies do not refuse from new mining projects, but focus more on their optimization and effective technologies development.

Reliable and low cost uranium resources is a key factor for sustainable long-term production development. Global uranium resources are more than sufficient to ensure the long-term needs of nuclear industry. At the same time, the great share of resources belong to high cost categories and after 2020 uranium producers may face the shortage of low cost resources [4]. During the last decade the total global known uranium resources increased by 21%, however resources in low cost category <80\$/kgU decreased by 48%.

Kazakhstan is currently a world leader in uranium production, but it may also face all above-mentioned challenges in future. Kazakhstan U resources amounted to about 1 MtU in 2015 [4], 70% of which are in low cost sandstone type, amenable for ISL. Remaining resources belong to lignite, vein and phosphate types. However, 95% of ISL amenable resources belong to operating and under construction mines. Kazakhstan plans to maintain current annual uranium mining capacities at a level of 65Mlbs until 2020, however actual uranium production during this period may be below capacities from 10 to 20% due to unfavorable uranium market. After 2020, Kazakhstan may face a gradual decrease in uranium production by 40% in 2030 and by 70% in 2035 due to resource depletion and old mines closing. In order to extend existing mining capacities for a long-term period, new uranium mines must start operation during the next five years, but potential for stand by uranium deposits development is limited.

The history of uranium discoveries in Kazakhstan shows that almost all deposits in Kazakhstan for ISL mining had a significant initial huge resource base (1,238 MtU), which was identified between 1970 and 1990. Uranium exploration during the last decade was focused more on prognosticated resources conversion into measured and indicated categories. The exploration potential to discover new large uranium deposits amenable for ISR mining within the largest uranium provinces in Kazakhstan is far from being exhausted. Favorable transparent legislation must facilitate investments in uranium exploration, when the investor has a State guarantee to mine discovered resources and possess produced uranium under strict compliance with established national standards and regulations.

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MAJOR INNOVATIONS IN ISL MINING AT URANIUM ONE MINES IN KAZAKHSTAN

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A successful innovative technical policy in conjunction with the unique deposits (by their geological and technical characteristics) provide a significant competitive advantage for Uranium One as the global company with the lowest cost uranium production. Uranium One has gained broad expertise in the various aspects of in situ leach (ISL) exploration and mining, including: uranium prospecting and exploration for sandstone hosted deposits from greenfield to mining phase; geological modelling and resources estimation; pilot ISL testing; and feasibility and engineering studies at all stages of deposit development.

The main areas of ISL innovative development and efficiency improvements at Uranium One's mines in Kazakhstan include: geological 3-D modelling for resource estimation; ISL process modelling and simulation for project design and its implementation in ISL process management; implementation of modern methods of well construction and restoration; estimation of additional technogenic and residual resources; and recovery of rare earth elements and other valuable components from leaching solutions [1–5].

Uranium One attributable resources in Kazakhstan, reported under Canadian National Instrument NI 43-101 codex, have tripled over 10 years through acquisitions, extensive exploration and by application of 3-D modelling in resource estimation. Previous technical reports on the NI 43-101 codex were based on geological information compiled from Kazakhstan national technical reports on resources (State Commission on Mineral Reserves - GKZ codex), which assumed a polygonal geostatistical method of resource calculation. Uranium One hired CSA Global to develop a robust methodology for 3-D geological modelling and mineral resource and ore reserve estimation for roll-front deposits in Kazakhstan. This methodology was applied from 2012 through 2017 to modelling the Budenovskoye and South Inkai deposits in Chu-Sarysu province, and the Zarechnoye and Kharasan-1 deposits in Syrdarya province [1].

The ISL modelling complex includes the set of integrated systems: geological data room and geological model, technological data room and ISL process simulation model, technical–economic system, ISL development and wellfield design system, and mine planning complex. The modelling complex may be applied for ISL process design and management at all stages of deposit development. The complex was developed by the Russian Federation's Seversk Technological Institute and originally implemented at the Dalur ISL mine in the Russian Federation [2,3]. In 2017, Uranium One started a pilot project on ISL process modelling and simulation at one of the areas of the Budenovskoye deposit, Akbastau mine. The developed ISL model of the main technical parameters has identified the main issues for ISL process optimization over the short, medium and long-term periods. The results obtained confirmed the high potential for simulating systems implementation at ISL mines in Kazakhstan.

Wellfield design and installation are two important components of ISL mine development. Drilling and wells installation costs comprise about 70% of mining CAPEX or 25–30% of the total uranium production cost. Major ISL mines in Kazakhstan use unified techniques and designs for technological well drilling and installation. The stable performance of wellfield units largely depends on the efficiency of well work over procedures focused on well flow-rate restoration and on elimination of plug impact. Plugging is the process when a well-known screen loses its capacity and the ore-bearing horizon loses its permeability. A new

method of well flow-rate restoration is based on well screen treatment by a mixture of reagents with the addition of ammonium bifluoride. The method has no comparable alternatives for the restoration of problematic wells, as traditional methods of chemical treatment of flow-rate recovery do not give significant results. Application of the method restores flow-rates to their original parameters and increases the workover cycle by 2.5–3 times.

Estimation and development of additional technogenic (or newly formed) and residual resources within existing wellfields is a particularly vital issue for a life-of-mine extension. By technogenic resources we mean uranium concentrations formed due to leaching solutions' exposure to primary mineralization and redeposition of dissolved uranium, including the remaining lenses of productive solutions. By residual resources we mean part of the uranium mineralization that remains in situ and which is not affected by leaching processes. In 2016, the Akdala mine completed research work focused on the forecast of areas with residual and technogenic resources [4]. Prospective areas for 419 tU of potentially residual resources were allocated within existing wellfield units. Further verification drilling confirmed the presence of residual and newly formed ores. Of the 25 wells drilled in 2017, 15 identified commercial uranium concentrations in leaching solutions and in hosting sediments.

Off-balance resources of valuable by-product components (rhenium, scandium and rare earth metals) have been identified within the uranium resources at ISL mines in Kazakhstan. All valuable components are partially dissolved in sulphuric acid during the ISL process. Six mines with Uranium One ownership pump out more than 120 Mm³ of productive solutions annually, which contain up to 1 mg/L of scandium and rhenium and 5–20 mg/L of rare earth elements [5]. Lanthanum, cerium and neodymium make up the major part of the rare earth elements. About 40 t of rhenium, 30 t of scandium and more than 2000 t of rare earth metals are pumped out annually in leaching solutions and returned back to aquifer. Major technologies for by-product extraction from sorption mother liquors have been developed. Sorption by cationic exchange resins or chemical precipitation are used for rare earth elements recovery. Rhenium is partially absorbed, together with uranium, by anionic ion exchange resins and its concentration in saturated resins may reach 950 g/t [5]. The key technological challenge is the selection of sorbents, which provide selective extraction of valuable components free of radioactive metal impurities.

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CONTRIBUTION TO THE CHARACTERIZATION OF THE HOST FORMATION OF THE FRANCEVILLIAN URANIUM MINERALIZATION (HAUT OGOOUÉ PROVINCE, GABON): PETROGRAPHY, SEDIMENTOLOGY, STRATIGRAPHY, AGE AND NEW ISOTOPIC DATA

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1. INTRODUCTION

Five uranium deposits (Boyindzi, Mikouloungou, Mounana, Okélobondo and Oklo) located within the Francevillian mineral lease and trapped in the Palaeoproterozoic sandstones of the unmetamorphosed Francevillian Basin (Gabon) were discovered in the 1960s and 1970s and exploited by the COMUF company. A total of 26 600 tU was extracted from open pit and underground mines over a 38 years period (1961–1999).

Recent exploration drilling completed by AREVA (Orano) at Bagombé, Mikouloungou and in the Suly district (close to the Oklo deposit) has highlighted the presence of pluri-centimetric fine-grained yellow sedimentary layers interbedded in the basal tidal FA sandstone formation, host to most of the mineralization. These original layers have been found in several drill holes on each explored area and were studied to determine their origin.

Also, new mineralization types have been discovered corresponding to uranium veins located in the basement. This discovery arouses interest in the genetic model for these occurrences. Thus, a general review of the uranium metallogeny of the district has been initiated, using modern techniques for isotopic dating and trace element measurement.

2. YELLOW LAYER CHARACTERIZATION

One of the more remarkable lithological and petrographic features of the Mikouloungou and Bagombé Francevillian FA sandstone formation is the presence of 'yellow strips', interbedded in the sandstone series. Macroscopically, the yellow strips are characterized by their contrasting yellow colour and fine- to medium-grained texture which exhibits strong lamination, as well as by their sharp contacts. They can be found within medium- to coarse-grained sandstone, conglomerate or at the unconformity between the granitic–metamorphic basement and the sedimentary cover. These yellow strips have a thickness of a few centimeters and disintegrate easily due to the local concentration of phyllitic material (micas and clay).

Assumptions made by on-site geologists for the yellow strip origin were: (i) small scale 'mylonitic' zones resulting from horizontal glide accommodation, (ii) bottom set of dunes, or (iii) volcanic layers (cinerites).

Ten yellow strip occurrences have been sampled in three areas separated from each other by about 30 km. Thin sections have been made of each sample and these have been studied using optical and scanning electron microscopy. All the thin sections present the same characteristics:

- a) Most abundant elements are quartz and a few feldspars. The quartz is limpid and often elongated, sometimes angular, occurring as splinters and often cup-shaped on the edges. Some quartz cristals are nearly euhedral and present evidence of crystalline hiatus (rhyolitic);
- b) There is a strong concentration of heavy accessory minerals such as zircon and monazite, as observed in volcanic tuffs;
- c) All the elements are floating in the matrix and are orientated, highlighting the stratification;
- d) The matrix, composed of fine micas and clays, is dominant (70–80%). Clays probably result from hydrothermal alteration and account for the yellow colour of the formation at the macroscopic scale.

These specific observations indicate that the quartz grains have a volcanic origin and that they are associated to local cineritic deposits (hypothesis (iii) above). They possibly represent favourable stratigraphic marker horizons on the regional scale and additional studies are necessary to correlate them. These studies could help to better constrain the age of the Francevillian basal FA sandstone formation. The identified volcanic layers within the FA sandstone could also contribute to the supply of uranium in the basin.

3. URANIUM MINERALIZATION

3.1. Sampling and analytical methods

Following the discovery of fractures filled with uranium in the basement, at the contact with the sedimentary FA formation in the Mikouloungou deposit, several mineralized samples of different types of uranium occurrence were collected. To compare them with known mineralization, samples from the Oklo deposit have also been re-analysed using the same modern techniques. Samples have been studied using traditional optical and electronic microscopy for petrographic observation and ion microprobe (CAMECA IMS1280) for point U–Pb isotopic dating. For the Oklo samples, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was used for point REE analysis of uranium oxides.

3.2. Mikouloungou results

The UO_2 mineralization displays three types of habit: (i) lining the interstices between the sand grains of the sandstones, (ii) incorporated within organic matter or in close relation to it and (iii) filling micro-fractures of basement samples just below the unconformity along with associated sulphides (chalcopyrite, galena and pyrite).

A total of 346-point U–Pb isotopic analyses have been carried out on several thin sections. This set of measures gives the following groups of ages:

- a) Around 800 Ma (between 860 and 750 Ma) mainly in basement fractures;
- b) Around 520 Ma (between 630 and 410 Ma) for pitchblende filling the voids between sandstone grains or uraninite crystals in organic matter, with some isolated values around 246 Ma or around 1730 Ma, the latter being linked to micro-inclusions of galena in the uraninite crystals;
- c) The Concordia diagrams sometimes show a low intercept at around 120 Ma, indicating a reset of the system at that time.

All the Mikouloungou mineralization analysed in this work gives only the younger ages described so far for the Oklo deposit [1]. The oldest ages previously published for the Oklo deposit [2] have not been found.

3.3. Oklo results

In order to confirm the oldest ages obtained on the Oklo mineralization with point analysis, some samples of massive pitchblende and of uraninite from the Oklo natural 'reactors' were recently studied with the ion probe to obtain U–Pb istopic data. Three samples from the quarry outcrops (supposed to be from the reactors) which included uranium mineralization filling cracks or associated with organic matter were also analysed.

3.3.1. Isotopic disequilibrium

The Oklo mineralization has been, in some places, affected by a natural fission reaction and termed a natural reactor. It has consumed a part of the ²³⁵U, leading to a disequilibrium compared with all the natural uranium occurrences [3, 4]. The set of isotopic analyses performed with the IMS 1280 ion probe has been adjusted for these special samples to measure more precisely the ²³⁵U and calculate the isotopic disequilibrium.

The standard used for calibration is a uraninite from Zambia. The $^{235}U/^{238}U$ of the standard is constant and gives a value of 0.007104. The ratio ($^{235}U/^{238}U$) sample/($^{235}U/^{238}U$) standard, should be 1 if the uranium isotopes are at equilibrium. Results from 4 samples from drill hole D73-S2 intersecting the reactor No. 10 give results of between 0.88 and 0.73, which confirms the disequilibrium.

3.3.2. Age

For the reactor samples, Concordia diagrams show a dispersed high intercept of the Discordia around 1700 \pm 100 Ma without ²³⁵U correction. Considering the ²³⁵U loss, it is possible to apply a correction factor which changes the slope of the Discordia, giving a focused range of high intercepts distributed between 1979 \pm 18 Ma and 2028 \pm 30 Ma. The three samples originating from the quarry present younger ages, ranging from 533 \pm 27 Ma to 557 \pm 6 Ma, similar to the main group of ages from the sandstone hosted uranium mineralization at Mikouloungou.

3.3.3. REE signature

On the Oklo reactor samples, REEs have been analysed by LA-ICP-MS. The REE spectra, normalized to the Chondrite C1, show reproducible spectra with identical forms, characterized by high LREEs and low HREEs and a gadolinium negative anomaly. Theses spectra present a double 'tetrad effect' in the LREEs and low REEs, as described in previous studies [5].

4. DISCUSSION

In this work, all the dated mineralization at Mikouloungou gives younger ages than those historically established for the mineralization of the Francevillian Basin [2]. The older ages, close to 2 Ga, are always linked to natural nuclear reactors. No evidence of these older ages has been found in the other types of mineralization. These ages are younger than the emplacement of dolerite veins (955–970 Ma) [6] and part of them are synchronous with the Pan-African deformation phase, between 500 and 600 Ma. The last group of ages, linked to the lower intercept in the Concordia diagram, could result from a resetting of the isotopic system linked to the opening event of the Atlantic Ocean.

5. CONCLUSION

These studies initiated by the Orano Mining Group exploration staff, combined with sedimentological, petrographic and metallographic works, bring new results: (i) on the volcanic origin of the yellow strips constituting a possible regional stratigraphic marker and possible syn-sedimentary sources for at least part of the uranium in the basin, (ii) on the ages of different mineralization types at Mikouloungou, younger than

the first mineralization event at Oklo, (iii) on the ²³⁵U loss in the uraninite crystals of the Oklo reactors due to natural fission and giving an age of around 2 Ga, as given by former data, with other analytical techniques [7], and (iv) on the original spectra with the double tetrad effect for the same Oklo uraninite crystals.

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A URANIUM ISOTOPIC PERSPECTIVE ON THE FORMATION OF ROLL-FRONT MINERAL DEPOSITS AND IMPLICATIONS FOR POST MINING REMEDIATION

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1. INTRODUCTION

Roll-front deposits are an important global economic source of uranium ore, commonly mined using in situ leach (ISL) methods. The simplified conceptual model for roll-front formation involves the reductive precipitation of U(VI) to $U(IV)_s$ as oxygen-rich groundwater interacts with subsurface reductants such as iron minerals, sulphide and anaerobic microbes, forming reduced U minerals such as uraninite and coffinite. While this model captures the broad mechanisms of roll-front formation, it does not directly address why roll-fronts form in only some reducing sediments, the timescale of formation and whether some roll-fronts are actively accumulating U and/or migrating. These questions are of geological interest but more importantly affect the economic and environmental decisions related to ISL mining.

In the USA, the primary concern with ISL mining is the fate of remnant aqueous U(VI) in the mined formation after the cessation of mining and active remediation (e.g. reverse osmosis). In many existing mines, at least some portions of the aquifer have U(VI) concentrations in excess of the pre-mining aquifer concentrations and it is unknown how far downgradient this U(VI) will migrate before it is reduced to U(IV) and precipitated. This so-called natural attenuation of residual aqueous U is an important component of designing the life cycle strategy for ISL mines. There are very few direct constraints on the kinetics of U sorption and reduction reactions that can be directly applied to roll-fronts, although some guidance on this topic comes from recent studies of U remediation across contamination sites in the US Department of Energy complex [1–4]. There are, however, significant differences in the hydrology and groundwater chemistry (e.g. organic carbon activity) in typical roll-front deposits compared with the (primarily) vadose zone studies.

Recent observations from groundwater and minerals in roll-front deposits show a remarkable variation in the isotopic ratio of $^{238}U/^{235}U$ [5–8]. The observations of U isotopes in groundwater combined with the theory that fractionation of the $^{238}U/^{235}U$ is largely due to reduction of U(VI) to U(IV) should make it possible to quantify the extent of U reduction in the subsurface, both before and after mining activities. Modelling the extent of U reduction has been complicated by (i) deviations in the extent of isotopic fractionation from theoretical models and (ii) heterogeneities in the isotopic composition of ore minerals. It remains unclear what processes affect the magnitude of isotope fractionation and give rise to heterogeneous mineral compositions. One suggestion is that both biotic and biotic U reduction will yield different isotopic effects and that mixtures of these two mechanisms could explain the variations [9, 10].

The purpose of this contribution is to investigate whether a two dimensional spatial analysis of U and U isotope distributions in a roll-front can resolve the aforementioned problems with interpreting the U data from associated groundwater. The paper demonstrates that the spatial distribution of U and the U isotope

ratios are not random but a result of reactive transport that can be approximated to a pipe flow model and that this information can be used to place constraints on the formation and migration timescales of the roll-front.

Geological and hydrogeological settings: The Smith Ranch–Highlands uranium mine is located 80 km northeast of Casper, Wyoming, United States of America, on the southern edge of the Powder River Basin. The U ore is concentrated in fluvial sandstones of the Palaeocene Fort Union Formation. Regionally, the strata dip to the east at $<0.5^{\circ}$ and groundwater flow is mostly in the same direction at 2–3 m/year [11]. Uranium is concentrated at redox boundaries (roll-fronts) that are typically 2–8 m wide and at depths of 61–366 m. Uranium typically occurs as uraninite (UO2) and coffinite (U(SiO4)0.9(OH)0.4) coatings on sand grains and is commonly associated with pyrite and carbonaceous matter, the presumed uranium reductants [12–14].

2. METHODS AND RESULTS

Three cores were collected through a single roll-front in the expected mineralized zone, along the depositional axis of the roll-front. The cores were spaced approximately 10 m from one another and are about 6–9 m in total length. The sediments range from silt and clay-rich horizons to coarse quartz arkose sands. The coarse sediments contain lignite fragments that show some rounding from fluvial transport. Preliminary visual analysis of the core is consistent with a fluvial deltaic type depositional environment. The cores were divided into 0.15–0.3 m sections in the core barrel and packaged in two food grade vacuum bags, evacuated and heat sealed for shipping to the laboratory. Each core hole was logged for gamma radiation, resistivity and conductivity.

At the laboratory, the cores were scanned with a handheld NaI gamma detector to identify sections of low and high radioactivity. Core sections were opened inside an O₂-free anaerobic chamber where an aliquot was preserved inside a glass bottle sealed with a rubber septum and the remainder was stored in gas impermeable Mylar bags. Samples of ~5 g were transferred to degassed 15 mL centrifuge tubes and leached successively with a KCl solution (pore water leach), NaHCO₃ solution (adsorbed U fraction) and HCl solution to extract the precipitated UO₂ fraction without sampling significant U from silicate minerals such as zircon. The acid leachates were then analysed for U concentrations, ²³⁴U/²³⁸U and ²³⁵U/²³⁸U in the Center for Isotope Geochemistry at Lawrence Berkeley National Laboratory.

Results: The cores are numbered 1–3 from upgradient to downgradient for description purposes. The sediments are quartz rich (SiO₂ 85.1–95 wt%) with large, pink potassium feldspar. Using the ternary chemical classification Na₂O-K₂O-FeO+MgO, all of the core samples plot within the arkose field. Uranium is the only trace element to show consistent enrichment above average upper continental crust, with most trace elements between 0.1 and 1 times the upper continental crust.

The concentrations of U in the U mineral leachate fraction vary from approximately 0.5 ppm to 1000 ppm. In each core there is a zone of high U concentration that tail to lower concentrations above and below giving a generally convex concentration profile when compared with depth. The $^{235}U/^{238}U$ ratios vary by approximately 2‰ amongst the analysed samples and show a convex relationship compared with the sample depth. The $^{235}U/^{238}U$ values are slightly enriched in the highest U concentration samples but are depleted in the lower concentration samples. In the axis of the roll-front, defined by the highest U concentrations, there is a decrease in the maximum $^{235}U/^{238}U$ ratio in the cores further downgradient.

The ${}^{234}U/{}^{238}U$ are reported relative to secular equilibrium (SE) as activity ratios (AR): ${}^{234}U/{}^{238}U_{sample}/{}^{234}U/{}^{238}U_{sE}$. The ${}^{234}U/{}^{238}U_{AR}$ vary from 0.771 to 2.257 but most samples cluster between ~0.84 and 1.65. In contrast to the ${}^{238}U/{}^{235}U$ and U concentrations, the activity ratios show a concave pattern when compared with sample depth, with the lowest ${}^{234}U/{}^{238}U_{AR}$ coincident with the highest U concentrations. The

highest ${}^{234}U/{}^{238}U_{AR}$ values are generally towards the top and bottom of the cores, although some of the highest values occur within 0.6 m of the lowest ${}^{234}U/{}^{238}U_{AR}$ in the most upgradient core.

The NaHCO₃ leachate is assumed to represent the adsorbed U component. The spatial distribution of $^{238}\text{U}/^{235}\text{U}$ (described as $\delta^{238}\text{U}$) and $^{234}\text{U}/^{238}\text{U}_{AR}$ in the adsorbed component are similar to the reduced fraction described above, although the absolute values are distinct. For comparison of the two components, both $\Delta^{238}\text{U}$ ($\delta^{238}\text{U}_{reduced}$ - $\delta^{238}\text{U}_{ads}$) and $^{234}\text{U}/^{238}\text{U}_{AR}$ (per cent difference) are described. Samples of the adsorbed component are both enriched and depleted $\Delta^{238}\text{U}$ compared with the reduced component, although most of adsorbed fractions are depleted in $\Delta^{238}\text{U}$ compared with the reduced fraction (range of $\Delta^{238}\text{U}$ -1.63 (-0.6 exclude outlier) to +0.26). All samples have $^{234}\text{U}/^{238}\text{U}$ enrichment in the adsorbed fraction varying in the range 16–271%. Most samples with [U]>10 ppm have $^{234}\text{U}/^{238}\text{U}$ enrichments of less than 75%, while most samples with [U]<10 ppm have enrichments greater than 75%.

3. DISCUSSION AND CONCLUSIONS

The distributions of U and U isotope ratios in the studied roll-front appear to have a systematic distribution, which is distinct from earlier isotopic observations that lacked the resolution to capture this phenomena [5, 7, 9] (but recognized by Ref. [15]). In order to understand the distribution of U and U isotope values, a simplified two dimensional reactive transport model was constructed. The model is constrained by the observed reservoir hydraulic conductivity and the spatial observations of U and U isotopes. In the first instance, the fluid velocities are set at the maximum value coincident with the high U concentration zone and calculated above and below using a no slip boundary condition at the top and bottom of the domain (i.e. pipe flow model). The model does not consider hydrodynamic dispersion or chemical diffusion. The U reduction rate is assumed to be a pseudo-zero reaction with a rate that is characterized by the width of the roll-front at 0.1 μ mol·L⁻¹·year⁻¹. The reaction order is reasonable if U reduction is catalyzed by enzymes or by mineral surfaces. The distribution of U and U isotopes is solved:

$$v\frac{dU}{dx} = -R$$

Where x is distance (m), v is fluid velocity (m/year), U is the uranium concentration in mol/L and R is the precipitation rate mol/year.

The simulation of uranium reduction over the model domain yields a convex distribution of δ^{238} U with the most enriched solids in the centre of the domain and more depleted values towards the upper and lower boundaries, similar to the observed pattern in the Smith Ranch–Highlands cores. This model is a single-pass analytical solution and does not integrate U addition over the lifetime of the redox boundary, meaning that the concentration profiles cannot be investigated directly.

The model uses a single ${}^{238}U/{}^{235}U$ isotopic fractionation factor and yields U solids that are both enriched and depleted in $\delta^{238}U_{(s)}$ compared with the starting solution composition. Thus, the enriched and depleted $\delta^{238}U_{(s)}$ occurring in close proximity to each other can be explained solely on the basis of advective transport and a single reduction reaction.

The model does make an additional prediction that the change in $\delta^{238}U_{(s)}$ with distance should be smallest in the high flow zone and greatest as the low flow zone adjacent to the zero flow boundaries is approached, which was observed in the dataset, though not to the extremes predicted in the model. In one other roll-front deposit, extreme values of $\delta^{238}U$ -4‰ were recorded in mineralized sands, which is consistent with similar effects as the model presented above [7]. *Preliminary conclusions:* The U isotopic compositions of roll-front ores can vary substantially over the metre scale and larger. These variations can be largely explained by advective transport during roll-front ore deposition without significant changes in the mechanisms of U mineralization. These findings also suggest that large changes in hydraulic conductivity in the reservoir may affect the ISL mining and remediation efficiencies.

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RADIOLOGICAL ASPECTS OF ALKALINE LEACH URANIUM IN SITU RECOVERY (ISR) FACILITIES IN THE UNITED STATES

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1. SUMMARY

In Situ Recovery or In Situ Leach (ISR/ISL) uranium facilities, also referred to in the past as "uranium solution mining" have operated since the late 1960s in the United States. In recent years ISR has accounted for over 70 % of United States uranium production and internationally almost half of worldwide uranium production.

This extended abstract presents a summary of the radiological characteristics of typical ISR processes currently employed in the United States. In addition, these ISR operations have traditionally used alkaline based lixiviants. The paper describes the health physics and radiological monitoring programs required to adequately monitor and control radiological doses to workers. Although many radiological aspects of ISR are similar to that of conventional mills, conventional-type tailings as such are not generated. However, liquid and solid by-product materials may be generated and impounded which can result in a source of occupational exposure. Under these conditions, specific monitoring considerations are required due to the manner in which radon 222 gas is evolved in the process. The major aspects of the health physics and radiation protection programs that have been developed at these facilities over many years and include:

- Airborne monitoring for long lived radioactive dusts;
- External exposure monitoring primarily in areas in which large quantities of uranium concentrates are processed and where radium precipitates may accumulate;
- Surface area and personnel contamination surveillance;
- Bio-assay (urinalysis) programs commensurate with the metabolic characteristics of the uranium species produced;
- Radon/progeny monitoring, particularly at front end of process where radon is most likely to evolve from solutions returning from underground.

2. BACKGROUND

Uranium deposits in the United States amenable to ISR methods are usually associated with relatively shallow aquifers, about 30 - 150 meters subsurface and are confined by non-porous shale or mudstone layers. Uranium was transported to these deposits over geologic time as soluble anionic complexes by the natural movement of oxygenated groundwater. Uranium deposition occurred in areas where the groundwater conditions changed from oxidizing to reducing. This produced a roll front deposit with uranium concentrated at the interface between the oxidized and reduced sandstones. This interface is commonly known as the Redox Interface.

In the United States, commercial scale recovery of uranium in ISR facilities is achieved through the use of alkaline solutions, known as the lixiviant, to dissolve the uranium in situ for recovery from wells (some historical R&D efforts have used acid based lixiviants and this is being further evaluated by one US operator today). Uranium is then removed from the lixiviant solution using ion exchange processes in in above ground processing facilities. The barren lixiviant is refortified and recycled through the process back into the well fields.

In the alkaline leach ISR process used in the US, groundwater is fortified with an oxidant (gaseous oxygen or hydrogen peroxide) and oftentimes an anionic complexing agent to solubilize the uranium within the ore body in order to enhance recovery of uranium. The oxidant converts uranium from the 4+ (reduced) to the +6 (oxidized) valence state, making it amenable to solubilization and complexation. The lixiviant composition is usually maintained at a slightly alkaline pH. Lixiviant composition is based on the local geochemistry and the relative importance of calcium species.

The uranium is chemically stripped from the ion exchange resin. The uranium is then eluted from the loaded resin and precipitated from the eluate. In recent designs, the resin may be eluted directly in the ion exchange vessel or transferred to a separate elution column or tank. The uranium precipitate, formerly ammonium diuranate (e.g., using sodium or ammonium hydroxide) or more recently uranyl peroxide (using hydrogen peroxide) is conveyed to a product drying/packaging area where it is converted to the final uranium oxide product. At facilities using high temperature calciners (800 - 1000° C), final products are typically U₃O₈ and/or UO₂. In designs using lower temperature vacuum drying (e.g., 300 - 400 °C), the final products are typically uranyl peroxide (UO₄) uranyl trioxide (UO₃), their hydrates and/or combinations thereof [1,2]. Some process strategies involve a final product of loaded resin or an intermediate precipitate only (satellite plant), and then ship this product to another uranium recovery facility for further processing. The final product may therefore be loaded resin, an intermediate product or slurry or relatively dry oxide powder.

3. RADIONUCLIDE MOBILIZATION AND ASSOCIATED PROCESS RADIOLOGICAL CHARACTERISTICS

Based on early studies performed in the United States at alkaline leach uranium solution mining plants [3] a relatively small percentage of the uranium progeny in the ore body is mobilized by the lixiviant and the majority of equilibrium radionuclides remain in the host formation [4]. Note that such values may be process specific (e.g., alkaline vs. acid leach, pH, etc.) and may also be facility age dependent. In the United States alkaline leach processes, it appears that the thorium 230 equilibrates and very little is dissolved by the lixiviant. Mobilized radium 226has the same chemical characteristics as calcium in alkaline leach processes and results in radium carbonates / sulfates in calcite slurry bleed streams and associated wastes.

The ion exchange (IX) resin used in United States ISR facilities is specific for removal of uranium. Appreciable amounts of thorium and other progeny are not expected in the process downstream of the IX columns (e.g., elution, precipitation, and drying circuits). The radionuclide mixture that can potentially become airborne and result in personnel exposure and area or equipment contamination in the precipitation, drying and packaging areas would be expected to be primarily a natural uranium isotopic mixture with a relatively small progeny component. Although in growth of the first few short-lived progeny (e.g., thorium 234, protactinium 234) is occurring, the in-process residence time is small relative to radionuclide half-lives and therefore time required for appreciable ingrowth. Accordingly, little contribution from these primarily beta emitters is experienced in the radiological aspects of in process materials.

In areas where solid wastes are processed, stored or during maintenance (resin tanks and columns, fabric and sand filters, clarifiers, etc.), mobilized radium 226 associated with calcium and carbonate chemistries may be an important external exposure and/or contamination source.

During some maintenance activities when systems need to be opened and/or penetrated, aged process material may be encountered containing scale and/or precipitates in pipes, tanks, pumps, etc., which can exhibit elevated beta activity due to ingrowth of short lived thorium 234 and protactinium 234.

Finally, large quantities of radon 222 gas can be dissolved in the lixiviant returning from the formation is brought to the surface. That portion of the total dissolved radon which is above the solution's saturation value is released when encountering atmospheric pressures and temperatures and can also be released during

the decay of radium contained in waste products (e.g., CaCO₃ /gypsum) being processed and stored at the surface [4, 5, 6]. However, despite potentially large quantities of the gas being evolved, it is "fresh radon" and the progeny equilibrium factors are typically quite low.

4. PRINCIPAL EXPOSURE PATHWAYS AND ASSOCIATED MONITORING REQUIREMENTS

The primary exposure pathways associated with ISR operations were identified in the summary section and are discussed in greater detail below.

1) Airborne monitoring for long lived radioactive dusts (LLRD):

Because ISR operations are essentially an aqueous process until drying and packaging, control and containment of spills in process areas via design consideration is essential to reduce the risk of resuspension of LLRD (essentially yellowcake dusts) in these areas. Additionally, during operations, it is important to affect expedient wash down and clean-up of spills to minimize dried material becoming an inhalation hazard via resuspended dusts.

Airborne monitoring for LLRD is necessary in back end process areas, e.g., beginning where the precipitate slurry is produced. Accordingly, LLRD exposure potential is primarily associated with the "yellowcake areas" of the process that include precipitation, drying and packaging. Applicable monitoring techniques include combinations of grab sampling, breathing zone sampling and continuous monitoring based on job functions and related radiological and work conditions.

2) External exposure monitoring:

External exposure monitoring (via survey and personnel dosimetry) is required primarily in areas in which large quantities of uranium concentrates are processed, packaged and/or stored. Additionally, depending on importance of calcium chemistry in situ and therefore radium mobilization, radium build-up can occur in resin tanks and columns, filter membranes from reverse osmosis water treatment units, fabric and sand filters, clarifiers, etc., where large quantities of radium bearing calcite wastes are precipitated, processed and stored. This can result in requirements for control and monitoring of external exposure during work near these processes, during filter changes and / or maintenance of these systems.

External exposure (particularly extremity exposure) from short lived beta emitting uranium progeny (Th 234, Pa 234 e.g.) can occur during maintenance activities when systems are penetrated and / or opened. Accordingly, care should be taken and beta / gamma and/or beta exposure rate monitoring may need to be conducted on a case-by-case basis to assess degree of this potential hazard. Potential for exposure of hands and forearms during these activities must be considered, although these types of exposure events would be expected to be occasional and of relatively short duration (minutes or a few hours at a time).

3) *Surface area contamination surveillance and control:*

ISR operations are primarily aqueous processes until product drying and packaging. Accordingly, these back end areas are typically the most important sources of potential surface contamination and resuspension. Standard contamination controls (containment, ventilation, radiological survey [areas and personnel]) and expedient response to process upsets involving spills or other loss of containment events minimizes the potential for this pathway. Contamination surveillance and control is necessary throughout plant and ancillary areas including of personnel and for the release of equipment and materials for unrestricted use into the public domain.

4) Bio-assay (urinalysis) programs:

As is the case with all uranium processing facilities, bioassay programs need to be designed commensurate with the metabolic characteristics of the uranium species produced. Modern ISR operations in the United Sstates are producing peroxide-precipitated products dried by low temperature vacuum dryers. These products appear to be quite soluble and meet the ICRP 71 criteria

for the Type F (fast) absorption category. For these products, chemical toxicity drives worker risk from intake - not radiation dose [1,7,8,9]. Accordingly, bioassay (urinalysis) programs at United States ISR operations involve frequent urinalysis sampling (can be weekly) and analysis for, in addition to uranium, the biomarkers associated with potential renal injury, e.g., glucose, lactate dehydrogenase (LDH) and protein albumen.

5) Radon and Radon Progeny:

Exposure to radon gas evolving in front end process areas from uranium bearing lixivants returning from underground are typically controlled because (1) these areas are of low occupancy and typically well away from other work areas and (2) it is relatively "fresh radon" and therefore the progeny equilibrium factors are typically quite low with the potential for worker exposure also low because the vast majority of dose results from the short-lived progeny and not the radon gas itself. Depending on design specifics, engineered controlled systems such local exhaust systems on front end tanks and vessels are sometimes necessary to collect and remove the fresh radon gas before significant progeny ingrowth can occur in work areas. Most of the gas is released within the first few process areas, wherever first exposed to atmospheric pressure. Depending on design specifics, this can be at surge ponds and tanks, at the tops of the ion exchange columns and/or at the interface between resin loading and elution processes. Process tankage and piping may need to be enclosed and maintained under negative ventilation where practical. In warm climates such as ISR facilities in South Texas, surge ponds located outdoors and/or open top ion exchange columns are often used and therefore most of the gas is released outside of enclosed process areas. In colder climates (Wyoming, Nebraska), the solutions are piped under pressure directly from enclosed well field valve stations and surge tanks to in plant recovery vessels including the IX tanks themselves. Some of the first generation ISR plants (1970s) used in plant IX surge tanks and up flow, open top IX columns requiring use of local exhaust systems to remove the gas from the vicinity of in-plant vessels before progeny ingrowth became an occupational exposure concern. Recent designs tend towards use of enclosed, pressurized systems for lixiviant recovery and ion exchange using local exhaust on the vessels themselves to remove radon prior to significant progeny in growth. This greatly reduces the potential for radon / progeny exposure in plant areas.

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USING CONTINENT-SCALE SPATIAL TARGETING TO DELINEATE PERMISSIVE AREAS FOR SANDSTONE-HOSTED URANIUM

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1 INTRODUCTION

An ambitious sandstone-hosted uranium mineral prospectivity model covering the entire Australian continent hints at undiscovered mineral potential. Australia was chosen to demonstrate the usefulness of huge-scale multi-criteria analyses due to the relatively large volume of publicly available data covering the entire continent and because it is host to a considerable number of spatially distributed and economically significant deposits (e.g., Beverley, Manyingee, Bigrlyi). It is important to note that although all of the deposits under consideration are similarly classed as 'sandstone-hosted', significant differences exist in their host rock and mineralisation ages, mineralogy and in their underlying mineralising processes. Can a single predictive model really be expected to account for the distribution of all these genetically diverse systems?

Traditional approaches to mineral potential mapping involve interpretation of individual maps, or manual overlay of groups of 'predictor maps' to delineate favourable exploration areas. In the (not so distant) past, simple overlays were commonly performed using light tables and analogue interpretation methods (i.e., a pencil). An inevitable consequence of the rapid advancement in both the availability of vast, high-resolution digital data sets and the inexorable growth in computing power has been that geographical information systems (GIS) and spatial analysis have rapidly become ubiquitous in mineral exploration. Traditional approaches have been supplanted by the use of GIS and digital overlays, allowing for the rapid interpretation of a huge variety of spatial data with an ever increasing assortment of analytical techniques. Multi-criteria spatial targeting is now being deployed routinely in the search for, and assessment of areas that have potential to contain economic concentrations of desirable minerals [1-9].

The ultimate goal of this study is to reduce a wide range of complex conceptual models of ore genesis to their most fundamental mappable components. These basic elements are then reconstructed in a targeting model which aims to imitate the thought processes of the exploration geologist. The underlying challenge is to construct a single mathematical model which adequately describes the distribution of known sandstone-hosted uranium deposits across a wide variety of terrains, ages and mineralisation (sub-)styles for an entire continent. The success criteria are that the model must be capable of effectively 're-discovering' all areas of known mineralisation, yet it must be discerning enough that it doesn't highlight vast areas which are confidently regarded as having limited upside potential. Areas highlighted by such a model which lie outside of known mineralised zones logically possess all of the critical components of sandstone-hosted uranium mineralising systems. These areas are potentially under-explored and may be worthy of further investigation.

2. METHODS AND RESULTS

The basic premise of this GIS-based mineral prospectivity analysis (MPA) is the recognition of the essential criteria of sandstone-hosted uranium deposits [10] and translation of those criteria into quantifiable spatial parameters which can then be handled mathematically. The first step is to acquire and assess any spatial data that may be turned into useful proxies for components of the mineralisation genetic model. This

generally requires a thorough audit of all publically available data. Data sets that were selected as being of potential use for the construction of the Australia-wide MPA include:

- surface geology (1:1m, 1:5m & 1:2.5m scale)
- crustal elements
- Australian geological provinces
- metamorphic grade and ages
- structural data
- radiometrics
- digital elevation models (SRTM and derivatives)
- drainage pathways
- sedimentary basin extents and thicknesses
- paleo-channel distribution

Australian explorers have access to an extraordinary amount of publicly available, multi-disciplinary data sets of very high quality. However, not all these data are useful for their straightforward inclusion in a continent-scale MPA. Some lack sufficient resolution, while others are too data-rich to be practical at the continent scale without significant modification.

A holistic mineral systems approach [11 - 13] is used to classify and combine the data so that a meaningful output can be generated. This approach considers all geological factors which control the generation and preservation of mineral deposits (including sources of metals, ligands and energy, fluid migration pathways and focusing mechanisms, and chemical and/or physical causes for precipitation at the trap site). A range of 'predictor maps', which represent mappable components of the mineralisation system under consideration, are derived from the spatial data. For this study, predictor maps are designed to represent individual components of the 'Source' (e.g., basement, uranium-enriched felsic igneous rocks), 'Transport' (e.g., faults, drainage pathways) or 'Trap' (e.g., reduced sediments, morphological barriers) parts of the mineral system. The creation of predictor maps and the subsequent analysis was performed in ESRI ArcGIS (Version 10.4.1).

Data preparation and the creation of predictor maps commonly involve some simplification and interpretation. For example, complex geology data can be re-classified into simpler stratigraphy and lithology predictor maps, each comprising a manageable number of classes. Multi-ring buffers can be constructed around features (e.g., granite bodies) to test proximity effects, with each concentric buffer being treated separately in the model. Thresholding can be used to simplify geophysical and other raster data into classes that can be handled more readily in the mathematical model. The construction of some of the 26 predictor maps used in this study is briefly outlined in this presentation.

A knowledge-driven approach (Fuzzy Logic) relies entirely on expert input to assign weights to individual predictor maps and their components to account for the relative importance of each feature in the mineralising system. A relatively simple method is used to calculate 'Fuzzy Membership' values in this study. 'Class weights' (0-10) are assigned to each feature within a predictor map based on the relative prospectivity of the feature. Additionally, 'Map weights' (0-10) are assigned to each predictor map based on the relative importance of the component it represents in the genetic model, and confidence in the underlying data. Multiplying the class by the map weights for each feature in a predictor map gives a 'class score' for that particular feature; dividing the class score by 100 results in a 'Fuzzy Membership' value between 0 and 1 for the feature. This is done for every feature in every predictor map. This is the value that is used in the final analysis. The (vector) predictor maps are converted to numerical raster grids based on the Fuzzy Membership value, allowing mathematical operations to be carried out on the newly created 'stack' of rasters on a cell-by-cell basis.

A logic network combining the input predictor rasters is carefully constructed such that it follows sound geological reasoning appropriate to the targeting model. The judicious use of Fuzzy 'AND', 'OR', 'SUM', 'PRODUCT' and 'GAMMA' logic operators allows quite complex relationships between components to be expressed in the model, reflecting the way in which a geologist might think but extrapolated up to the scale of the analysis (continent-scale in this example) and over a multitude of simultaneous input criteria. In our model, the three major mineral system components (Source, Transport and Trap) are treated separately before being combined in the final stage of the logic network. Solving the logical arguments for each corresponding cell in the stack of weighted predictor map rasters, results in a numerical grid that is interpreted to represent spatial variations in prospectivity. This can then be reclassified and displayed as a colour-coded, multi-class favourability map.

3. DISCUSSION AND CONCLUSION

We consider the fuzzy logic mineral prospectivity model presented herein to be a successful first-pass GISbased analysis for sandstone-hosted uranium deposits on the Australian continent. Crucially, the majority of known sandstone-hosted uranium deposits and provinces occur within areas of elevated to very high favourability in the resulting favourability map, demonstrating the geological validity of the model. Additionally the model identifies several regions that should contain all the ingredients for sandstone-hosted uranium but may have been overlooked or underexplored by previous explorers.

However, the model has substantial limitations that must be kept in mind when interpreting the resulting favourability map. At the continental scale and due to the necessary use of highly simplified and modified versions of the spatial data, substantial uncertainties in the properties of the inputs remain. This is particularly true of the heavily modified geology (simplified lithology and stratigraphy) predictor maps but affects all data sets to some extent. Due to these uncertainties, the continental-scale model presented herein is not considered useful for delineating specific exploration targets but is particularly effective at identifying broader permissive areas, as well as regions of elevated favourability within these zones.

It is also important to note that the output generated from this model represents just one of an infinite number of possible solutions. Every step in the process, including initial data selection, predictor map design, assigning weights to features and maps and construction of the logic network was driven by a very small group of 'experts'. While we maintain a high level of confidence in our analysis, the opinions of alternative 'experts' are likely to differ (at least somewhat). A significant advantage of this type of analysis over more traditional approaches is that it allows for rapid iterative modification. New data, weights or modified logic network designs that target specific deposit types, or that consider alternate genetic models (for example) can be readily accommodated and tested.

The MPA methodology has the ability to quickly reduce the search space, highlighting specific zones of elevated mineral potential. These targets can then be ranked and prioritised for more detailed follow-up, ground-truthing or higher resolution MPA. At a continental scale, such target zones effectively highlight so-called 'permissive tracts' [14], representing geological regions that have potential to host undiscovered mineral deposits. The delineation of a permissive tract can contribute to estimating the potential number and size of undiscovered mineral deposits in an area, which has a variety of important economic, land, resource and environmental planning applications [15 - 16].

The continent-scale Fuzzy Logic MPA for sandstone-hosted uranium in Australia demonstrates that GISbased targeting concepts can be used to objectively delineate and visualise permissive areas for uranium, thereby dramatically reducing the search space and assisting with area selection and decision making processes. This study demonstrates how multiple specifically designed and weighted input predictor maps can be combined using a carefully constructed logic network to create a spatial representation of relative favourability for a specific mineral deposit type at the continental scale. This study clearly benefits from the relatively large volume of high quality, relevant and publicly available spatial data for the Australian continent. However, this type of study is possible in areas where less (or different) data are available because the analysis is built up around to the type of mineralising system under consideration and according to the available data. The veracity of any MPA depends heavily on the quality of suitable input data ("rubbish in – rubbish out") so questionable data should be rejected as part of the preliminary data assessment. A simpler model is always preferable to one containing erroneous data.

If performed carefully and meticulously, GIS-based Fuzzy Logic mineral prospectivity modelling can provide an extremely powerful visualisation and decision-making tool.

A comprehensive account of the methods used in this study, including the rationale for using particular data sets, the construction of predictor maps, assigning fuzzy membership values and construction of the logic network is presented as a chapter in an upcoming IAEA TecDoc on "Spatial and quantitative modelling of undiscovered uranium resources" [17].

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UDEPO: THE IAEA URANIUM DEPOSITS DATABASE

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1. HISTORICAL BACKGROUND

In 1995, the IAEA published a map, World Distribution of Uranium Deposits [1], which was followed in 1996 with a World Guidebook [2] to accompany the map. The guidebook contained information on 582 uranium deposits (\geq 500 tU, \geq 0.03% U), describing 13 parameters that included location, status, resource range, average grade range, age, host rock and tectonic setting. However, at that time, for many deposits, this knowledge was very limited.

In the late 1990s, a considerable amount of information on uranium deposits, particularly from the former Eastern Bloc countries became available. Subsequently, a sharp increase in the price of uranium in 2005 led to greatly increased exploration and the discovery of many new deposits.

The guidebook and the database on which it is based is known as UDEPO (Uranium **DEPO**sits). The database has been published on the IAEA web site since 2004 and has been continuously updated to include new deposits and provide more information on the uranium geology and technical characteristics of the deposits.

In 2009, a technical document, World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification [3], was published by the IAEA with data for 874 uranium deposits (\geq 500 tU, \geq 0.03% U, 37 parameters described).

A new report published in 2018, World Distribution of Uranium Deposits (UDEPO) – 2016 Edition [4], contains information on 1807 uranium deposits (\geq 300 tU, no grade restriction) and uses the new classification of uranium deposits adopted in 2013 by the IAEA [5–7]. It contains summary tables, diagrams and figures illustrating the diversity of the uranium deposits.

The database is continually updated and improved and although not publishing exact values of resources and grades, is nevertheless an interesting and useful tool for geologists and researchers. In addition, a world map of uranium deposits has been published by the IAEA to accompany the database.

2. THE UDEPO DATABASE

As of late 2017, a total of 2939 deposits and resources are listed in the database. All deposits with resources greater than 1 tU are included, regardless of their grade or status. The economic value of a resource is not taken into consideration for its inclusion.

In the latest 2016 version of the Red Book, a uranium deposit is defined as "a mass of naturally occurring mineral assemblage from which uranium has been or could be exploited at present or in the future" [8]. For the IAEA UDEPO database, which is primarily a geological database, the definition has been broadened to include any identified geological concentration of uranium resource regardless of the tonnage or grade. Thus, UDEPO lists conventional deposits/resources and also large to very large low grade unconventional resources [4, 9].

The database contains data distinguished on the basis of a total of 49 parameters and grouped into four categories: (i) general data, (ii) geological data, (iii) resource data, and (iv) mine data. The entered parameters in the database are as follows:

- i) *General data*: (1) Deposit ID, (2) Country Name, (3) Deposit Name, (4) Synonym Names, (5) Political Province, (6) Latitude, (7) Longitude, (8) Deposit Status and (9) References;
- Geological data: (10) Uranium Province Name, (11) Geological Province Name, (12) Deposit Type, (13) Deposit Subtype, (14) Deposit Class, (15) Historical Background, (16) Regional and Local Geological Setting, (17) Deposit Description, (18) Depth to the Top of Mineralization, (19) Mineralization Description, (20) Elemental Association, (21) Stratigraphic Host Rock Age, (22) Radiometric Host Rock Age, (23) Mineralization Stratigraphic Age, (24) Mineralization Radiometric Age and (25) Metallogenic Aspects;
- iii) Resource Data: (26) Resource (tU), (27) Resource Range (tU), (28) Ore Tonnage, (29) Grade (U%), (30) Grade Range (U%), (31) Date of Estimate, (32) Type of Estimate, (33) Source of Data and (34) Description of Resources;
- *Mine Data*: (35) Cumulative Production (tU), (36) Production Grade (U%), (37) Mined Ore Tonnage, (38) Remaining Ore Tonnage, (39) Mining Methods, (40) Production Centre, (41) Milling Process, (42) Commodities Recovered, (43) Production Period, (44) Remaining Resources, (45) Grade of Remaining Resources, (46) Production Cost, (47) Technical Remarks, (48) Operator and (49) Owners and Shares.

Currently, deposit's coordinates (6, 7), discrete grades and resources (26, 29) and production costs (46) are not published by the IAEA even where some of these data are available on the web. Only ranges of grade and resource are listed on the UDEPO public site (<u>http://www-nfcis.iaea.org/</u>). UDEPO is organized in a relational database format comprising one main table and several associated tables. The structure of the database allows filtering and systematic querying of the database. UDEPO is designed to facilitate the retrieval of datasets on various deposit related topics ranging from specific information on individual deposits to statistical information on deposits worldwide. Data can be searched according to deposit type, status and country, using the filter tools provided.

3. RESOURCES IN UDEPO

In UDEPO, resources include all current resource categories and, where available, details of past production. For some historical districts (i.e. Canada, Czech Republic, France, Germany, United States of America, etc.) and in many other cases, only the production data are available. Where resources for a deposit have been estimated (NI 43-101, JORC, etc.) at several cut-off grades (which is generally the case in company reports and press releases), resources at the lowest cut-off grade are adopted. All data are given in metric tonnes of uranium (tU).

As of the December 2017, the database includes 2939 deposits distributed among the 15 types (with some unknown), 38 subtypes and 14 classes defined in the IAEA geological classification of uranium deposits [5–7]. The 15 types with their numbers of deposits and their aggregate geological resources are listed below:

Type 1. Intrusive :	129 deposits	2 847 000 tU
Type 2. Granite-related :	586 deposits	527 000 tU
Type 3. Polymetallic iron oxide breccia complex :	21 deposits	2 562 500 tU
Type 4. Volcanic-related :	204 deposits	1 908 500 tU
Type 5. Metasomatite :	152 deposits	1 070 000 tU
Type 6. Metamorphite :	225 deposits	663 000 tU
Type 7. Proterozoic unconformity :	114 deposits	1 547 500 tU
Type 8. Collapse breccia pipe :	18 deposits	19 500 tU
Type 9. Sandstone :	951 deposits	4 827 000 tU
Type 10. Palaeo-quartz-pebble conglomerate :	144 deposits	2 504 000 tU
Type 11. Surficial :	123 deposits	532 000 tU
Type 12. Lignite-coal :	75 deposits	7 406 500 tU
Type 13. Carbonate :	34 deposits	184 000 tU
Type 14. Phosphate :	73 deposits	14 326 000 tU
Type 15. Black shale :	75 deposits	21 749 000 tU
Unknown :	15 deposits	

As of late 2017, total geological resources of uranium in UDEPO stand at approximately 62 673 000 tU, within the 2755 deposits with known/estimated resources. The largest resources are contained in unconventional resource deposit types such as those associated with polymetallic iron oxide breccia complex (IOCG-U), phosphate, lignite–coal and black shale. It should be noted that for the polymetallic iron oxide breccia complex deposits, 80% of the resources are contained within a single deposit, Olympic Dam. The most important conventional resource deposit types are the sandstone hosted type followed by the Proterozoic unconformity type and the volcanic-related type.

Eighty-three countries have uranium deposits/resources listed in UDEPO.

Conventional geological resources within UDEPO can be compared with the 'economic' Red Book data [8]:

- World historical uranium production to 2016: 2 802 230 tU;
- Red Book 2016 conventional resources (<\$ US260/kgU): 7 641 600 tU;
- UDEPO conventional resources (including Olympic Dam): 14 034 700 tU.

The sum of world historical production and Red Book resources is 10 443 830 tU. Therefore, UDEPO identifies an additional 3.5 M tU as conventional geological resources.

4. VALUE OF UDEPO

The various data contained in the database, even if not currently complete, enable the compilation of deposit types, subtypes and classes, country resources, uranium provinces resources, statistical diagrams using various parameters, cumulative frequency diagrams, grade–resource–tonnage scatter plots for each type and subtypes, etc. With the addition of new data, it will be possible to derive statistical geological information on parameters such as tectonic setting, age of mineralization and associated elements, and also on various mining parameters, etc.

The number of deposits as of late 2017 for each resource range and their total geological resources is:

>1 000 000 t U :	11 deposits	41 013 600 tU
100 001-1 000 000 :	39 deposits	8 081 000 tU
50 001-100 000 :	52 deposits	3 016 000 tU
25 001-50 000 :	89 deposits	3 200 000 tU
10 001-25 000 :	218 deposits	3 342 500 tU
5001-10 000 :	250 deposits	1 795 300 tU
2501-5000 :	300 deposits	1 098 000 tU
1001–2500 :	428 deposits	721 000 tU
300–1000:	580 deposits	355 700 tU
1–300 :	788 deposits	87 000 tU

General information such as the uranium endowment ($tU/km^2 \times 100$) for each continent can be calculated using conventional resources numbers:

North America:	12
South America:	2
Asia:	7
Europe:	13
Africa:	13
Australasia:	12

The lower numbers for South America, as well as Asia, possibly indicate that they are underexplored in comparison to other continents.

5. PRESENT AND FUTURE OF THE DATABASE

In terms of data presented, the UDEPO database is unique as it provides freely accessible information on global uranium deposits. However, it must be emphasized that:

- Data entry of 49 parameters for each deposit/resource is time consuming as for most databases. Large portions have not yet been completed;
- Coordinates are commonly collected, but are not published. Collected data has permitted the publication of a world map of uranium deposits in 2018;
- Exact numbers for resources and grades are not published owing to the loose definition of resources in an economic sense and the aggregation of different categories of resources. However, the IAEA will allow the publication of these data in the near future if the official references to the numbers are presented in the database;
- Some countries, for example, China, Kyrgyzstan, Pakistan and Uzbekistan, have no information available or very little or incomplete deposit information;
- The recent inclusion of small deposits within the range 1–300 tU has dramatically increased the number of deposits which were previously aggregated into historical mining districts or ignored (i.e. Czech Republic, France, Germany, USA, etc.). For example, currently, the USA has 406 deposits/resources listed in UDEPO, but a recent compilation indicates that the number of deposits/resources is of the order of 4000!
- Future new additions will most likely come from unconventional resources/deposits associated with intrusive plutonic, phosphates, black shale and coal-lignite deposit types. It is inferred that most of these host rock formations contain at least some uranium concentrations in the range 10– 200 ppm U, but no information is available concerning their specific grades. Estimates of the number of such geological formations suggest there could be in the range of 5000–6000 additional unconventional deposits [9].

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UNCONVENTIONAL RESOURCES IN IAEA URANIUM DEPOSIT DATABASE (UDEPO)

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1. INTRODUCTION

Unconventional resources are defined in the 2016 edition of the 'Red Book' [1] as

"Resources from which uranium is only recoverable as a minor by-product, such as uranium associated with phosphate rocks, non-ferrous ores, carbonatite, black shale and lignite."

Unconventional resources of uranium are recorded in UDEPO, the IAEA's Uranium **DEPO**sit database [2, 3]. They correspond to low to very low grade, generally very large geological resources where uranium can only be extracted as a co- or by-product of other mining production. In most cases, this cannot currently be done economically with existing technologies.

In the IAEA geological classification of uranium deposits [4, 5], most unconventional resources are associated with the following deposits types and subtypes: intrusive plutonic, polymetallic iron oxide–copper–gold breccia complexes (IOCG-U), volcanic-related, Au-rich palaeo-quartz-pebble conglomerate, placers, lignite–coal, phosphorite and black shale [6]. The largest unconventional resources are in seawater, with resources estimated at 4 billion t at an average 'grade' of 3.3 ppb (3.3 mg/m³). This resource is not included here.

2. UNCONVENTIONAL URANIUM RESOURCES IN UDEPO

In mid-2017, UDEPO's 'inventory' of total geological uranium resources stood at 62 674 137 tU hosted within 2755 deposits with known or estimated resources. Their repartition is as follows:

- Conventional uranium resources of 11 857 089 tU, hosted within 2475 deposits with known/estimated resources;
- Unconventional resources of 50 817 048 tU, hosted within 280 deposits with known/estimated resources. Deposits such as Olympic Dam (IOCG-U) are included in the UDEPO unconventional resources category, which explains some of the differences in the figures when compared, for example, with Red Book data.

UDEPO is, first and foremost, a geological database and therefore there are no economic connotations taken into consideration. Unconventional resources or deposits are those that cannot be mined solely for uranium (co- and/or by-product) and include:

- Very large (generally >1 MtU), low grade (20–200 ppm U) resources such as those in volcanic formations (northern Latium province, Italy), lignite–coal (northern Great Plains, United States of America), phosphorites (Morocco basins) and black shale formations (Baltoscandian district);
- Large (10 000–100 000 tU), low grade (50–250 ppm U) resources located within peralkaline plutonic intrusions (Kvanefjeld, Greenland) and carbonatites (Palabora, South Africa), polymetallic iron oxide breccia complexes (Olympic Dam, Australia) and Au-rich palaeo-quartz-pebble conglomerates (Witwatersrand Basin deposits, South Africa);
- Very low grade ('background') uranium (10–30 ppm U) in porphyry copper deposits (Bingham Canyon, USA), volcano-sedimentary formations (El Boleo, Mexico) and base metal deposits (Talvivaara mine, Finland);
- Placer deposits.

In UDEPO, 12 of these unconventional resources contain more than 1 MtU:

- Phosphoria Formation (USA): 7 Mt, 0.005—0.015% U (phosphorite);
- Tarfaya Basin (Morocco): 6.4 Mt, 0.008% U (black shale);
- Baltoscandian district (Estonia): 5.667 Mt, 0.0085% U (black shale);
- Chattanooga Shale (USA): 5 Mt, 0.006% U (black shale);
- Northern Great Plains (USA): 5 Mt, 0.006% U (coal-lignite);
- Oulad Abdoum Basin (Morocco): 3.2 Mt, 0.012% U (phosphorite);
- Olympic Dam (Australia): 2.125 Mt, 0.023% U (IOCG-U);
- Timahdit (Morocco): 2.1 Mt, 0.005% U (black shale);
- Meskala Basin (Morocco): 2 Mt, 0.010% U (phosphorite);
- Randstad Inlier (Sweden): 1.7 Mt, 0.021% U (black shale);
- Gantour Basin (Morocco): 1.2 Mt, 0.012% U (phosphorite);
- Northern Latium province (Italy): 1 Mt, 0.005% U (volcanic-related, volcano-sedimentary).

Other than the Olympic Dam deposit, which is an operating mine, precise estimation of these large geological resources is very difficult owing to the size of the formations and the poorly characterized distribution of uranium grades within them. For example, the Phosphoria Formation (USA) covers an area of about 350 000 km², with a thickness of 60–150 m for the mineralized phosphatic layers and uranium grades are estimated to be around 50–150 ppm U. Thus, depending on the parameters used, the calculated uranium resource ranges between 5 and 60 MtU (7 Mt in UDEPO from historical data). In the past, 184 tU was extracted from localized enriched areas with tenors attaining 1% U.

3. REPARTITION OF THE UNCONVENTIONAL RESOURCES

In detail, unconventional resources are associated with several deposit types and subtypes:

— Type 1: Intrusive, plutonic subtype, with 3 classes (quartz monzonite, peralkaline complex and carbonatite). Resources: 1.907 MtU in 33 deposits;

- Type 3: Polymetallic iron oxide-copper-gold breccia complex (IOCG-U). Resources: 2.760 MtU in 18 deposits;
- Type 4: Volcanic-related, volcano-sedimentary subtype. Resources: 1.004 MtU in 2 deposits;
- Type 10: Palaeo-quartz-pebble conglomerate, Au-rich subtype. Resources: 1.860 MtU in 100 deposits. Also, in South Africa, 16 areas with tailings resources contain an estimated 175 500 tU;
- Type 11: Surficial, placer subtype. Resources: 67 000 tU in 13 deposits ;
- Type 12: Lignite-coal, stratiform subtype. Resources: 7.223 MtU in 21 deposits;
- Type 14: Phosphate, minero-chemical phosphorite subtype. Resources: 14.148 MtU in 48 deposits ;
- Type 15: Black shale, stratiform subtype. Resources: 21.473 MtU in 29 deposits.

However, the types and subtypes listed above also contain deposits previously mined for uranium and those which could be mined in the future for uranium only owing to their high grades (generally >0.05% U). In these instances, the deposits are not considered unconventional in UDEPO. Examples include the coal-lignite deposits mined in the past in Germany (Freital district), the black shale deposits of Uzbekistan and the organic phosphorite deposits mined in Kazakhstan.

a) Type 1: Intrusive, subtype 1.2 plutonic:

All quartz monzonite (porphyry copper) and most peralkaline complexes and carbonatites correspond to unconventional resources where low to very low grade (10–250 ppm U) uranium is associated with Cu, Ag, Au, Mo, REE, Th, Nb, Ta, Zn and Zr. Some exceptions are Bokan Mountain (USA) and Poços de Caldas (Brazil) where uranium was mined in the past as a primary commodity. Uranium was produced in the past at Bingham Canyon (USA), Twin Buttes (USA) and Palabora (South Africa). Uranium production is planned in the near future at the Kvanefjeld project (Greenland) in association with REE and Zn production;

b) *Type 3: Polymetallic iron oxide–copper–gold breccia complex (IOCG-U):*

Deposits of this type, with grades of 30–250 ppm U, correspond to large to very large iron–copper– gold–silver deposits occurring in the Gawler Craton (Australia) and in Carajas Province (Brazil). Uranium is extracted as a co-product along with copper–gold–silver at Olympic Dam, the world's uranium resource with 2.2 MtU. Deposits from the Mount Painter area in South Australia, which have grades of 0.05–0.20% U, are considered conventional. Some of these deposits have already been mined in the past for radium or uranium alone;

c) *Type 4: Volcanic-related, stratabound and volcano-sedimentary subtypes:*

The Quaternary alkaline volcanics of northern Latium (Italy) contain an average 20–70 ppm U, for geological resources of more than 1 MtU. Sub-marginal resources in the volcano-sedimentary formations are in the range 5000–10 000 tU at a grade of 300–600 ppm U. The El Boleo project (Mexico), a Cu–Co–Ni–Mn mine, is planning the extraction of very low grade (10 ppm) uranium;

d) *Type 10: Palaeo-quartz-pebble conglomerate, Au-rich subtype:*

Uranium is mined as a by-product of gold in the Witwatersrand Basin (South Africa). The average grade is around 250 ppm U and uranium geological resources exceed 2 MtU. In addition, there are plans to extract uranium and gold from low to very low grade (35–75 ppm U) tailings which are a legacy of gold mining over the past 130 years. Total resources in 16 areas are estimated to be of the order of 175 500 tU;

e) Type 11: Surficial, placer subtype:

Placer deposits are accumulations of heavy minerals formed by gravity separation during sedimentary processes. The principal minerals containing thorium and uranium are zircon, monazite and xenotime. India has very large resources of monazite from which uranium could be extracted, in addition to Th and REEs;

f) *Type 12: Lignite–coal:*

Most coal and lignite deposits contain very low grades, of the order of 1–5 ppm U. However, some coal deposits (such as those in Kazakhstan, Kyrgyzstan, the Russian Federation, South Africa and Ukraine) record unusually high uranium contents (0.05–0.15% U) and these are not classified as unconventional in UDEPO. In the past, uranium was extracted from fracture-controlled coal deposits in the former German Democratic Republic (Freital district). Very large quantities of tailings from coal processing around the world are enriched in uranium (5–20 ppm U) representing significant unconventional resources;

g) Type 14: Phosphate:

Phosphorites typically cover very large surface areas and represent large, low grade (50–150 ppm U) resources of uranium. Total world phosphate resources are estimated at 300 billion tonnes and, assuming an average grade of 100 ppm U, these would contain about 30 MtU. Between 1978 and 2000, 17 225 tU were extracted from the phosphorite formations in Florida. Continental phosphate deposits (Central African Republic) and organic phosphorites (Kazakhstan, Russian Federation) are listed as conventional resources due to their grade (0.05–0.3% U). Some of the Kazakhstan organic phosphorite deposits were historically mined for uranium as a major product;

h) *Type 15: Black shale:*

In UDEPO, the uranium resources of black shales are currently estimated at 21.5 MtU, with stratiform black shale formations hosting the largest geological, low grade (20–200 ppm U) uranium resources in the world. The uranium is associated with various other metals such as Ni, Co, Cu, Zn and V. Historically, uranium was mined as the primary product from this type of deposit in the Gera–Ronneburg district (former German Democratic Republic).

4. PLANNED AND POTENTIAL MINING PROJECTS

As of 2018, several operating mines or new mining projects could produce uranium as a by- or co-product. These include:

- Chuquicamata (Chile): Cu–Mo (porphyry copper), potential production of 85 tU/year from ore containing 5–10 ppm U;
- Kvanefjeld (Greenland): REE–Zn-U (peralkaline complex), planned production of 400 tU/year from ore containing 200–250 ppm U;
- Round Top (USA): REE–Be (peralkaline complex), planned production of 115 tU/year from ore containing 20–50 ppm U;
- El Boleo (Mexico): Cu-Ni-Co-Mn mine (volcanic-related), potential production of 60 tU/year from ore containing 10–20 ppm U;
- Talvivaara (Finland): Cu–Ni–Co–Mn mine (black shale), potential production of 350 tU/year from ore containing 10–15 ppm U;
- Haggan (Sweden): Mo–Ni–Zn–V-U (black shale), planned production of 385 tU/year from ore containing 120–150 ppm U;
- MMS Vicken (Sweden): Zn–Ni–Cu-U (black shale).

5. SUMMARY

Currently, 280 uranium deposits and resources listed in UDEPO are classified as unconventional resources associated with eight deposit types and containing geological resources of the order of 51 MtU. Considering the number of analogous geological host rock examples worldwide, potential additions of unconventional deposits and resources to the UDEPO database can be estimated to be of the order of 5000–6000, comprising:

- Type 1: Intrusive plutonic deposits: 1660 occurrences worldwide (33 deposits in UDEPO);
- Type 3: Polymetallic iron oxide-copper-gold breccia complex (IOCG-U) deposits: 50 occurrences worldwide (18 deposits in UDEPO);
- Type 11 : Surficial placer deposits: 500–1000 occurrences worldwide (13 deposits in UDEPO) ;
- Type 12: Lignite-coal deposits: about 1600 occurrences worldwide (21 deposits in UDEPO);
- Type 14: Phosphate deposits: 1635 occurrences worldwide (48 deposits in UDEPO);
- Type 15: Black shale deposits: around 1000 occurrences worldwide (29 deposits in UDEPO).

This indicates that potential geological unconventional resources of uranium worldwide are enormous. Of course, most of these resources will never produce uranium owing to their very low grades and the environmental impact resulting from their exploitation. However, unconventional uranium resources in conjunction with the concept of 'comprehensive extraction' will probably play an important role in future world uranium production.

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ESTIMATION OF URANIUM REQUIREMENTS FOR PLANNED NUCLEAR POWER PLANTS AND SUPPLY CAPACITY OF URANIUM RESOURCES IN TURKEY

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1. INTRODUCTION

The Turkish economy has a projected average annual growth rate of 7–8% for the near future. Therefore, the country has an increasing demand for, and consumption of, electricity. According to the tenth five-year development plan, primary energy demand of Turkey will increase by 25% while the total electricity demand will increase by 34% during this period [1]. In an effort to achieve energy supply reliability and diversity, Turkey has undertaken two nuclear power plant (NPP) projects: one with the Russian Federation at Akkuyu in the Mediterranean region, the other with Japan at Sinop in the Black Sea region. Additionally, Turkey has plans to initiate a third NPP project and increase nuclear power capacity gradually.

Ongoing NPP projects are based on the external supply of nuclear fuel. However, it is still important to evaluate the identified domestic resources of uranium, explore more extensively and determine the possible domestic contribution to the fuel needs of the NPP projects. On this basis, uranium exploration and mining activities have been accelerated in recent years.

This study aims to assess the fuel supply capacity of the uranium resources in Turkey for the Akkuyu and Sinop projects. First, the data related to the identified uranium resources in Turkey are reviewed, then the lifetime uranium requirements for the planned NPPs are estimated and the domestic potential to meet these requirements is assessed.

2. NATIONAL NUCLEAR POWER PROGRAMME

Turkey signed an agreement with the Russian Federation in 2010 for installation of four VVER-1200 units with a total capacity of 4800 MWe at the Akkuyu site. It is expected that first unit of Akkuyu NPP will be in operation in 2023. A second agreement was signed with Japan in 2013 to build four ATMEA-1 units with a total capacity of 4500 MWe at the Sinop site. Both projects are based on the build-own-operate model.

At the Akkuyu site, Akkuyu Nuclear Power Plant Electricity Generation Joint Stock Company (APC), which is a subsidiary of the Russian Federation's State-owned nuclear company, Rosatom, will build, own and operate the plant. According to the intergovernmental agreement, APC will be responsible for fuel supply, radioactive waste and spent fuel management, and decommissioning of the facility. Provisions of the agreement related to fuel supply states that the nuclear fuel will be sourced from suppliers based on long term agreements between APC and the fuel suppliers [2]. It can be foreseen that APC will deliver fuel from the Russian fuel company TVEL, which is the fuel supplier to almost all WWER reactors in operation. APC only recently obtained the limited construction permit from the Turkish Atomic Energy Authority and is expected to apply for a construction licence in the near future. The limited construction permit allows for some construction activities which do not have a direct bearing on nuclear safety.

The Sinop plant will be built, owned and operated by a consortium established by Mitsubishi Heavy Industries, Itochu Corporation, GDF Suez and the Turkish State-owned Electricity Generation Company (EÜAŞ). The fuel supply issue is not detailed in the intergovernmental agreement and will be determined after the completion of the feasibility study. Currently, work related to the site and the environmental impact

assessment is continuing. Most recently, the environmental impact assessment file for the Sinop project has been submitted to the Environment and Urban Planning Ministry.

As a result of these developments, Turkey is expected to have at least 9300 MW(e) of installed nuclear electric capacity in the next 15–20 years.

Additionally, the Chinese State Nuclear Power Technology Corporation, the US Westinghouse Electric Company and the Turkish EÜAŞ signed a memorandum of cooperation in 2014 to launch negotiations on constructing four NPP units, which apply the advanced passive PWR CAP1400 and AP1000 technology. For the third project, site selection studies are ongoing. With respect to this, a cooperation agreement between China and Turkey on the peaceful uses of nuclear energy was ratified by the Turkish Parliament in 2016 [3].

3. URANIUM EXPLORATION AND MINING STUDIES AND DOMESTIC RESOURCES

In Turkey, radioactive raw material research and uranium exploration work were initiated in the 1950s by the General Directorate of Mineral Research and Exploration (MTA). In early stages, the work was concentrated on the vein type deposits in igneous and metamorphic rocks. After identification of some uneconomic uraninite mineral occurrences, efforts were then directed towards sedimentary type deposits. Up to now, total resources of 12 614 tU have been identified in various regions of Turkey, most of them of sedimentary type [4].

According to MTA reports, the Temrezli deposit in the Yozgat-Sorgun region is the largest and the highestgrade U resource, with 6700 tU at an average grade of $0.1\% U_3O_8$. Other resources are located in Manisa-Köprübaşı, with 3487 tU at an average grade of $0.04-0.07\% U_3O_8$; in Uşak-Eşme-Fakili, with 3490 tU at an average grade of $0.05\% U_3O_8$; in Aydın-Demirtepe, with 1729 t U at an average grade of $0.08\% U_3O_8$ and in Aydın-Küçükçavdar with 208 tU at an average grade of $0.04\% U_3O_8$ [4].

Uranium exploration and mining activities have gained momentum due to the recent developments in the national nuclear power programme. In addition to the studies carried out by MTA, Adur, a private Turkish mining company and is a subsidiary of the US-based Uranium Resources Inc. (URI), is conducting drilling activities for resource evaluation on the Temrezli and Sefaatli deposits located in the Yozgat-Sorgun region. A preliminary economic assessment of the Temrezli project was completed in 2015. At present, URI is planning to develop an in situ leaching operation at the Temrezli site. Siting and environmental impact assessment studies of the Temrezli project are ongoing.

4. URANIUM REQUIREMENTS FOR THE PLANNED NPPs

Annual fuel consumption of a nuclear power plant can be calculated from Eq. (1):

$$M_{fuel} = \frac{P_e \times CF \times 365}{\eta_{th} \times BU} = \frac{P_{th} \times CF \times 365}{BU}$$
(1)

where P_e is the installed electrical capacity (MW(e)), P_{th} is the thermal power (MW(th)), *CF* is the capacity factor, η_{th} is the thermal efficiency and *BU* is the average discharge burnup of the fuel (MW·d/tU).

The mass balances of the enrichment process yield the following expression (Eq. (2) for natural uranium requirement per unit of reactor fuel load,

$$\frac{M_{NU}}{M_{fuel}} = \frac{x_{fuel} - x_{tails}}{x_{NU} - x_{tails}}$$
(2)

where x_{fuel} is the fuel enrichment, x_{NU} is the ²³⁵U content of natural uranium (assumed to be 0.711 wt%), and x_{tails} is the enrichment of tails (assumed to be 0.25 wt% in this instance). Using the above equations and the technical data for the Akkuyu and Sinop NPPs, lifetime natural uranium requirements can easily be calculated.

Each unit of the Akkuyu NPP (a WWER 1200 design) has a rated electrical power of 1200 MW(e) and a thermal power rating of 3200 MW(th). Total lifetime for each unit is 60 years. According to the environmental impact assessment report, fuel enrichment is 4.79 wt% and the average discharge burnup is 55 800 MW · d/tU [5]. Using these numbers and an assumed capacity factor of 0.90 in the first equation, the annual fuel load for each unit is calculated as 18.8 tU. The $\frac{M_{NU}}{M_{fuel}}$ ratio is found to be 9.85 from the second equation. Then, the lifetime natural uranium requirement for the four units is calculated to be 18.8 × 9.85 × 60 = 11 110 tU.

The Sinop NPP consists of four ATMEA-1 units with a total electrical power of 4500 MW(e). The technical features of the plant will be detailed after the completion of the feasibility report. Therefore, the standard design properties of ATMEA-1 reactors are used to calculate the natural uranium requirement for the Sinop case. The ATMEA-1 design has a thermal power level of 3150 MW(th) (for each unit), a capacity factor of 0.90 and a service life of 60 years. The fuel load is 5 wt% enriched and the discharge burnup is 62 000 MW·d/tU [6]. With these data, the annual fuel load for each unit is found to be 16.7 tU and the $\frac{M_{NU}}{M_{fuel}}$ ratio to be 10.3. The lifetime natural uranium requirement for four units is calculated to be $16.7 \times 10.3 \times 60 = 10$ 320 tU.

Combined lifetime natural uranium requirements for both Akkuyu and Sinop NPPs total 21 430 t.

5. DOMESTIC SUPPLY CAPACITY

Currently, Turkey's identified resources total 12 614 tU. As estimated above, the lifetime requirement of natural uranium for the Akkuyu and Sinop NPPs is (11 110+10 320=) 21 430 t. Consequently, it may be considered that the domestic uranium supply can roughly meet the lifetime natural uranium requirements for one of the projects (either Akkuyu or Sinop). Nevertheless, there are other issues to be taken into consideration, including economics and losses.

According to the preliminary economic assessment of the Temrezli project by URI, the deposit (6700 tU) is cost effective. Unfortunately, the same cannot be said for the other identified resources in Turkey; further investigation is required. As noted above, in situ leaching is to be applied at the Temrezli mine. The recovery ratio in in situ leaching is less than that in the underground mining and may vary significantly from one site to another (recovery of about 70–90% of uranium ore) [7]. URI has not reported on the expected recovery ratio for the Temrezli mine. Additionally, the losses in the other processes leading to the production of nuclear fuel assemblies should also be taken into account.

Noting that the Temrezli deposit is currently the only economic resource (that is, reserves under the costprice conditions) in Turkey. Assuming that 20% of the reserve is lost during mining and milling, refining, enrichment and fabrication, the domestic U supply can more or less meet the lifetime natural uranium requirements for either one the Akkuyu or Sinop plants.

6. CONCLUSION AND DISCUSSION

At present, the uranium reserves in Turkey amounts to 6700 tU. Assuming a 20% loss in all the processes in the front end of the nuclear fuel cycle, this reserve is almost sufficient to feed two units of either Akkuyu or Sinop plants for 60 years. This may seem to be insignificant, but the total amount of electricity producible

from the two units in 60 years is 1135×10^9 kW·h for Akkuyu and 1064×10^9 kW·h for Sinop. Turkey's total electricity consumption was 278×10^9 kW·h in 2016 [8]. The possible contribution of nuclear electricity from this reserve is therefore not insignificant.

Attempts to explore for and locate uranium resources over the entire country and to convert the identified resources into reserves are likely to bear fruit. It is also reasonable to focus on research and development in mining and milling, refining and fuel fabrication in concert with the planned NPP projects.

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INVESTIGATION OF KEY PARAMETERS FOR EFFECTIVE SDU PRECIPITATION

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1. INTRODUCTION

Precipitation of sodium diuranate (SDU) from leach liquors has been practiced commercially since the 1950s. However, there is limited information on the impact of operating conditions on the efficiency of uranium precipitation from the 'low tenor' liquors that are produced from the carbonate leaching of carnotite in calcrete ores.

ANSTO Minerals recently carried out a programme of work investigating direct SDU precipitation from carbonate/bicarbonate leach liquors. A number of variables were examined to assess their impact on the precipitation efficiency, including carbonate feed concentrations, terminal caustic concentration and seeding. In addition to a batch test work programme, a continuous mini-plant was also operated.

2. WORK PROGRAMME

Test work was completed on pregnant leach solution (PLS) produced from bulk leaching of a carnotite in calcrete ore. Two different leach regimes were used to generate PLS with differing concentrations of Na₂CO₃ and NaHCO₃ (high bicarbonate: 12 g/L NaHCO₃ and 33 g/L Na₂CO₃; low bicarbonate: 7 g/L NaHCO₃ and 31 g/L Na₂CO₃). The uranium concentration was \sim 1 g/L U₃O₈ in both cases. The same solutions were used in both batch laboratory scale tests and in a continuous mini-plant.

Laboratory batch tests were conducted by heating the PLS to the target temperature (70–80 °C) and then adding a pre-determined quantity of SDU seed or uranium stock solution to achieve a target total U_3O_8 concentration (1–6 g/L U_3O_8).¹ Typically, a 2 h seeding time was allowed at target temperature to promote dissolution of the seed. After the seeding time, NaOH (50 wt% solution) was added to consume the NaHCO₃ and obtain the target caustic concentration (6 or 8 g/L) in solution. Samples were withdrawn regularly for analysis by ICP for U and V concentrations.

3. RESULTS AND DISCUSSION

3.1. Impact of bicarbonate and total carbonate concentrations

A series of tests were completed to examine the impact of total carbonate concentration in the PLS on SDU precipitation. Total $[Na_2CO_3]$ ranged from 38 to 78 g/L after reaction of all of the NaHCO₃ with NaOH. Lower uranium concentrations in barren solutions were achieved from solutions containing lower carbonate concentrations. When considered in the context of an entire flowsheet and the preceding leach conditions, this is an important observation. Bicarbonate is required for uranium extraction but it is also generated during the leaching of carnotite in calcrete ores. The chosen $Na_2CO_3/NaHCO_3$ reagent concentrations at the start of the leaching process will therefore define the composition of the PLS being fed downstream to SDU precipitation. The higher the terminal bicarbonate concentration in the leach solution, the more caustic is required to neutralize it (Eq. (1)), thereby resulting in a greater total Na_2CO_3 concentration.

 $^{^{1}}$ The total U₃O₈ target included the uranium dissolved in solution (PLS) and the uranium contained in SDU, both dissolved and undissolved.

$$NaHCO_3 + NaOH \rightarrow H_2O + Na_2CO_3$$

(1)

A higher concentration of bicarbonate in the PLS was shown to increase the dissolution of the added seed material, resulting in a higher dissolved uranium concentration prior to precipitation. However, the improved dissolved uranium concentration prior to precipitation was offset by the increased total carbonate concentration obtained, resulting in higher concentrations of uranium in barrens.

3.2. Impact of seeding

Seeding is recognized as an important component of SDU precipitation in a continuous operation and our results support the need for seeding. The best uranium in barrens achieved in tests completed in the absence of seeding was 163 mg/L U_3O_8 (138 mg/L U) whereas the presence of seeding under the same operating conditions reduced the uranium in barrens to 57 mg/L U_3O_8 (48 mg/L U).

Comparison of target seed concentrations (4 and 6 g/L U_3O_8), however, showed that while there was a reasonable improvement in the amount of dissolved U after seeding at 6 g/L U_3O_8 , the final difference in U in barrens was minimal. It should be noted that with greater seed dissolution, more caustic is subsequently required to re-precipitate the uranium (Eq. (2)).

$$6 \text{ NaOH} + 2 \text{ Na}_4 \text{UO}_2(\text{CO}_3)_3 \rightarrow \text{Na}_2 \text{U}_2 \text{O}_7 + 6 \text{ Na}_2 \text{CO}_3 + 3 \text{ H}_2 \text{O}$$
(2)

Further testing investigated the impact of 'total dissolved' uranium concentration on precipitation (over the range of $1-6 \text{ g/L } U_3O_8$), by spiking the PLS with a uranyl carbonate solution rather than seeding with solid SDU product. A dissolved U_3O_8 concentration of 3 g/L was shown to be optimum for producing the lowest uranium concentration in the barren solution, with the lowest unit consumption of caustic. There was a small kinetic impact on precipitation at higher concentrations (4, 5 or 6 g/L U_3O_8), which may permit a reduced reaction residence time, although at the cost of higher unit caustic consumption.

3.3. Impact of caustic concentration

A higher terminal caustic concentration has a positive impact on the kinetics of precipitation. Considerably lower uranium concentration in the barren solution was observed at 8 g/L NaOH, compared with 6 g/L, particularly after the first 30 min of residence time. With increasing residence time, the gap narrows, although the final uranium concentration in the barren solution after 8 h was still lower at 8 g/L NaOH (by 9-16 mg/L U). This result suggests that operating at a lower NaOH target may be offset by increasing the precipitation residence time and has the added benefit of reducing costs due to a lower caustic requirement.

3.4. Impact of temperature

Comparable tests completed at 70 and 80 °C showed a significant increase in seed dissolution at the higher temperature, therefore increasing the concentration of dissolved uranium in solution. The subsequent impact on SDU precipitation, however, was not significant.

4. CONCLUSIONS

Carbonate and bicarbonate concentrations in the feed liquor were determined to have a significant impact on the success of SDU precipitation. Our investigations have shown that a higher total carbonate concentration in the feed solution is a key factor impeding SDU precipitation, resulting in an increased concentration of uranium in the barren solution. The concentrations of the preceding leach reagents (Na₂CO₃ and NaHCO₃) are therefore important as this will define the total carbonate concentration in the SDU precipitation circuit. The caustic concentration was demonstrated to have a kinetic effect on the precipitation reaction and consequently residence time may also be critical, depending on the terminal caustic concentration selected for a given flowsheet. A higher temperature was shown to improve the dissolution of the added seed material but did not show a significant impact on the final precipitation result.

Greater seed dissolution was also achieved in the PLS that contained a higher concentration of bicarbonate, although the resulting total sodium carbonate concentration was higher from this PLS and this had a negative impact on the precipitation and final U concentration in the barren solution.

Seeding was demonstrated to be necessary for effective precipitation. The complex relationship between dissolved uranium concentration and the presence of seed on SDU precipitation has been investigated to fully define the nature and amount of solid seed required.

HYDROMETALLURGICAL TESTS FOR VANADIUM EXTRATION FROM BLACK LIMESTONES FROM PUYANGO SECTOR, LOJA PROVINCE, ECUADOR

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1. INTRODUCTION

The following study is directed at vanadium hydrometallurgy, a trace element distributed throughout the Earth's crust and which has great commercial and economic importance. It is used in the steel industry to form alloys with titanium (for aerospace applications) and iron in order to improve its mechanical properties such as hardness, resistance to fatigue and stress [1], and in addition is used as a catalyst in the form of vanadium pentaoxide, in the manufacture of sulphuric acid, replacing platinum and in the production of batteries (e.g. in Li_3V_2 (PO₄)₃ for electric cars) [2].

In the Puyango sector of Ecuador, high vanadium and uranium values have been detected in samples of black bituminous limestones, which have recorded levels of about $1.6\% V_2O_5$. However, when starting with samples of a type of ore different from the one commonly processed in other countries, it is necessary to carry out specific studies to determine the physical, chemical and mineralogical characteristics of the samples, thereby obtaining the necessary information on their composition, the nature of the mineral phases with which vanadium is associated, and to carry out hydrometallurgical tests using the acids necessary for its extraction.

2. METHODS AND RESULTS

2.1. Preparation of the sample

The sample was subjected to a series of processes for particle size reduction, starting with a primary fragmentation of the material into more manageable pieces followed by drying. Then, the sample was crushed in a jaw crusher, to a grain size of 2 mm. The powder was the homogenized and a representative sample was obtained by quartering (both mechanically and manually). A 100 g of sample was taken and weighed prior to being pulverized in a disc mill for 3 min running at 700 rpm. The resulting powder has a D_{80} of mesh 200 (0.075 mm).

2.2. Determination of head grade of V₂O₅

A preliminary chemical analysis of the different samples collected in the field was carried out to determine the percentage of V_2O_5 present in them, using portable a X ray fluorescence instrument (pXRF). The highest measured vanadium content of V_2O_5 was 1.6%. This sample was used for subsequent processes.

2.3. Mineralogical characterization

The mineralogical analysis was carried out by X ray diffraction (XRD). The following mineralogical composition has been obtained: calcite (79%), quartz (15%), uranospatite (3%), apatite (1%), sherwoodite (1%) and minor amounts (<1%) of illite, biotite, kaolinite, rossite and ronneburgite.

2.4. Operating condition

The following operating conditions were established: leaching time of 3 h, solid:liquid ratio of 1:10, granulometry of 0.075 mm, conditions taken from other hydrometallurgical tests of vanadium in the literature [3-5]. The agitation speed, was set at 300 rpm, since in previous tests it was verified that at the speed of 200 rpm there was no longer any dependence between the agitation speed and the extent of leaching [6].

2.5. Leaching with distilled water

Ten grams of powdered sample were weighed in a beaker (in triplicate). To these samples were added 100 mL of distilled water and they were brought to constant agitation for a period of 3 h at an agitation speed of 300 rpm, which ensured that all the powder was in contact with the water [3].

For this procedure, the operating variables were the leaching temperatures of 35, 48 and 61°C, which were fixed experimentally. After the leaching time expired, the obtained mixtures were allowed to settle for 10 min and the liquid was centrifuged at 7830 rpm for 15 min to completely separate it from the solid. The remaining solid was dried in an oven at 105°C for 12 h and was finally analysed by pXFR.

To calculate the percentage of leaching, the percentage of V_2O_5 present in the head grade of the sample was subtracted from the percentage of V_2O_5 in the residual solid (leaching tail). In the sample used, a 6.25% leaching of V_2O_5 with distilled water was registered, a value that denoted the presence of vanadium (V) slightly adsorbed onto the surface of organic matter and detrital minerals. [3].

2.6. Leaching with hydrochloric acid (HCl)

For this process, 5 g of pulverized sample were weighed in four beakers and the initial operating conditions were kept fixed, in addition to the leaching temperature, which was maintained at 25°C to evaluate the action of the acid alone [3].

The operational variable was the concentration of hydrochloric acid. To each glass was added 50 mL of HCl at different concentrations: 15%, 21%, 27% and 32%.

After 3 h of leaching, the mixture was allowed to settle, the liquid part was centrifuged and the remaining solid was dried on a heating plate at a temperature of 150° C. The resulting solid was analysed by pXRF, its vanadium content was subtracted from the initial concentration of V₂O₅ and the percentage of leaching with HCl was calculated. To this result, the percentage of V₂O₅ leached with distilled water was subtracted to obtain the percentage of vanadium (V) (V) strongly adsorbed onto the surface of organic matter and detrital minerals, which corresponds to 43.11% of the vanadium from the sample used for the processing [3].

2.7. Leaching with sulphuric acid (H₂SO₄)

Finally, leaching was carried out with different concentrations of sulphuric acid, because of the universal use of this acid for vanadium leaching in other projects and also because of the low percentage of aluminosilicates, which precludes the use of HF [6].

As in the previous leaching tests, factors such as agitation speed, leaching time, solid:liquid ratio and temperature of 25°C were kept constant. Four beakers were prepared, where 5 g of pulverized sample was weighed in each one and 50 mL of sulphuric acid were added at different concentrations: 7%, 15%, 25% and 35%. As with HCl, it was decided to base these concentrations on the highest available concentration of sulphuric acid. Leaching was carried out with higher concentrations of sulphuric acid (50% and 75%), but no improvement in results were recorded over those previously obtained at lower concentrations.

After 3 h of leaching, the samples were allowed to settle and then the solid phase was separated from the liquid phase. The liquid was taken to a centrifuge, where speed and time parameters of 7830 rpm and 15 min were set, respectively. The resulting solid was dried on a heating plate at 150°C and analysed by pXRF.

The percentage of V_2O_5 leached with sulphuric acid was calculated with respect to the concentration of V_2O_5 present in the head grade, which in turn was subtracted from the sum of the percentage of vanadium leached with distilled water and the one from leaching with HCl to obtain the percentage of vanadium in the fifth valence state (V), which is strongly adsorbed onto the surface of the minerals and vanadium (IV) that is strongly linked to organic matter [3], giving a resultant value of 33.13 wt%.

Adding the three percentages of leaching ($H_2O + HCl + H_2SO_4$) aims at calculating the percentage of total vanadium leaching in valence states (IV) and (V), which, when subtracted from 100% of the head grade, results in 17.5% of vanadium existing in valence state (III), the same as that unable to be leached with the use of acids [4].

2.8. Hydrometallurgical tests of vanadium

Variables such as the choice of leaching acid, the optimum acid concentration, the optimum temperature at which to carry out the process and whether the oxidation of the sample is significant before and after being 'attacked' by the selected acid were assessed in these tests.

2.9. Choice and determination of the concentration of the leaching medium

As a result of the vanadium speciation, the leaching percentage information was used with each of the media and leaching was carried out with nitric acid at different concentrations when there was no satisfactory leaching, when the highest percentage of vanadium was left in the residual solid (tailings). Finally, it was determined that the best conditions for leaching occurred when using sulphuric acid at a concentration of 15%, leading to a leaching yield of 82.5%.

2.10. Variation of temperature

The operating conditions verified in the previous tests were fixed and the sulphuric acid was selected as a leaching agent at a concentration of 15%. The variable used in this test was the temperature, which was maintained at levels of 25, 37, 50 and 75°C, since above this range (as used in other methodologies [1, 6, 7]) there was no adequate separation between the solid residue and the leachate, owing to the high viscosity of the mixture.

As with the previous experimental processes, the mixture was left to settle for a period of 10 min and subsequently centrifuged at 7830 rpm for 15 min. The solid was then separated from the leachate and dried on a heating plate at 150°C and analysed by pXRF, which recorded lower leaching percentages compared with those obtained at 25°C.

2.11. Oxidation of vanadium (III)

The solid residue, produced from leaching at 25°C with 15% H_2SO_4 was used as starting material for the oxidation process.

It started with the division of the solid waste into three equal parts and, according to its weight, a quantity of hydrogen peroxide solution at 10 volumes (concentration of 3%) was added, in concentrations of 10, 20 and 30 g/L [7, 8] to maintain a solid:liquid ratio of 1:10. The agitation time and speed were of 3 h and 300 rpm, respectively, and a temperature of 25°C was maintained.

Once oxidized, the material was left to rest for 10 min and the liquid was centrifuged at 7830 rpm for 15 min, then the solid was spread onto a watchglass to allow drying at room temperature. With the help of a spatula, the solid was removed and measured using a pXRF. The result was maintained, so there was no loss of vanadium in this process.

2.12. Second leaching

Each solid residue resulting from the oxidation was weighed and, according to this, a volume *of* acid was added to maintain the solid:liquid ratio of 1:10, in addition to the other operating conditions. The medium used for the second leaching was sulphuric acid at a concentration of 15%. Optimal conditions were maintained according to the previous tests.

After 3 h of leaching time, the solid was allowed to settle and again centrifuged in the same conditions and the solid was dried on a heating plate at 150°C, its vanadium concentration measured by pXRF. Finally, it was determined that the concentration of hydrogen peroxide required to achieve the highest oxidation of vanadium to the valence state (III) was 20 g/L. Subsequently, the percentage of the total vanadium yielded from the leaching process was 96.95%.

3. DISCUSSION AND CONCLUSIONS

In the case of the selected bituminous black limestone sample, vanadium was found mostly in valence state (V) (approximately 43.12%), occurring in minerals such as sherwoodite and, to a lesser extent, in minerals such as ronneburgite and rossite, notwithstanding a notable percentage (33.13%) occurring as vanadium (IV), strongly bound to organic matter and, finally, 17.5% of vanadium (III) replacing Al in the illite crystal lattice.

Owing to its efficient leaching action, sulphuric acid was selected as a means for vanadium leaching, giving approximate percentages of 82.5% in the first process. After carrying out the oxidation of vanadium (III) to vanadium (IV) or (V), the yield of the process increased to 96.95%. This is the reason why the oxidation process, with H_2O_2 as an oxidizing agent, must be taken into account to obtain a more efficient leaching process.

4. CONCLUSIONS

The most efficient leaching agent was H_2SO_4 at a concentration of 15%, the other operating parameters being a temperature of 25°C, solid:liquid ratio of 1:10, and the duration and agitation speed being 3 h and 300 rpm, respectively.

It has been shown that vanadium (III) cannot be leached by acids (with the exception of HF), unlike the other states (IV and V). It is for this reason that oxidation is an indispensable process by which to increase the total yield. The best concentration obtained from the experiments was 20 g/L of H_2O_2 (10 volumes).

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CANADA'S URANIUM MINING INDUSTRY: 75 YEARS OF PRODUCTION AND FUTURE PROSPECTS

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1. HISTORICAL BACKGROUND

Pitchblende ore was mined at the Port Radium mine in the Northwest Territories from 1932 to 1940 to extract radium for medical use [1]. However, Canadian uranium production did not begin until 1942, when, at the request of the Government of Canada, the Port Radium mine was reopened to supply uranium for the Manhattan Project [2]. With the onset of the Cold War, military demand for uranium soared, creating a uranium exploration boom in which thousands of uranium occurrences were discovered throughout Canada [1]. Canada's second uranium mine opened in northern Saskatchewan in 1953 and by the late 1950s there were 20 uranium production centres in Ontario, Saskatchewan and the Northwest Territories [1, 3]. Annual production peaked in 1959 at 12 200 tU, but declined rapidly as US and UK military demands had been met and contracts were not extended. Only 8 mines remained in operation in 1961 [1] and by 1966, production had fallen to less than 3000 tU with only 4 mines remaining in production [2]. In 1965, Canada made a policy decision that all future uranium sales would be for peaceful purposes only, and while the development of nuclear power was expanding, it was not until the 1970s that uranium demand had risen substantially and exploration and development activity increased [4]. By the late 1970s, new uranium mines were being developed in Ontario and Saskatchewan. Annual uranium production grew through the 1980s, with the focus of production shifting to the high-grade uranium deposits of the Athabasca Basin of northern Saskatchewan [5]. Uranium mining in Ontario ceased in 1996, leaving Saskatchewan as the sole producer of uranium in Canada.

2. URANIUM PRODUCTION

Canada is currently the world's second largest producer and exporter of uranium, with a 22% share of world production in 2016 [6]. More than 85% of uranium production is exported, making it Canada's largest clean energy export. Canadian uranium exported for use in nuclear power helps combat climate change by avoiding some 600 million tonnes of CO_2 equivalent emissions annually. In addition to being a reliable supplier of uranium, Canada has also long been recognized as a responsible producer of uranium as a result of policies and practices that ensure protection of the environment, corporate social responsibility and nuclear non-proliferation.

The McArthur River and the Cigar Lake mines are the world's largest and second largest uranium mines, respectively, in terms of annual production [6]. These mines have ore grades of up to 20% U, one-hundred times higher than the world average. Canada's annual uranium production has risen substantially since the startup of the Cigar Lake mine in 2014, increasing by 42% in 2015 and increasing a further 5% in 2016 to reach a record annual production level of 14 039 tU [6].

Low demand and low prices resulted in a 6.5% decrease in Canada's uranium production for 2017. Owing to continued depressed market conditions, 2018 production is expected to decrease by a further 40% as production at the McArthur River mine and Key Lake mill are suspended for ten months. This action will reduce operating costs, while uranium concentrates will continue to be supplied to customers from the excess inventory that is currently stored at the Key Lake mill [7].

While only the Cigar Lake mine and McClean Lake mill are currently in production, both the Cigar Lake and the McArthur River mines have extremely high-grade uranium deposits with low production costs. As

a result, the Canadian uranium industry is able to remain viable in a low uranium price market and could quickly ramp up production to meet an increase in demand. In addition, the Rabbit Lake mine and mill, which has been on care and maintenance since mid-2016 due to low uranium prices, could be brought back into production should uranium prices increase substantially.

3. URANIUM RESOURCES

Canada has 9% of the world's low-cost uranium resources (<US \$130/kgU) and has the world's highestgrade uranium deposits, ensuring that Canada will continue to be a major supplier of uranium well into the future [8]. Canada's low-cost uranium resources have risen by 60% since 2009 owing to increased exploration efforts. When uranium demand and prices increase, two advanced uranium projects in Saskatchewan, which have been put on hold due to low prices, could enter production and provide additional feed for the existing mills. Ore from the proposed Millennium mine would likely be processed at the Key Lake mill, while ore from the proposed Midwest mine would provide additional feed for the McClean Lake mill [8]. There are also additional undeveloped uranium deposits at McClean Lake that could be brought into production.

The Athabasca Basin continues to be highly prospective for discovering new deposits and several large high-grade uranium deposits have been identified that could be developed into mines in the future. Recent large discoveries in the eastern Athabasca Basin include the Roughrider deposit (Rio Tinto), the Phoenix and Griffon deposits (Denison Mines) and the Fox Lake deposit (Cameco) [8]. In the western Athabasca Basin, the Triple-R deposit (Fission Uranium) and the Arrow Deposit (Nex-Gen Energy) are currently the two largest undeveloped uranium deposits in Canada [8]. Through continued exploration, Canada's uranium resources are expected to increase further.

4. PUBLIC ACCEPTANCE

The success of Canada's uranium industry is not only the result of having a good resource base and the use of modern and sustainable mining methods, but also the result of having an appropriate policy and regulatory regime which fosters a high degree of public acceptance. These policies and regulations address public concerns on health, safety and the environment, as well as nuclear non-proliferation and foreign ownership. The industry itself has adopted best practices through which it has earned a high degree of public support, especially among local indigenous communities with which they have developed partnerships that provide much needed local employment and business opportunities.

5. SUMMARY

This presentation will briefly outline Canada's 75-year history in uranium mining as well as examine Canada's current uranium production and the policy and regulatory regime that governs the Canadian uranium industry. Future prospects for uranium mining in Canada will be discussed, as well as the importance of developing community support.

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SPATIAL ANALYSIS OF PROSPECTIVITY FOR SURFICIAL URANIUM DEPOSITS: A CASE STUDY IN BRITISH COLUMBIA, CANADA

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1. INTRODUCTION

Surficial uranium (U) resources exist in the southernmost part British Columbia (Canada). The known U resources in the region (hereafter denoted as SBC) are comprised by four surficial U deposits and 32 small prospects/showings. The prospectivity of the SBC for surficial mineralization has, however, not been entirely evaluated yet. Here, results of spatial analysis of prospectivity for surficial U in the SBC, using a geographic information system (GIS) and following the mineral systems approach [1], are presented.

2. SURFICIAL U MINERAL SYSTEM IN THE SBC

In the SBC, surficial U mineralisation consists of fluviatile and/or lacustrine/playa U occurrences within loose, pervious fluvial sediments of Late Miocene age along paleodepressions or paleochannels [3]. The mineralisation is composed largely by uranyl carbonates [2] and/or uranous phosphates such as autunite (uranyl phosphate), ningoyite (U(IV) phosphate) and saleeite (uranyl phosphate) [3].

The rocks that are probable sources of U in the SBC include small units of uraniferous pegmatites in the Shuswap Metamorphic Complex of Palaeozoic age, granitoids of Jurassic–Cretaceous and Eocene–Oligocene age, and volcanic rocks of Eocene age [2], [3]. Data on leachable U content of rocks [3] suggest that Okanagan granites/pegmatites of Jurassic–Cretaceous age are major sources of U in the SBC. The release of U from the potential sources has probably been favoured by repeated tectonism and multiphase intrusions that have taken place during the geologic history of the SBC [3].

Interconnected faults/fractures in the intrusive rocks also favoured deep-seated flow and wide-distribution of U-bearing groundwater, which ultimately permeated pervious sediments along paleodepressions or paleochannels [2]. The U, in these surficial environments, exists as soluble uranyl carbonate complexes carried by oxygenated alkaline groundwater [4]. Flow of groundwater is focused through pervious paleodepressions or paleochannels filled with permeable fluviatile sediments. Energy for flow of groundwater is chiefly due to gradient along paleodepressions or paleochannels.

In lacustrine environments or in pervious zones of channel fluviatile environments, organic-rich soils or sediments act both as physical and chemical traps for surficial U formation [2]. In either environment, surficial U forms mainly by either evaporation (especially in very surficial formations) or by reduction. The latter is due to bacteria or to sediments that are rich in organic matter. However, because no common U minerals are known in the SBC, the role of evaporation in the SBC is less likely, as groundwater is not saturated with respect to typical U phosphates [5]. Thus, in the surficial U mineral system in the SBC, adsorption onto organic-rich sediments is the most probable factor of surficial U mineralisation, followed by reduction owing to bacteria or organic-rich sediments [2], [5].

3. SURFICIAL U MINERALISATION: CRITERIA FOR TARGETING, SPATIAL PROXIES

The deposits/occurrences of surficial U in the SBC are alike but dissimilar to the most significant fluvial valley or lacustrine-playa sub-types of surficial U deposits worldwide, namely calcrete-hosted carnotite [6],
[7], [8], [9]. Therefore, mapping of surficial U prospectivity in the SBC will make use of criteria for targeting and respective spatial proxies that somewhat differ from those used exactly for the same purpose in the Yeelirrie area (Australia) [1]. The criteria for targeting that were used here include: a) source rocks for U; b) pathways, and c) traps.

A single U source targeting criterion, namely felsic volcanic or intrusive rocks with leachable U, was used. The corresponding spatial proxy used was presence of and/or proximity to felsic volcanic or intrusive rocks with leachable U. Instead of using Euclidean distance to model proximity, fuzzy proximity (representing probability-like values) was used because the fuzzy set theory [10] was used here for mapping surficial U prospectivity. To model fuzzy proximity, Euclidean distances were transformed through a logistic function [11] to non-linearly decreasing values ranging from 1 for the nearest distance to 0 for the farthest distance. Three maps of fuzzy proximity to probable U-source rocks (i.e., Jurassic–Cretaceous Okanagan Batholith, Eocene–Oligocene Coryell Plutonic suite, Eocene Volcanics) were combined into a single map of fuzzy proximity to U-source rocks, by applying a weighted fuzzy algebraic sum operator whereby the weights are defined from the leachable U content of each of the three rock units.

A single pathways criterion, namely Tertiary to Recent paleochannels, was also used. The corresponding spatial proxy used was fuzzy proximity to paleochannels. The paleochannels were remotely-sensed using a digital elevation model and night-time ASTER thermal infrared data [12], [13].

For chemical traps, two criteria were used: (1) bicarbonate contents of fluvial waters; and (2) U-rich groundwater. The respective spatial proxies used were: 1) fuzzy alkalinity of fluvial waters, modelled by applying a non-linear logistic function to data on stream water pH [14]; and 2) fuzzy U-abundance of fluvial waters, modelled by applying a non-linear logistic function to data on U content of fluvial waters [14]. These spatial proxies essentially point to the enrichment of aqueous uranyl complexes in surface waters, and thus are more indicative of transport of U and complexing ligands rather than chemical traps (i.e., alkaline waters at near surface temperatures would carry U as soluble uranyl phosphate and uranyl carbonate complexes). However, while fluvial waters signify mixed sources upslope/upstream of any sampling site, physico-chemical properties of fluvial waters captured during sampling would also reflect physico-chemical conditions at sampling sites. Therefore, alkalinity of stream waters and U-richness of stream waters are also products (and thus proxies) of chemical trapping processes at sampling sites. Bicarbonate contents of strongly alkaline fluvial waters in the SBC range from 50 to 600 ppm. This considerably boosts the ability of soils/sediments in paleodepressions of paleochannels, which act as trap sites, to concentrate U [2]. Dispersion of U from source rocks and its enrichment in surface water and groundwater permits huge quantities of this element to reach trap sites wherein surficial U mineralisation ensues.

For physical traps, two criteria were used: 1) paleodepressions or paleochannels, for accumulation of nearlystationary fluvial water [1]; and 2) size of source area [1]. The corresponding spatial proxies used were: 1) presence of and fuzzy proximity to nearly-level topographic depressions, modelled by applying a non-linear logistic function to topographic slopes derived from a digital elevation model; and 2) fuzzy surface water flow accumulation, modelled by applying a non-linear logistic function to sizes of catchments derived from a digital elevation model. Because surficial U precipitates from nearly-stationary fluvial water in paleodepressions or paleochannels [1], depressions in the topography with level or nearly-level slopes were used as spatial proxies because it can be expected that substantial fluid modification occurs in such locations but not in locations having dissimilar topographic characteristics. Because locations where fluvial water flow accumulates from huge U-source rock areas are prone to amass, enrich, and precipitate more U, a map of surface water flow accumulation was used as spatial proxy because it could represent areas that accumulate drainage water flow from large U-source rock areas are likely to collect, enrich, and concentrate more U and, thus, may contain significant potential U-source rocks for surficial U mineralisation.

4. MODELLING OF REGIONAL-SCALE SURFICIAL U PROSPECTIVITY

The spatial proxies generated were combined in systematic way that mimics the interaction of processes involving sources, pathways and traps, which result in surficial U mineralisation. This was achieved by adapting an inference engine that symbolise hypotheses or knowledge regarding the interactions of a variety of processes that are relevant to a surficial U mineral system [1], [15]; thus, a mineral systems approach. Therefore, a fuzzy inference engine was used to model regional-scale surficial U prospectivity in the SBC according to the above-discussed surficial U mineral system and regional-scale criteria for targeting (and respective spatial proxies) for surficial U mineralisation in the SBC. Considering its simplicity and flexibility, the fuzzy set theory [10] is regarded by [16] to be the most appropriate for integrating spatial data to model the interaction of certain geologic processes.

For every step in the fuzzy inference engine used, a suitable fuzzy operator was used to combine at least two spatial proxies to mimic the interaction of at least two processes pertinent to surficial U deposit formation. The fuzzy inference engine and the fuzzy operators that were used formed a sequence of logical rules that successively combined the fuzzy spatial proxies, and they also served to negate the influence of spatial proxies with significant uncertainty.

As mentioned earlier, a map of integrated U sources spatial proxy was derived by using a weighted fuzzy algebraic sum operator to combine the potential U-source rocks spatial proxies. A map of integrated chemical traps spatial proxy was derived by using fuzzy AND operator to combine the U-abundance and alkalinity of fluvial waters spatial proxies. That is because both U-abundance and alkalinity of fluvial waters are needed for surficial U deposits to form. A map of integrated physical traps spatial proxy was derived using fuzzy OR operator to combine the flow accumulation and nearly-level depressions spatial proxies. That is because adequate physical constrain on surficial U deposit formation may be provided by either catchment with voluminous flow accumulation or nearly-level depressions. Finally, a map of surficial U prospectivity was derived by using fuzzy AND operator to combine the pathways spatial proxy with the integrated U sources, chemical traps, and physical traps spatial proxies. That is because formation of surficial U deposit requires all the processes symbolised by these spatial proxies. Experiments on different map combinations were then performed to determine (a) sensitivity of the prospectivity to input spatial proxies, (b) which spatial proxies are best predictors, and (c) which prospectivity map can be best used to guide further exploration for surficial U deposits in the SBC. The predictive performance of each out prospectivity map [17] was determined by using the four known deposits and 32 prospects/showings of surficial U in the SBC.

5. RESULTS AND DISCUSSION

The two best maps of surficial U prospectivity that were generated here are inclusive of the proximity to potential U-source rocks spatial proxy, indicating the significance of data on leachable U content of rocks in modelling of surficial U prospectivity and the efficacy of the weighted fuzzy algebraic sum operator to integrate such kind of data in spatial analysis of surficial U prospectivity. The two best prospectivity maps are exclusive of the nearly-level depressions spatial proxy, indicating the inadequacy and thus inaptness of this spatial proxy in modelling of surficial U prospectivity in the region, or the better efficacy of the flow accumulation spatial proxy. However, if, among the traps spatial proxies, only the U-abundance of fluvial waters spatial proxy was combined with the pathways and potential U-source rocks spatial proxies, the output surficial U prospectivity map is just very slightly less predictive than to the two best prospectivity maps. This demonstrates that either the flow accumulation spatial proxy or alkalinity of fluvial waters spatial proxy just has very little influence on the predictive capacity of prospectivity mapping even though they are important criteria for targeting of surficial U in the region. Nevertheless, the results show that alkalinity of fluvial waters is more efficient than U-abundance in fluvial waters as spatial proxy of U-transporting ability of surface waters. These limitations demonstrate that the prospectivity model requires updating when more appropriate data become available.

The two best-performing prospectivity maps derived here suggest the presence of undiscovered surficial U resources in the SBC. However, the identified prospective areas mostly identified are those where the known deposits/occurrences of surficial U are mostly present in the SBC. This indicates that two best-performing prospectivity maps carry type II (or false-negative) error with respect to possible undiscovered resources of surficial U in other parts of the SBC, whereas the two worst-performing prospectivity maps carry type I (or false-positive) error with respect to the known deposits/occurrences of surficial U in the SBC. The type I and type II errors are equivalent to over- and under-estimation of prospectivity, respectively. Avoiding type I error is crucial as this will render failure to discover new deposits, whereas type II error will render missed chance for discovery of new deposits.

6. CONCLUSIONS

The above-discussed methodology for spatial analysis of regional-scale prospectivity for surficial U in southern British Columbia (Canada) is quite straightforwardly implementable by using a geographic information system. A more intricate fuzzy inference system consisting of more elaborate logical rules representing expert reasoning for delineating zones prospective for surficial U [1] is likely to be as instructive for researchers with more profound insight to the surficial U system in the region.

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THE IMPACT OF GLOBAL NUCLEAR FUEL INVENTORIES ON FORWARD URANIUM PRODUCTION

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1. INTRODUCTION

The March 2011 Fukushima accident has not only led to a significant reduction in global uranium demand, but it has resulted in the enormous growth of nuclear fuel inventories. Uranium producers have been unable to compete with the current situation of large and growing nuclear fuel inventories and have recently begun to curtail primary production as these low-cost inventories have pushed uranium prices to levels below the production cost of many uranium projects, making these projects uneconomic in the near- and medium-term.

DESCRIPTION

Global nuclear fuel inventories are held by numerous entities, including:

- End-user nuclear power utilities and their relevant nuclear fuel procurement/management subsidiaries,
- Suppliers throughout the supply chain, including uranium producers, converters, enrichers, fabricators, and even reprocessors and mixed-oxide (MOX) fuel fabricators,
- Investors, traders, and financial institutions, as well as other non-end users, and
- Governments that have historically been involved in the production of nuclear fuel for both civilian and military applications.

Among global utility inventories, UxC data shows that the desired level for 2017 was 392 Mlb U₃O₈e (150,769 tU), with actual inventories amounting to 759 million pounds U₃O₈e (291,923 tU), or an excess of 367 million pounds U₃O₈e (141,154 tU) [1]. The U.S. Energy Information Administration (EIA) reported in its 2016 Uranium Marketing Annual Report that U.S. utility inventories held nearly 129 million pounds U₃O₈e (49,615 tU) at the end of 2016, up 43% from 90 million pounds U₃O₈e (34,615 tU) in 2011 and 182% higher than the historical low of 46 million pounds U₃O₈e (17,692 tU) in 2003 [2]. The Euratom Supply Agency (ESA) shows that European Union (EU) utility inventories increased from 123 million pounds U_3O_8e (47,308 tU) in 2011 to a peak of 142 million pounds U_3O_8e (54,615 tU) in 2013, but have since decreased slightly to 134 million pounds U₃O₈e (51,538 tU) [3]. Interestingly, given numerous reactor closures since 2011, EU utilities now hold more inventories per reactor than just a few years ago. Given the highly uncertain situation regarding the future of reactor restarts in Japan, the question of the country's utility inventories has become even more important to the uranium market. UxC estimates that Japanese utility inventories total 126 million pounds U₃O₈e (48,462 tU), with very little consumed since 2011, and enough fuel to last most Japanese utilities through most of the next decade and some utilities even beyond 2030. UxC's Base Case reactor restart/operations forecast for Japan assumes that only 21 of 40 operable units will eventually restart [4].

China's three main utilities – China National Nuclear Corporation (CNNC), China General Nuclear Power Corporation (CGN), and State Power Investment Corporation (SPI) – are estimated to hold 450 million pounds U_3O_8e (173,077 tU) at the end of 2017, an increase of 151% compared to an estimated 179 million

pounds U_3O_8e (68,846 tU) in 2011. Starting in 2010, the import of uranium supply tripled, and net uranium imports have surpassed domestic uranium demand by a huge margin in every year since.

Supplier inventories have also built up inadvertently to the extent that global uranium demand has dropped off and utilities cancel out of previously contracted commitments. Traders hold inventories as well, although they do not produce or consume uranium. Since traders facilitate the flow of supply in the market, in some cases with offtake agreements, they end up holding inventories. After Fukushima, traders also became heavily involved in mid-term contracting wherein they purchased low-priced spot uranium to hold in inventory for future delivery.

Another recent development stemming from the Fukushima accident and subsequent reactor shutdowns has been the use of excess SWU capacity to underfeed enrichment plants and/or re-enrich depleted tails to natural uranium. This underfeeding of enrichment plants has caused the demand for newly produced uranium to decline even further. Thus, enrichers have been "creating" or accumulating uranium inventories and have turned around and sold this excess uranium into the market. Additionally, depending on how enrichers elect to use their excess capacity, they can choose to build inventories in the form of enriched uranium product (EUP).

UxC estimates that inventories from all the world's suppliers, traders, and investor-related entities totaled \sim 231 million pounds U₃O₈e (88,846 tU) at the end of 2017, with this group holding 53 million pounds U₃O₈e (20,385 tU) more than it did in 2015.

Governments, including the U.S. and Russia, continue to hold uranium inventories for military purposes. Much of the uranium is held in the form of highly-enriched uranium (HEU) contained in nuclear warheads and strategic stockpiles, which can enter the market if it is considered excess to national security interests. U.S. Government inventories, declared as excess or commercial, total ~145 million pounds $U_3O_{8}e$ (55,769 tU), but its disposition of natural UF₆ and HEU inventories are expected to be largely completed by the end of this decade. The true wildcard going forward is the success of the U.S. Department of Energy's proposed tails re-enrichment program.

The Russian government is the holder of an estimated 368 million pounds U_3O_8e , (141,538 tU) although most of its material must undergo some type of processing to be utilized. A large portion of the inventory consists of depleted uranium. Furthermore, tails that are deemed to be suitable for re-enrichment have low assays, but with Russia's large excess enrichment capacity, the volume of re-enriched tails has increased since the Fukushima accident. Two other major components of Russia's inventory are slightly irradiated uranium and reprocessed uranium. Among the country's inventory that does not require further processing is primarily natural UF₆ stemming from the monitored inventory that became available following the end of the HEU Agreement.

2. DISCUSSION AND CONCLUSION

Although current inventory accumulation has taken several years to take shape, it has clearly become a major concern for market participants in the post-Fukushima environment. There is clearly no single opinion about the inventory situation, but most market participants agree that dealing with the growing level of inventories is crucial to rebalancing supply and demand fundamentals and creating a more sustainable future.

In early 2017, the world's largest producer Kazatomprom stated that it would reduce planned 2017 production in Kazakhstan by $\sim 10\%$, noting that its decision "was based on the current glut of the uranium market [5]." And in late 2017, Kazatomprom announced its intention to further reduce Kazakh planned uranium production by 20% under Subsoil Use Contracts of Company enterprises for the 2018 through 2020 period, "in order to better align its output with demand [6]." More importantly, the cuts come to a country

with the majority of its production in the lowest cost tier, with UxC showing a weighted average full cost of \sim \$15 per pound U₃O₈ across Kazakh operating uranium projects in 2016 [7].

Other producers have not been immune to the impact of inventories on the market. In November 2017, Cameco Corporation elected to suspend production from its low-cost McArthur River mine in Saskatchewan for a period of at least 10 months starting in January 2018 [8]. A primary driver in cutting production by \sim 16 million pounds U₃O₈ (6,154 tU) in 2018 was the fact that Cameco's inventory position had ballooned up to \sim 28 million pounds U₃O₈ (10,769 tU), which is nearly twice the level of its preferred 6-month inventory position. More than a year earlier, in April 2016, Cameco suspended production at its Rabbit Lake mine in Saskatchewan and began curtailing production at U.S. in-situ recovery (ISR) operations, resulting in the aggregate decline of \sim 6 million pounds U₃O₈ (2,308 tU) per year [9].

In Africa, AREVA has reduced production from its two operating projects, SOMAIR and COMINAK, in Niger by 25% since 2015, citing difficult market conditions. Meanwhile, Paladin Energy made an adjustment to its Langer Heinrich mine plan in August 2016, choosing to process stockpiled low and medium grade ores through 2019 and effectively shift higher-grade ore processing into later years when uranium prices may be higher [10]. As a result of the change, Langer Heinrich production was about 1.6 million pounds U_3O_8 (615 tU) lower over the last year.

Going forward, the mostly likely scenario entails additional inventory growth in the near-term, followed by the gradual disposition of utility, supplier, and trader inventories, which cumulatively will be greater than any additional buying on the part of utilities or other market players in the post-2020 period. Inventories will displace primary uranium production on a larger basis, especially after 2020, and as such, they will continue to have a price suppressive effect on the uranium market as existing supply outweighs new demand for inventories. However, this situation should slowly dissipate by the late 2020s, especially with significant uranium resource depletion projected in the mid-2020s. Accordingly, any new production decisions within the next several years will likely be premature unless market fundamentals change significantly in that timeframe.

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GEOLOGICAL SAMPLES PINPOINT FOR NUCLEAR FORENSICS EXAMINATION IN THAILAND

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1. INTRODUCTION

The nuclear forensics laboratory was established in 2013 at Office of Atoms for Peace (OAP), Ministry of Science and Technology, Bangkok, Thailand [1]. One of its functions is to collect data on uranium and thorium resources in Thailand. A Memorandum of Understanding between the Department of Mineral Resources (DMR), the Ministry of Natural Resources and Environment and the Thailand Institute of Nuclear Technology, Ministry of Science and Technology. The purposes of the Memorandum of Understanding include the collection and the sharing of information about rare earth elements (REE) and naturally occurring radioactive material (NORM) to improve knowledge on the management for mineral resources; NORM monitoring; development of a national nuclear forensics database; and development of REE and nuclear material determination techniques [2].

Uranium, thorium and REE which occur within monazite ore were surveyed by the DMR. The results show that U, Th and REE are associated together with tin and tungsten minerals. The REE occur in the form of phosphate minerals. In early 1970s, geologists discovered REE and other heavy minerals in significant amounts as secondary deposits and in the alluvial tin deposits in southern Thailand [3]. In the 1980s, the DMR cooperated with Japan International Cooperation Agency in the evaluation of REE mineral deposits in northern Thailand. The highest REE contents found in southern Thailand was 0.092 wt% [4]. Kritsananuwat et al. studied the REE, Th and U concentrations in marine sediments in the Gulf of Thailand and found a correlation between the source and element type [4].

Currently, there are several techniques with which to identify the major and trace element contents of geological samples. The data from several analytical methods can be used for nuclear forensics purposes, which means that scientists examine the nuclear forensic signatures of geological samples. Nuclear forensics is the procedure for determining the origin of radioactive materials, nuclear material and contaminated evidence. The nuclear forensic laboratory undertakes the analysis of samples in order to identify material types, manufacturing company and fabrication process in support of any investigation [5].

The Mary Kathleen mine in Australia is a classic case study for combining nuclear forensic capabilities with mining resources [6]. This study compared the uranium and other trace element concentrations with several sources by using 13 characterization techniques.

2. DESCRIPTION

The DMR collected geological samples from southern Thailand and gave the Nuclear Forensic Laboratory 150 crushed geological samples. These samples were labelled, dried in an oven at 110°C for 3 h, ground again and then stored in desiccators at room temperature. Nuclear forensics scientists examined the samples by using both non-destructive and destructive analysis techniques.

3. CHARACTERIZATION OF SAMPLES

The samples have 3 colours: light grey, brown and red. The samples were well-mixed or homogenized. It

was found that samples from the same area could have different colours.

For non-destructive analysis, four techniques were employed:

- (i) A scanning electron microscope with energy dispersive spectrometry (SEM/EDS) from Vega3 LMU (TESCAN, Czech Republic) was used to examine the surface and microstructure [4] of soil samples with magnification ranging from 13x up to 1 000 000x. It was found that the heavy elements, especially uranium, thorium and REE, were brighter than the other elements in back-scattering mode. Thus, the scanning electron microscope could be used to examine in geological samples which they have small amount of these elements.
- (ii) An X ray diffraction unit with D2 Phaser (Bruker AXS GmbH, Germany) was used to study crystal structure. Two major crystal structures were identified: quartz (SiO₂) and microcline (KAlSi₂O₃), which has a silicon dioxide or quartz and aluminium oxide component.
- (iii) An X ray fluorescence unit by S1 TITAN (Bruker AXS GmbH, Germany) was used to identify the major elements in samples, i.e. silicon dioxide (SiO₂), aluminium oxide (Al₂O₃) and iron oxide (Fe₂O₃) being the major components in the samples.
- (iv) A high purity germanium detector for gamma spectrometry (ORTEC Gem Series, United States of America) was used to measure the radioactive material in samples. The samples, about 150 g, were packed into wide-mouth bottles. The measurement time was 10 000 s per sample. It was found that natural radioactivity in samples such as K-40, Th-232 and U-238 and the variation of radionuclide components in the sample could aid in determining the distribution of the geological source [7].

For the destructive analysis method, inductively coupled plasma mass spectrometry (Agilent 7700x, Agilent, Japan) was used. The samples were prepared as a solution by using fluxer (K1 Prime Katanax, Canada) which added a quantity of lithium borate flux. The samples major elements and trace elements contents were then determined (detection limit in parts per billion). It is an accurate technique and it can be used to distinguish small elemental concentrations, providing valuable information with respect to the mining and/or rare earth element ore processing [8, 9].

4. DISCUSSION AND CONCLUSION

The analysis of several elements in geological samples can be used to identify the source of origin. In this study, it was found that the trace elements and REE are the geochemical signature of the samples. The XRD spectra show that they would be quartz and microcline. Owing to the fact that the samples from many provinces in southern Thailand, these geochemical data (including uranium, thorium, REE and other trace elements) can used in the nuclear forensic database and trace the precise location, using a global positioning system, and make a direct comparison with unknown sample locations.

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REGIONAL FRAMEWORK FOR THE CLASSIFICATION OF URANIUM DEPOSITS: AFRICA'S APPROACH TO ADOPTING UNFC-2009 THROUGH IMPLEMENTATION OF AFRICAN MINING VISION

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1. INTRODUCTION

Minerals are found where they occur! Unfortunately, the existence of minerals in a certain place does not necessarily take into consideration proximity to the supporting infrastructure such as energy, roads, railways, water, human capital and many other requirements. The existence of a particular mineral in an area is wholly dependent on the geology of the area. It requires the host countries of any mineral(s) to know where exactly these minerals are found, their quantities and qualities, parameters which can determine the mineral's capacity to be exploited and even the expected environmental considerations to be taken on board.

To determine the existence and quantities of a particular mineral, it takes intensive work on the part of geological experts using appropriate technology. It is widely understood that knowing the occurrence of a mineral alone is not adequate for any potential investor to make an investment decision. There is always a great need for comprehensive studies on the mineral deposit to determine quantities and qualities. It is when the investor is fully convinced with respect to these two key parameters that they can be classified as *reserves* or *resources*.

Owing to inadequate geological information in Africa, companies across the globe make decisions to invest in the African region on a high-risk basis. They invest with an expectation that they will conduct exploration activities up to the point where there will be huge certainty of occurrence of the ore deposit. Despite this, as a legal requirement in most governing laws in Africa, companies are required to classify their mineral deposits and report them so that host States can make sound decisions on the investment arrangements. In some cases, companies prepare the national preparedness matrix to check the stage that they are at and their readiness to exploit such a resource. Uranium deposits have often been treated in the same manner.

For many years, investors in Africa have been using different reporting and classification frameworks and this further showed the challenges of host State governments to understand such technical reports and report the same to all other stakeholders. In most sectors in Africa, there has been chaos in the way the sectoral reports on uranium have been reported to institutions requiring such information. This has resulted in the receiving party being provided with inconsistent information on a single deposit or in the case of different deposits which were classified and reported using different reporting frameworks.

In Africa, the investors have been using frameworks such as the Australian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC code), the South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC), the Committee for Mineral Reserves, International Reporting Standards (CRIRSCO), Canadian Instrument 43-101 and others. Unfortunately, these have been considered as frameworks used for purely commercial purposes. In this regard, African Member States considered this challenge and through the African Mining Vision, which was adopted by African Heads of States in 2009, recommended that regional reporting and classification instruments be developed.

Considering the urgent need for such a regional reporting framework and the associated long period in which to develop a 'home grown' framework, a decision was made through African Minerals Development Centre (AMCD), which is an organ of the African Union, to consider adopting the United Nations Framework for Classification of Mineral Resources (UNFC-2009).

The AMDC noted that Member States are fully aware of the existence of the UNFC-2009 and that some African experts took part in developing it. The continent's participation was supported by the IAEA with the intention of using the framework for reporting uranium deposits in Africa. Through AMDC, African geologists decided to expand its usage from purely uranium deposits to encompass other minerals where possible.

UNFC-2009 was crafted in such a way that it supports the African Mining Vision and hence, it was easy for Africa to consider its immediate adoption. Even though this is the case, Africa organized several regional meetings on harmonization, adaptation, implementation and development of the framework, in line with the African Mining Vision. In this case, it was proposed that the UNFC-2009 will be the benchmark which will be supported by the African Minerals Resources Classification and Management System (AMREC) and that this will be used for reporting uranium and other mineral deposits at national levels in Africa.

It is following this development that this paper will tackle the genesis of AMREC and Pan-African Reserve and Resources (PARC) Codes for the reporting of minerals. Emphasis will be placed on how the AMREC–PARC Code will be used to report uranium deposits.

2. UNDERSTANDING UNFC-2009, AMREC AND PARC AND THEIR RELATIONSHIPS

The UNFC-2009 is a universally acceptable and internationally applicable scheme for the classification and reporting of fossil energy and mineral reserves and resources. It is currently the only classification in the world to do so. The UNFC-2009 reflects conditions in the economic and social domain, including markets and government framework conditions, technological and industrial maturity and the omnipresent uncertainties. It further provides a single framework on which to build international energy and mineral studies, analyse government resource management policies, plan industrial processes and allocate capital efficiently [1]. UNFC-2009 has mainly three classes which are abbreviated as E, F, G, which represent:

- 1) E: Economic and social viability;
- 2) F: Feasibility and field project status;
- 3) G: Geological knowledge.

The UNFC-2009 categories classify each mineral deposit according to these three classes, which are also subdivided into subcategories.

As a way of simplifying mineral reporting tasks and making sure that UNFC-2009 is adopted with an African slant, as supported by several continental strategies for development, the AMREC scheme was born. Spearheaded by AMDC, AMREC is the continental framework that will harmonize, adapt and develop the UNFC-2009 according to the principles of the Africa Mining Vision [2]. In addition to the development of AMREC, a proposal to develop PARC, which will be a code for transparent financial reporting, was also discussed and agreed. Both AMREC and PARC conform with the UNFC-2009 provisions and greatly support the African Mining Vision.

3. DISCUSSION AND CONCLUSION

Mineral resource reporting is crucial and vital to any resource-rich country. Most countries in Africa lack capacity in areas such as interpretation and usage of the available reporting frameworks, which are normally used for commercial purposes. The submitted reports are used for commercial purposes and national

(public) purposes. As regards public usage, the reports can enable the State to make exploration and exploitation plans. The reports can also be used by some other international institutions to raise awareness of a particular country's resource and investment potential. Such institutions include the United States Geological Survey, which produces data on mineral potential, exploration results and production records of almost every Member State. Failure to report correctly leads to incorrect information being given to potential investors or to any other interested party (stakeholders).

The African Mining Vision supports the idea of public resource reporting and the linkage which exists to frameworks such as UNFC-2009 and AMREC–PARC addresses this need. Currently, most African States are using UNFC-2009 and AMREC to report uranium reserves and resources to aid development of a country preparedness matrix and hence plan for the strategic exploitation of yellowcake.

After considering the African challenges at hand, and the need to have a user-friendly resource reporting framework, this paper highly recommends the adoption of the three frameworks: UNFC-2009, AMREC and PARC.

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THE ULTIMATE ORIGIN OF URANIUM PROVINCES

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1. INTRODUCTION

The global distribution of mineral deposits on the Earth shows that some areas concentrate large resources (with high endowment), whereas others are almost devoid of any resource. This led de Launay [1] to the introduction, for the first time, of the term 'metallogenic province'. The first definition of a uranium province was proposed by Keppler and Wyant [2]:

"Economic uranium deposits resulted from original inhomogeneity's of uranium distribution in the Earth's crust that commonly persisted through long periods of time, and through a combination of orogenic, metamorphic, and sedimentary processes produced rocks with enriched uranium contents. The initial enriched uranium domain was successively remobilized and concentrated into new enrichments of one or more magnitudes above normal background forming uranium ore deposits".

The nature, origin, evolution, and distribution of U provinces and the characteristics of some of the major U provinces will be presented. The delineation of such provinces is of major importance for U exploration and the evaluation of the potential resources of such areas.

2. IS AN ANOMALOUS METAL ENRICHMENT NECESSARY TO GENERATE ORE DEPOSITS?

A controversy exists about the necessity of an initial metal enrichment in the source rocks being required to generate ore deposits. Following Launay [1], the term 'metallogenic province' was defined by Hawkes and Webb [3] simply, as a domain on the Earth with an unusual abundance of ores of a particular metal or type (e.g. Cu province of Chile). However, several authors, such as Refs [4–6], in addition to Ref. [2], propose that metallogenic provinces are associated with a previous metal enrichment in the Earth's crust or even in the mantle, and this idea has led to the concept of geochemical provinces, regional geochemical specialization, or metal domain. This concept has been further clarified by Routhier [7] with the introduction of what he termed the 'basic theorem' of metallogeny, whereby

"The concentrations of a metal appear at the intersection of a metal domain (actually a volume capable of reaching down to the mantle), bearing during very long periods of time (permanency and heritage) a metal potential (that is the primordial metallotect), and of other metallotects, acting as revealers of this potential".

The term 'metallotect' was in fact introduced first by Laffitte et al. [8] and defined as "any geological feature or phenomenon associated with lithology, paleogeography, structure, geochemistry, etc. which has contributed to the formation of a mineral concentration". However, a metallogenic province cannot be simply assimilated into a geochemical province for which the definitions are highly variable [9] and the ore forming processes are not considered.

Conversely, other authors such as Skinner [10] propose that hydrothermal ore deposits of Cu, Pb, Zn or Ba, with crustal abundances higher than 10 ppm, do not require any pre-concentration in the crust for their formation. The main parameters controlling ore deposit formation would be the availability of a large volume of fluids able to extract and transport the metals and then to deposit them thanks to an efficient trapping mechanism. Similarly, Lehman [11] defends the proposition that Sn deposits result purely from a progressive concentration of the metal during magmatic processes from an initial average crustal Sn content.

However, this model has been contradicted by Romer and Kroner [12] taking as an example the Sn–W deposits of Western Europe, for which they propose their derivation from the partial melting of Sn–W enriched pelites. The source enrichment is related to intense chemical weathering of continents and to their fragmentation, leading to the accumulation of metal-rich sediments at the margin of fragments of those continents. The ore deposits within a single belt may be of different types and may be formed recurrently.

Recently, a more quantitative estimation of the distribution of some metals in craton, terranes and districts, called metal endowment, is proposed with the use of cumulative frequency curves [13]. It is suggested that differences in the metal endowment of these domains is proportional to the intensity and duration of metal accumulation caused by a much larger system of energy and mass flux in a similar way to that indicated by Skinner [10]. The role of possible initial metal enrichment of some crustal segments is not considered.

3. SELECTIVE URANIUM ENRICHMENT OF SPECIFIC CONTINENTAL CRUSTAL SEGMENTS

After core segregation, U has been extracted from the mantle and transferred to the Earth's crust through mantle partial melting, the strong incompatible behaviour of U leads to its fractionation in the resulting silicate melts. Prior to the Meso-Archaean (<3.2–3.1 Ga), these processes led to the formation of a relatively thin continental crust, dominantly of mafic composition, made essentially of komatilitic and tholeilitic basalts. Two opposite models of U extraction rate from the mantle over time are proposed: (i) either a rapid and early extraction of a large part of the U from the mantle corresponding to a generation of most of the continents before 4 Ga or (ii) a progressive extraction through geological time accompanying the progressive growth of the continents [14]. The Moon probably represents the state that the Earth at about 3.5 Ga, before subduction processes started on Earth. It illustrates how magmatic fractionation processes may have led, very early in the Earth's history, to significant heterogeneities in Th and U enrichments over specific areas, up to 7 times their average concentration in the lunar crust, in the Procellarum KREEP Terrane (up to 2.1 ppm U and 7.3 ppm Th) [15].

From the Meso-Archaean to Early Palaeoproterozoic (3.2–2.4 Ga), U continued to be essentially fractionated by magmatic processes but another U enrichment mechanism is necessary to generate the first granites/pegmatites able to crystallize uraninite. The major change leading to higher U contents in magmatic rocks probably started when plate tectonics and subduction processes became significant [16]. The first granites with enough enrichment in U and with sufficiently low Th/U ratios to permit the crystallization of uraninite have been discovered in the Barbeton Belt as aplites and pegmatites derived from high K, calcalkaline granites, and dated to about 3.1 Ga [17]. These uraninites are at the origin of the first U deposits on Earth associated with quartz pebble conglomerates, and also to the initial U endowment of one of the oldest U provinces on the Earth: The South African U Province.

At about 2.3–2.2 Ga, the oxygen level in the atmosphere was high enough [18] for meteoric water, containing dissolved CO_2 in contact with U, to pass it into solution as uranyl carbonate complexes. Uranium was dissolved from U oxides having crystallized in highly fractionated U-rich granites, from metamict U-rich silicate minerals in plutonic or sedimentary rocks, from devitrified U-rich volcanic acidic glasses, and the uraninite accumulated in the pre-2.2 Ga palaeoplacers.

The increase in oxygen levels in the atmosphere and oceans was sustained by high organic carbon burial, within sediments (black shales), especially in marginal sea environments. This occurred during the so-called 'Shunga event' [19], which permitted the trapping of large quantities of U, mobilized by oxygenated meteoric water, in the reduced post-2.2 Ga epicontinental platform sediments. These Early Palaeoproterozoic sedimentary units have represented a huge U reservoir for the formation of a variety of U deposits during the following tectono-thermal events. Typical examples are the FB Formation in the Franceville Basin (Gabon), the Upper Zaonezhskaya Formation, north of Onega Lake (Russian Federation),

and metamorphosed equivalents such as the Wollaston Belt in northern Saskatchewan (Canada) and the Cahill Formation in the Northern Territory (Australia), which are all associated with significant U deposits.

Between 2.1 and 1.8 Ga, most of these Early Palaeoproterozoic U-enriched epicontinental platform sediments were metamorphosed during a worldwide orogenic event that built the Nuna (also named Columbia), the first relatively well characterized supercontinent [20]. High grade metamorphism led to the fractionation of U from these sediments to anatectic melts, which crystallized as uraninite-rich pegmatoids (also termed alaskites), which occur worldwide. These pegmatoids may represent sub-economic U deposits as at Charlebois Lake in northern Saskatchewan and are a major source of U for later hydrothermal U deposits, such as the unconformity-related deposits of the Athabasca U Province. Similar episodes of extensive U trapping in epicontinental sediments has occurred during at least two other periods, also corresponding to the formation of supercontinents: (i) at about 1.3–1.1 Ga with the Grenvillian type orogens and the formation of the numerous U-enriched pegmatoids of the Grenvillian Belt in Canada (e.g. Bancroft, Mont Laurier), and (ii) around 800–600 Ma with the Pan-African Orogeny and the formation of the alaskite type deposits of the Damara Belt (Namibia) and the syn-metamorphic deposits of the Lufilian Belt (Democratic Republic of Congo and Zambia).

4. A WELL-CHARACTERIZED URANIUM PROVINCE: THE ATHABASCA U PROVINCE

Five to six steps of U enrichment have been characterized in the Athabasca U Province. The Archaean basement mainly consists of U-poor magnetite-bearing tonalites, but locally potassic orthogneisses with high U contents are known. For example, at Key Lake, high K granitic gneisses have, on average, 6.8 ppm U of which 4.1 ppm is leachable [21]. The decisive step in U enrichment in the Athabasca U Province occurred during the Upper Palaeoproterozoic with the U enrichment in the epicontinental platform sediments of the Wollaston–Mudjatik Belt, which consist of carbonaceous schists, metacarbonate and calc-silicate rocks, mica schists, feldspathic quartzites, para-amphibolites and meta-evaporites.

The next important step of U reconcentration during the Palaeoproterozoic occurred in the eastern part of the Athabasca Basin basement with the formation of abundant leucogranites and anatectic pegmatites during the Hudsonian Orogeny (~1.8 Ga). These occur as syn- to late orogenic plutons, sheets, dykes and stockworks derived from the partial melting of the U-rich lithologies of the Wollaston–Mudjatik Belt metasediments [22]. These are variably enriched in U, Th, Zr and REE [23]. The U content of these pegmatites is generally of the order of some tens to hundreds of parts per million but may reach several thousands of parts per million. For example, the Charlebois Lake pegmatoids represent a sub-economic resource with 17 500 tU at about 600 ppm U. During the Palaeoproterozoic, a new input of U is represented by the emplacement of large amounts of high K calc-alkaline granitoids in the western part of the Athabasca Basin basement [24]. These belong to the southern extension of the Taltson Belt. In the eastern part of the Athabasca Basin basement, a U-rich potassic porphyritic granite, is reported in the Wheeler River district [22] and in the Eagle Point mine [25]. A further Palaeoproterozoic stage of U reconcentration, prior to Athabasca Basin deposition, led to the formation of the Late Hudsonian (1.8 Ga) vein and episyenite type U deposits (e.g. Beaverlodge) [26]. The Beaverlodge area has produced 25 939 tU [27].

A last stage of U enrichment would have occurred during the deposition of the Athabasca sandstones [28, 29] and would have represented the major U source for the unconformity-related deposits, with an initial U content of 70 ppm mainly hosted in detrital fluorapatite and zircon. It is believed that the initial U content of the Athabasca sandstone was low because of its low detrital accessory and clay mineral contents, the lack of efficient U traps, such as organic matter, and its highly oxidized character [30].

5. URANIUM PROVINCES OF THE WORLD

Numerous U provinces are known throughout the world, but the successive steps of U enrichment within these provinces are not always well characterized. Their geographical extension is highly variable and

sometimes difficult to define. The history of many U provinces starts during the Archaean (e.g. South Africa U Province and Athabasca U Province), whereas others are relatively young (e.g. the mid-European U Province and the Central Asian U Super-Province), some have a relatively small geographical extension (e.g. Athabasca U Province and Central Ukrainian U Province), whereas others are very large (e.g. Central Asian U Province and the Karoo U Super-Provinces). A map of the most important U deposits will be provided in the new edition of the World Uranium Map [31].

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CHALLENGES AND OPPORTUNITIES OF SMALL URANIUM MINES IN THE SMR DEVELOPMENT ERA

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1. INTRODUCTION

Many countries, in particular those within the African continent, face increasing energy demands and gaps in supply. Currently, most countries in Africa generate electricity from oil and natural gas. In the future, however, they will be obliged to develop an energy mix strategy in order to fulfil the long-term energy demand of end users. Small- and medium-sized modular nuclear reactor (SMR) technologies, using small quantities of uranium fuel, will be a serious option for many least developed countries (LDCs) within Africa that currently do not yet have a profound knowledge of the entire nuclear power technology field and related technologies. In addition, a growing interest in mining uranium deposits that have smaller resources will grow and even become strategic with regards to cooperation and marketing for both newcomers, expanders and providers of nuclear power services.

The population within the African continent was estimated to total 1.014 billion in 2010. The population within the continent is predicted to reach 1.318 billion by 2020 and rise to 1.780 billion by 2035 [1]. Further, predictions show that the population will double by 2052 to 2.112 billion [1]. With the majority of people living in urban areas, there will be an increase in demand for services such as electricity. These are high priority needs for all social and economic development of communities and countries. People without reliable access to electricity in Africa is estimated to number about 600 million. Access to a reliable electricity supply varies from country to country and ranges from approximately from 2% to greater than 95%, depending on the country [1, 2].

Oil reserves in Africa are estimated at over 130 billion barrels, representing 9.5% of the world's reserves. More than 80% of these reserves are located in the northern and western parts of the continent [1, 2].

Electricity generation in many LDCs is largely provided by fossil fuel with a contribution reaching over 75%. This contribution from fossil fuel based power is followed by hydroelectric power which represents around 22%, with nuclear and renewable power sources contributing about 5% [1, 2].

Africa's energy demand greatly exceeds its current energy supply. The electrical energy demand was over 1465 GW h for 2010, but this only served about 40% of the population [1]. The electrical demand is predicted to grow to 2401 GW h by 2030 and 2717 GW h by 2035[1]. As regards the depletion of energy resources, especially fossil resources, the African continent must develop a long-term energy strategy and determine what options can be considered for sustainable development.

At present, only South Africa uses nuclear energy for power generation and it is considering expanding its nuclear power programme. Twenty-one countries within the African continent have taken political decisions

to embark on nuclear power and it is foreseen that at least 10 of these will develop and operate their first nuclear power plant for electricity generation within the next 10–20 years [1].

This could be a way to encourage and expand nuclear power in more countries and embrace the opportunities nuclear power provides.

2. APPROACHES AND ANALYSIS

A decision to advance nuclear power includes many considerations, such as scientific and technological preparedness, financial capability, safety and security preparedness, responsibility and commitment in terms of safeguards among African countries and the whole world.

One of the considerations is to ensure that the country has a well-developed policy and strategy for the front end of the nuclear fuel cycle. This should include information on the supply and procurement of nuclear fuel over both the short and long terms and options to be considered when a country seeks to develop a nuclear power programme. In addition, this policy and strategy should cover a purchasing strategy for nuclear fuel services, including natural uranium, conversion, enrichment, fuel manufacturing and wastes arising from the front end of the fuel cycle. This can constitute the basis for cooperation between nuclear operators and those countries holding significant resources of uranium. The results of this kind of cooperation can involve financial compensation, after exploitation and exportat of the uranium. Consequently, a new approach may be considered in the context of energy resource depletion and rapid growth in electrical energy demand in LDCs within Africa and in the context of expansion and maturity of SMR technology.

This means that countries with sufficient uranium resources for sustaining commercial activities related to SMR technology can develop, over the next decades, a nuclear power programme based on their limited uranium resources with nuclear operators in a win–win approach.

Sixteen countries held the majority of known resources of uranium in 2015. Australia, Kazakhstan and the Russian Federation collectively hold over 52 % of these reserves. African Member States that have uranium resources are mainly Botswana, Namibia, Niger, South Africa and the United Republic of Tanzania [1].

The current global demand for uranium exceeds 63 000 tU/year and this is used for nuclear applications such as power reactors and research reactors. Consequently, there is significant interest in exploration effort, due partly to increased costs and perhaps to geostrategic considerations. During the period from 2004 to the end of 2013, about US \$16 billion was spent on uranium exploration on over 600 projects. During this period over 400 new junior exploration companies were established [2].

Recycled uranium and plutonium is another source worthy of investigation and amounts to an annual production of 1700–2000 tU of primary supply, depending on whether just the plutonium or also the uranium is considered. This is forecast to increase to 3000–4000 tU/year by 2020 [2]. The energy equivalence of natural uranium depends on the efficiency of uranium utilization, such as the rate of consumption of depleted uranium during the enrichment phase. If this rate is weak, it is better to take advantage of the U-235 component [2]. The rejection choice results from a compromise between the cost of uranium and that of the SWU (separative work unit), the rate of uranium combustion in a reactor, the possible reuse of the plutonium produced and the processing uranium from a reactor [2]. The values obtained in the PWRs are greater than 10 000 toe per tonne of natural uranium for a rejection rate of around 0.3% and without recycling processes. Therefore, the energy equivalence is about 500 000 toe per tonne of natural uranium. In water reactors with no recycled plutonium, it is possible to have one tonne of natural uranium provide 420 000 GJ or 10 000 toe or 14 334 tce [2].

Currently, most of the reactor unit capacities vary from 60 MW(e) to more than 1600 MW(e). At the same time there have been several hundreds of smaller and medium power reactors in operation, or under construction or planned [3, 4]. The IAEA considers a small reactor to be one with a power rating under 300 MW(e). The IAEA considers reactors with a power rating of about 300–700 MW(e) as a medium sized reactor [3].

The IAEA refers to small and medium sized reactors by the term SMRs. Nowadays, due partly to the competitive capital cost and safety, interest in SMRs is growing in some countries with small economies and small to medium sized electrical grids [3, 4]. A 2009 assessment by the IAEA under its Innovative Nuclear Power Reactors and Fuel Cycle (INPRO) programme concluded that there could be 96 SMRs in operation around the world by 2030 in its high case forecasting scenario, and 43 units in the low case one.

The lack of profitability of small uranium deposits is still changing and the interest of the nuclear operators and industry may change for a number of reasons, including:

- a) Interest in developing SMRs which use smaller quantities of uranium;
- b) Possibilities for operators to exploit small uranium deposits by using the same infrastructure with bordering countries;
- c) Interest of cooperating with LDCs in Africa which express a desire and the commitment to embark on a nuclear power programme.

In general, and as example, energy accessibility in Sub-Saharan Africa is lower than the average level in the whole of Africa. For example, the search for uranium, which had a significant evolution in Senegal between 1965 and 1984, was relaunched in 2007 in the Eastern Saraya licence. The graphitic shales of Mako and Dialé have also generated interest in uranium exploration and reserves found to date are estimated between 5000–10 000 tU.

Also, in Mali, some 5000 tU are located in Faléa, a municipality in an isolated region, close to the borders of Senegal and Guinea [6]. In November 2012, a feasibility study indicated that the Faléa areas contain about 12 000 tU, four times the quantity of the Arlit mine in Niger. In Guinea, the discovery of uranium from Murchison's analysis of samples collected, in particular, from the Firawa site in Kissidougou, located 600 km south-east of Conakry, gave promising results. In addition, several other uranium exploration licences in Guinea have been issued.

3. DISCUSSION

Small deposits of uranium in African countries and in many LDCs constitute a potential source of cooperation for energy for nuclear power, in the context of the reduction of energy resources in Africa and, in particular, in the sub-Saharan region over the coming years (up to 2035).

In order to advance uranium recovery in these areas, provisions need to be taken to rectify a lack of security and safety and to comply fully with safeguards. For a successful and sustainable nuclear power programme, these international legal instruments and guides have to be applied at national, sub-regional and regional levels.

The regional initiative under the Pelindaba Treaty under which the African Commission on Nuclear Energy was established as the body responsible for, inter alia, ensuring compliance with States' obligations needs to be strengthened. The Forum of Nuclear Regulatory Bodies in Africa, with its 33 Members (as of 2015), needs to be supported in terms of human and financial resources.

AFRA-NEST (Network for Education for Science and Technology), with the support of the IAEA and international cooperation is also a way to ensure compliance. The African countries have to implement Emergency Preparedness Review services in a number of Member States and to fortify their cooperation to mitigate the risk of illicit trafficking of nuclear material. To enhance assurance of supply, international fuel reserves which comprise low enriched uranium (LEU) storage facilities are very important and will provide support for LDCs in Africa over the next decades.

There are a number of initiatives to provide assurance of supply of nuclear fuel. The IAEA LEU Bank in Kazakhstan is a storage facility for low enriched uranium owned and controlled by the IAEA and is available as a last resort to IAEA Member States experiencing a disruption in supply, provided all safeguards obligations are met. The LEU Guaranteed Reserve in Angarsk, Russian Federation, was also established under IAEA auspices. A third initiative is under US auspices and is also available to meet the requirements of Member States in situations arising from supply disruption. These initiatives have to be supported at a higher level by all IAEA Member States.

4. CONCLUSION

Small uranium deposits in Africa present growing interest for mining by interested nuclear operators. Exploration and research licences are also increasing. In fact, the small uranium deposits could be sustainable when used for serving fuels for SMRs which need small quantities of fuel.

SMRs could also be an option for those countries needing to increase electricity supply, in the context of a reduction of oil resources, over the coming decades. Safety considerations need to be addressed now to avoid nuclear material proliferation in future nuclear power plants in the region and indirectly during transport, fuelling and refuelling processes and waste processing. Attention also needs to be paid to uranium mine safety as safety regulations for nuclear power plants may also be applied to the smaller uranium mines in Africa.

The political stability of many countries and regions is a major risk and concern regards to nuclear proliferation and a fact that can discourage international cooperation, particularly with western countries, from cooperating in the development of nuclear power programmes in Africa.

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HISTORY OF NUCLEAR FUEL CYCLE DEVELOPMENT, FACILITY DECOMMISSIONING AND SITE RESTORATION AT IPEN – CNEN/SP, BRAZIL

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1. INTRODUCTION

With the decommissioning of the pilot plants of the nuclear fuel cycle at the Nuclear and Energetic Research Institute (IPEN-CNEN/SP) an important period of the IPEN is being concluded. From its foundation in 1956 until the 1990s, the technological domain of the various stages of the fuel cycle was perhaps the most important activity of IPEN, in terms of the number of researchers and technicians involved, as well as the financial resources used.

Since the inception of IPEN, its growth was associated with the IEA-R1m, a pool type reactor which has been in operation since 1957. IPEN is located at the west side of Sao Paulo, on the campus of the University of São Paulo. IPEN occupies an area of nearly 500 000 m² (20% of the buildings). It is associated with the University of São Paulo for teaching purposes. Through a partnership with University of São Paulo, IPEN conducts a post-graduate programme. The IPEN research centres have been engaged in multidisciplinary areas such as nuclear radiation applications, radioisotope production, nuclear reactors, nuclear fuel cycle, radiological safety, dosimetry, laser applications, biotechnology, materials science, chemical processes and environmental applications. As ann example of a significant national impact, the IPEN has been a producer and supplier of radiopharmaceuticals. About 2 million diagnostic and therapeutic nuclear medicine procedures have been performed annually since 2004 with products supplied by IPEN.

Currently, IPEN's main facilities include: the nuclear research reactor IEA-R1m that reached criticality in 1957 (built with United States of America's support under the Atoms for Peace Program) and has been upgraded recently to operate at 5 MW(th); a zero power reactor (IPEN/MB-01 (critical assembly)); two cyclotrons (CV 28 and Cyclone 30 MeV for radioisotope production); two electron beam accelerators of 1.5 MeV for irradiation applications in industry and engineering; two Co-60 irradiators (11 000 and 5000 Ci); dispersed fuel fabrication facilities (for research reactors); laboratories for chemical and isotope characterization, and micro-structural and mechanical tests [1].

IPEN had an important role in the development of uranium and thorium fuel cycles in Brazil. Further, since its inception, IPEN has played a decisive role in the development of all aspects of nuclear science and technology in Brazil. It was established with the main purpose of performing research and development of nuclear energy for peaceful applications. IPEN's recent history has shown significant participation in the technological development of all steps of the nuclear fuel cycle. Nuclear fuel cycle R&D activities at IPEN, ranging from uranium purification to hexafluoride conversion and fuel fabrication for research reactors, besides thorium and zirconium purification, were undertaken at pilot plant scale. Most facilities were built with an expected lifetime of 70–80 years and were destined to be the technological domain for several stages of the fuel cycle. The facilities were used to promote human resources and scientific research and to gain a better understanding of fuel cycle technologies.

The pursuit of autonomous technological development has been emphasized at IPEN over several decades, having experienced a considerable impact when the Brazil–Germany agreement was signed in 1975. Initially, IPEN's researchers felt unmotivated by the option of acquiring technology. However, the agreement was beneficial in terms of training and qualification opportunities for the technical teams.

IPEN had a new period of stimulated when cooperation with the Brazilian Navy began in the early 1980s. Autonomous technological development had once again become important and mobilized a large contingent of personnel at IPEN. One example of the important engagement of IPEN in technological development in the nuclear fuel cycle area is the isotopic enrichment of uranium by ultra-centrifuge, currently in the process of industrial implementation. This significant achievement was performed in cooperation with the Brazilian Navy. Another important achievement was the building of IPEN-MB01, a research reactor built at IPEN in cooperation with the Brazilian Navy and using UO₂ pellets produced at IPEN's pilot plant.

In the 1990s, radical changes in Brazil's nuclear policy resulted in the interruption of the fuel cycle research activities and, ultimately, the closing down of the associated pilot plant. Unfortunately, those changes interrupted decades of autonomous research and development efforts in the nuclear fuel cycle field at IPEN, with significant losses for the country. Despite the existence of a domestic nuclear industry currently consolidated in Brazil, it is necessary to distinguish clearly between autonomous development and acquisition of technology.

Since then, IPEN has faced the challenge of dismantling and/or decommissioning its ageing nuclear fuel cycle pilot plants. Most nuclear fuel cycle facilities have had their activities interrupted since 1992–1993. These facilities have played a role in technological development and personnel training, with transfer of technology to institutions entrusted with the 'scaling up' of the units. Most of the interruption in activity at the pilot plants occurred more than 25 years ago, owing to the lack of resources required to sustain the research [2].

2. HISTORY OF URANIUM DEVELOPMENT AT IPEN

This section summarizes the progress of research with respect to uranium fuel cycle development at IPEN. This includes research on the production of raw yellowcake to uranium hexafluoride, including the reconversion of uranium hexafluoride to ammonium diuranate (ADU) and, at a later period, to ammonium uranyl carbonate. In addition, IPEN conducted research into purifying thorium compounds that originated from concentrates produced via processing of monazite-bearing ores.

About sixty years ago, IPEN began a systematic R&D programme focused on establishing uranium and thorium technology as part of the Brazilian programme for developing nuclear energy for peaceful purposes. The main activities were focused on the recovery of uranium from domestic ores, purification of uranium and thorium raw concentrates and their transformation into compounds with a purity and properties suitable for fabrication into fuel elements for research reactors. The strategy adopted for the uranium cycle was to evolve from a laboratory scale, to bench and pilot scales and finally to commence industrial production.

The first studies associated with the installation and operation of a pilot unit for uranium purification at IPEN were initiated in the Division of Radiochemistry of the IEA (at that time IPEN was named IEA (Atomic Energy Institute)), in 1953 under the guidance of Prof. Dr. Fausto W. Lima [3, 4]. After preliminary laboratory scale studies, a pilot plant was installed which went into operation in 1960 and continued until 1963, when its first stage was closed. The starting product was sodium diuranate, which was produced via industrial processing of monazite by a private company (Orquima) in São Paulo. The final product was a high purity ADU with characteristics appropriate for conversion to uranium oxides and ultimately to uranium tetrafluoride. It was also envisaged in a long term programme to produce uranium hexafluoride. This first facility for uranium purification was based on an ion exchange process. During its operation, the pilot plant produced approximately 4 t of ADU. This ADU was converted into uranium dioxide (UO₂) and used in the manufacture of fuel elements by the IEA's Division of Nuclear Metallurgy [5], which was founded in1962 under the leadership of Prof. Dr. Tharcísio D. Souza Santos. These fuel elements were destined to be used in a sub-critical unit, RESUCO, which was installed at the Nuclear Energy Institute of the Federal University of Pernambuco, in Recife.

During that time, sodium diuranate obtained by the industrial processing of monazite and containing, among others, sodium, thorium, rare earth elements (REEs), iron, phosphorus and silicon as the main impurities was used as uranium concentrate. It should be noted that this uranium concentrate obtained from monazite is different from most uranium concentrates obtained from other ores. The presence of thorium, REEs and phosphate demands special considerations about the purification process which is dependent on the chemistry process employed [4]. In this case, the sodium diuranate was dissolved with nitric acid for the preparation of a uranyl nitrate solution. The main concern was the removal of Th and REEs. To achieve a pure uranium-bearing solution, the loaded cationic resin was washed with water and then with diluted HNO₃ and finally the uranium was eluted with ammonium sulphate. ADU was precipitated by mixing the uranium-bearing eluate with ammonium hydroxide and keeping the reaction medium at a pH of not less than 6.5 to maintain the co-precipitated sulphate at a minimum level (< 0.5% U₃O₈) [6]. Following completion of the first stage of its operation, this pilot plant was dismantled [3].

Following the construction of the building of the Chemical Engineering Division in December 1966, under guidance of Prof. Dr. Alcídio Abrão, the installation of new laboratories was initiated as well as the construction of a new uranium purification pilot plant, which utilized solvent extraction [7, 8]. This unit was based on the conventional liquid–liquid extraction technique. The facility comprised a section for yellowcake dissolution and three pulsed columns with perforated plates for the extraction of uranyl nitrate with TBP-varsol, scrubbing and stripping of pure U. The development of U purification by pulsed columns was carried out some years before the assembly of the pilot plant [9].

Besides the development of purification processes related to monazite concentrates, some alternative techniques were evaluated for the extraction of U, Mo and V from sulphuric acid liquors since, at that time, a leachate solution was produced via an acid leaching process of the uranium-bearing ore from Poços de Caldas in Minas Gerais [10]. Dissolution of the resulting impure yellowcake was accomplished using 2M HNO₃ at ~100°C and the free acid concentration was adjusted to 300 gU/L. The extraction was done in countercurrent fashion with an organic/aqueous ratio of 2.2. The loaded organic phase (TBP-varsol) with 135 gU/L was scrubbed with HNO₃. The organic phase was stripped with water, resulting in a purified uranyl nitrate solution.

A pilot plant was constructed to precipitate ADU by bubbling anhydrous $NH_3(g)$ into uranyl nitrate with a concentration of 100 gU/L, at 60°C. The unit could be operated in batch as well as continuous mode. The process pH was an important parameter to be controlled, depending on the process selected for the ADU. For production of UF₄, it was important to keep the pH in the range 4.0–4.5, to avoid oxide agglomeration. However, for obtaining UO₂ with better ceramic reactivity, it was important to keep the pH at 7.0–7.5 [10]. The calcination of ADU to UO₃ (for UF₄ conversion) was accomplished in a belt furnace at 500°C, with the ADU loaded in trays of stainless steel.

After some preliminary studies, a pilot plant facility for UF₄ production was developed. The establishment of this unit was achieved with the collaboration and technical assistance of the IAEA. The UF₄ pilot plant operated using a moving bed process. The starting material was UO₃, reduced to UO₂ via reaction with cracked NH₃ and anhydrous hydrogen fluoride for the conversion to UF₄ [11–13]. Laboratory scale development work was also conducted to produce UF₄ by an alternative method via uranium dioxide reaction with hydrofluoric acid (wet method). A semi-pilot unit for this technology was also installed, with the construction of a polyethylene reactor with mechanical agitation, which had a capacity of 100 kg UF₄/batch.

An alternative method to refine ADU into UO_3 was accomplished through the construction of a denitration pilot plant. This facility used a fluidized bed process for conversion of uranyl nitrate solution to uranium trioxide and recovery of nitric acid. The bed of UO_3 was fluidized by upward flowing of air in a 76-mm diameter tube (reaction chamber) heated by external electric heaters. Uranyl nitrate solution was injected at the bed level by a nozzle. UO_3 seeds had been previously placed to form the bed and the decomposition of uranyl nitrate occurred around the seeds. Throughout this process, the spherical form of UO_3 was preserved. Obtaining UO_3 directly via the denitration of uranyl nitrate avoids the precipitation, filtration and drying of ADU which occurred in the conventional process.

The next step was the construction of an electrolytic fluorine generator and a pilot plant for UF₆ production, having produced the UF₄ in the moving bed reactors, which was used as starting material. During its operational life, the unit produced tens of tonnes of UF₆. This was then used in development of ammonium uranyl carbonate precipitation process. The development of the AUC process was of fundamental importance in the production of the UO₂ fuel pellets for the IPEN-MB01 research reactor that was fully designed and constructed domestically through cooperation between the IPEN and the Brazilian Navy.

In parallel with uranium related research and development, a programme for thorium purification and production was conducted at IPEN. The alkaline process for cracking the monazite had been in operation by the private company Orquima since 1948. Processing of the monazite sands with the aim of exporting REEs and other materials resulted in the production of thorium concentrates suitable for purification by solvent extraction. As a result, a pilot plant was built and production and purification of thorium compounds was carried out at IPEN for about 18 years using solvent extraction technology. During this period, the main product sold was high purity (nuclear grade) thorium nitrate. Over 170 t of pure thorium nitrate was produced over this period. The raw materials used were thorium concentrates obtained from the processing of monazite sands. Thorium nitrate was supplied to the domestic industry and particularly used for portable gas lamps (Welsbach mantle). The thorium compounds produced initiated several studies with the objective of creating nuclear grade thorium oxide suitable for the manufacture of fuel pellets, mixed oxide pellets (U, Th)O₂, thorium tetrafluoride and its reduction to metallic thorium. In addition, studies were carried out to determine the properties of UO₂–ThO₂ solid solutions [14, 15].

Theses process advancements, in addition to construction and operation of pilot plants, resulted in several additional related developments such as effluent treatment, construction of a fuel reprocessing laboratory, production of Sol-Gel microspheres, analytical procedures for quality control, as well as the development of further metallurgical processing of uranium and thorium compounds and studies on strategic materials such as Zr and REEs.

3. DISCUSSION AND CONCLUSION

In the 1990s, immediately following the nuclear R&D programme interruption, the uncertainties relating to an eventual restart of the program created some political hesitation about the decision taken to dismantle facilities. As restarting the R&D nuclear programme had been rejected, decommissioning seemed to be the obvious choice. The condition of associated facilities had been downgraded owing to a lack of resources for maintenance. There were evident signs of deterioration in infrastructure and equipment within the facilities. The existence of these facilities also required the need for constant security surveillance, representing additional obligations, costs and problems.

With the decommissioning of nuclear fuel cycle facilities at IPEN [2, 16] an important cycle of the institution's life is being closed. The first years of IPEN as a new research centre in the 1960s were full of problems and challenges, but these were overcome by the professional personnel employed at there. This paper is a record and tribute to the achievements of those pioneers who began their studies on the nuclear fuel cycle and related materials in Brazil.

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ADVANCES IN GEOPHYSICAL METHODS USED FOR URANIUM EXPLORATION AND THEIR APPLICATIONS IN CHINA

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1. INTRODUCTION

Geophysics is one of the most useful techniques for uranium exploration. It supports the development of geological models through the definition of lithological, structural and alteration characteristics of metallogenic environments under evaluation. With exploration at increasing depths, the traditional radiometric method is no longer effective for uranium exploration. Uranium mineralization is not closely related with observable gravity, magnetic and impedance anomalies. Gravity, magnetic and electromagnetic techniques can be used to survey the subsurface geological background of an area and can be efficient in detecting deeper uranium deposits [1]. The progression and development of geophysical methods, measurement techniques, data processing, computer modelling and inversion have permitted improvements in the field of uranium exploration [1, 2].

It is well known that progress in geophysical methods has contributed to successful field investigations in the exploration for deeper deposits (including uranium). Xu et al. [2] have reviewed the latest advances and developing trends in geophysical and geochemical methods and techniques applied to uranium resources exploration in China [2]. Following this work, this paper summarizes the research carried out by the East China University of Technology during the past decade. This includes 3-D inversion of magnetic data and 3-D electromagnetic methods tested in the Xiazhuang area over granite type uranium deposits [3, 4] and in the Xiangshan area over volcanic type uranium deposits [5]. Results indicate that some of the objectives, including mapping of basement structures, rock interface and lithology recognition, can be achieved.

2. APPLICATION TO DEEP URANIUM DEPOSITS IN THE XIAZHUANG AREA

The Xiazhuang uranium orefield where granite-related uranium deposits are present was selected as a case study for the use of magnetic 3-D inversion and electromagnetic imaging. In this area, uranium deposits related to diabase are mainly located in the eastern part of the Guidong granite body [6–8]. This type of uranium deposit was named 'intersection type' and is located at the intersection of diabase dyke swarms with a near E–W strike and a silicified fault system with a NNE extension. After the discovery of new mineralization at depth, attention focused on the Xiazhuang uranium orefield.

Integrated geophysical methods, including gravity, magnetic and electromagnetic, were used to delineate granitic rocks and faults at depth. The goal of this study was to test the applicability of the abovementioned methods to exploration for uranium deposits and to predict the presence of mineralization during prospection. For this purpose, eight profiles were assigned for an AMT and gravity survey and a 20 km² magnetic survey was performed along an area on which several uranium orebodies were known from deep drill hole data.

After surveying the profiles, the data were processed using 2-D or 3-D inversed and interpreted. The results effectively identified the granitic rocks at significant depths and the imaged distribution of these units was consistent with information obtained from the local geology. Finally, by integrating the results from the gravity, magnetic and electromagnetic data, three locations were suggested for drilling. Two of these intersected uranium mineralization at a depth of around 1000 m while one was unmineralized. After drilling of the three locations, cores were studied and compared with the results obtained from the geophysical

methods which resulted in confirmation of the geophysical findings. Furthermore, this work showed the efficiency of the geophysical methods in exploring for deeper granite hosted uranium deposits.

3. APPLICATION TO THE GEOLOGICAL STRUCTURE OF THE XIANSHAN VOLCANIC BASIN

As the third largest volcanic type uranium orefield in the world, the Xiangshan volcanic basin is attracting great research interest and important investment from the mining industry. A 3-D geological structure survey and modelling project was undertaken in 2011. The purpose of the project was to delineate the volcanic calderas (limits still not confirmed over the past 60 years) and to investigate the deeper geological structure of the basin. It was based on the physical property measurements of around 1400 samples from drill cores and of rock samples taken along the geological profiles. Also, 3-D inversion of regional gravity and magnetic data were conducted and 19 magnetotelluric profiles covered the Xiangshan volcanic basin. These magnetotelluri data were inverted using 2-D and 3-D inversion algorithms developed in-house [9, 10]. With the integration of the geophysical survey results and with information from drill holes and local geology, a 3-D geological and geophysical model was developed. It was then concluded that the Xiangshan volcanic basin comprises two basement units, a metamorphic one and a granitic one of Caledonian age. A low resistivity layer exists between the metamorphic basement and the overlying volcanic-sedimentary formations, corresponding to an unconformity interface. A mushroom shaped low resistivity geological body with a radius of around 2 km located in the Xiangshan Mountains is inferred as corresponding to the Ehuling Formation. Seven NE striking, four NW striking and one N-S striking faults were delineated on the basis of the geophysical results.

4. CONCLUSIONS

Integrated geophysical surveys for deeper uranium deposit exploration and 3-D geological structure surveys were initiated in south China. Combined with geological and borehole data, these results support the need for deeper uranium exploration in these areas. It is concluded that geophysical methods can give results useful for uranium exploration. The selection of the geophysical methods to be used depends on the physical properties of the target and on the nature of the rock formations, the geological setting and the environment. Integration of several geophysical methods and other disciplines is necessary in most cases to achieve better results.

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PRELIMINARY STUDY ON URANIUM ORE GRADE CONTROL TECHNIQUES FOR THE HUSAB MINE, NAMIBIA

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1. INTRODUCTION

The Husab mine is situated within the Namib Desert in the Erongo region of western Namibia, 6 km south of the Rössing mine, which is majority owned by Rio Tinto, approximately 60 km east of the coastal town of Swakopmund and less than 100 km north-east of the Walvis Bay Port, the largest deepwater port in south-western Africa. It has good communications links and extremely favourable infrastructure conditions for development. As the most important uranium deposit to have been discovered since 2000, the Husab mine has a total uranium resource of nearly 300 000 t of U_3O_8 with ore reserves of 300 Mt containing 156 000 t of U_3O_8 at average grade of 518 ppm U_3O_8 .

The Husab mine is the first ultra-large uranium mine to be constructed and operated by the China General Nuclear Power Corporation (CGN). Mine construction and pre-stripping commenced in 2013, ore mining commenced in May 2015 and the first barrel of uranium oxide was produced on 31 December 2016. The Husab mine has a designed annual mining capacity of over 100 Mt, an annual ore processing capacity of 15 Mt and an annual output of 6500 t of U_3O_8 . It will be the largest open pit uranium mine with the largest mining capacity in the world.

With more than one year's mining production and operation, the production management, equipment maintenance and technical management systems have been fully established at the Husab mine and its operational activities, such as the process plant and mining production, has gradually progressed. However, problems have arisen owing to the greater variation in the shape of orebodies than expected, inaccuracies in the measurement of uranium grade, large scale mine haulage fleets and precision loading errors, etc. Several outstanding issues have been identified in respect of consistency between the grade of resource model and that of mined ore, control of dilution, loss in the course of mining such as high dilution and loss ratios, and large variation in grade in the mining process. These issues will all have a negative effect and impede the stable production at the Husab mine. It is therefore urgent to carry out a study on the key techniques of uranium ore grade control in order to solve these mining production issues.

This study focuses on the entire process of mining production and has conducted the following optimization work including: establishment of a geological resource–grade control model system, optimization of the mining production procedures, application and optimization of controlled blasting technology to ensure a higher precision and application of rapid and accurate grade measurement by down-hole gamma logging. This optimization work will effectively improve the ore dilution and loss during mining and will further improve the production capacity and economics of the Husab mine.

2. ADVANCEMENT ON THE STUDY OF ORE GRADE CONTROL TECHNIQUES

2.1. Establishment and improvement of the three-stage resource-grade control model system

Currently, the 'two stages' resource–grade model system has been adopted at the Husab mine, which comprises a geological resource model based on the exploration database and grade control model based on down-hole gamma logging data from drill holes. The annual plan for mining production, blasting block

design, mining and stripping production plan and blast hole design are proposed on the basis of the geological resource model, and the mining block definition (composite model) and loading plan are proposed on the basis of the grade control model. However, owing to the fact that the drilling exploration grid is mostly $25 \text{ m} \times 25 \text{ m}$ to $50 \text{ m} \times 50 \text{ m}$ or larger and the fact that the geological resource model is not updated using the mining production data, the geological resource model has low accuracy and reliability with respect to mining production and thus it cannot be used to effectively guide the annual mining production plan, blasting block design, blast hole design or their optimization. At the same time, however, some model parameters reduce the accuracy of grade control model and thus it cannot accurately define the ore–waste boundary so as to meet the requirements of loading and ore blending.

On the basis of extensive discussion and site visits to other large scale open pit mines, combined with a review of actual mining at the Husab mine, this study proposes a hierarchical, segmental and stable 'three stages' geological resource model system consisting of a geological resource/reserve model, an interim model and a grade control model that can be updated dynamically. The grade control model is based on down-hole gamma logging data from blast holes by interpolating the ore grade for the block model of a specific blasting block and is used to guide the definition of mining blocks, wire connections for blasting, ore loading and blending. The geological resource model is created by using the geological database incorporating drill-hole data from resource drilling and blast holes from mining production. It interpolates the ore grade distribution for all the orebodies within the mining district and is used for optimization of the ultimate open pit boundary, for both mid-term and long-term mining, and for both stripping and annual mining production plans. The interim model proposed in this study is a transitional model between the geological resource and grade control models that establishes the interconnection between these models to form a comprehensive geological model system. This interim model is created by using down-hole gamma logging data from blast holes drilled for 2–3 benches above the current bench and resources drill-hole data below the current bench, it interpolates the grade distribution for the downward one or two benches from the current bench. It is used for the monthly and weekly mining and stripping plan, blasting block design and blast hole design and thus improves both blasting and mining efficiency.

2.2. Optimization and improvement of mining production procedures

Since pre-stripping, which commenced in 2013, and ore mining, which commenced in 2015, a set of mining production procedures were established and the mining production rate gradually increased. However, in the absence of a more accurate geological resource–grade control model, there is still much uncertainty to the entire mine production. It is therefore difficult to meet requirements with respect to the tonnage and grade of ore to be mined and thereby ensure the smoothness of mine production. The geological resource models are re-created and updated for the first stage of mining areas in Pit #1 and #2 based on an understanding of the mine geology and combined with grade data. This further defines the spatial distribution of the orebodies and the grade distribution, which will provide guidelines for preparing the midterm, long term mining and annual mining plans. The interim model proposed in this study provides more accurate ore–waste boundaries within the benches to be mined and thus it lays a better foundation for preparing the monthly and weekly mining plans, blasting block design and blast hole design. These more scientific and reasonable grade control models and accurate ore–waste boundaries will greatly enhance the blasting efficiency and the output of mined ore, and reduce the ore dilution and loss and at the same time. It is also favourable to blend ore directly within the pit to reduce ore transport.

2.3. Application of advanced controlled blasting technology and its optimization

Up to now, mining production has focused on increasing the stripping capacity at the Husab mine and is not completely transitioned to focus on mining capacity to provide the ore in the tonnages and grades required by the process plant. Therefore, relatively simple blasting technology and blasting scheme are adopted currently at the mine. Different blast schemes have not been adopted owing to differences in the mechanical properties of rocks within different blasting blocks. In addition, the advanced blasting technology has not

been adopted to effectively separate the ore and waste. It is therefore necessary to improve blasting efficiency. In this study, the quality of rock mass was assessed on the basis of studying the physical and mechanical properties of the main ore and rocks within the mining district. The rock masses are divided into two categories according to their blastability. The first is rock that is easy to blast and comprises near-surface loose and poorly cemented sandstone and calcrete. The second category is rock mass that is difficult to blast and mainly consists of hard units of granite, marble, gneiss, schist and quartzite.

On the basis of analysis of the blasting parameters currently used at the mine, and considering the requirements of ore loading, hauling and primary crushing of ore, it is believed that the current blasting parameters are effective for blasting within the ore-bearing areas. However, it is not reasonable that these parameters be used for blasting within the areas of waste without any modification and these could be improved greatly. Consequently, significant research work has been conducted to improve blasting parameters for use within the areas of waste, and desktop analysis and digital simulation are also undertaken. The next step is to carry out the field trials on-site after which they can be applied at the mine.

In addition, it is difficult to control the ore dilution and loss owing to the fact that there is no interim model or accurate grade control model to guide mine production and the so-called special technologies, such as pure blasting, separating blasting and slag-remaining blasting. These are not applied at the Husab mine and, therefore, the field trial of blast induced movement monitoring does not provide a satisfactory result. It is proposed in this study that different blasting technology be adopted, including schemes to control the blasting and successfully separate the ore and waste according to their distribution within the mining area, based on the more accurate interim and grade control models. For the large-scale blocks with extensive areas of ore and waste, it is proposed that individually designed blast holes on the block of ore or waste be used to successfully separate the ore and waste when the ore area or waste area meets the requirements of an individual block. When the area or waste area is not large enough to be designed an individual block, modification of the blasting parameters such as the blast hole design, charge structure, blast delay time and initiation mode is proposed in order to generate physical zones that are easy to identify. Such zones could show visible difference in sizes within the ore or waste areas and flutes at the boundaries of ore and waste and by this means the ore and waste can be finally distinguished and guide the ore loading, thereby reducing ore dilution and loss.

2.4. Application of uranium grade measurement technology by down-hole gamma logging

Currently, the uranium content of ore is determined primarily by chemical analysis and assisted by radiometric measurement at the majority of uranium mines in the world except those in China and elsewhere in central Asia. It not only takes a considerable time but it is also expensive to determine uranium by chemical methods of analysis and thus it is difficult by this means alone to ensure the smooth operation of the Husab mine. A radiometric measurement system has been established, including the technology, equipment, operating manuals and technical standards, etc., over a period of several decades, drawing on the practices employed in the exploration and production of uranium mines in China. Since the start of the Husab mine, the radiometric measurement system and related operating manuals and standards were introduced gradually. This included key equipment facilities such as the down-hole gamma logging system, truck scanner system, belt scanner system at the primary crushing station and corresponding calibration of technical parameters, and the construction of standard calibration models on the site. This ensures that the grade of ore will be determined accurately and on time, fully meeting the production requirements at the Husab mine.

3. CONCLUSIONS

A set of comprehensive set of mining production procedures and technical standards were initially established when the Husab mine was put into production. The continuous research achievements in this study show that effective results have been achieved in the fields of the resource–grade control models,

optimization of the mining production procedures, controlled blasting technology and radiometric measurement technology. Thus, the mining capacity and efficiency has been improved effectively and the ore dilution and losses have been reduced, laying a strong foundation for the ramp-up in production at the Husab mine.

THE REMOVAL OF RADIATION AND OTHER IMPURITIES FROM COPPER SULPHIDE CONCENTRATES

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1. INTRODUCTION

High grade, copper sulphide concentrates, (typically greater than about 25% w/w Cu), are commonly treated via pyrometallurgical routes, whereas hydrometallurgical routes are typically favoured for lower grade or impurity-bearing concentrates. The processing routes for the treatment of copper concentrates can also be influenced by the presence of minor valuable metals such as silver, gold, uranium, palladium and platinum, as well as deleterious metals such as nickel, cobalt, lead and zinc.

Many copper iron sulphide concentrates contain radioactive uranium and its progeny. Other elements such as zinc, nickel, cobalt and aluminium also add to the impurity load. This paper summarizes a process that has been successfully demonstrated as being able to remove very significant levels of the original radioactivity, while at the same time upgrading the concentrate so that it attracts reduced transport and treatment costs at smelters. The upgraded concentrates have demonstrated that they satisfy the IAEA Regulations for the Safe Transport of Radioactive Material (2012) [1] for the transport, trade and processing thereof.

2. IMPURITY REMOVAL APPROACH

The objective of radionuclide and impurity removal is to produce a smelter quality copper–iron–sulphide concentrate which can be sold, transported across borders and smelted with zero harm. To minimize the prospect of attention at border crossings or ports, the concentrate should contain no more than 0.3–0.4 Bq/g for ²³⁸U, ²³⁰Th and ²²⁶Ra and no more than 0.8–0.9 Bq/g for ²¹⁰Pb and ²¹⁰Po. The radionuclides removed can be disposed of with the concentrator tailings in an appropriately lined tailings storage facility.

Impurities are invariably locked within the valuable mineral particles. If not locked, they would typically be separated in the flotation process. It is postulated that where the mother (²³⁸U) resides, the daughter products, resulting from decay over long time periods, are in close proximity, and so if a pathway can be developed to remove the mother (²³⁸U), then the same pathway could be exploited to access the progeny. In addition, the superficially transformed nuclides of ²¹⁰Pb, ²¹⁰Bi and ²¹⁰Po possibly exist in a different chemical form to those same nuclides locked in the sulphide minerals.

The concentrate leach in a combined sulphate and chloride lixiviant provides not only the opportunity for the removal of radionuclides but also for the removal of other impurity elements such as nickel, cobalt, lead and zinc. Additionally, the copper concentrate is upgraded, resulting in a lower mass 'super concentrate' and hence this will reduce the transport costs. In some cases, with this mass loss, silver can be rendered 'payable' in the upgrade process. If the removal of radionuclides is not required, then a more targeted concentrate leach in a sulphate lixiviant can be applied.

3. IMPURITY REMOVAL MECHANISM

Early work on impurity removal was conducted in South Africa. It was recognized at the time that the only way for an upgrade to be effective and for the majority of the copper and sulphur to remain unleached was to adopt the classical metathesis and hydrothermal approach [2–4] employed in some southern African autoclave systems.

The hydrothermal mechanism is kinetically slower than the preferred metathesis metallurgy. As in the case of the metathesis mechanism, the hydrothermal step also requires a mild oxidant for it to be effective.

Metathesis is an electrochemical process in which the soluble cupric cation exchanges for a more electronegative element in the concentrate. For example, in the case of iron, the more electronegative element is solubilized while the copper cation is received into the concentrate matrix in a reduced form. These two mechanisms create pathways into the mineral structure for the other locked elements to escape.

Mineralogically, the mineral metathetic alteration commences as a 'rimming' effect in which covellite (CuS) is formed and thereafter further sulphur depletion ensues to form chalcocite/digenite minerals. Depending on the copper activity in the aqueous phase, sulphur depletion (oxidation) and hence final copper in concentrate grade can be influenced.

The use of a combined sulphate and chloride lixiviant is suited for the mobilization and extraction of other elements that have preferred sulphate or chloride lixiviation metallurgy.

The hydrothermal alteration of chalcopyrite is thought to proceed in a different manner. The chalcocite layer, once nucleated in the hydrothermal process, moves both outwards and inwards to convert chalcopyrite to covellite. However, the total conversion to chalcocite may not be economic and, consequently, the process is normally terminated with covellite being the dominant mineral in the alteration process [5].

To permit treatment and to maximize the value of a copper concentrate, the levels of impurities in the concentrate needs to be reduced below the limits set by the smelters and in some cases the regulatory authorities in the producing and receiving countries. This paper presents a method of impurity (specifically radionuclides) removal for copper concentrates.

4. CHEMISTRY

Copper concentrates are upgraded via the metathesis process in an autoclaving step known as Nonox (a mildly oxidative high temperature environment). The typical chemical equations of the upgrading process are as shown in Eqs (1) and (2).

$$3CuFeS_{2(s)} + 6CuSO_{4(aq)} + 4H_2O_{(l)} \rightarrow 5Cu_{1.8}S_{(s)} + 3FeSO_{4(aq)} + 4H_2SO_{4(aq)}$$
(1)

$$Co_{3}S_{4(s)} + 4CuSO_{4(aq)} + H_{2}O_{(1)} \longrightarrow 3CoSO_{4(aq)} + Cu_{4}S_{3(s)} + S^{\circ}_{(s)} + H_{2}SO_{4(aq)}$$
(2)

Possible chemical reactions for the alteration of other non-sulphide impurities in the concentrate leach are described in Eqs (3)–(8). In sulphate only lixiviant, ²³⁸U and ²³⁰Th are able to be removed to a level below 1 Bq/g in the copper concentrate. In addition, impurities such as cobalt and nickel are removed. In chloride only lixiviant, there will be no transformation. In sulphate and chloride lixiviant, ²³⁸U, ²³⁰Th, ²²⁶Ra, ²¹⁰Pb, ²¹⁰Bi can be removed to a level below 1 Bq/g and to a level below 2 Bq/g for ²¹⁰Po.

$$\text{Uranium: } \text{UO}_{2(s)} + 2\text{CuSO}_{4(aq)} + 2\text{H}_2\text{SO}_{4(aq)} \qquad \leftrightarrow \qquad \text{H}_4(\text{UO}_2)(\text{SO}_4)_{3(aq)} + \quad \text{Cu}_2\text{SO}_{4(aq)} \tag{3}$$

Thorium:
$$ThSiO_{4(s)} + 2H_2SO_{4(aq)} \leftrightarrow Th(SO_4)_{2(aq)} + 2H_2O_{(l)} + SiO_{2(aq)}$$
(4)
Radium: $RaSO_{4(s)} + 2NaCl_{(aq)}$	\leftrightarrow	$RaCl_{2(aq)} + Na_2SO_{4(aq)}$	(5)
Bismuth: $Bi_2(OH)_2(SO_4)_{2(s)} + 6NaCl_{(aq)} + H_2SO_4$	$i_{(aq)} \leftrightarrow$	$2BiCl_{3(aq)} + 3Na_2SO_{4(aq)} + 2H_2O_{(l)}$	(6)
Lead: $PbSO_{4(s)} + 4NaCl_{(aq)}$	\leftrightarrow	$Na_2PbCl_{4(aq)} + Na_2SO_{4(aq)}$	(7)
Polonium: $Po_{(s)} + 2Na_2CuCl_{4(aq)}$	\leftrightarrow	$Na_2PoCl_{4(aq)} + 2CuCl_{(aq)} + 2 NaCl_{(aq)}$	(8)

5. FLOWSHEET

The principal reagents and conditions required in the concentrate treatment flowsheet are a copper ion source, water, sodium chloride (salt) and elevated temperature.

In a typical [6] two stage autoclave flowsheet, the copper concentrate to be upgraded is repulped in recycled brine before it is fed into the Nonox leach autoclave. The copper ions required in Nonox are supplied from a separate close coupled oxidative copper pressure leach (CPL) autoclave. A portion of the Nonox product is employed in a CPL autoclave under which oxidative conditions are autogenous in temperature. Steam is injected into the Nonox autoclave to control the autoclave at approximately 210°C. Typical conditions in the Nonox autoclave are as follows:

- 2–3 h leach time;
- 15–30% w/w concentrate in the autoclave feed slurry;
- Greater than 35 g/L chloride in Nonox with a chloride/sulphate ratio >0.3;
- 2500 kPa(g);
- Eh of 250–280 mV (Ag/AgCl 3.8M KCl) and pH of 0.7–1.2.

The Nonox autoclave discharges into a flash tank. The Nonox discharge slurry is filtered and the filtrate is transferred to the barren liquor treatment circuit for treatment while the filter cake is repulped in clean water.

In the event that it is economic to recover uranium and thorium as by-products, the filtrate from the Nonox discharge filter can be treated through a continuous ion exchange unit where uranium and thorium can be recovered. The barren liquor from the ion exchange is then processed to recover the brine.

A portion of the repulped Nonox product is fed to the CPL autoclave while the remainder is treated in scavenging atmospheric leach (SAL) to further remove ²²⁶Ra, ²¹⁰Pb and ²¹⁰Po. In the SAL, the concentrate is treated with a two-stage alkali–acid sodium chloride lixiviant. The product from the scavenging atmospheric leach is filtered to produce the final copper concentrate product and the SAL filtrate is incorporated in the barren liquor treatment circuit.

In the barren liquor treatment circuit, the Nonox filtrate is treated using limestone to precipitate the dissolved iron and radionuclides. The barren liquor treatment discharge slurry is then filtered and the filtrate is recycled to the concentrate repulp. The barren liquor treatment residue contains iron and gypsum and essentially all the impurities, including radionuclides, that were leached in the Nonox autoclave. The filter cake could be disposed of in the concentrator tailings facility.

In a preferred variant of the flowsheet, a single stage autoclave can be employed to replace the two-stage Nonox plus CPL. In the single stage autoclave, a strong oxidative leach is undertaken on the concentrate in the early compartments which produces a cupric lixiviant and this then passes to a mildly oxidative final section of the vessel. These single stage autoclaves have been employed in similar duties in Europe and Africa and are not without precedent.

6. RESULTS

The copper concentrate treatment process has been able to reduce the radionuclides and other impurities to lower levels. A summary of impurity removal and upgrade results for secondary copper sulphide concentrates was as follows:

- ²³⁸U level reduced from 1.4 Bq/g to 0.12 Bq/g;
- ²³⁰Th level reduced from 1.5 Bq/g to 0.56 Bq/g;
- ²²⁶Ra level reduced from 0.99 Bq/g to 0.73 Bq/g;
- ²¹⁰Pb level reduced from 6.4 Bq/g to 0.35 Bq/g;
- ²¹⁰Po level reduced from 7.0 Bq/g to 0.62 Bq/g;
- Copper in the concentrate feed was simultaneously upgraded from 48.6% to 56%;
- The feed concentrate contained the following copper minerals: bornite (39%), chalcocite (32%), chalcopyrite (13%) and pyrite (8%);
- The upgraded concentrate contained predominantly of chalcocite/digenite (64%), covellite (17%) and pyrite (7%).

Primary concentrates displayed a similar trend in radionuclide and other impurity element removal in a twostage leach. However, there was a more significant upgrade in copper in the primary concentrate compared with secondary concentrates:

- Copper was upgraded from 28% to 60% consisting primarily of chalcocite (82%), pyrite (10%) and idaite (7%);
- Chalcopyrite (57%), pyrite (24%) and bornite (14%) were the dominant minerals in the feed concentrate.

In a single stage autoclave leach, a primary concentrate was upgraded as follows:

- Copper from 28% to 59%;
- Silver from 20 ppm to 43 ppm;
- Gold from 13.5 ppm to 25 ppm;
- The product concentrate contained predominantly chalcocite (46%), covellite (29%) and pyrite (19%) with a mass loss of approximately 50% and no loss of gold and silver.

7. DISCUSSION AND CONCLUSION

The concentrate treatment process has the potential to reduce radionuclides ²³⁸U, ²³⁰Th, ²²⁶Ra, ²¹⁰Pb, ²¹⁰Bi to a level below 1 Bq/g and to a level below 2Bq/g for ²¹⁰Po. In addition to radionuclides, other impurities that may attract penalties at the smelters, such as nickel, cobalt and lead, are also removed in the concentrate treatment process [5, 6]. Economically recoverable uranium can be recovered as by-product by employing ion exchange. Simultaneously, the copper in the final concentrate is raised to 55–60%. This upgrade and hence mass reduction results in reduced transportation and treatment costs. Most importantly, there are minimal copper and silver losses. Gold losses are negligible.

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SOCIETAL BARRIERS TO URANIUM MINING: A STUDY CASE FROM BRAZIL

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1. INTRODUCTION

Attitudes of different communities against uranium mining can impose severe constraints in uranium mining operations, potentially leading to insuperable barriers to project implementation and development. Some studies have investigated public opinion on uranium mining in different countries. One of these studies in Australia revealed that in 2008 just under half of the public supported the mining of uranium, while 36% opposed it [1]. The study also informed that over the previous decades, public support for nuclear energy in Australia had declined, while support for uranium mining had remained relatively stable. In Canada, a study prepared by AREVA Resources [2] indicated that

"the uranium mining and uranium mining companies continue to hold a place of importance in the minds of Saskatchewan residents. Support remains high among survey respondents, both province-wide and in the North... as the result of the perception... that the primary companies operating in the industry operate safely and responsibly, and contribute positively to the province".

A study developed by the University of Eastern Finland, Litmanen and others [3] indicated that public opinion was more critical of uranium mining operations in comparison to other types of mining activity such as (other) metals and industrial minerals. Only 1–4% of the interviewed individuals considered these activities as being unacceptable, while in the case of uranium mining this level was determined to be between 38 and 51%. Six variables were examined in the study: environmental attitudes, perceptions of the disadvantages and benefits, knowledge of the mining, trust, trust in officialdom and acceptability of foreign mining companies. Familiarity with operations correlated strongly with the acceptance. Drawbacks have a stronger impact on acceptability than have the benefits. Trust in the authorities and legislation is strongly and positively correlated with acceptance. Finally, it was seen that the people who are more willing to accept foreign mining companies were also those more inclined to accept uranium mining.

Regarding Africa's situation, the place of the continent in the global nuclear market was examined in 2012 [4]. This study considered that international and African tools either exist or are being set up to improve the governance of uranium mining in Africa. It concluded that improvement requires attention to strengthening government capacity and ensuring wider consultative processes.

2. PERSPECTIVES FROM THIS WORK

In the scope of this work, over one hundred entries on the internet that captured individual views on uranium mining from all over the world were examined. This strategy did not follow any strict scientifically based methodology. The intention was to achieve a preliminary assessment of the hypothesis that basic perception towards uranium mining was the same all over the world and, if so, what were the main aspects driving people's views and positions. As a result of this investigation, it was found that attitudes were affected by four main issues: (i) misuse of scientific evidence that ends up propagating fear, (ii) influence of historical (legacy) sites, which in many cases were developed outside the proper regulatory framework, that are associated with practices that are no longer accepted or even seen as good practices, (iii) long term issues,

i.e. mining sites remain dangerous even after their closure, (iv) the perception that these operations bring considerable burden to indigenous people (this is because mining operations in many circumstances take place in remote areas). These points above seem to be fully consubstantiated by a wide diverse publications/reports available in the literature. Some examples are provided below.

The Quebec Mineral Exploration Association and the Quebec Mining Association wrote an open letter protesting the "attempts to manipulate public opinion against the mining industry and the uranium industry in particular" [5]. The manifesto refers to the announcement made by a group of doctors that would be leaving the area of a future mining operation. The open letter states that the group of doctors were claiming that the principles of precaution and prevention should be considered in any decision regarding the implementation of a new uranium mining project and led to a more extreme claim for a "moratorium on uranium mining and exploration in Quebec". The letter signatories indicated that the overall manoeuvre against uranium mining was intended "to instil doubt and fear in the largest possible number of citizens of good faith, including doctors".

A report on perceptions and realities in modern uranium mining was released by the OECD Nuclear Energy Agency in 2014 [6]. The publication concludes that public perception of uranium mining is largely based on the adverse health and environmental impacts resulting from past practices, i.e. those that took place during an essentially unregulated early phase of the industry.

Brugge and Goble (2002) [7] claimed that the Federal Government in the USA "deliberately avoided dealing with a health disaster among Navajo uranium miners". The authors claimed that even after two decades after the harmful effects of uranium mining were known, the implementation of protective measures had not been undertaken.

No doubt that what makes uranium mining even more subject to public scrutiny than other mining activities or industrial operations is the radioactive properties of uranium and its progeny. In addition, one cannot ignore the obvious link of mining operations to atomic bombs (in the past) and nuclear power (nowadays). It is also a critical aspect that the legacy sites created with the operations that were initiated during the 1940s and 1950s up to the 1980s now need governmental funding to finance the remediation required to render the sites safe and stable. Funding to be allocated for the remediation of these sites will compete, especially in countries with less advantaged economies, with other demands, particularly those of a social nature (e.g. education and health) and this will not be well perceived by the public. An obvious reaction is that societies with this perception will stand against future operations based on the experience gained from past operations.

3. THE CONTEXT IN BRAZIL

In Brazil, the only ongoing uranium mining and processing operation started in 2000 and is located at Caetité (Lagoa Real province), a semi-arid region in the central south-west part of Bahia state [8]. The extraction of uranium from the ore is achieved by means of a heap leach process. Owing to scarcity of water, local populations rely, to a considerable extent, on the abstraction of groundwater for living purposes. Enhanced concentrations of uranium in these waters become an issue for the local population as it is not seen as being due to natural processes but rather as a result of the uranium mining operations.

In April 2008, a team from Greenpeace collected eight samples of groundwater (allegedly used for human consumption) in an area with a radius of 20 km of the uranium facility. It has been reported that two of these samples presented uranium concentrations "far above" the guideline proposed by the World Health Organization [9].

The report refers to some publications that are intended to support the hypothesis that undesirable health effects allegedly caused by the uranium operations in the region are being observed. The Greenpeace report,

in page 17, states that in one of the studies the uranium incorporation rates by inhabitants of Caetité were 25 times higher than those presented in a control region. The referenced study in the report was indeed an M.Sc. dissertation that was subsequently published in a peer review journal [10]. In the journal, the information is presented in a different way i.e. "uranium concentrations in teeth from residents of Caetité are about 8 times higher than those from the control region". A discrepancy is present between the information contained in the report (uranium incorporation rates 25 higher than that presented in the control area) and the one in the article (incorporation 8 times higher) is observed. The article [10] also reveals that from a total of 41 tooth samples collected in Bahia state, 17 came from the city of Caetité and only 2 from the city of Lagoa Real area where the mine is located. The results are not depicted in tables, but rather in graphics. It can be seen that the two samples came from an individual of around 17 and another one of 31 years old. While the first sample presented uranium concentration of something around 5 ng/g the other one showed a value 10 times higher. On the basis of these results, the authors infer that higher values could correspond to overexposure cases potentially due to food and water ingestion. As a conclusion and based on the dataset mentioned above, the article suggests that "uranium body levels in residents of Caetité are also much higher than the worldwide average and because of that daily ingestion of uranium in Caetité, from food and water, is equally high". Finally, it is proposed that "the populations of the studied localities, and Caetité, are subject to radiobiological risks much higher than those for populations living in other regions of Brazil or abroad".

It is recognized that few data are available that adequately describe the dose–response toxicity of uranium after an oral exposure in humans but in the case of high levels of exposure, transient renal dysfunction would be expected. The point to be made here is that if any health effects would be expected due to chronic ingestion of uranium these would have been kidney disfunctions instead of radiation induced effects. Along the same lines, a great deal of fear is caused by the potential effects of radon gas associated with the mining operations. In this regard, an oncologist suggested that the number of lung cancers in Caetité was twice the average for the state of Bahia and three times higher than the number observed in the south-west region of the state. It is also suggested that the increased number of lung cancers is due to the radon concentration in the air that is said to be "10 times higher than the value recommended by the World Health Organisation". Association between neoplasm increase and mining operations in Caetité is also proposed by another study [11], particularly thyroid cancer and leukaemia. Reference levels for radon in dwellings set out in the IAEA International Safety Standards is of the order of 300 Bq/m³ [12]. Radon concentrations in open air of a uranium mining area is reported to vary in the range of 1.75–25.6 Bq/m³ [13].

The Canadian Nuclear Safety Commission states in its home page addressing the question "Do uranium mines and mills increase radon levels in the environment?" states that studies have shown that uranium mining and milling activities do not increase radon levels above background levels in the environment away from the mine site [14]. In addition, it is said that "Radon exposure to members of the public from CNSC-regulated activities is virtually zero". With these pieces of information in mind and considering that: (i) the main health effects of uranium are not related to its radiological properties, (ii) the main health effect of radon is lung cancer, not leukaemia or thyroid cancer and (iii) with the typical environmental concentrations of radon, even in areas close to uranium mining, no increase in adverse health effects would be expected.

It can be stated that all the issues raised so far in NGOs' reports, blogs, social media and other sites in the internet are not consistent and constitute perfect examples of how (pseudo/inconsistent) scientific information can be used to propagate fear, as indicated above. They cause huge negative psychological impact in the populations that are exposed to these pieces of information.

4. IAEA-RELATED ACTIVITIES IN CAETITE

In 2010, the IAEA organized a mission of the Uranium Production Site Appraisal Team (UPSAT) to review the uranium production site of Caetité [15]². It was found that the operations at Caetité were run with no evidence of adverse environmental impact outside the mining licence area. The UPSAT team also noted that within the mining production area, some environmental impacts in groundwater were noted and these should be further studied.

Between 2012 and 2015, the IAEA supported Brazil, under the IAEA's Technical Cooperation Programme, in implementing a project entitled Sustainable Water Resources Management in a Uranium Production Site (BRA 7010). This project was intended to contribute to the formulation of proposals that could lead to the sustainable management of water resources in operations in Caetité, with due consideration of the environmental aspects of water management, in addition to social issues. The main counterpart of the project was the Institute of Radiation Protection and Dosimetry (IRD) from the Brazilian Nuclear Energy Commission (CNEN).

Taking into consideration the many concerns of the population in relation to the contamination of the environment, an expert mission³ to Brazil to advise the project team on the best approaches to be used in the communication of the project results to the relevant audiences was implemented under the auspices of the BRA 7010 project. To support a wider understanding of the overall perception in relation to mining operations, a wide-ranging survey was conducted that included analysis of information provided in local blogs, electronic newspapers and materials and texts available on NGO sites, as well as recorded interviews with residents available on YouTube. The acquisition of information by means of the above survey did not follow any rigorous science based method of information acquisition and should be considered of a qualitative nature.

5. DISCUSSION AND CONCLUSION

The survey confirmed that the dissemination of inaccurate information is very intensive. While public opinion (local community) is built on information of questionable scientific consistency, the results provided by more robust technical/scientific work is not made available⁴ to local stakeholders and/or is simply disregarded by those interested in promoting unjustified fear. This approach was accompanied by an expressed and considerable lack of transparency as regards mining operations.

Opinions formed on the basis of what is perceived to be reliable scientific investigations which appear to indicate that cases of cancer in the region have risen after the operations of the mining company began. The study on the concentration of uranium in teeth of the population of Caetité mentioned above [10] has been widely used to sustain the idea that people are being exposed to uranium isotopes. It is also suggested that some of the observed cancer cases are related to high radon concentrations in air. It has also been observed that complaints about the mining and milling operations go beyond the radiological impacts. On the social dimension, it is argued, among other things, that the company did not employ a significant number of workers from the region. It was also indicated that selling the agricultural products cultivated in the region became rather difficult because of a belief that these products are contaminated with radioactive elements. In addition to the radiological impacts, complaints about the dust coming from mining operations (resulting from blasting) do also occur. There are also complaints on the scarcity of water springs that, apparently in the past, would allow the irrigation of soil in which different agricultural products were cultivated. Finally, the collected information indicates that complaints also extend to the nuclear regulatory body. The notion

² The complete report was not released.

³ Three experts from Finland, Slovenia and the United Kingdom participated in the mission.

of a lack of transparency, a lack of information and, ultimately, a lack of independency is present. This attitude, however, seems not to apply to other regulatory bodies (e.g. the environmental regulator).

As a conclusion, the perception that the official organizations and local authorities are not 'protecting' the local population gives room for NGOs from outside the region to fill this 'vacuum'. By adopting an antinuclear discourse and emphasizing the risks related to the mining operations, these organizations align themselves with the population. They gain the trust of residents and, by providing concerted information suggesting the inappropriateness of the operations, lead the population to take a stand against the development of mining operations in the region. In this regard, it can be clearly seen that the arguments put forward by the NGOs in the different channels of communication are reproduced by members of the community in their interviews.

The analysis of this situation suggests that there is not a consistent communication/engagement plan by the mining company or regulator. As happens on many occasions, operators tend to be reactive and not proactive. That means, by not having in place a continued mechanism of interaction with the population, room is left for the action of groups and individuals that clearly demonstrate an attitude against nuclear energy and related activities. Some of the statements made go far beyond the issues that directly affect the local population and bring to local discussions an agenda that is far broader and one which belongs to an international conversation.

6. THE PATH FORWARD

Owing to the many concerns expressed by the population of Caetité about environmental contamination (more specifically contamination of groundwater), it is of utmost importance that all information acquired with the IAEA supported Technical Cooperation Project is communicated to the relevant stakeholders. The expert mission to Caetité served as the first step in a process to help improve a situation that is currently hindered not only by a lack of trust between the actors but also because of a lack of proper understanding of the potential environmental impacts associated with uranium mining and the operations in Caetité. The expert mission was complemented with additional work investigating information available on different web sites on the internet as noted before. With these considerations in mind, it was proposed that in any similar situation, a set of actions could be considered, which are discussed below.

A more proactive attitude should be in place in terms of communication with the different stakeholders, not only with the different regulatory bodies and other relevant organizations, but also, and perhaps mainly, with the local communities. It must be recognized that the lack of engagement allows other organizations to continue filling the existing gap and aligning themselves with these communities. Therefore, the NGOs will be perceived as those who really care about the local community's lives and well-being. Under these circumstances, it is not a surprise, as this study revealed, that members of the local communities will adopt the discourse and ideas presented to them by these organizations. In this regard, meeting with people from local communities, especially those living in areas where water samples were collected, can be useful. The meetings could then start with information on the mining project (why? how? what?). Subsequently, explanations on natural radiation should be provided, making comparisons with exposures to radiation in our daily lives. Scientific project results should then be presented. In support to these meetings, press releases should be prepared. These should be short, with easily understandable information and photos. An important issue to be considered will be how to involve NGOs in these meetings. They should also be participating in the discussions and their arguments should be carefully listened to and discussed, but not in a confrontational way.

It must be ensured that that the aims and ethics of science are clearly understood and that the consequences, lessons learned and future steps in the BRA 7010 project are explained. With respect to this point, a specific part of the IRD web site should be devoted to the project and an online information channel should be

opened with as many relevant summaries and scientific abstracts as possible, but written in language comprehensible to the layperson. Scientific articles on the project results should be prepared and published.

Beyond the project scope, educational material on environmental and natural background radiation for different levels of students and children and for community groups could be developed.

A last point to be carefully considered refers to the expectations of the local communities on the social role to be played by a mine operator. Taking into consideration that such communities might need basic assistance (to be provided by the State), a natural expectation is that some of the needed actions could be provided by the mine operator. It is not expected that a company will replace the role of the State in addressing the basic needs of a population. However, within the scope of so-called 'corporate social responsibility', it might be the case that the mining company can address, to a certain extent, some of these needs. In this regard, the notion of social responsibility goes beyond the concept of "justifying the company existence and documenting its performance through the disclosure of social and environmental information" [16]. Social aspects impacting on uranium mining operations are also discussed in Ref. [17]. The author states that "some projects start poorly on environmental and social aspects; they must then fight to gain trust and counteract adverse aspects of their environmental and social impacts, real and perceived". This statement reflects quite well the situation of the uranium mining operations in Brazil.

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SUSTAINABLE WATER RESOURCE MANAGEMENT AT A URANIUM PRODUCTION SITE

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Abstract

Uranium mining and processing facilities have the potential to contaminate groundwater, although the identification of these impacts is not straightforward. In areas recording uranium mineralization, it is important to distinguish geogenic sources of contamination from those due to uranium mining activities remains an ongoing challenge. In this context, the identification of the impact sources is essential to define the protection criteria to be adopted (planned or existing exposure situations). The only currently active uranium production centre in Brazil is located in Caetité (Bahia State) and exploits a single deposit in an area where other uranium anomalies have been mapped. The impact of this installation on local water resources and the high concentrations of uranium found in some wells have been sources of concern for the local community and regulatory authorities. This situation was used as a case study, integrating the concept of sustainability and best practices in a national project (BRA7010) supported by the IAEA and launched to improve the understanding of the interaction between the hydrogeological system and human health. The results indicate a fast groundwater turnover, suggesting these aquifers are most vulnerable to contamination. However, the estimated effective doses due to groundwater ingestion are below the 1 mSv/year level and do not represent significant radiological impact.

1. INTRODUCTION

Uranium mining and processing (the front-end of the nuclear fuel cycle) have the potential to affect the workers, the public and the environment. The impacts of these activities depend on site-specific conditions and the efforts made to mitigate and control potential impacts. Therefore, the operation of these facilities in accordance with modern international best practice is a key aspect in reducing radiological impacts. In most respects, uranium mining has the same potential to affect the environment as any other metal mining operation, and protection systems must be implemented to avoid any off-site pollution. However, additional controls need to be applied to deal with radioactivity associated with the uranium ore. Radon exhalation from mill tailings has frequently been identified as the primary cause of radiological impacts from this type of installation. However, significant potential environmental risks may also be associated with release of contaminants from these facilities to surface water and groundwater [1]. In arid and semi-arid regions where the water is scarce and the groundwater is the most valuable resource, this situation can be worsened. The Brazilian uranium production centre is located in a sensitive semi-arid area of the northeastern region of the country (at Caetité in Bahia State), where the sustainability of mining and milling operations, as well as the survival of the local community, are highly dependent on the availability of groundwater resources. This

installation faces not only the challenges associated with the sustainable use of water but also the mitigation of potential contamination processes due to mining activities.

Thus, since the beginning of the operation of this facility in 2000, the local community has been concerned with the impact of the uranium production activities on water resources [2]. This conflict situation has led to the judicialization of these relations, causing interruptions or delays in the operation of this installation and threatening the Brazilian nuclear programme. The characterization of the impacts of uranium mining and processing on the quality and sustainability of groundwater use is a complex task and requires that both the natural baseline of groundwater chemical composition and the functioning of the hydrogeological system be well understood in advance. Much of this complexity is related to the fact that in areas of uranium mineralization it is difficult to distinguish whether the high uranium concentrations observed in some wells derive from water-rock interaction or have originated from some industrial activity [3]. The frequent long time lags observed in hydrogeological systems between polluting activities and the detection of contamination in groundwater can also make it difficult to identify the impacts. Another question that needs to be answered is whether the groundwater is safe to be used for different purposes and what the risks (radiological and non-radiological) associated with these uses are, with special concern given to chronic water ingestion. All concepts and aspects described above were integrated into a logical framework and applied to the Caetité (Uranium Concentrate Unit (URA)) production centre through a national project (BRA7010). This project was developed in technical and financial cooperation with the IAEA and was attended by the research institutes of the nuclear regulatory authority (Brazilian Nuclear Energy Commission (CNEN)) and the Federal University of Rio de Janeiro (UFRJ), besides the collaboration of the uranium mine operator (Nuclear Industry of Brazil (INB)). This project was launched to improve the understanding of the interactions between the hydrogeological system and human health in a watershed known as the Caetité Experimental Basin (CEB). The purpose of this paper is to synthesize the main results obtained by the BRA7010 project with a focus on the protection criterion used.

2. STUDY AREA

The CEB covers an area of approximately 75 km² and lies between latitude 13°56'36" S and longitude 42°15'32" W. This basin is drained by the Vacas stream, which discharges into the Contas river, one of the main hydrographic basins in the State of Bahia. This stream is ephemeral, flowing for a few hours or a few days after a rainfall event. The nuclear installation (URA) occupies a small part of the CEB and accounts for the entire uranium supply that is used by Brazilian nuclear reactors. The low-grade uranium ore is mined by open pit and the chemical extraction process is performed by heap leaching with sulphuric acid, followed by solvent extraction operations. The Lagoa Real complex (LRC) is the main stratigraphic unit of the CEB and comprises alkaline to sub-alkaline granites, orthogneisses, albitites and leucodiorites. The uranium mineralization is associated with albitite bodies and shear zones, uraninite being the main ore mineral. INB is exploring one (AN-13 with 17 000 tU) of the 38 mapped anomalies in the region [4]. The main soil classes found in the CEB are oxisols, ultisols and inceptisols. The CEB's main economic activities comprise small farm agriculture (with the production of manioc, corn, sugar cane and black beans) and grazing (cattle that are also raised along with pork and poultry) [5]. The climate is defined as hot semi-arid with an average annual rainfall of 750 mm (measured for the period 2000–2013). The 200 families residing within the CEB are heavily dependent on the water supply from tubular and dug wells [6].

3. METHODOLOGICAL APPROACH

The establishment of the methodological approach used in this project was preceded by an assessment of the state of the science produced about the CEB. Existing geological, hydrological, meteorological and chemical data were compiled and evaluated. The main source of data came from the reports produced by the well drillers, hydrogeological studies and environmental/effluent monitoring programmes conducted by INB. The academic publications and databases of the National Institute of Meteorology and the Global Network of Isotopes in Precipitation were also used. The general approach adopted in this project included:

(i) isotope hydrology techniques complemented by conventional techniques (from hydrogeology and hydrochemistry) to generate reliable data for aquifer characterization, (ii) soil hydrology techniques to gain an understanding of the water infiltration mechanisms across the unsaturated zone, (iii) groundwater modelling, (iv) water quality diagnosis (based on national and international standards), and (v) human health risk assessment of radiological and non-radiological contaminants due to groundwater ingestion using USEPA Superfund risk and dose assessment methodologies.

4. RESULTS AND DISCUSSION

The direction of groundwater flow follows the topography with a general sense from west to east [7]. Soil texture is very similar among soil types and land use classes. Soils from all classes and under all types of use and coverings presented high infiltration rates [8]. The results obtained from a transect installed along a hillslope (1.5 km in extent) in the CEB, measuring the soil-water matrix potential in the soil profile down to a depth of 3.0 m, showed that the amount of water stored in the soil decreases as vegetative cover density increases. During wet periods, hillslope topography is the most important factor controlling soil moisture distribution, while during dry periods, soil properties play the major role [9]. The isotopic data (¹⁸O and ²H) provided evidence that recent precipitation was the main source of groundwater recharge, suggesting that the aquifer system in the CEB has a relatively short turnover time. Localized recharge of water evaporated from superficial water bodies were also identified. The three methods used to estimate recharge gave concordant results. Using chloride mass balance and modelling with Visual Balan v. 2.0, the estimated multiannual averaged recharge value was less than 8%, while by means of the water table fluctuation method the estimated annual recharge gave values of up to 20% of rainfall. Owing to climatic and geological/environmental conditions, the percolation of infiltrating water through the river beds seems to be the most important recharge mechanism of the CEB. Preliminary results concerning the groundwater flow regime simulated using the FEFLOW code showed that the flow direction follows the topography with a maximum velocity around 7.93×10^{-3} m/d. Most of the groundwater samples can be considered fresh water type (<1000 mg/L salinity). The dominant cations were Na⁺ and Ca²⁺, while HCO₃⁻ and Cl⁻ were the principal anions. The distribution of uranium in groundwater is controlled by the presence and proximity of uranium anomalies. This means that uranium concentration drops to background levels with increasing distance from anomalous areas. However, the uranium decay products do not follow this pattern and their distribution seems to be associated with local geochemical processes. Geochemical diagrams revealed that the chemical weathering of the aquifer rocks (mostly silicates) and Ca-Na exchanges were the dominant mechanisms in controlling the chemical composition of the groundwater within the CEB. The evaporation process was important only for few samples. The suitability of groundwater for drinking from the CEB and others basins (Contas River Basin and San Francisco River Basin) was evaluated, considering the standard and the guideline established by Brazilian Ministry of Health [10] and the World Health Organization [11], respectively. The chemical parameters of drinking water analysed were Sb, As, Ba, B, Pb, Cu, Cr, F, Ni, NO₃, Se, U, Al, Mn, Fe, Zn, Na, Cl, SO₄, pH and TDS. Concentrations of Al, Sb, As, B, Cd, Pb, Cu, Cr, Mn, Ni, SO_4 and Zn for all samples were below the guide values recommended by the WHO and the maximum contaminant levels established by the Brazilian Ministry of Health for drinking purposes. All groundwater samples in the SFRB comply with the regulation. Concentrations of F, NO₃, U and Mn exceeded the limits not only within the CEB, but also in the Contas River Basin, while the other contaminants Ba, Na, Cl, Fe, TDS and pH exceeded the limits only within the CEB. However, not all wells are used for human consumption. The human health risk analysis in both screenings (conservative and nonconservative) showed the direct ingestion of groundwater was the most significant exposure pathway for radioactive and chemical pollutants. No radionuclide was identified as potentially of high priority in future investigations and only the nitrate was considered as a potentially high priority contaminant in a nonconservative approach. The estimated mean effective dose due to the intake of ²³⁸U, ²²⁶Ra, ²¹⁰Po, ²¹⁰Pb, ²³²Th and ²²⁸Ra in groundwater (considering an annual water consumption of 730 L) was less than 1 mSv/year. In line with the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (the BSS), drinking water is considered as a commodity associated with the existing exposure situation and a reference level of about 1 mSv/year should be applied. However, under

the influence of a nuclear installation such as the URA (a typical planned exposure situation), where exposures and risks are subject to control, a dose limit of 1 mSv/year for public exposure cannot be exceeded. Although the dose values are the same, the mechanism for controlling exposures is different.

5. CONCLUSIONS

Groundwater from the fractured rock aguifers in the CEB follows the topography with a general sense from west to east. Soils from all classes and under all types of use and coverings present high-water infiltration rates. Data from isotopes studies indicate that the origin of the groundwater (before evaporation) corresponds to the recent precipitation and that this system has a relatively fast recharge and a greater vulnerability to contamination from surface activities. The three different methods used to estimate the recharge confirm the low average recharge rates (less than 8% of precipitation) commonly found in fractured aquifers under semi-arid climate. Hydrochemical studies reveal that the chemical weathering of the silicates, ion exchange mechanisms and to a lesser extent evaporation processes are the dominant factors controlling the chemical composition of the groundwater within the CEB. Water quality studies reveal that the noncompliance values of Ba, Na, Cl, Fe, Mn, TDS and pH are restricted to a few wells within the study area, and most of these wells are not used for human consumption. The high nitrate concentrations found in several wells scattered around the study area are the result of anthropogenic contamination of the groundwater (mainly animal manure or manure piles). The concentration limit established for nitrate by the Brazilian Ministry of Health is five times more restrictive than the value established by the World Health Organization. On the other hand, the occurrence of a high fluoride concentration in groundwater seems to be associated with geogenic sources, such as the dissolution of minerals containing F. There are no health hazards associated with natural radioactivity in this groundwater, since all doses are below 1 mSv/year. However, if the chemical toxicity of uranium is taken into account, some wells are not safe to use for drinking. The human health risk assessment performed for local communities ratifies the analysis of water quality and identifies nitrate as the only potentially high priority contaminant of concern in a nonconservative approach. The criterion for protection and control to be adopted (planned or existing exposure situations) should be established by taking practical considerations into account.

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ECONOMIC EVALUATION OF URANIUM PROJECTS: NIGER CASE STUDY

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1. OVERVIEW OF NIGER

1.1. Geography

Niger is a landlocked country located in West Africa and covers an area of 1 267 000 km². It has a population of 17.1 million. Niger is a democratic country with stable institutions and elected representatives at all levels. It is a decentralized country with eight regions: Agadez, Diffa, Dosso, Maradi, Niamey, Tahoua, Tillabéri and Zinder. Niamey is the capital.

1.2. Geological framework

The geological framework of Niger is characterized by the presence of four basement formations, which are host to both metallic and non-metallic resources:

- 1) Liptako Gourma (north-east of the West African Craton) with gold, lithium, phosphates, iron, copper, molybdenum, zinc, titanium, dolomite, vanadium, chromite and manganese;
- 2) The Air mountains in the northern part of the country possess reserves of uranium, coal, gold and molybdenum;
- 3) Damagaram Mounio and South Maradi in the central southern part has gold;
- 4) Djado to the north-east has gold, gypsum, phosphates and uranium.

2. OVERVIEW OF URANIUM POTENTIAL IN NIGER

Uranium minerals have been found in the Iullemmeden Basin. This sedimentary basin comprises two subbasins:

- 1) The Tim Mersoi sub-basin, which is located in the north;
- 2) The Ader Doutchi sub-basin which is located to the south-west.

The Iullemmeden Basin contains reserves of coal, phosphate, gypsum, limestone, bentonite, manganese and oil. Uranium occurs mainly in the first sub-basin. Two types of uranium mineralization are present: (i) tetravalent uranium minerals (pitchblende and coffinite) characteristic of reduced deposits, and (ii) hexavalent uranium minerals (vanadates, phosphates, silicates, arsenides and molybdates) which are characteristic of oxidized deposits. These two types of uranium mineralization have been used to identify two types of uranium deposits: (i) Carboniferous uranium deposits (Akouta, Afasto–Ouest, Arlit, Madaouela, Tassa N'Taghalgué), and (ii) Jurassic and Cretaceous uranium deposits (Imouraren, Azelik, Assaouas).

2.1. Uranium resources of exploration projects

Two major exploration projects were carried out in the 1980s:

- The Sekiret project (1985–1986), undertaken by ONAREM–PNC [1]. All the activities were centred on the Iullemmeden Basin. Drill holes have cross-cut the Tchirezrine 2 to the Guezouman Formations. In the Guezouman Formation, uranium mineralization was detected over a 2.25 m interval with a grade of 0.04% eU₃O₈;
- 2) The Techili project (1989–1990) evaluated the uranium resources of the Madaouela and north Arlit sectors [2]. The thickness of the mineralization was 3.40 m with an average grade of 0.20%.

2.2. Uranium resources of the mining projects

Four companies were formerly extracting uranium in Niger. Unfortunately, owing to the fall in the uranium price, two companies (IMOURAREN and SOMINA) have mothballed their projects. The two remaining companies (SOMAIR and COMINAK) have initiated a social plan to reduce the number of employees.

3. ECONOMIC EVALUATION PROCESS OF URANIUM PROJECTS IN NIGER

Economic evaluation of mining projects includes the examination and the assessment of technical, financial, social and political aspects of the environment in which the mineral deposit is located. They include the estimation of mineable ore deposits, the production rates, capital expenses and cost of operations. The financial assessment will be set according to the fiscal regime of the host country to generate standard project evaluation criteria such as the net present value and the internal rate of return.

3.1. Steps of uranium projects evaluation

In Niger, any mining project evaluation is based on a specific guideline known as 'canevas' and as well as the deliberations of a working committee. The guideline is based on the following points:

- 1) General presentation of the project;
- 2) Presentation of the investors;
- 3) Juridical analysis;
- 4) Market analysis;
- 5) Environmental and social impact assessment;
- 6) Technical analysis;
- 7) Financial and profitability analysis;
- 8) Risks analysis.

The activities conducted by the working committee will be based on this schedule. For this, some ministries and other related structures will have representative making up this committee.

3.2. Parties involved in the evaluation process

The parties involved in the evaluation process come from the following entities:

- The General Secretary or representative;
- The General Director of Mines;
- The Director of Mines;
- One representative of the Ministry of Finances;
- One representative of the Ministry of Environment;
- One representative of the General Direction of Customs;

- One representative of the Ministry of Water Resources;
- One representative of the Ministry of Agriculture and Wildlife;
- One representative of the General Direction of Taxes;
- One representative of the Bureau of Environmental Impact Assessment;
- One representative of the Presidential Cabinet;
- One representative of the Prime Minister's Cabinet;
- One representative of SOPAMIN;
- One representative of each technical Direction within the Ministry of Mines.

After the selection, the committee will be set up by decree signed by the Ministry of Mines. The General Secretary or the General Director of Mines will be the president of this committee.

The report of the feasibility study will be completed through the following chapters:

- Chapter I: Introduction, summary and conclusions;
- Chapter II: Geology and hydrogeology;
- Chapter II: Resources;
- Chapter IV: Mines;
- Chapter V: Mineral processing;
- Chapter VI: Alternative mines and processing designs:
- Chapter VII: Infrastructure;
- Chapter VIII: Transports and logistics;
- Chapter IX: Employment and training;
- Chapter X: Structure and organization of the project;
- Chapter XI: Environment;
- Chapter XII: Health, security and radiological protection;
- Chapter XIV: Communication;
- Chapter XV: Economic evaluation;
- Chapter XVI: Social impacts on the country.

It is important to note that the demand for an exploitation licence is accompanied by the licence of environmental impact assessment and the report of environmental assessment. The report of the feasibility study will be sent to each member of the committee at least one month before the meeting of the committee. Before the convocation of this meeting, the Direction of Mines will present a preliminary economic evaluation.

Once the committee has convened, some working groups are to be set up according to the area of expertise of each participant. A place and time will be allocated to each working group. It should also be noted that representatives of the company submitting the feasibility studies will attend the workshop to answer the questions of the committee and to justify their work.

Once each group has made a decision to accept or reject the part on which they have worked on, all the groups will meet to take a final decision. A succinct summary of the deliberations may include either:

"The feasibility study submitted by such company is accepted, subject to integration of the observations made by the committee"; or

"The feasibility study submitted by such company is rejected for lack of conformity, insufficiency, etc.".

The economic evaluation of mining projects is mainly based on the net present value and the internal rate of return, which are two parameters used to evaluate the degree of profitability of a project through its

lifespan. To determine these two parameters, a financial model needs to be built to confirm the results of the economic evaluation presented in the feasibility study.

After building the financial model, the sensitivity analysis will define which are the technical or economic parameters that most impact the net present value.

3.3. Sensitivity analysis

3.3.1. Sensitivity to the ore grade

The impact of a variation in the ore content may be small or significant in terms of cash flow, but the increase in the reserve may cause a decrease or increase in metal recovered, depending on the type of treatment applied (static or dynamic).

3.3.2. Sensitivity to the type of ore processing

This analysis always shows that the ore processing efficiency varies with the ore grade.

3.3.3. Sensitivity of technical and economic parameters

The analysis consists of evaluating the impact of certain parameters on cash flow. These parameters include: cost of mining the ore, cost of ore processing (static or dynamic), cost of metal treatment (static or dynamic), recovery rate of the plant according to type of treatment (static or dynamic), fixed costs and sale price.

4. THE SOCIOECONOMIC BENEFITS FOR THE COUNTRY

The socioeconomic benefits include the following:

- a) Job creation;
- b) Capacity building;
- c) Creation of revenues (dividends, royalties, taxes);
- d) Sustainability of mining activities;
- e) Building of infrastructure, such as schools, health centres, roads, water infrastructure, etc.

5. RISK ANALYSIS

The risk analysis is based on the study of specific parameters, such as the political context of the country, security, stability of the fiscal regime, long term market price, etc.

6. CONCLUSION

Mineral project assessment requires the evaluation of technical inputs such as mineable reserves, production rates, recoveries, costs and revenues. These parameters form the basis of mine project evaluation, together with the tax regime of the host country.

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URANIUM EXPLORATION AND MINING ACTIVITIES OF TURKEY AS A NEWCOMER

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Countries embarking on a nuclear power programme are referred to as a 'newcomer' need to ensure that the development of their legal, regulatory and support infrastructure is aligned with the construction of the nuclear power plant itself. This is done to ensure that the programme proceeds in a safe, secure and sustainable way.

Through several initiatives, the transfer of information and knowledge is required from States with extensive experience in uranium mining and production to so-called newcomers to the sector. Growing demand from a much-anticipated nuclear power renaissance and the subsequent potential significant increase in the cost for nuclear fuel have recently spurred greater investment in uranium exploration in an increasing number of countries.

Nuclear power is an inevitable option for Turkey to meet energy security. Turkey has distinctly progressing its nuclear energy program in nuclear milestones. As being aware of that uranium mining and activities would be a significant role in supporting energy security by realizing domestic nuclear energy fuel for the nuclear power plant projects. This paper wholly provides the recent uranium exploration activities, drilling efforts, identified conventional resources, environmental activities and regulatory regime of Turkey with the details.

1. BACKGROUND: URANIUM FOR NUCLEAR POWER

Access to uranium resources are an integral part of the nuclear fuel cycle. To increase the capability of interested Member States in planning and policy making on uranium production, the IAEA works together with the OECD Nuclear Energy Agency (NEA) to collect and provide information on uranium resources, production and demand.

With uranium production ready to expand to new countries, efforts are being made to develop transparent and well-regulated operations similar to those already established elsewhere to minimize potential environmental and local health impacts [1].

The general energy policy of Turkey focuses on the supply of secure, sustainable and affordable energy by diversifying energy supply routes and source countries, promoting usage of domestic resources and increasing the energy efficiency and renewable energy usage in order to decrease the energy intensity of production. Nuclear energy is considered an option within Turkey for diversification of electricity generation and also for reduction of greenhouse gas emissions from the energy sector.

The Akkuyu nuclear power plant project started with an Inter-Government Agreement between Turkey and the Russian Federation for construction and operation of 4 WWER-1200 reactors in Akkuyu site, which is situated on the Mediterranean coast of Turkey. Akkuyu NPP Project Company (PC) has also submitted Site Parameter Report (SPR) which is one of the mandatory documents before construction license application to Turkish Atomic Energy Authority (TAEK). The SPR has been approved by TAEK in February 2017 and application for construction licence was made by PC in March 2017 to TAEK. A comprehensive environmental impact assessment report was prepared by the PC, taking into consideration the requests from a wide range of stakeholders. The project was approved in December 2014. Energy Market Regulatory Authority (EMRA) had granted an electricity generation licence in June 2016 which will form the basis of

the Power Purchase Agreement (PPA). The revised site parameters' report was approved by the Turkish Atomic Energy Authority on February 2017 and granted a limited work permit for construction of non-nuclear safety related facilities in October 2017.

On the other hand, PC submitted Environmental Impact Assessment (EIA) Report to Ministry of Environment and Urbanism (MoEU) on 6th December 2013. An affirmative decision was given on 1st December 2014. Besides, PC obtained an Electricity Generation License for 49 years from Energy Market Regulatory Authority (EMRA) on 15th June 2017. Moreover, PC and state-owned Turkish Electricity Wholesale and Contracting Company (TETAS) signed a Power Purchase Agreement (PPA) on 30th December 2017.

On 30 March 2018, PC obtained construction license. On 3 April 2018, it has formally launched construction of 1st unit of Akkuyu NPP with the pouring of concrete for the sub-base foundation of the nuclear island.

The other nuclear power plant project IGA which includes construction and operation of 4 units of ATMEA-1 reactors in the Sinop site and an Inter-Government Agreement for the development of nuclear industry in Turkey was signed between Turkey and Japan in 2013 and ratified in 2015.

The second NPP project (Sinop Project) will be conducted by a Turkish-French-Japanese Consortium and as a Turkish partner is state-owned Turkish Electricity Generation Company (EUAS). In the context of Sinop Project, feasibility studies are ongoing for verification of site suitability and development of financial scheme. It is expected that feasibility studies will be completed within the year of 2018. After the feasibility study, Sinop Project Company (SPC) will be established. On the other hand, EUAS International Incorporated Cell Company (EUAS ICC) was established in 2016 as an international nuclear private company of EUAS and it will have up to 49% of share in the SPC on behalf of EUAS.

In the context of Sinop Project, feasibility studies are ongoing for verification of site suitability and development of financial scheme. It is expected that feasibility studies will be completed within the year of 2018. After the feasibility study, Sinop Project Company (SPC) will be established.

The strategic goal of nuclear energy usage in Turkey is mentioned in the strategic plan of MENR under the goal for optimum energy resource diversity. Turkey has high energy imports and fossil fuel dependency which makes it vulnerable to external fluctuations in global markets. Nuclear energy is considered as one of the options, together with local resources and renewable energy, to strengthen the energy sector in Turkey. Exploration for radioactive minerals has been conducted in Turkey since the 1950s. Development requires further studies to define the feasibility to start production [2]. As a result, the strategic plan includes a target for reserve determination of radioactive minerals, together with their respective feasibility studies for usage in the nuclear energy sector [3].

2. DESCRIPTION

2.1. General Directorate of Mineral Research and Exploration (MTA)

Uranium exploration in Turkey began in 1956–1957 and was directed towards the discovery of vein type deposits in crystalline terrain, such as acidic igneous and metamorphic rocks. As a result of these activities, some pitchblende mineralization was found but these occurrences were not determined to be economic deposits. Since 1960, studies have been conducted on the sedimentary rocks surrounding the crystalline rock and some small orebodies containing autunite and torbernite mineralization have been found in different parts of the country. In the mid-1970s, the first 'hidden' uranium deposit with black ore, lying below the water table, was found in the Koprubaşı area of Manisa. As a result of these exploration activities, a total of 9129 t U₃O₈ (7740 tU) of in situ resources were identified in the Manisa–Köprübaşı (2852 t U₃O₈; 2419 tU), Uşak–Eşme (490 t U₃O₈; 415 tU), Aydın–Koçarlı (208 t U3O8; 176 tU), Aydın–Söke (1729 t U3O8; 1466 tU) and Yozgat–Sorgun (3850 t U3O8; 3265 tU) regions.

2.2. Eti Mine Works General management (Eti Maden)

State-owned organization Eti Maden is responsible for a total of six uranium mine sites with known uranium resources. Geological exploration has been performed by MTA at these sites in the past. In 1960–1980, uranium exploration was undertaken by aerial prospecting, general and detailed prospecting on-site, geological mapping studies and drilling activities. These uranium sites were transferred to Eti Maden management as possible mines which can be operated by the State under Law No. 2840 on the Operation of Boron Salts, Trona and Asphaltite Mines and Nuclear Energy Raw Materials (10 June 1983).

2.3. Recent and ongoing uranium exploration and mine development activities

2.3.1. General Directorate of Mineral Research and Exploration (MTA)

In 2012, granite, acidic igneous and sedimentary rocks around Manisa, Denizli and Aydın (an area of approximately 5000 km²) were explored for radioactive raw materials. Exploration for radioactive raw materials was also performed at sites licensed by MTA at Manisa, Uşak and Nevşehir.

In 2013, granite, acidic igneous and sedimentary rocks around Aydın and Denizli (an area of approximately 5000 km²) were explored for radioactive raw materials. Exploration for radioactive raw materials was also performed at sites licensed by MTA at Manisa, Uşak and Nevşehir.

In 2014, exploration for radioactive raw materials was conducted in sites licensed by MTA at Manisa, Uşak and Nevşehir. In 2015, exploration for radioactive raw materials was conducted in sites licensed by MTA inside Manisa and Nevşehir [4].

2.3.2. Private sector exploration

Adur, a wholly-owned subsidiary of Anatolia Energy, a Turkish uranium exploration company with current and active drilling programmes at the Temrezli and Sefaatli uranium sites, has carried out exploration and resource evaluation drilling with a total of 206 drill holes completed for a total drill advance of over 26 000 m since 2011 at both Şefaatli and Temrezli sites. Over 16 000 m of drilling was completed in the Temrezli region. Until now, 112 holes have been completed at the Temrezli site. The drilling at Temrezli, mostly to confirm the earlier MTA drill holes but also including in-fill and step-out holes, confirmed work conducted in the 1980s and extended the uranium mineralization to the northeast over a strike length of more than 3000 m.

In 2011, CSA Global Pty Ltd prepared a JORC compliant mineral resource estimate for the Temrezli deposit of 13.282 Mlb U_3O_8 (6025 tU) (measured, indicated and inferred) of in situ uranium at an average grade of 1157 ppm U (0.117% U_3O_8).

Preliminary metallurgical bottle-roll leach test work confirmed MTA's earlier work and recorded uranium recoveries of 93% and 90% for acid and alkali leach methods, respectively.

Several hydrological test wells have been constructed at Temrezli since 2012 in order to assess the regional groundwater conditions and to conduct hydraulic testing of the mineralized horizons on a scale typically seen at in situ recovery (ISR) operations. Test work was performed by HydroSolutions, a US-based hydrogeological company with considerable experience in groundwater conditions relating to uranium ISR operations throughout western United States of America. The hydrological test confirmed the aquifer has a sufficient flowrate to permit ISR mining.

Regional exploration identified new prospective areas of mineralization at West Sorgun and Akoluk. The rotary and diamond drill programme tested a number of regional sites that are considered prospective for Eocene sediment hosted uranium mineralization, similar to that at the Temrezli uranium deposit.

Since early stage studies have indicated that the Temrezli uranium deposit will be amenable to ISR mining, a preliminary economic assessment (PEA) contract was awarded to US-based WWC Engineering of Sheridan, Wyoming. The preliminary economic assessment is complete and was followed by pre-feasibility study which was awarded to Tetra Tech and completed and issued in early 2015. This study indicated that the project is economically feasible, with a total expected recovery of 9.7 Mlb U₃O₈ over 12 years, with operating costs of less than US \$17/lb U₃O₈ (US \$44.2/kgU). Adur initiated the environmental impact assessment process by preparing and submitting a project description to the Ministry of Environment and Urban Planning in 2015. Adur will also initiate the permitting process with the Turkish Atomic Energy Commission with regard to licensing the Temrezli site as a nuclear facility because ISR operations are considered nuclear facilities. In 2015, the permits and licences will be obtained prior to initiating construction in early 2016.

3. DISCUSSION AND CONCLUSION

3.1. Identified conventional resources (reasonably assured and inferred resources)

Identified conventional uranium resources in Turkey that have been determined from exploration activities performed by MTA in the past are listed below, with the addition of JORC compliant resources identified through recent work by Adur:

- Manisa–Köprübaşı: 2419 tU in ten orebodies at grades of 0.04–0.05% U₃O₈ (0.034–0.042% U) and hosted in fluvial Neogene sediments;
- Uşak–Eşme: 415 tU at 0.05% U₃O₈ (0.042% U) hosted in Neogene lacustrine sediments;
- Aydın–Koçarlı: 176 tU at 0.05% U₃O₈ (0.042% U) hosted in Neogene sediments;
- Aydın–Söke: 1466 tU at 0.08% U₃O₈ (0.068% U) hosted in gneiss fracture zones;
- Yozgat–Sorgun: 4633 tU at 0.117% U₃O₈ hosted in Eocene deltaic lagoonal sediments.

The Temrezli (Yozgat–Sorgun) uranium deposit is one of Turkey's largest and highest-grade uranium deposits, with a JORC compliant mineral resource estimate of 13 282 Mlb of contained uranium at an average grade of 1157 ppm (0.117%) U₃O₈ with an average depth of 120 m.

3.2. Undiscovered conventional resources (prognosticated and speculative resources)

Temrezli Project: The ongoing exploration and development drillings is to be continued and is expected to increase the resource by a potential of 1-3 Mlb U_3O_8 .

Şefaatli Prospect: Exploration and development drilling was conducted in 2015 and this is expected to increase the known uranium resource values by approximately 5-6 Mlb U_3O_8 . The recent drill hole results include 1.1 m at 2150ppm eU_3O_8 from a depth of 39 m [4].

3.3. Unconventional resources and other materials

None reported, but grassroots exploration is ongoing.

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COMPARISON BETWEEN THE URANIUM DEPOSITS IN THE ALLIGATOR RIVER URANIUM FIELD AND THE WESTMORELAND AREA (NORTHERN TERRITORY AND QUEENSLAND, AUSTRALIA)

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1. INTRODUCTION

The Northern Territory (Australia) hosts about 30% of Australia's low cost uranium sources, numbering 361 uranium occurrences [1]. The production of U₃O₈ concentrates in the Northern Territory up to 2012 has totalled 128 017 t. The uranium deposits of the Northern Territory can be subdivided into five main types [2]. The two types on which this study is focused are the 'unconformity-related' and the 'Westmoreland-Murphy' types. The Alligator River Uranium Field (ARUF) hosts numerous unconformity-related deposits such as Ranger, Nabarlek, Jabiluka and Koongarra. They are located exclusively in basement rocks, near the unconformity between an Archaean-Paleoproterozoic basement complex (~2670-1818 Ma) and the Palaeoproterozoic–Mesoproterozoic McArthur Basin (1815–1492 Ma) and mostly grade above 0.1% U₃O₈ [1, 3, 4]. In the Westmoreland area, on the southern margin of the McArthur Basin, former uranium mines and current prospects belong to the Westmoreland–Murphy type (e.g. Eva in Northern Territory and Redtree and Junnagunna in Queensland). They are located within the Westmoreland Conglomerate and Seigal Volcanics that are part of the McArthur Basin, near the unconformity with the Palaeoproterozoic Murphy Inlier (1855–1830 Ma) and grade 0.07-0.1% U₃O₈ [1]. As the two types of deposit share similar settings and are associated with the same basin (McArthur Basin), it is critical to establish a detailed comparison of their timing, mineralogy and geochemistry in order to determine whether they could be linked to the same ore forming event or ore forming processes. While unconformity-related deposits have been extensively studied [5–9], much less is known about the Westmoreland–Murphy type deposits [10, 11]. In this paper, the authors complement existing data on ore mineralogy, geochemistry, geothermometry, age dating and fluid inclusion data on Westmoreland–Murphy type deposits and compare them with published data from unconformity-related deposits.

2. METHODS AND RESULTS

The new data obtained on U deposits from the Westmoreland area are based on mineralized samples collected in the Westmoreland conglomerate from the Junnagunna and Redtree deposits.

Petrographic investigation was carried out using optical microscopy and SEM at the GeoRessources laboratory (Vandœuvre-lès Nancy, France). Early diagenesis is represented by haematite and quartz overgrowths on detrital quartz grains. This was followed by an episode of quartz dissolution that corresponds to the onset of peak diagenesis [10]. Quartz precipitates after this episode and haematite, chlorite and then apatite, clays minerals and uraninite $(10-50 \ \mu m)$ (hereafter referred to as 'intergranular uraninite') alternate in filling intergranular voids between quartz grains in the sandstone. Intergranular uraninite is texturally associated with clay minerals and haematite and also occurs as micrometre sized grains within haematite grains [10]. Apatite is older than the intergranular uraninite because small fractures within apatite grains are filled with uraninite, which also surrounds the apatite grains. After these diagenetic events, veins containing quartz, uraninite (hereafter referred to as 'vein uraninite'), pyrite and chalcopyrite develop. In this study, the authors focused on both intergranular and vein uraninite. By comparison, the main stage of uranium mineralization in the ARUF consists of very fine-grained (10–50 μ m diameter) euhedral uraninite (U1) disseminated within chlorite and intergrown with tourmaline. A second generation of uraninite (U2) is represented by fine-grained uraninite inclusions within veinlets of disordered graphitic carbon. The final stage of uranium mineralization is represented by veinlets of massive uraninite (U3) [6].

Intergranular and vein uraninite were dated by U-Pb using SIMS at the CRPG laboratory (Vandœuvre-lès Nancy, France). The average age for both generations yielded by the analysis is 559 ± 33 Ma, which is consistent with the youngest age already obtained for these deposits [10]. The oldest published ages (1606 \pm 80 and 1655 \pm 83 Ma) in the Westmoreland area are ²⁰⁷Pb/²⁰⁶Pb ages from two analyses obtained by LA-HR-ICPMS on very fine-grained intergranular uraninite inclusions in haematite ($6-8 \mu m$) [10]. This very fine uraninite has not been dated yet in this study. The U-Pb dating of a thin (1 mm) layer of euhedral apatite grains has also been carried out by SIMS. Apatite exhibits an abnormally high U content, probably due to the vicinity of uraninites or to extremely small UO_2 inclusions. As a consequence, of 31 spot analyses, only 9 could be used to constrain an age of 1685 ± 65 Ma, consistent with the diagenetic processes dated in illite [10]. According to the analytical uncertainties, the oldest published age for small intergranular uraninite is compatible with that of the apatite dated by the authors [10]. By comparison, the ages obtained on uraninites in the ARUF show a first mineralizing stage at around 1720–1680 Ma [6, 7, 9]. Numerous uraninite ages are younger than 1400 Ma and this wide range of ages does not allow any relevant comparison between the two areas [6, 8–10]. Significant amounts of illite have K-Ar ages that indicate crystallization between \sim 1680 and 1520 Ma in the ARUF [12]. This corresponds to the initiation of diagenetic/hydrothermal fluid circulation. Illite from the Westmoreland Conglomerate has a plateau ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ age of 1680 ± 18 Ma that confirms basinal brine migration in the Westmoreland Conglomerate at this period [10].

REE patterns on dated intergranular and vein uraninites from Westmoreland have been established by LA-ICP-MS at the GeoRessources laboratory. The uraninite REE patterns in Westmoreland do not exhibit the 'bell shape' (i.e. high concentrations of Tb and Dy) typical of unconformity-related U deposits [13]. The REE patterns on intergranular UO₂ are enriched in LREE in comparison with patterns from unconformity-related, basement hosted deposits from ARUF (Nabarlek and Koongarra) [13]. For vein uraninite, the patterns exhibit some similarities with vein type deposits worldwide although the latter are generally considered to be formed at higher temperatures in the presence of magmatic and/or metamorphic fluids. Even if some post-crystallization modification of the REE patterns may have contributed to the LREE enrichment, such a phenomenon is not sufficient to explain the differences in the REE patterns between the two zones. Therefore, the REE patterns of UO₂ differ between the northern and southern parts of the McArthur Basin, which indicates different modes of U transport and deposition.

The major element composition of chlorite associated with intergranular UO₂ was determined using EPMA at the GeoRessources laboratory. Major element (Si, Al, Fe and Mg) composition was used to determine the chlorite species, which turn out to be chamosite, and to calculate crystallization temperatures [14]. Numerous compositions give temperatures in excess of 300°C according to the model used [14]. Previously published data on chlorite from the Seigal Volcanics and the Westmoreland Conglomerate indicate that chlorite formed at $230 \pm 30^{\circ}$ C [10]. However, the composition of some chlorites from the conglomerate

indicate high temperatures of crystallization (364° C) that was explained by the vicinity of the Seigal Volcanics, which could have provided excess Fe leading to the higher calculated temperature. The reasons for these high calculated temperatures in both previously published and new data are under investigation but could also be linked to the emplacement of the Seigal Volcanics just above the Westmoreland Conglomerate that might have brought additional heat to the system. In the ARUF, chlorite gives temperatures between 200°C and 310°C [8]. Temperature estimates on syn-ore illite were calculated on the basis of illite crystallinity. They compare well between the Westmoreland area ($200 \pm 30^{\circ}$ C) [10] and the ARUF 180–230°C [8, 9].

Previously published data on the salinity, temperature and pressure of the fluid inclusions hosted in diagenetic quartz overgrowths and quartz veins have also been investigated. The compilation of all the available primary or pseudo-secondary fluid inclusion data have been plotted in a homogenization temperature (Th) versus salinity diagram. In both areas, the data lie in a triangular pattern defined by a low temperature (100-150°C) and high salinity (35 wt% eq. NaCl) end member and two low salinity end members, one at high temperature (until 350°C) and one at low temperature (100°C). In the ARUF, mineralizing events occur in a small range of temperature (100-175°C) [8, 9, 15-18]. In the Westmoreland area, at least two stages of fluid mixing associated with the U-Cu mineralization occurred. Firstly, there was mixing between a $CaCl_2 \pm LiCl$ rich brine and a NaCl rich brine to produce a fluid of intermediate composition. This fluid then mixed with a low salinity fluid [11, 19]. In the ARUF, Cl/Br and cation ratios indicate that the high salinity brine is probably a primary one, resulting from the evaporation of seawater [16]. Reconstructed isotopic (O, H) compositions based on the composition of quartz veins and associated alteration minerals have been also been compiled. In Westmoreland, compositions include the following: $\delta^{18}O = 4 \pm 1\%$ and $\delta D = -31 \pm 6\%$ [10], whereas in the ARUF $\delta^{18}O = 3.5 \pm 2\%$ and $\delta D = -25 \pm 15\%$ [5, 8, 9]. According to these isotopic compositions, the brines are evolved basinal brines with comparable δ^{18} O and δD values in the two regions.

3. DISCUSSION AND CONCLUSION

From the previously published and newly acquired data presented in this paper, it appears that Australian unconformity-related U deposits from the ARUF and Westmoreland–Murphy type U deposits share some striking similarities in terms of alteration, ore mineralogy, temperature and fluid composition, but also noticeable differences.

Age dating suggests that uranium mineralization could have started about 65 Ma earlier in the ARUF compared with the Westmoreland area. However, the measured errors are sometimes substantial and some crystallization stages could be synchronous. A common ore forming event is recorded around 1680–1600 Ma, which corresponds to the primary mineralization in the Westmoreland and Pine Creek regions. Both deposit types have undergone successive episodes of U remobilization/recrystallization since then, which significantly disturbed the isotopic and chemical compositions of the uranium oxides.

REE patterns for UO_2 , which are diagnostic features of deposit types, differ significantly between the two zones. It seems that the oldest UO_2 generation in both areas have distinct REE patterns. Therefore, probable contemporaneous ore forming events at both localities were related to distinct ore forming processes.

Further work is planned to compare the composition of the Na–Ca–Cl brines which appear to be involved in both areas. A comparison of fluid inclusion characteristics (pressure, temperature, composition) show that the mixing between low salinity fluids and brines is a key process for ore deposition in both areas. Raman spectrometry of fluid inclusions will allow identification of trace gases in the mineralizing brines (CO₂, CH₄, N₂, H₂, O₂), which may provide information on the redox state of the brines, the mechanisms for UO₂ deposition and fluid–rock interaction. The LA-ICPMS analysis of fluid inclusions will allow determination of the major and trace element (including U) content of the brines, which will provide crucial information on their origin, the fluid–rock interaction they underwent and their metal transporting capacities. Finally, noble gas and halogen analysis of fluid inclusions will provide invaluable information on the origin of the salinity and the interaction of the fluids with various surficial and crustal reservoirs (atmosphere, sediments, basement rocks, etc.).

From an exploration point of view, it seems that defining the pathways for the Na–Ca–Cl brines along both sides of the unconformity could be critical for discovering new U deposits in the Westmoreland area. This could be carried out, for example, by careful lithogeochemical studies and mapping of alteration minerals in basal conglomerates and sandstones, as well as along the unconformity and major cross-cutting structures [20]. However, conceptual models for origin of the brine and potential pathways based on detailed fluid inclusion analysis, as planned in this project, will be an important prerequisite for more efficient exploration targeting.

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"IT'S NOT ALL ABOUT THE RADIATION!" PRACTICAL RADIATION MANAGEMENT

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1. INTRODUCTION

For uranium miners and producers, the control of environmental, worker and public exposure to radiation is a critical management objective. Corporate obligations, statutory requirements and public expectations generally manifest as radiation management plans (RMPs).

It is important for worker, public and regulator confidence that the RMP is practical and competent. From an operational perspective, it is also important that the RMP is an integral part of the broader health, safety and environmental management plans. This is because, in practice, the radiation risk is generally low in most uranium mining and processing operations and it is important to ensure that the radiation risks remain in perspective with other environmental and safety risks.

This paper explores experiences from case studies at mining and processing facilities to identify practical tools for effective development and implementation of appropriate and quality RMPs and for ensuring that radiation risks remain in perspective.

The author's experiences are from a range of operating facilities that have had to deal with the presence of naturally occurring radioactive materials. This includes uranium mines and processing facilities, through to rare earth producers, whose main exposures come from the Th-232 decay chain, through to other mining operations where NORM is present. Experiences are generally common across the sectors, although, the expertise and competencies in the uranium sector greatly exceeds that in other sectors.

2. BACKGROUND

The radiation exposure to workers in the modern uranium mining and processing industry have been demonstrated to be low and well controlled [1]. Extensive efforts in the early decades of the life of the industry acted to identify and quantify the risks and establish standards that greatly improved conditions. This resulted in the current high standards of radiation protection that exist in the industry today. Such controls included minimising exposures to radon decay products in uranium mines with effective ventilation, through to ensuring that final product dusts are eliminated or contained.

Legacy sites continue to be problematic but provide a constant reminder of the costs and risks of not providing adequate levels of control for radiation.

3. EFFECTIVE RMPS

The RMP is an important document and there is a number of practical factors that can be considered to ensure that it remains relevant and fit for purpose. These factors are based on practical experiences elsewhere.

3.1 Clarifying the Role of the RMP

In some cases, an RMP is developed to purely comply with regulatory requirements. In these cases, the RMP is seen as a compliance document rather than a practical management plan for radiation at the site or operation. Legislative requirements and guidance documents are useful and should be used as the platform

or the framework for the RMP, however, the content and details should be developed and owned by the operator.

Ownership of the RMP and its content is important, because at the end of the day, the operator has primary responsible for the safety and wellbeing of the workforce under their management and control - not the regulator. The operator is also responsible for protecting the environment and members of the public. Merely complying with regulations does not guarantee an adequate level of protection.

At an operational level, the RMP should be practical and able to be used by management and workers alike. It should provide the necessary tools and justifications for implementing and enforcing controls. It should outline accountabilities and responsibilities and relevant training. It should also cover reporting requirements and incident investigations. Many guides exist on the minimum content for RMPs [2,3].

Sometimes, the RMP is incorrectly seen as being a Radiation Monitoring Plan, with radiation monitoring seen as the means for management. This has two consequences. It can provide a false sense of security because all that gets measures is all that exist in the monitoring plan. Secondly, the desire for investigative monitoring is lost is favour or compliance monitoring.

Pure compliance monitoring can also result in complacency. If, for example, the routine radiation monitoring shows that results are low, no additional work in done and it is assumed that radiation is under control.

3.2 Non-Technical Characteristics of a RMP

Experience shows that RMPs should also have the following characteristics:

- Practical and able to be understood by operations personnel,
- Balanced and consider the actual risks from radiation,
- Appropriately conservative as not to be seen to be dismissive of radiation and able to provide confidence that the radiation levels are controlled,
- It should exist within the broader site health safety and environmental management plans,
- Of sufficient quality to provide confidence and also maintain recognised standards.

It is relevant to note that none of the above characteristics give an indication of what should be in the RMP itself. The characteristics assume the technical component of the RMP and provide the framework for the balance, quality and practicality of the document.

3.3 Supported by Appropriate Knowledge and Competence

An expected characteristic of uranium explorers, miners and producers is that there will be a high level of competence in radiation protection.

However, what does this mean in practice?

It means having sufficient internal knowledge to make informed decisions and staff who are competent to make the decisions.

To support the RMP and understand the radiological risk, such knowledge that needs to be considered includes:

• Characterisation of the materials being handled, from geological samples through to process materials and wastes – this includes characterising both the radiological and non-radiological properties,

- Understanding the natural background levels in the region and its variability in order to provide some perspective to the anticipated potential exposures,
- Understanding the behaviour of radionuclides through the whole process.

Competent staff should be able to:

- Predict and measure the potential radiological impacts to workers, the public and the environment, using recognised international standards,
- Effectively communicate with senior managers through to workers and the public,
- Contribute to the broader discussion on radiation protection, rather than just complying with regulatory requirements,
- Learn,
- Be professional in all matters.

3.4 Effective Two-Way Communications

The most significant portion of radiation management is communication and discussion. It is essential for a number of reasons:

- Being able to identify problems before they arise,
- Providing a non-confrontational means of information sharing,
- Building knowledge.

Communicating the existence and contents of the RMP to management, the wider workforce and to the community is important. It demonstrates the company's commitment to formalising its approach to radiation management. It is equally important to communicate the results and reviews that occur under the RMP.

A practical form of communication involves informal and regular discussions with the workforce, for example at lunch or while on the job. When management or the radiation adviser provides a presence in the workplace, it is easier for the workforce to engage in discussion.

However, radiation and radiation protection is a complex area. In some situations, the radiation staff can be known as "boffins", and sometimes make communications quite unnecessarily complex and difficult. Radiation does not need to be made any more complex than it already is and enabling workers and the public to ask questions is important. A saying is that "in radiation, there are no dumb questions!" Saying this up front enables people who genuinely have a question feel more at ease asking the question.

A parallel situation occurs with the public in relation to environmental radiation and public dose impacts from the project. The overall intent is to ensure that there is an unconstrained space where questions can be asked and answered properly communicated.

3.5 Maintaining Perspective

An important part of a RMP is ensuring that it fits within the broader operational health, safety and environmental management plan. Apart from the presence of uranium, the exploration site, the mining operation and the processing facility are just industrial sites with their own particular hazards. Too often, the radiological risks are seen to take priority. Other chronic and acute hazards need to be properly recognised and there must be assurance that resources are properly allocated to controlling the higher risks.

For most operations, the radiological risks are low.

In some cases controls for radiation can act to control other workplace hazards. For example, ventilation acts to control exposures to radon decay products, but also provides protection against the build-up of dusts and gases (and heat for underground mines).

4. CONCLUSION

This paper has aimed to provide some practical considerations for the effective development and implementation of a RMP based on experiences at various mines and processing facilities. The key messages are that RMPs should:

- Be more than a compliance document,
- Be part of a broader health, safety and environmental management system,
- Be supported by internal knowledge and competent staff.

The matters outlined in this paper are from the author's experiences across a number of uranium and NORM-related operations.

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VOLCANIC TYPE URANIUM DEPOSITS IN NORTH CHINA

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1. INTRODUCTION

The volcanic type uranium deposit is one of the four largest types of uranium deposit in China (volcanic, granite, sandstone hosted and carbonaceous–siliceous–argillaceous types) and is an important source of uranium. In the 1990s, prior to the large scale application of in situ leach technology (ISL) in sandstone hosted uranium deposits, the volcanic type uranium deposit was one of the main targets for exploration and exploitation in China. Uranium reserves in volcanic and granite type deposits account for 61% of China's total reserves [1]. As recently as 2015, the volcanic type still represented 35.48% in terms of annual output [2]. Contrary to granite type deposits, which are mainly developed in southern China and sandstone type uranium deposits which are mainly developed in northern China, the volcanic type has been found in both southern and northern China. Volcanic type deposits in southern China are located within the Gan-hang uranium metallogenic belt, and in northern China within the Guyuan–Hongshanzi and the Qinglong–Xingcheng uranium metallogenic belts. In the two northern metallogenic belts, 17 volcanic uranium deposits and more than 100 showings have been found, which comprise an important uranium mining area in China.

2. TYPICAL URANIUM DEPOSITS

The Guyuan–Hongshanzi and Qinglong–Xingcheng uranium metallogenic belts are located at the northern margin of the North China Craton (NCC) uranium polymetallic metallogenic province of the circum-Pacific metallogenic zone [3]. The former is located in the middle section of northern margin of the NCC and the latter is located in the eastern section of the northern margin of the NCC. According to the characteristics of the ore-bearing rock and ore controlling structures, volcanic type uranium deposits can be divided into 5 subtypes, namely the volcanic breccia, sub-volcanic, dense fracture zone, interlayer fracture zone and pyroclastic subtypes. The volcanic type uranium deposits in north China mainly comprise the sub-volcanic and the pyroclastic rock subtypes. The Zhangmajing, Daguanchang and Hongshanzi deposits, located within the Guyuan–Hongshanzi uranium metallogenic belt, are representative of the sub-volcanic subtype, and the Gangou and Dayingchang deposits from the Qinglong–Xingcheng uranium metallogenic belt are representative of the pyroclastic rock subtype. The geological characteristics of the typical uranium deposits are briefly described.

The Zhangmajing uranium deposit is located at the northern edge of the Zhangmajing volcanic collapse depression in the Guyuan volcanic basin, in the southern part of the Zhangmajing–Hongshanzi uranium metallogenic belt, and is controlled by a sub-volcanic type caldera. The ore-bearing rock is a potassium rhyolite, representing the fifth layer in the third lithology of the Upper Jurassic Zhangjiakou group and a rhyolitic porphyry (the main ore host rock). The Zhangmajing uranium deposit is a typical sub-rhyolite uranium–molybdenum porphyry deposit. It is the product of multi-phased volcanic magmatic hydrothermal activity dated to the Late Jurassic, Early Cretaceous and Palaeogene–Neogene. The mineralization ages are 122, 89 and 23.7 Ma.

The Daguanchang uranium deposit is located at the southern edge of the Daguangchang volcanic collapse depression in the Guyuan volcanic basin, within the southern part of Zhangmajing–Hongshanzi uranium metallogenic belt, and is controlled by a sub-volcanic type caldera. The ore-bearing rock is a potassium rhyolite of an effusive facies (the main ore-bearing host) from the Upper Jurassic Zhangjiakou group and a rhyolitic porphyry of a intrusive facies. The Daguanchang uranium deposit is a typical crypto-explosive

potassic rhyolite type uranium–molybdenum deposit. It is the product of multi-phased volcanic–magmatic hydrothermal activity which happened during the Early Cretaceous and Palaeogene. The mineralization has been dated to 67 and 30 Ma.

The Hongshanzi uranium deposit is located to the western and eastern edges of the Hongshanzi volcanic collapse depression where rhyolitic porphyry and granite porphyry occur as rings in the northern part of the Zhangmajing–Hongshanzi uranium metallogenic belt. They are controlled by the contact zone of a sub-volcanic type crater. The ore-bearing rock is a trachyte of the Mid–Upper Jurassic Manketouebo group and a rhyolite porphyry. The Hongshanzi uranium deposit is a typical contact zone of sub-volcanic controlled volcanic hydrothermal type uranium deposit. It is the product of multi-phased volcanic magmatic hydrothermal activity that occurred during the Late Jurassic and Early Cretaceous. The main metallogenic ages are 156 and 120–130 Ma.

The Gangou uranium deposit is located at the southern edge of the Gangou Middle Jurassic volcanic fault basin and belongs to the eastern part of the Qinglong–Xingcheng uranium metallogenic belt. The orebearing rock is a sedimentary pyroclastic formation of the Middle Jurassic Haifanggou Group, with strong mafic and alkaline volcanic magmatic activity occurring during the mineralization stage. The Gangou deposit is a typical uranium deposit related to a mixing between volcanic hydrothermal fluids and meteoric water , and is the product of a multiple geological evolution with syn-depositional uranium pre-enrichment and multi-stage volcanic hydrothermal fluid activity with superimposed meteoric water mineralization. The main metallogenic ages are 121 and 76 Ma.

The Dayingchang uranium deposit is located in the magmatic belt at the intersection of the NE trending Hongluoshan–Wuzhishan regional fault and the EW trending Qinglong–Jinxi regional fault, in the western part of the Qinglong–Xingcheng uranium metallogenic belt. The ore-bearing rock is a medium- to coarse-grained quartzite of the Middle Proterozoic Changzhougou Group and Jurassic acidic granitic and basic magmatism are the main sources of mineralization. The Dayingchang uranium deposit is related to multiple volcanic–magmatic–hydrothermal superimposed activity. The uranium mineralization is characterized by synsedimentary preconcentration with superimposed volcanic–magmatic–hydrothermal activity. The main metallogenic epochs are Late Jurassic–Early Cretaceous (142–123 Ma).

3. DISCUSSION AND CONCLUSION

Through comprehensive studies of the geological and mineralization characteristics of several typical uranium deposits, the volcanic type uranium deposits in north China are characterized by the following features:

- (i) Metallogenic geological background: In general, the volcanic uranium deposits occur on palaeolandmasses, especially on the edge of such landmasses. The continental volcanic eruption belts are dominated by acidic (partially alkaline) volcanic rocks. Volcanic type uranium deposits often occur in the composite parts of regional faults and volcanic basins formed by multistage volcanic activities.
- (ii) Metallogenic epoch: All uranium deposits are characteristized by multistage superposition of mineralization events. Palaeoproterozoic, large scale potassic migmatization at the northern margin of the NCC caused a preliminary uranium enrichment and represents the main uranium source horizon in north China. Multistage volcanic hydrothermal activity during the Late Jurassic– Early Cretaceous are the main sources of heat driving the activation and migration of uranium-bearing fluids. The intermediate–mafic volcanic magmatic activity during the Palaeogene– Neogene is responsible for superimposed mineralization events. The dates of the main mineralization events are concentrated between 156–120, 89–67 and 30–23.7 Ma.

- (iii) Mineralization characteristics: Polymetallic mineralization is common in the volcanic uranium deposits of north China. The Guyuan–Hongshanzi uranium metallogenic belt is mainly characterized by uranium–molybdenum mineralization, and the intensity and range of molybdenum mineralization may be greater than that of uranium, such as in the Zhangmajing deposit, where the reserves of molybdenum exceed 100 000 t, much larger than the uranium reserves (8000 tU). From the southern section of the Zhangmajing uranium deposit, from the Daguanchang uranium deposit to the northern section of the Hongshanzi uranium deposit and including the Guangxingyuan uranium deposit, the uranium minerals are mainly pitchblende and coffinite, but molybdenum-bearing minerals varied from jordisite to molybdenite. The temperatures of formation estimated from fluid inclusion studies were in the range 137.7–217.7°C in the Guyuan area, and 218–275°C in the Hongshanzi area. Ore-forming temperatures seem to increase from south to north. The Qinglong–Xingcheng uranium metallogenic belt is mainly monometallic, but hosts minor amounts of Mo, Pb, Zn, Cu, Ag and other metals [4]. Uranium-bearing minerals are present in minor proportions and mainly consist of pitchblende, with small amounts of uraninite and hexavalent uranium minerals.
- (iv) Ore controlling factors: Neoproterozoic–Palaeoproterozoic potassic migmatitic granite basement; Mesozoic uranium-rich volcaniclastic rock, volcanic rocks and sub-volcanic rocks; Late Jurassic volcanic-sedimentary basin, volcanic collapse basin and features such as caldera, volcanic dome and collapse structures. These three factors are the major ones controlling the formation of volcanic type uranium deposits in north China, together with regional faults which control the location and scale of the uranium deposits. The uranium deposits in the Qinglong–Xingcheng uranium metallogenic belt are generally controlled by strata and the uranium orebodies are stratified and lenticular in occurrence. The uranium deposits in the Guyuan–Hongshanzi uranium metallogenic belt are controlled by volcanic or sub-volcanic rock and tectonics, and the orebodies occur mainly as disseminations or veins. The host rocks in the two belts are diverse, such as volcaniclastic rock, rhyolites, trachyte and rhyolite porphyry.
- (v) The ore forming fluid mainly originated from the mantle: Isotopic signatures indicate that the ore forming fluid of the Guyuan–Hongshanzi uranium metallogenic belt has a weakly varying Pb isotopic composition, with ²⁰⁶Pb/²⁰⁴Pb: 16.857–19.934, ²⁰⁷Pb/²⁰⁴Pb: 15.413–15.726, ²⁰⁸Pb/²⁰⁴Pb: 37.596–38.904. The signatures indicated a mantle or lower crust or orogenic belt composition, although closer to mantle. The Sr isotopic ratios (⁸⁷Sr/⁸⁶Sr)_i of 0.707–0.727 comprised values for the depleted mantle (0.7022–0.7035) and the upper crust of north China (0.7120–0.7200). The Sr content (14.7–19.8 × 10⁻⁶) is very low, corresponding to the Sr content for depleted mantle, interpreted as indicating that the ore forming fluid has the characteristics of a mantle source. The δ^{34} S value of pyrite in the Gangou deposit varies in the range 1.2–5.7%, close to the isotopic sulphur composition of meteorite. The La/Yb–total rare earth element diagram shows that the rocks belong to continental alkali basalt series, suggesting that the sulphide (and also the ore deposit material) was mainly derived from the upper mantle.
- (vi) Metallogenic regularity: Since the Mesozoic, volcanic activity was frequent in north China, with regular episodes of basic-intermediate acid intrusion, eruption and multicycle activity. Uranium polymetallic deposits are mostly produced in transition zones between gravity high and low fields. The deposits are controlled by structures (including faults and volcanic structures), sub-volcanic rocks, reducing ore forming fluids with high temperature and high pressure derived from mantle, superimposed alteration and are associated with Mo, Pb, Zn, Ag and other elements. Uranium is enriched in late melts or fluids and the date of mineralization has been investigated [5]. All the preceding features are typical of hotspot uranium metallogenesis [6]. The uranium mineralization appears to be related to mantle plume activity in north China.
In conclusion, the volcanic type uranium deposits in north China have similar metallogenic ages, genesis and characteristics which may be related to the same tectonic settings, indicating that the northern margin of the NCC has undergone simultaneous and relatively large scale episodes of volcanic uranium mineralization since the Mesozoic.

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CHARACTERIZATION OF URANIUM, THORIUM AND RARE EARTHS IN THE DECOMPOSITION PROCESS OF THAI MONAZITE ORE SAMPLES BY X RAY POWDER DIFFRACTION AND WAVELENGHT DISPERSIVE X RAY FLUORESCENCE TECHNIQUES

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1. INTRODUCTION

In the Phuket and Phang-nga regions of Thailand, monazite ore has been found in association with tin (mine tailings) and in beach sand deposits. The Thailand Institute of Nuclear Technology has performed the separation and purification of rare earth elements (REE) from monazite for industrial applications. The principal processes can be summarized as follows:

1) The monazite ore (325 mesh) was first digested with 50 wt% NaOH at 140°C for 3 h. The reaction is:

(Ce, REE, Th, U)PO₄ + NaOH
$$\rightarrow$$
 (Ce, REE, Th, U)OH + Na₃PO₄ (1)

2) The obtained hydrous metal oxide cake of Ce, REE, Th and U was dissolved in 35% w/v HCl. The HCl was used to neutralize and react with hydroxides to generate a chloride compound solution as follows:

$$(Ce, REE, Th, U)(OH) + HCl \rightarrow (Ce, REE, Th, U)Cl + H_2O$$
(2)

- 3) The uranium (Na₂U₂O₇) and thorium (Th(OH)₄) phases can be obtained by the selective precipitation of the chloride compound solution with 20% w/w NaOH at pH4.5. The solvent extraction using 5%v/v of tributyl phosphate (TBP)/kerosene process was utilized to separate uranium and thorium. The extracted uranium was precipitated with NH₄OH to form yellowcake or ammonium diuranate, (NH₄)₂U₂O₇. The ThO₂ was produced by the extraction of solution obtained after uranium extraction with 40% v/v TBP/kerosene [1];
- 4) The filtrated mixed REE solution was treated with BaCl₂ and H₂SO₄ to remove radium, (a daughter product of uranium) and precipitated at pH11 with NaOH. The obtained REE(OH)₃ intermediate was leached with HNO₃ at pH6. The ion exchange process was used to extract and purify Ce, La and other REEs from the leaching solution [2, 3].

Inductively coupled plasma optical emission spectrometry (ICP–OES) and neutron activation analysis (NAA) were used for the determination of rare earths, uranium, thorium and other associated minerals in the samples during monazite processing [4]. The ICP–OES can analyse REEs with a high sensitivity and increased accuracy, and although it requires digestion of the ore in concentrated acid, it is also suitable for some low concentration REEs [4, 5]. For NAA, this technique implies long irradiation and long decay times [5]. X ray fluorescence (XRF) is a non-destructive technique for analysis of REEs, uranium and thorium. It has been reported that this tool could determine the REE, uranium and thorium concentrations in various samples such as in mixed REO concentrates, CeO₂, (REE)₂O₃ [6], thorium in the presence of uranium [7],

in monazite processing samples [8] and in phosphate ore [9]. X ray powder diffraction (XRD) has been applied for identification and quantification of the mineralogy as well as for the crystalline phase structure and composition in various ores, in monazite and in phosphate rock [8, 9].

In this paper, the wavelength dispersive X ray fluorescence (WD–XRF) and the X ray powder diffraction (XRD) techniques were developed to characterize uranium, thorium and REEs in Thai monazite processing samples.

2. MATERIALS AND METHODS

The samples used in this study were Thai monazite ore, $REE(OH)_3$ intermediate, U_3O_8 , ThO_2 , La_2O_3 and CeO_2 , as obtained from the decomposition process of Thai monazite ore by the alkali method. All samples were dried at 110°C for 12 h and then ground to a fine powder. The chemical and mineralogical analyses of the samples were carried out using WD–XRF and XRD techniques.

For WD–XRF analysis, samples were mixed with a reagent grade flux (mass ratio of lithium metaborate and lithium tetraborate 1:4). The ratio of sample and fluxing agent was 1:9. Ammonium iodide was then added as a releasing agent. The total amount of mixture was 6.9 g. The mixture was poured into a platinum crucible and fused at 1000°C for 2 min using a fusion machine (Katanax K2–classic automatic fluxer). The sample fused disc was analysed for uranium, thorium and REE concentrations using a Bruker S8 Tiger WD–XRF spectrometer.

For XRD analysis, the XRD patterns of the samples were obtained with a Bruker D8 ADVANCE diffractometer using Cu K α radiation ($\lambda = 1.5406$ Å) operating at an accelerating voltage of 45 kV and a current of 40 mA. The patterns were recorded in the 2θ range of 10–90° with a 2θ step size of 0.039° and 177 s/step.

3. RESULTS AND DISCUSSION

The monazite ore sample was ground to 325 mesh prior to XRD and WD–XRF analysis. The XRD pattern of the sample showed that the ore consisted of Ce-monazite–(Ce, La, Nd)PO₄ with a monoclinic structure. All diffraction peaks can be indexed according to the JCPDS card No. 00–046–1295 with lattice constants of a = 0.6811 nm, b = 0.7039 nm, c = 0.6501 nm, $\alpha = \gamma = 90$ and $\beta = 103.54$. The major peaks were observed at $2\theta = 21.63$, 25.79, 26.95, 28.78, 29.8, 31.07 and 34.34. The average crystallite size of the sample of 38.52 nm was observed. REEs including CeO₂ (30.74 wt%), La₂O₃ (11.07 wt%), Nd₂O₃ (10.71 wt%), Y₂O₃ (2.80 wt%), Pr₆O₁₁ (1.84 wt%), Gd₂O₃ (1.15 wt%), Dy₂O₃ (0.51 wt%) and Er₂O₃ (0.14 wt%), as well as ThO₂ (8.89 wt%) and UO₂ (0.50 wt%) were detected by WD–XRF.

The REE(OH)₃ intermediate sample formed after the digestion of monazite ore by the alkali method following the separation of thorium and uranium. The XRD pattern of the sample indicated the presence of a cubic phase of cerium and neodymium oxide with the standard card (JCPDS 00–028–0266). The characteristic diffraction peaks appeared at 2θ = 28.31, 32.67, 47.05, 55.88, 56.11, 68.67, 75.78 and 87.72 (a = b = c = 0.5458 nm and α = β = γ = 90) with a small crystallite size of 8.13 nm. The concentrations of CeO₂ (65.84 wt%), Nd₂O₃ (14.48 wt%), La₂O₃ (5.97%), Y₂O₃ (3.57 wt%), Pr₆O₁₁ (3.01 wt%), Gd₂O₃ (1.90 wt%) and Dy₂O₃ (0.84 wt%) were determined. The ThO₂ and UO₂ could not be detected by this WD–XRF technique.

The U₃O₈ sample was obtained by the solvent extraction of Th and U cake with TBP/kerosene extractant. The obtained $(NH_4)_2U_2O_7$ was calcined at 900°C to form the U₃O₈ cake. The XRD pattern of the sample exhibited predominantly peaks of uranium oxide at $2\theta = 23.61, 24.97, 25.24, 27.69, 27.96, 34.65, 44.37$ and 46.08 (JCPDS card No. 00–028–0164). The average crystallite size of the sample was 19.00 nm. The

WD–XRF result showed that the sample was composed of UO₂ (87.77 wt%) and ThO₂ (6.21 wt%). The concentration of UO₂ obtained by WD–XRF agreed well with that determined by XRD technique (UO₂ 87.00%).

After the separation of uranium, the TBP extraction process was used to purify Th and then the ThO₂ cake sample was formed by NaOH precipitation. The sharp characteristic peaks of the sample located at $2\theta = 27.65$, 32.01, 45.85, 54.36, 57.01, 66.84, 73.76, 76.02 and 84.80 can be assigned to a cubic phase of ThO₂ which matched well with the standard data (JCPDS card No. 03-065-7222). The lattice parameters were a = b = c = 0.5596 nm and $\alpha = \beta = \gamma = 90$ with the average crystallite size of 95.16 nm. The concentration of ThO₂ in the sample was found to be 83.74 wt% with a small amount of UO₂ (0.61 wt%).

The CeO₂ and La₂O₃ present in the REE(OH)₃ intermediate were separated and purified by the ion exchange process. For the CeO₂ sample, all the diffraction peaks can be indexed to the face centered cubic phase of cerium oxide with lattice constant a = b = c = 0.5412 nm and $\alpha = \beta = \gamma = 90$. The sharpness and high intensity of the predominant peaks at $2\theta = 28.51$, 33.06, 47.44, 56.31, 59.03, 69.37, 76.68, 79.05 and 88.38 (JCPDS card No. 01–081–0792) indicates the crystalline nature of the CeO₂ sample. The average crystallite site of the sample was found to be 64.2 nm. The WD–XRF result indicates that the CeO₂ sample contained 99.47 wt% of pure CeO₂ which matched well with the result from XRD.

In the case of the La₂O₃ sample, a typical diffraction peak of La₂O₃ at $2\theta = 27.34$, 27.96, 31.62, 35.93, 39.51, 42.15, 48.65, 55.26, 64.00 and 69.56 (JCPDS card No. 01–076–0572) was observed. The characteristic peak is attributed to a hexagonal structure with lattice parameters of a = b = 0.6523 nm, c = 0.3855 nm, $\alpha = \gamma = 90$ and $\beta = 120$ and average crystallite site of 17.16 nm. The La₂O₃ sample analysed by WD–XRF is composed of La₂O₃ (89.70 wt%) and CeO₂ (8.15 wt%).

4. CONCLUSION

Monazite ore found in the tailings from tin mining in southern Thailand has been used as source of REEs, uranium and thorium. The decomposition process using alkali method, solvent extraction and ion exchange techniques were used to separate and purify those elements. XRD and WD–XRF as fast, accurate and non-destructive methods were extremely useful for the determination of REE, uranium, thorium and associated mineral concentrations in the samples obtained during the process. The elemental compositions of all samples measured by WD–XRF agreed well with that determined by the XRD method. In addition, the concentration of uranium oxide in the U_3O_8 cake sample determined by WD–XRF (87.77 wt%) showed very good agreement with that obtained by the XRD method (87.00 wt%). The same result was obtained for the CeO₂ sample, with concentrations of 99. 47 wt% and 99.90 wt% detected by WD–XRF and XRD, respectively.

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URANIUM EXPLORATION BY REMOTE SENSING METHODS IN THE KALEYBAR AREA, NORTH-WESTERN REGION, ISLAMIC REPUBLIC OF IRAN

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1. INTRODUCTION

The study area discussed in this paper is located in the Alborz–Azerbaijan structural zone. Lithologies in this area include rhyolitic to andesitic Eocene volcanics and granitic to granodioritic intrusions. Most of the Cu, Fe and other mineralization occur in recent lithologies. Geological and geochemical researches in the Kaleybar area by Iranmanesh et al. [1] show that uranium and thorium anomalies are hosted in silica and clay altered areas and are associated to Cu and Au anomalies.

Since 2000, advanced spaceborne thermal emission and reflection radiometer (ASTER) multispectral imagery has offered improved spectral and spatial details of prospective areas. ASTER shortwave infrared bands are excellent for mapping clastic and carbonate formations in volcanic environments and are also effective in predicting the occurrence of certain mineral groups and specific minerals (kaolinite, alunite, illite, muscovite, montmorillonite, chlorite, calcite, dolomite, serpentine, etc.). Unfortunately, ASTER has a limited utility in mapping and characterizing FeO_x and other Fe minerals because of its narrow visible and near infrared bandwidth. Hydrothermally altered rocks have received considerable attention because of their potential economic implications and their favourable spectral characteristics for remote identification [2–6].

2. METHODS AND RESULTS

2.1. Atmospheric correction

To remove atmospheric effects from data, the quick atmospheric correction (QUAC) was used. Hence, a spectrum generated from data treated using the QUAC method will be more closely comparable to its corresponding library spectrum. As the QUAC algorithm reduces noise from atmospheric effects, the processed ASTER data will allow comparison of the synthesized spectrum with those from the library.

More than 40% of vegetation in areas studied by remote sensing generate problems in data processing and in analysing the resultant images. To solve this problem, the normalized difference vegetation index algorithm was used to identify the vegetation in the studied area and then to remove it by masking those areas with vegetation.

2.2. False colour composite method

Experimental analysis shows that a 468 colour composite combination is a good red–green–blue scheme for distinguishing alteration zones. In this composite colour, propylitic alteration will appear as green and a

phyllic alteration zone with a large quantity of Al–OH minerals will appear as a pinkish–yellowish colour owing to the b4 band. Alunite, kaolinite and white mica minerals exhibit more reflection than in the b6 and b8 bands [7].

Argillic alteration is present in the south-eastern part of the research area and in Kaleybar city. This alteration zone is combined with a propylitic alteration zone which displays a green colour. This type of alteration combination is a good indicator for copper exploration. As reported by Iranmanesh et al. [1] in the Kaleybar area, there is a good correlation between uranium and the argillic altered zones.

2.3. Band ratio method

Use of band ratios enhances the spectral differences between bands and reduces the effects of topography; dividing one spectral band by another produces an image that provides relative band intensities. The image enhances the spectral differences between bands. ENVI can output band ratio images in either floating point (decimal) format or byte data format, where floating point format is the default. Three ratios can be combined into a colour ratio composite image to determine the approximate spectral shape for each pixel spectrum. For example, kaolinite spectra are shown in the ASTER–shortwave infrared range. Band 5 has the lowest digital number and band 6 has the highest digital number, so in this case there is some way to enhance the kaolinite-bearing pixels using the band ratio method. The simplest way is

$$BR = \frac{Band6}{Band5}$$

However, in this calculation, the result shows some correlation with the alunite pixels because there is a high digital number in band 6 for alunite too. Another calculation is

$$BR = \frac{Band \ 4 + Band \ 6}{Band 5}$$

This is a better way than the first one, but Nynomiya [8] has introduced an improved formula to calculate band ratio:

Argillic zone index = (band 4/band 5)
$$\times$$
 (band 8/band 6)

The Nynomiya ratio has been used on the image to enhance the argilic zone in the Kaleybar area. As it appears in the resulting image of band ratio for argilic zone, this method shows a good correlation with the FCC resulting image to identify the kaolinite (argilic) alteration zones.

Alunite zone index = (band 7/band 5)
$$\times$$
 (band 7/band 8)

In hydrothermal zones, gold could be anomalous as is Cu and according to the correlation between Au–As and also As–U, uranium could be also anomalous in these types of alteration. Thus, an attempt was made to detect and enhance alunite alteration zones as an exploration key in order to find potential mineralized areas for gold. Alunite alteration areas appear to be correlated with kaolinite areas and this type of alteration combination is a good indicator for gold mineralization.

The principal component transformation is a multivariate statistical technique that selects uncorrelated linear combinations (eigenvector loadings) of variables in such a way that each successively extracted linear combination or principal component has a smaller variance. The principal component analysis is widely used for alteration mapping in metallogenic provinces [4, 9].

The Crosta technique is also known as feature oriented principal components selection. Through the analysis of the eigenvector values it allows identification of the principal components that contain spectral information on specific minerals, as well as the contribution of each of the original bands to the components in relation to spectral response of the materials of interest. This technique indicates whether the materials are represented by bright or dark pixels in the principal components according to the magnitude and sign of the eigenvectors loadings. This technique can be applied on four and six selected bands of TM data [6].

2.4. Principal component analysis

The purpose of using principal component analysis is to reduce the size of the data, in this case the number of original bands and to maximize the amount of information from the original bands into the fewest number of principal components. A set of correlated variables (original bands) is transformed in other uncorrelated variables (principal components) which contain the maximum original information with a physical meaning that needs to be explored. According to principal component analysis, PC6 was used as argillic alteration detection index and PC10 was used as propylitic alteration detection index.

2.5. Spectral angle mapper (SAM)

SAM is a classification method that permits rapid mapping by calculating the spectral similarity between the image spectrums and a reference reflectance spectrum [6]. The reference spectra can either be taken from laboratory or field measurements or extracted directly from the image. SAM measures the spectral similarity by calculating the angle between the two spectra, treating them as vectors in *n*-dimensional space [2]. Small angles between the two spectra indicate a high similarity and high angles indicate a low similarity. This method is not affected by solar illumination factors because the angle between the two vectors is independent of the vector length [6, 10]. The main advantages of the SAM algorithm are that it is an easy and rapid method for mapping the spectral similarity of image spectra to reference spectra. It is also a very powerful classification method because it diminishes the influence of shading effects to accentuate the target reflectance characteristics. In this study, the authors resampled mineral spectra from the US Geological Survey library to 14 bands according to the ASTER bandwidths. Area data were then scanned using the SAM methods for kaolinite, montmorillonite, chlorite, sericite minerals and their alterations.

3. DISCUSSION AND CONCLUSIONS

In this study, false colour composite, band ratio, principal component analysis and SAM methods were used to detect and separate alteration patterns. First of all, the studied area by the false colour composite method was investigated, resulting in the detection of some areas with argillic and propylitic alterations. Then, using the band ratio method with appropriate ratios for each alteration, areas were extracted more exactly. The principal component analysis and SAM methods were used to find areas exhibiting closer correlation in their alterations. As a result, four new areas were detected as clay alteration areas. After completing a radiometric survey over these areas, two of these areas were identified as anomalous. New methods were used in this study and achieved good results for the detection and the separation of alterations in the Kaleybar area. These methods can be used as tools to search for similar areas.

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GEOLOGY, MINERALOGY AND PETROGRAPHY OF ROCKS WITH RADIOACTIVE ELEMENT MINERALIZATION IN ANOMALY 6 OF THE KHOSHUMI AREA, ISLAMIC REPUBLIC OF IRAN

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1. INTRODUCTION

One of the most important matters affecting all of humankind's existence and development is access to energy. Currently, the main energy resources are fossil fuels. These resources are non-renewable and are associated with high levels of environmental pollution, implying that the use of new energy resources to replace fossil fuels, and by extension, the utilization of nuclear fuel technology, become very important, if not vital.

The nuclear fuel cycle starts with exploration and exploitation [1]. This paper, based on geological and mineralogical studies, attempts to identify different generations of radioactive elements in anomaly 6 of the Khoshumi area. The area is situated in Yazd province, 50 km south-west of Saghand village. The village is located 160 km from the Yazd–Tabas road. This area is, in fact, part of the rugged heights of the Anjir valley. Anomaly 6 has an approximate surface of 320 hectares and is located between 55° 05' to 55° 11' E and 32° 20' 00'' to 32° 21' 30'' N.

2. METHODS

Studies performed during this work include lithological processing of ETM⁺ satellite imagery in order to provide geological maps and field operations and geophysical surveys, along with sampling of rock units of the area to investigate the lithological background of the radioactive elements.

3. RESULTS

3.1. Geology

The Khoshumi area is located in Yazd province, which is situated in central part of the country and forms part of the Bafq–Saghand metallogenic zone, which was connected to the Arabian Peninsula. This metallogenic zone was formed from mantle fluids during the Pan-African tectono-thermal phase. Bimodal volcanism, alkaline ultramafic intrusive bodies, metasomatism and uranium, thorium and REE mineralization are related to this tectono-thermal activity.

Older formations correspond to metamorphic rocks, such as gneiss, marble, mica schist, amphibolite and migmatite, which constitute the Proterozoic metamorphic basement of the country (Chapedoni, Baneshur and SarKuh metamorphic complexes). Anatectic granites and migmatitic rocks cover extensive parts of the studied area. The metamorphic rocks have been covered by thick detrital and pyroclastic rocks such as shale,

sandstone and tuff comprising the Tashk Series and belonging to the Cambrian era. On top of the Tashk Series is an assemblage of carbonate–detrital sedimentary rocks, tuff, basaltic lavas and rhyolitic rocks comprising the Rizu Series. Igneous and metamorphic rocks of this area originate from granitic continental crust deformation which included intensive folding and fracturing and calc-alkaline granites and migmatites formed during these deformation processes [2].

3.2. Petrology

After several stages of sampling and preparation of thin sections, a total of 178 rock and mineralization samples from lithological units and alteration zones containing radioactive elements, were studied. The results from these lithological and mineralogical studies of the samples showed that the radioactive elements in the area are related to the gneisses and pegmatites representing the main lithologies at anomaly 6 in the Khoshumi area. In these rocks, the minerals containing radioactive and rare earth elements formed during three successive phases.

3.2.1. Gneisses

Microscopic studies indicate that the main minerals of the gneisses include quartz and plagioclase, especially albite and alkali feldspars such as orthoclase and microcline. Biotite in these rocks is the dominant ferromagnesian mineral. The matrix is foliated and some of the minerals, such as quartz and feldspars, have been crushed and form sub-grains. Biotite is also observed as large crystals and as small secondary crystals. Minor accessory and alteration minerals of these rocks include zircon, sphene, apatite, allanite, amphibole, carbonate, chlorite, zoisite and clinozoisite with epidote and sericite.

The main alterations of these rocks are potassic, sodic, carbonaceous and siliceous. The potassic alteration occurred during the hydrothermal process with the formation of orthoclase, microcrystalline biotite and with small amounts of silica. In sodic alteration, albitization is characterized by the formation of small sized albites and secondary fine-grained quartz. In some samples, quartz veins and veins of quartz–albite are microcrystalline and contain radioactive yellow silicate minerals and secondary iron hydroxides that increase the radioactivity of these rocks. Silicification and carbonatization are also found in the gneisses along fractures and cataclastic zones, especially in the mylonitic district.

3.2.2. Pegmatites

Pegmatites are also present in the Khoshumi area and contain quartz, with medium to large grained albite, perthite and microcline. Biotite is the only ferromagnesian mineral and present low levels in comparison to the gneisses. Minor minerals in variable amounts include zircon, allanite, monazite and apatite and these are found mostly in biotites. Tourmaline and garnet sometimes develop at the contacts with the silica veins in the matrix of these samples. Sphene, chlorite, sericite and carbonate are alteration minerals. The main alterations observed in pegmatites are carbonate, along with argillic–silica and sometimes sodic alterations. In the carbonate alteration, calcite is found in biotites. Colloidal and breccia textures are also important textures of silica alteration in the pegmatites [3].

3.2.3. Mineralization

On the basis of studies of thin and polished sections from samples of the Khoshumi area, it has been found that the main radioactive minerals include coffinite, uraninite, ferroallanite and yellow coloured silicates of uranium. A closer examination of the uranium silicate minerals through scanning electron microscope studies indicates the presence of minerals such as boltwoodite, soddyite, sklodowskite, cuprosklodowskite, curite, uranophane and even thorium silicates, such as thorogummite.

Other minerals include pyrite in the form of small crystals lining the fractures generally filled with carbonate and silica. Arsenopyrite can also be detected as very small particles in these samples. Small amounts of martitic magnetite, ilmenite with rutile needles, as well as haematite with exsolution textures are also present. Zirconolite and baddeleyite are other important minerals that can be identified in polished sections and are generally found in biotites. Anatase is another mineral associated to titanite, sphene or rutile.

In the samples, pitchblende consists of highly fractured crystals exhibiting colloform and deformed textures. It can be distinguished by its dark grey reflection colour, isotropy and with fractures filled with secondary minerals and iron hydroxides. On the surface of the sections, pitchblende is generally in contact with albite, and carbonate and silica minerals. Uranium silicates, especially coffinite, are found in pegmatitic rocks of the area in the form of needle-like crystals with generally spherulitic textures, inside the silica–albite–carbonate veins containing micro-crystals of pyrite. These minerals are also found in the matrix of certain ferromagnesian minerals such as hornblende. Haematite minerals and iron hydroxides line the fractures that often display open voids.

4. DISCUSSION AND CONCLUSIONS

Microscopic studies indicate that within anomaly 6 of the Khoshumi area, the lithological units containing the radioactive elements correspond to gneisses and pegmatites. Mineralization generally consists of three groups of minerals containing radioactive and non-radioactive rare earth elements. Minerals containing rare earth elements include zircon, zirconolite, baddeleyite, allanite, ferroallanite, apatite and sphene. Monazite was observed in a number of pegmatitic samples only as small, anhedral grains inside biotites. Radioactive minerals identified in these sections are uraninite and uranium silicates, including coffinite. Uranium silicate minerals, or yellow radioactive minerals, include needle-like crystals with cumulative spheroidal textures that appear in cavities and veinlets of the samples and occasionally in secondary chlorite and sericite minerals. These minerals are associated with alteration and oxidation zones and are generally secondary.

Non-radioactive minerals identified correspond generally to iron and titanium minerals such as pyrite, arsenopyrite, ilmenite, magnetite, haematite, goethite, lepidocrocite, rutile and anatase. Also, in some parts of the ilmeno-rutile, topaz and copper minerals, including chalcocite, bornite and malachite, have been identified. In this case, the frequency of hydroxide and iron oxide minerals is higher than that of other minerals. Mineralization in the Khoshumi area is enriched in rare earth elements, U, Cu, Mo and Ni, and in some parts Th minerals occur in veins. Mineralization is related to three phases, pegmatitic, hydrothermal and deuteric. In the pegmatitic stage, the enrichment of U and rare earth elements occurred in minerals such as zircon and allanite, along with sphene and monazite. Hydrothermal mineralization occurs as a second phase with elements such as Cu, Mo, Ni and Au, which have formed minerals such as pitchblende, nickeline and arsenopyrite. The deuteric phase also caused the alteration of the primary uranium minerals which, given the mobility of U and other ions, enriched uranium and other elements along the fractures of the host rocks.

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EFFECTIVE RADIATION MONITORING: BACK TO BASICS

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1. INTRODUCTION

Radiation monitoring programs are a key aspect of the role of radiation practitioners in the uranium mining and mineral processing sector. An effective monitoring program enables ongoing assessment of the integrity of existing radiation exposure controls; an upward trend in monitoring results can indicate failure of controls or the need to design and implement additional controls. Outputs from radiation monitoring programs allow operations to demonstrate compliance with regulatory requirements, and provide a solid base of factual data that can be drawn upon for communication of relative risk or in the event of scrutiny from regulators, from the workforce, or from community representatives. Importantly, competent radiation monitoring conducted with a good awareness of the mining or mineral processing operation can provide feedback to assist in decisions which optimise both production and radiation exposures at the same time.

2. BACKGROUND

Uranium mining and mineral processing operations are regulated under a range of frameworks administered at international, national and local levels. Underlying the frameworks and regulatory systems is the ICRP "System of Radiological Protection" [1]. This consists of:

- Justification where a project should only proceed if the benefits outweigh the risks;
- Optimisation where doses and impacts should be as low as reasonably achievable (ALARA); and
- Limitation where absolute upper limits are established.

To put this framework into practice, operations are generally required to implement a radiation management plan (RMP). In Australia the Mining Code [2], requires each operation to produce an RMP, which will typically include an outline of operational parameters, exposure pathways and controls, and a radiation monitoring program. Radiation management plans are structured so that compliance with the document demonstrates compliance with relevant regulatory frameworks, and are reviewed and approved by the appropriate regulatory body.

Practicality and ease of implementation are key factors for successful RMPs. Radiation management is most effective when it takes a risk-based approach, specific to the operation – and the assessment of risk needs to be based on a comprehensive understanding of potential radiation exposure pathways.

It is therefore essential that an operational radiation monitoring program is both relevant and effective with an end goal of being valuable both for demonstrating regulatory compliance and for informing operational radiation management decisions.

Radiation monitoring programs in uranium mining and processing operations should aim to:

- Characterise exposures;
- Prove the effectiveness of controls;
- Ensure that controls are commensurate with the risk;
- Be practical;

• Communicate results effectively.

It is difficult to compare the effectiveness of monitoring program because they need to be suitable for the particulars of the operation. Traditional management KPIs may therefore be, to some extent, misleading for measuring the effectiveness of programs. Observation and review of monitoring in various uranium mining and mineral processing operations at all stages from exploration to closure indicates that while the effectiveness of a monitoring program is difficult to quantify, there are common factors which characterise good operational radiation management.

2.1 Awareness of radiological characteristics (in other words "know your processes!")

Undertaking an evaluation of the radionuclide balance through process and effluent streams during the early stages of operation helps to ensure that potential radiation exposure pathways are understood. The differing characteristics of naturally occurring radionuclides can cause concentration or dilution as a consequence of chemical or physical properties – or as a consequence of ingrowth or decay depending on the age of products relative to the half-lives of any radionuclides present.

Characterisation of radionuclide deportment allows a radiation monitoring program to be correctly structured and adequately resourced with the correct equipment to measure potential exposures from the radionuclides that are expected to be present in any given area or circuit.

2.2 Adaptability and Ability to Respond to Changing Conditions

As operations naturally evolve over time, a flexible monitoring program that avoids complacency and maintains a curious and considered approach will help to ensure that changing exposure scenarios are captured.

2.3 Ability to Undertake Investigative Monitoring (Moving from Compliance Monitoring to Risk Based Monitoring)

Adequate resourcing is required so that radiation management can exceed basic compliance, to focus on industry best practice and optimisation of exposures. Using this approach, compliance is naturally achieved as a consequence. There are key differences between radiation monitoring for regulatory compliance and radiation monitoring to support a target of best practice radiation management.

A focus on achieving regulatory compliance will promote a minimal approach which targets fulfilment of monitoring quotas. It seeks to demonstrate compliance and allows little scope to deviate from the prescribed program to capture any operational changes or un-programmed work.

Mining and mineral processing operations are typically driven by cost optimisation, and in that climate it is often difficult to attract the additional resourcing that enables radiation monitoring and management to go beyond a basic compliance focus. The benefits of a robust and curious radiation monitoring program are not easily captured as an operational cost benefit or under traditional management KPIs, but are important for any operation with an interest in continuous improvement.

When monitoring programs are resourced effectively with capacity for a flexible approach, measurements can be broadly considered under two categories. Compliance monitoring provides information satisfying regulatory scrutiny, demonstrating compliance, and for quantifying occupational, community and environmental exposures. Investigative monitoring focuses on proving controls, determining whether existing controls are performing effectively, and on identifying potential risk from exposures that may not be captured by a routine compliance monitoring program.

Adequate resourcing for both monitoring streams enables an operation to optimise practices for radiation exposures rather than purely for cost.

2.4 Identification of Problems for Timely Response

To be effective and relevant and to support the principle of optimisation, a monitoring program should be cognisant of the actual risk associated with operational practices.

The breadth and depth of a monitoring program should be adequate to identify any failure of controls or trends in exposure pathways, but should not persist in monitoring at a high frequency where actual risk is continuously shown to be low and where operational practices are static, without any potential for effect on occupational dose.

This may require practitioners to revisit approved plans and engage with regulators, adapting the monitoring program to focus on new areas of concern and reduce monitoring in areas with consistently low risk of exposure.

2.5 Maintenance of Technical Capacity (in other words "Make Sure People Know What They Are Doing")

Business efficiency requirements and advances in technology can drive uptake of technology and software, or outsourcing of maintenance to specialist contractors. These advancements reduce general workload, but can lead to dependence and a loss of basic technical ability.

Uranium mining and mineral processing operations are often remote, located in areas far from specialist technical support, and the challenges of the remote environment can impede or even cripple a monitoring program that is not supported by appropriate expertise within the operation.

Retaining an understanding of basic calculation and interpretation of results allows rapid calculation and assessment of results in the field or in the event of technological outage, and enables monitoring to provide feedback to the operation promptly.

New monitoring equipment can incorporate both measurement and calculation of results, but to cover any periods when equipment is off site or unserviceable, retention of equipment and skills for simple monitoring methods ensures that a monitoring program can be maintained under any circumstances.

In house repair of equipment may not meet the requirements of a standardisation or quality framework (e.g. ISO, NATA etc), but where measurements are not used for dose assessment the requirement for accuracy may be less important than the requirement to provide prompt feedback. Field repairs to equipment may have a small effect on efficiency or calibration, but the effect is unlikely to be significant and the end goal to optimise exposures may be better executed by providing rapid assessment.

2.6 Operationally Useful, Engaged and Curious

A competent radiation monitoring program should have capacity to engage with the operation as a whole, and to respond to permanent or temporary operational changes without impacting compliance monitoring programs.

Radiation practitioners, equipped with information returned by a robust radiation monitoring program, should be actively engaged with operational decision makers to ensure that the need for controls is effectively communicated. Radiation monitoring data and the correct interpretation of legislation and of actual risk can be key to determining the need for control of any potential hazards, and in assisting in design of appropriate and effective controls.

When changing exposure situations are identified quickly, operations can respond to implement interim controls and plan for installation of permanent control measures during planned maintenance outages. A delay in identification of an exposure issue can allow the situation to spiral, causing unplanned interruptions to operations and a loss of production.

Having competent and trained staff who understand the operation and how to effectively monitor it ensures that when things go wrong (i.e. component or system failure), accurate information can be provided promptly to those needing to make decisions, thereby ensuring continued production.

Operations with proactive radiation and hygiene monitoring regimes have demonstrated an ability to positively influence operational controls, and where operational limitations (such as throughput), exist due to concern around hygiene exposure, a comprehensive understanding of a process system can ensure operators have sensitive operational responses allowing greater production levels to be achieved.

3. SUMMARY

Radiation monitoring programs should not be regarded as purely a requirement for regulatory compliance. Monitoring results are invaluable in achieving continuous improvement objectives, and in determining controls required to reduce occupational exposures to employees. Monitoring can assist operations to optimise production, and can intercept failures early so that unplanned interruptions to production for maintenance or repairs can be avoided.

The structure and focus of a radiation monitoring program informs and drives operational radiation management, and a monitoring program that actively engages with the operation has value both in the optimisation of radiation exposures and in supporting continuous improvement in all aspects of operation.

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ADVANCED QUANTITATIVE GAMMA SPECTROMETRY SOFTWARE FOR OPTIMIZED ENVIRONMENTAL ASSESSMENT DURING 'CRADLE-TO-GRAVE' URANIUM EXPLOITATION MANAGEMENT

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1. INTRODUCTION

Reliable, fast and cost-effective assessment of various environmental parameters related to exploration, mining, production and decommissioning/remediation is an essential input parameter for 'cradle-to-grave' ('exploration-to-remediation') uranium project management. In this paper, ANGLE software for advanced quantitative gamma spectrometry is briefly outlined and its applicability to that aim discussed.

In any gamma spectrometric measurement conducted with semi-conductor or scintillation detectors, the question of converting the number of counts (collected in a full energy peak) into the activity of the sample/source cannot be avoided. There are, in principle, three approaches to this problem [1]:

- Relative approach, where one tries to imitate as well as possible the source by a standard (or vice versa), while maintaining the same counting conditions for the two. With enough care being taken, the result is, in general, so accurate that it cannot be surpassed by any other method. However, in practice 'enough care' is not always implemented. Combined with inflexibility in respect of varying source/container parameters (shape, dimensions, material composition), this represents the raison d'être of approaches (ii) and (iii);
- 2) Absolute approach, which is similar to Monte Carlo calculations, yielding full energy peak efficiency for a given counting arrangement. It is essentially a statistical treatment of the events which photons undergo from being emitted by a source atom up until the interaction with the detector active body including the treatment of, as applicable, the so produced electrons, positrons and other subsequent energy carriers. This approach is beautifully exact, on condition that consideration is given to a sufficiently large quantity of incident photons, and that the details about an extensive number of physical parameters characterizing the process are known. After many years of practice, these still remain limiting factors for its applicability;
- 3) *Semi-empirical* approach, which attempts to reconcile the previous two. Semi-empirical models commonly consist of two parts: (i) experimental (producing one kind or another of reference efficiency characteristic of the detector) and (ii) 'relative-to-this' calculation of peak efficiency. Inflexibility of the relative method is avoided in this way, as well as the demand for some of the physical parameters needed in Monte Carlo calculations. Numerous variations exist within this approach, with emphasis either on the experimental or the computational part. Most of these (over)simplify the physical model behind, i.e. the treatment of gamma attenuation, geometry and detector response.

Stemming from the above, ANGLE's purpose is to allow for simple, but accurate determination of the activities of gamma spectroscopic samples for which no 'replicate' standard exists, in terms of geometry and matrix. It employs a semi-empirical 'efficiency transfer' approach, which combines advantages of both absolute and relative methods in determining sample activity by gamma spectrometry. In doing so, practical limitations of the latter methods are reduced, while the potential for systematic errors in the former is minimized [1, 2].

The physical model behind is the concept of the effective solid angle, a parameter calculated from the input data on the geometrical, physical and chemical (composition) characteristics of the source, the detector and counting arrangement ('geometry'). These three parameters are accounted for through a simultaneous differential elaboration, which leads to complex mathematical expressions, although these are easily managed by means of numerical integration with ordinary computers (PCs). A sound theoretical foundation was therefore laid at the start of ANGLE development [1–4].

ANGLE was conceived and developed at the University of Montenegro and commercially distributed by AMETEK-ORTEC, United States of America [5]. International cooperation has been an essential part during its evolution. Numerous scientific and technical papers, as well as PhD theses, have emerged from ANGLE progression and utilization.

2. OUTLINE OF ANGLE SOFTWARE

All relevant information about ANGLE, including theoretical background, features, downloads, references, papers, questions, etc., can be found in detail on its web site [6]. During its development, care was taken to reflect on and take into account the needs of numerous gamma spectrometrists and their perspectives and feedback. User communication/support has thus been an important part of the software development. Four main versions have emerged since 1994 (the current one being ANGLE 4), with nearly 300 updates.

The main features of ANGLE 4 can be summarized as:

- High accuracy, where typical uncertainties in results obtained (quantitative gamma spectrometry report) are of the order of a few per cent, which are introduced by input data, not the software itself;
- Broad range of applicability (e.g. in environmental monitoring, fuel cycle and nuclear industry, waste management, regulatory control, nuclear security and safeguards, medicine, research and education);
- Ease of use, as there is a highly user oriented and intuitive interface, supported by graphical scaled visualization;
- All parameters characterizing efficiency calculations are shown on one screen and are thus easy to control and comprehend;
- Short computation times, which are an order of magnitude shorter than those of Monte Carlo methods; even the most complex calculations are executed within minutes on ordinary PC machines;
- Flexibility with respect to input parameters and output data;
- Easy communication with other software and thus can be regarded as modular software;
- Suitability for teaching/training purposes;
- Calculates detection efficiencies for most common counting arrangements;
- Software supports include:
 - Semiconductor and scintillation detectors;
 - Closed end, open end, planar, well-type detectors;
 - Cylindrical, marinelli, disc, point sources;
 - Various source containers;
 - Any source dimension;
 - Any matrix composition.
- Detector calibration is undertaken by the user;
- There is no need for detector factory characterization and/or recharacterization;

- It is compatible with most common (ORTEC and Canberra) spectrum emulation software (GammaVision, Genie2000);
- One copy of the software can serve all detectors in the laboratory, regardless of detector type, age or manufacturer;
- Transparent, hands-on software (no 'black box' for the user) where all parameters of the detector, sample, counting geometry, etc., are under control and subject to modification;
- Practical educational and training tools for gamma spectrometry courses at all levels;
- Highly convenient for scientific research;
- Software design is aimed at bringing the user to a higher level of gamma spectrometry practice;
- Preview possibility for input data, which visualizes counting arrangement (detector, source, geometry) and indicates potential systematic errors (blunders);
- Enables easy programming of large batch jobs for efficiency calculations and therefore suitable for monitoring, research (e.g. error propagation studies), optimization, etc.;
- Has a modular nature and made to easily fit into more complex programs, which supply data to it and/or make use of its output results;
- Highly informative web site;
- Software architecture offers potential for accommodating other efficiency calculation methods of semi-empirical or absolute (Monte Carlo) type;
- Its current scope of applicability can readily be extended to further/particular user's needs and/or fields of interest and as such can be regarded as an 'open-ended' computer code;
- Multi-language interface currently exists in English, French, Spanish, Russian, Chinese and Japanese, but new languages can readily be added by translating (through a dedicated subroutine) an Excel file of about 700 short strings.

A key aspect and difference from other approaches, which greatly enhances practicality, is that no 'factory characterization' of the detector response is required. In fact, any HPGe detector may be used as long as some basic knowledge concerning its construction is available. These technical data are normally supplied to the customers by detector manufacturers in the form of accompanying data sheets, or can be obtained upon request. Care should be taken for the data to be as accurate as possible, since the accompanying uncertainties are propagated into final analytical results as systematic errors.

As to reliability, an IAEA organized comparison exercise was conducted in 2010 by the European Commission's JRC-IRMM facility (Geel, Belgium) [7]. Ten laboratories took part, applying nine prominent efficiency transfer calculation codes: semi-empirical (source derived) and absolute (Monte Carlo). The exercise revealed that systematic errors (differences occurring between experimental and calculated efficiency results) are, for the most part, not due to the calculation methods/procedures themselves (including attenuation coefficients, cross-sections and other physical parameters), but more to uncertainties in input data (detector, source, materials, geometry). ANGLE was one of the participating codes, scoring 0.65% average discrepancy from the exercise mean values, with no evidence of systematic bias.

3. APPLICABILITY TO URANIUM EXPLOITATION MANAGEMENT

ANGLE applicability in uranium exploitation management is evident and straightforward and its simplicity, flexibility and fast performance allows for quantitative analysis of large numbers of samples in short periods of time, regardless of type, origin, size, shape, matrix composition, etc. In practice, this translates into the ability to quantitatively analyse thousands of gamma spectroscopic probes within the counting capacity

limits of the equipment, including samples of geological, environmental, industrial, biological and medical origin, as these may be encountered during uranium exploitation management from exploration to the remediation phase (cradle-to-grave). This constitutes a considerable source of reliable first-hand information, which is essential to the decision-making process.

Applying ANGLE in uranium related matters is not a new story. In its various forms, ANGLE has been in use for 25 years in hundreds of gamma spectrometry laboratories worldwide, including many dealing with different aspects of uranium exploitation either directly (in exploration, mining, processing, environmental and workplace monitoring, QC/QA and other applications) or indirectly (e.g. within regulatory, health, research, educational or other institutions) [8]. However, some form of topical (uranium) standardization, for instance in form of a dedicated 'U module' would be a welcome future development in this respect.

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THE MINING SECTOR CAPACITY IMPROVEMENT IN THE KYRGYZ REPUBLIC THROUGH BUILDING EFFECTIVE COOPERATION AMONG GOVERNMENTS, MINING COMPANIES AND LOCAL COMMUNITIES

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1. INTRODUCTION

Mining practices began as early as the 19th century in the Kyrgyz Republic. In 1890, coal mining started in Naryn, followed by the Kok-Zhangak mine in 1896 and the Kyzyl-Kiya Suluktinskoye mines in 1898 [1]. The Kyrgyz Republic greatly contributed to the mining industry of the Soviet Union. In the history of the development of the atomic industry and energy of the Union of Soviet Socialist Republics, Kyrgyz uranium deposits played a very significant role, and the first Soviet radium was mined at the Tyu-Muyun field in the south of the Kyrgyz Republic. The first uranium ore was mined in 1946 at the Gylish uranium-coal deposit. At some point, the total extraction of minerals in the Kyrgyz Republic reached 15-18% of the total production of the Soviet Union, including 40-100% of mercury, 100% of antimony, 30% of rare earth metals and 15% of uranium [2].

The mining industry is the basis of industrial production in Kyrgyzstan. It is of great importance in the development of the economy. In 2013 the share of the mining industry in GDP was 10.1% with 47.1% of the total exports and 16.8% of tax revenues [3]. The share of foreign direct investment in 2014 was about US\$113 million, which accounted for 26% of the investment in fixed assets in the mining industry [4]. At present, there are substantial deposits of gold, uranium, antimony, mercury, tin, molybdenum, coal and brown coal, oil and gas, non-metallic minerals, groundwater, and other types of minerals. So, according to the State balance of mineral resources of the Kyrgyz Republic as of January 1, 2017, there are 3555 t of uranium. Development of mineral resources is a necessary condition for the successful development of the economy of the Kyrgyz Republic and for remote mountainous areas is often the only possible way of improving the social welfare of the population.

However, further development in the mining sector has been derailed by various problems and challenges. One of the major problems in recent years, the Kyrgyz Republic has experienced serious conflicts between mining companies and local communities. Many investors attribute the cause to the weak law enforcement mechanism of the Kyrgyz Republic in handling conflicts with the local population. This claim is partly correct. From 2005 to 2010, for example, opposition forces against mining took advantage of political instability and increased the number of confrontations with authorities [5].

2. DESCRIPTION

There are various causes of mining conflicts, such as environmental problems, socio- economic disparities, and health-related concerns and cultural misunderstandings. So far, the main cause of conflicts over the mining industry in the world is environmental issues. According to the EJOLT report [6], all 24 analyzed mining conflicts were partly caused by environmental concerns, including water issues.

During the period between 2012 and 2013, conflicts increased between the local population and mining companies. According to several researchers [7], main causes of these conflicts were attributed to (1) environmental problems, (2) distrust in mining companies, (3) distrust in government bodies, (4) social problems, (5) inadequate information from companies and government bodies about the proposed mining

operations, and (6) lack of dialogue between stakeholders. One of the main concerns of local people was the negative impact of mining on the environment. In the Republic there are still uranium tailings, which have been left after the exploitation of various deposits during the Soviet period. According to the State Cadaster on mining waste, there are 92 tailings and mountain dumps located in the country. Among these tailings, 28 are radioactive and 5 are toxic. Also, 25 tailings are radioactive mountain dumps [8]. Local people near former mines worried about water and air pollution, the destruction and degradation of pastures and agricultural lands, negative impacts on crops and livestock, and damages to infrastructure and roads [9].

Opposing local communities often systematically obstructed mining preparation and operation activities by blocking access roads and engaging in violent direct actions again mining companies [10]. Some of the protestors demanded investors and government officials to recognize community's right to receiving some part of mining benefits. Some others demanded to have sufficient information about the impact of mining on local ecosystems. Many herders and others were afraid of irreversible damage on grazing areas or other local livelihood activities. Some conflicts between local communities and mining companies (e.g., Solton-Sary gold mine) intensified and company representatives were forced to leave the fields for their own safety [5] as some protestors' demands included the complete cessation of the miningwork and the termination of licenses [5].

To illustrate the scale and scale of conflicts in the mine in the country, one incident can be considered, which occurred in 1998 at the Kumtor mine. To date, the Kumtor area has nation's largest gold ore deposit. Kumtor's contribution to GDP ranged from 6.8 % in 2009 to 9.4 % in 2013. Its industrial output reached 48.6 %. exports (41.2 %). The Kumtor Gold Company, which has financed the mining operation, is one of the largest investors in the Kyrgyz Republic. Its share in total capital investments of the country in 2012 was 15.6 %. Share in total gross FDI in 2011 was 51 % [11]. The rapid expansion of this mine resulted into the environmental disaster at the mine site. It made a huge impact on subsequent conflicts [9].

3. METHODOLOGY

The research was based on the qualitative research method including a literature review of documents, policy documents, statistical information, scientific publications, reports and web pages from non-governmental organizations. The literature review was aimed at studying the nature of conflicts in the mines in the Kyrgyz Republic and around the world between local communities and mining companies through comparative analysis and the search for positive experience in the prevention and resolution of conflicts in various countries of the world.

4. DISCUSSION AND CONCLUSION

This research has attempted to understand mining conflicts in the Kyrgyz Republic and around the world through comparative analysis. Its findings show that the main causes of these conflicts were environmental problems, socio-cultural misunderstanding, socio-economic conditions, mistrust and lack of dialogue among stakeholders. It examined good practices to prevent and resolve mining conflicts in different countries. It found that some Canadian mining companies worked closely with the local population in the early stages of the project. This public engagement from the initial stage resulted into its own benefits and the improved living standard of local people as well as improved environmental conservation status [12].

The cases in Canada demonstrate that the earlier the mining company begins to interact with local communities, the better for all stakeholders. The early participation of the community gave it an opportunity to learn more about local community's concerns for the environment and their socio-economic wellbeing. Those Canadian companies largely responded to the needs in a timely manner. In Canada, conflict resolution and prevention measures involve research institutions and universities that upon request conduct specific

researches. This Canadian experience provides some useful insights in improving the practice of mining companies in the Kyrgyz Republic.

After independence, in order to improve the investment attractiveness and transition from a planned economy to a market economy, the government of the Kyrgyz Republic has made several attempts to overcome shortcomings of the regulatory system of the mining industry and to streamline administrative controls. In order to invite more foreign investments and effectively develop mineral resources, the State Agency for Geology and Mineral Resources began reforming subsoil use policies. As a result, a new law on the subsoil was adopted on 9 August 2012. This law, which is currently in force, (1) establishes the ownership of subsoil and mineral resources; (2) identifies the powers of state administrations, local governments, and other subsoil use regimes; and (3) establishes types of licenses and the procedure for issuing, renewing and terminating licenses [13].

In recent years, the State Committee for Industry, Energy and Subsoil Use has been working hard to reduce conflicts between mining companies. It has conducted a number of field visits to mining areas and explained to local people about the activities of the mining industry. It has held training seminars, conferences with the participation of governments, local self-government bodies, mining companies and local communities. As a result, the number of conflicts has decreased according to the author's interview with the State Committee chairman D. Zilaliev on 26 May 2017. He also noted that local self-government bodies began to provide assistance in resolving conflicts [14]. This means that the close interactions among government officials, mining companies and the local community can reduce conflicts. In the author's opinion, the problem of conflicts in the mining industry can never be solved for good. However, it is possible to reduce or minimize them. Experience shows that the resolution of conflicts by the state force does not resolve conflicts. This oppressive action sometimes exacerbates conflicts instead [15]. In resolving or preventing mining conflicts, the state can act as an intermediary, as it is interested in business development, local citizens' social and economic development, and the minimization of the negative environmental impacts.

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URANIUM POTENTIAL IN NIGERIA

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1. INTRODUCTION

The Nigeria Atomic Energy Commission was established by Decree 46 (now Act 46) in August 1976 and became operational in July 2006 as a specialized National Focal Agency with the mandate to promote and develop atomic energy and for all matters relating to the peaceful uses of atomic energy. The Nigeria Atomic Energy Commission was further mandated to prospect for, and mine, radioactive minerals, manufacture or otherwise produce, buy or otherwise acquire, treat, store, transport and dispose of any radioactive substances.

The uranium potential in Nigeria is considered to be favourable, with several known uranium occurrences having commercial levels of mineralization [1, 2]. Given the limited uranium exploration carried out in Nigeria to date, significant potential is presumed to exist based on observations and the knowledge of favourable geological environments for hosting uranium deposits (sandstone and unconformity-related deposit types) [1, 3].

2. GEOLOGICAL SETTING OF NIGERIA

The geology of Nigeria comprises four main groups of strata [3, 4], namely:

- 1) The basement complex;
- 2) Younger granites;
- 3) Sedimentary series strata;
- 4) Tertiary–Recent volcanics.

The basement complex comprises the migmatite gneiss complex, pegmatites, schist belts composed of metasedimentary and metavolcanic rocks, and the pan-African granitoids comprising the older granites and the associated charnockitic rocks. The younger granites are of Jurassic age and are found as ring complexes cropping out within the basement complex areas [3, 4].

3. NIGERIAN URANIUM OCCURRENCES

Uranium potential in Nigeria is considered to occur as sandstone hosted and vein type mineralization. Sandstone hosted deposits occur in sedimentary/volcano-sedimentary sequences in the structurally controlled Bima sandstone at Zona and Dali, while the vein type mineralization occurs in the deformed migmatites and granitoids in the Gubrunde, Kanawa, Ghumchi, Mika and Monkin–Maza deposits [5–7]. Substantial uranium mineralization occurs in the Ririwai area of southern Kano. According to Obaje et al. [8], uranium occurs in peraluminous and peralkaline granites and the content of uranium in peraluminous granite is in the range 16–32 ppm U.

The Mika, Gumchi, Zona and Mayo Lope areas of Adamawa State have good uranium exploration potential, localized in the mylonitized, sheared and brecciated fine-grained to porphyritic granites. Analysis of cores from 40 drill holes gave values of 2000 ppm U [2].

4. HISTORY OF URANIUM EXPLORATION IN NIGERIA

In Nigeria, uranium exploration started in 1973 and to date uranium has been recorded in six States, namely: Cross River, Adamawa, Taraba, Plateau, Bauchi and Kano. Uranium mineralization occurs at Guburende, Kanawa, Zona, Dali, Mika and Monkin–Manza and were all discovered by three Government agencies [9]:

- GEOLOGICAL SURVEY DEPARTMENT: In 1974, the Geological Survey Department discovered uraniferous pyrochlore in Ririwai hills in Kano State and Kigo Hills in Plateau State. The grade is 0.012% uranium oxides;
- 2) THE NIGERIAN MINING CORPORATION:

The Nigerian Mining Corporation (now defunct) had an exploration campaign in Kogi State (northern Nigeria) and collaborated with the Nigerian Uranium Mining Company in the exploration of some areas in north-eastern Nigeria in 1980;

3) NIGERIAN URANIUM MINING COMPANY:

Established in 1979 with the mandate to explore for, and exploit, all available uranium ore deposits in Nigeria. It was in public/private partnership with Total Compagnie Miniere of France, which owned 40% of the company as a technical partner. In 1989, Total Compagnie Miniere pulled out of the partnership owing to lack of funding. The company carried out exploration programmes at reconnaissance and semi-detailed levels. Areas of activities covered about 112 346 km² in north-eastern Nigeria, in the area bordering Cameroon [2]. Areas of interest included Gubrunde, Mika and Ghumchi, which are all underlain by the rocks of the basement complex, and the Mayo Lope area, which is underlain by Cretaceous continental sedimentary rocks [9].

5. FINDINGS AND CURRENT PROGRESS

The following results have been summarized from the various exploration campaigns:

- 1) The uranium reserve at Mika is estimated at 52 tU at a grade of 0.63% U and a vertical extent of 130 m;
- 2) The uranium reserve at Ghumchi is estimated at 100 tU at a grade of 0.90% U and a vertical extent of 200 m. The cut-off grade is 0.03% U [2].

Currently, the mandate for exploration of uranium in Nigeria is vested in the Nigeria Atomic Energy Commission. The Nigeria Geological Survey Agency and three university research centres are currently carrying out limited exploration for uranium in the potential areas owing to restricted funds.

6. CONCLUSION

Uranium exploration in Nigeria is still ongoing and being carried out by the Nigeria Geological Survey Agency and three university research centres under the coordination of the Nigeria Atomic Energy Commission.

At present, the investigated deposit size and potential are still insufficient to encourage resource drilling and feasibility studies. A classical geophysical method applicable to fault detection is also needed. Economic viability of extraction has not been determined owing to insufficient information. The Nigeria Atomic Energy Commission is, therefore, encouraging serious investors in this area to come to Nigeria and invest in the uranium potential that is known to exist in commercial quantities.

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URANIUM/THORIUM RESOURCE ASSESSMENT IN SAUDI ARABIA

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Abstract

As part of the ambitious Saudi vision to 2030, the minerals sector has been considered as one of the key industries in Saudi Arabia. Uranium, among all minerals, has received intensive attention due to its strategic value in securing the nuclear fuel required for future nuclear reactors. The occurrence of uranium mineralization was indicated by prospecting surveys made in 1979–1984. These surveys have identified nine nominated exploration areas, with 35 inner sites. Studies also revealed five important geological environments for uranium resources. The project Uranium/Thorium Resource Assessment in the Kingdom was launched in April 2017 as a collaboration between King Abdullah City for Atomic and Renewable Energy and the Saudi Geological Survey. It is a two-phase project aims to encourage investment in uranium mining and enhance the local human and technical expertise in this area. The work includes the following activities: radiometric and magnetic airborne surveys; geological survey; image processing of remote sensing interpretation; anomaly verification and evaluation; gamma ray spectrometer and radon surveys; geophysical survey; trenching, borehole drilling and sampling; chemical analysis mapping; radiometric analysis mapping and geo-database construction. Also, a systematic exploration drilling and core sampling programme will be developed for any prospective targets.

1. INTRODUCTION

The project aims to evaluate uranium and thorium resources in Saudi Arabia according to JORC standards and to achieve this through two exploration phases. The first phase began in April 2017 and is planned to be completed in two years and will evaluate any uranium and thorium resources (inferred definitions). The second phase will utilize the results and recommendations from the previous exploration phase to identify any resource and undertake an estimation according to indicated and measured definitions. This phase is anticipated to take three years. In the first phase, the project activities will concentrate on the nominated exploration areas and 35 inner sites defined from previous exploration during 1965–1987. The Project Partners are King Abdullah City for Atomic and Renewable Energy (KACARE), as project owner, the Saudi Geological Survey, as exploration project manager, and the China National Nuclear Corporation (CNNC), as exploration contractor. The project's scope and JORC compliance will be supervised for quality assurance and control by Geological Survey of Finland.

2. DESCRIPTION

Saudi Arabia's geology consists of two major units: Arabian Shield and sedimentary cover rocks that contribute to the existence of different geological environments favourable to the formation of various types of uranium and thorium deposit.

Uranium and thorium deposits are located in different geological environments and divided into several types based on their geological setting. Therefore, uranium and thorium may be present as major minerals in deposits and/or as secondary minerals with precious metals ores such as copper, silver and rare earth elements.

There are several studies and reports related to radioactive ores deposits and contamination phenomena were completed by many government institutes such as (Mineral Resources Ministry, Saudi Geological Survey,

King Abdulaziz City for Science and Technology and universities and consultants (Minatome, BRGM, US Geological Survey) more than 50 years ago.

These studies concluded that the presence of uranium/thorium ore deposits in the can by classified as follows:

- Sandstone deposits;
- Vein deposits (Granite-related);
- Intrusive deposits;
- Volcanic- and caldera-related deposits;
- Surficial deposit;
- Phosphorite deposit.

An airborne spectrometric survey was incorporated into phase four of prospecting for uranium mineralization. This was completed by MINATOME on behalf of the Ministry of Petroleum and Mineral Resources of Saudi Arabia. The survey area covered was approximately 26 000 km², divided into nine areas. The airborne field operations were carried out by the Arabian Geophysical and Surveying Company (ARGAS) between December 1981 (first flight) and March 1982 (last flight). During these field operations, 28 519-line km were flown, comprising 26 083 line km along a 1 km line spacing grid initially scheduled and 2436 km with a 0.5 km line spacing to cover those areas where more detail was considered necessary. These follow-up areas were selected on the basis of spectrometric results obtained during the survey or after geological reconnaissance. Measurements were made with a 256-energy channel spectrometer GR800D from GEOMETRICS detector.

The spectrometric survey used in the prospecting stage records radioactivity in the uranium, potassium and thorium channels in order to detect any uranium anomalies and also ascertain the uranium potential of these nine areas and to contribute geological and radiometric information for their further study.

In the first phase of the project, the exploration contractor (CNNC) planned the work over two stages. In Stage 1, verifying prospecting anomalies and uranium resources exploration in the nine areas (35 inner sites); CNNC has conducted the following technical work:

- 1) Geological route survey (scale 1:50 000), cross-sections and mapping (scales 1:10 000 and 1:5000);
- 2) Gamma ray spectrometric measurements (scales 1:10 000 and 1:5000), either airborne or along geological sections;
- 3) Soil radon survey (scales 1:10 000 and 1:5000), either airborne or along geological sections;
- 4) Uranium-thorium radioactive anomaly verification and evaluation;
- 5) Integration of geological survey data, XRF and gamma ray spectrometric data and/or soil radon survey data into profiles;
- 6) Remote sensing image processing, interpretation and field evaluation;
- 7) Geo-database construction;
- 8) Major and trace elements analysis, petrographic analysis, SEM, EPMA and data processing of rock/ore samples;
- 9) Map compilation.

On the basis of the known geological conditions, and on previous work, CNNC planned to complete a detailed investigation in Stage 2 of the project. This includes completing remote sensing interpretation and geological survey and anomaly verification in order to determine the regional metallogenic conditions and provide a preliminary assessment of the U–Th mineralization potential. Next, CNNC will perform geological mapping on 1:10 000 or 1:5000 scales, and conduct ground gamma ray spectrometric and radon surveys in soil in key sectors in order to evaluate the scale and U–Th contents of the mineralization and

provide the basis for further geophysical, geochemical, drilling and borehole logging work. After the field work has been finalized, the indoor laboratory analyses, map compilation and comprehensive research work will be completed.

3. DISCUSSION AND CONCLUSION

Current reconnaissance exploration has identified several uranium anomalies inside the designated exploration sites and the discovery of a number of new uranium anomalies near the border of the exploration areas. Apart from the above successful discoveries, the exploration programme failed to verify some of uranium anomalies identified in the previous exploration and radiometric airborne survey. This failure may be due to poor accuracy of the GPS used in the previous prospecting programme, which lead to an error in coordinates. This was in addition to the contribution of the combined effect of the relatively lower sensitivities of the survey instrumentation and their efficiency in such surveying parameters as airborne line spacing. The difficulties associated with the mountainous topography and wide extent of the exploration areas posed additional limitations to verification of the discovered uranium anomalies. This was in addition to the complexities of the geological structures themselves.

In an attempt to resolve these exploration difficulties and to obtain a more accurate uranium resource estimation, the following recommendations will be implemented:

- A new planned radiometric airborne survey (four channel radiometry–spectrometry) combined with a magnetic survey will be implemented;
- Maintain/support the role of a QA/QC supervisor to ensure JORC code compliance;
- Owing to the expense of diamond drilling, CNNC will plan a drilling programme that has greater precision. This should start only after comprehensive studies have been completed and which cover all prospective areas to allow targets to be ranked in terms of economic potential and to ensure that no viable target is overlooked;
- he project timeline may be expanded, if necessary.

URANIUM: WASTE OR POTENTIAL FUTURE RESOURCE?

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1. INTRODUCTION

From the early days of the nuclear power industry, Australia witnessed a 'yellowcake rush', with prospectors scouring our countryside for uranium resources. Large resources of the metal were identified and a relatively buoyant market led to investment and a uranium export industry, despite a challenging political environment. A prevailing weak market for uranium since the March 2011 Fukushima incident has slowed exploration, seen some resources change commercial operators and constrained investment in the sector. Drawing on mixed commodity resources, which include uranium, a number of companies are developing large mines to extract copper, gold, phosphate and rare earth oxides. Rather than extract the uranium, the operators plan to direct it to tailings repositories. While the resources in question may have been developed for uranium with vigour in the past, market conditions dictate a situation whereby several thousand tonnes of uranium resources will be stored in tailings dams. Should the uranium market improve in the future, it is possible that these resources will become readily extractable uranium resources. The expense of mining, crushing and grinding ore represent sunken costs. Future developments may be considered where uranium is extracted from the tailings resources, by either inexpensive digging and reprocessing, or perhaps by chemical extraction.

2. CASE STUDY: CARRAPATEENA

The Carrapateena copper and precious metals mine is currently being developed by Oz Minerals. Located in South Australia, some 400 km NNW of Adelaide, Carrapateena is a vertical breccia hosted, haematite dominant iron oxide copper gold (IOCG) deposit overlain by 470 m of Neoproterozoic sediments extending 2000 m below the unconformity. Following geophysical targeting of gravity and magnetic anomalies in the Proterozoic basement of the eastern margin of the Gawler Craton, drilling discovered the Carrapateena mineralization in 2005. Carrapateena is characterized by sulphide mineralization disseminated as 0.1–4 mm diameter grains comprising predominantly pyrite, chalcopyrite and bornite. Rare earth elements at Carrapateena are bound in monazite along with uraninite-bearing mineralization. Both monazite and uraninite are closely associated with the bornite. The total reported resource at Carrapateena, as of November 2016, was 134 Mt of ore with a copper grade of 1.5%, gold at 0.6 g/t, silver at 6.6 g/t and an average orebody grade of 239 ppm U [1].

Milling and processing of Carrapateena ore will primarily recover copper, gold and silver, but could also result in the capture of some uranium which would be present as a penalty constituent in the production streams. The project proponent, Oz Minerals, estimates that the tailings radionuclide composition will be similar to that of the initial mineralized ore. For the purposes of calculating uranium remaining in the tailings stream, a 10% recovery level is estimated, resulting in 90% of the original uranium in the processed ore being deposited in the Eliza Creek Tailings Storage Facility (TSF). Over the mine life, an estimated 145 Mt of dry tailings will be transported to the TSF, resulting in over 31 000 t of uranium being stored in the TSF [2].

3. CASE STUDY: NOLANS BORE

The Nolans Bore project is currently being developed by Arafura Resources. Located in Australia's Northern Territory, some 140 km NNW of Alice Springs, the 1550–1510 Ma Nolans Bore pegmatite suite is situated in the 1860–1720 Ma metasedimentary rocks of the Aileron Province. First identified in 1995 following a thorium and uranium radiometric survey, the complex Nolans Bore primary mineralization is overprinted by hypogene mineralization and subsequently supergene mineralization. Coarse primary fluorapatite crystals (1–8 cm size) occur within a microcrystalline fluorapatite matrix which dominates the vein texture and contains rare earth elements (REEs) and uranium. The second stage of mineralization tends to exhibit lower grades of REEs and uranium in fluorapatite–allanite breccias. The final stage of supergene mineralization has variable distribution, with extensive clay and kaolin alteration. The globally significant Nolans Bore REE deposit is open at depth and is characterized by comparatively high neodymium content. The total resource reported at Nolans Bore as of December 2016 was 56 Mt, with a total REE oxide content of 2.6%, a phosphate (as P₂O₅) content of 12% and a uranium grade of 200 ppm U₃O₈ [1].

Project proposals by Arafura in 2010 included the extraction of the uranium and production of uranium oxide. However, a later development application by the company excluded this option. Milling and other processing of the Nolans Bore ore to recovery primarily REEs and phosphate could result in the capture of some uranium, possibly representing a penalty constituent in the production streams. The project proponent, Arafura Resources estimates that the tailings radionuclide composition will be similar to that of the initial mineralized ore. For the purposes of calculating the uranium remaining in the tailings stream, a 10% recovery level is estimated, resulting in 90% of the original uranium in processed ore being deposited in the above ground tailings TSF. Over the mine life, an estimated 56 Mt of dry tailings will be transported to the TSF, resulting in over 10 000 t of uranium being stored in the TSF.

4. CASE STUDY: TOONGI

The Toongi mine is operated by Alkane Resources and exports rare earth and hafnium product streams from Australia. Located in New South Wales, about 300 km NW of Sydney, the Jurassic age Toongi rare metal deposit is part of a 100 km² Jurassic aged alkaline trachyte volcanic province intruding and overlying a folded Silurian–Devonian volcanic–sedimentary sequence. Weak radioactivity in the area was identified in 1951 by the Bureau of Mineral Resources (now Geoscience Australia) and fieldwork conducted the following year identified trachytic volcanics as the source. Following up on the potential identified in regional exploration in 1982 for a resource of zirconium, hafnium, niobium, tantalum, yttrium, uranium and REEs within the Toongi trachyte, commercial testing commenced in 2000. The Toongi orebody exibits some shallow weathering and minor oxidation down to 40 m and some chilled margins at the boundary of the trachyte. Mineralization is generally fine-grained with some crystal clusters, veinlets and vug infilling. The total resource reported at Toongi is 73.2 Mt comprising 1.96% ZrO₂, 0.04% HfO₂ and 0.75% rare earth oxides [1].

The project proponent at Toongi, Alkane Resources, has indicated no interest in the recovery and production of uranium from the resource for a number of reasons, not least of which is the current ban on mining and production of uranium in New South Wales and also that the additional capital requirements and process flowsheet development costs are simply not economic. The company comprehensively addresses the risks of radioactivity at Toongi, but has not sought approval to produce uranium. Current mining of Toongi to recover primarily REEs and hafnium may result in the capture of some uranium, possibly representing penalty constituents in the production streams. The tailings radionuclide composition is considered to be similar to that of the initial mineralized ore. For the purposes of calculating the uranium remaining in the tailings stream, a 10% recovery level is estimated, resulting in 90% of the original uranium in processed ore being deposited in the above ground TSF. Over the mine life, an estimated 60 Mt of dry tailings will be transported to the TSF, resulting in over 7000 t of uranium being stored in the TSF.

5. HISTORICAL CASE STUDY: ROSEBERY MINE

The reprocessing of old tailings can lead to increased product recovery and improved financial outcomes for some mining operations. For example, through the early 1990s, the Rosebery mine in Tasmania was able to reprocess tailings produced from the 1880s to the 1930s in order to produce additional gold/silver doré. Although the older processing technology had recovered the majority of the zinc, lead and copper from the finely crystalline Rosebery ore, significant quantities of gold and silver still remained in the crushed tailings. The tailings were readily dug from the old dams around the Rosebery mine site and transported to the mill for reprocessing. Utilizing advanced recovery technology not available to earlier generations, the Rosebery mill successfully treated the fine-grained crystalline sulphides and recovered additional saleable gold/silver doré. An additional benefit from the tailings reprocessing was environmental, as the tailings repositories that were reworked were readily rehabilitated, firstly with a rock layer and then soil cover, which not only facilitated the growth of vegetation, but also improved the visual impact of the older tailings dams.

Other global examples of tailings reprocessing projects include:

- (a) De Beers Consolidated Mines project to extract overlooked diamonds from 360 Mt of old tailings surrounding the Kimberley mines in South Africa;
- (b) DRD Gold's South African Witwatersrand operations to extract gold from tailings utilizing new recovery technology;
- (c) South African projects to recover platinum group elements and chrome from Bushveld Complex tailings;
- (d) Carbine Resources' feasibility work on recovering gold and copper from tailings at Mount Morgan in Queensland.

6. CONCLUSIONS

The technology for reprocessing tailings left behind from old mining operations has proven profitable for a number of corporations globally. Advances in metallurgical technology, changing social, environmental or aesthetic considerations and higher commodity prices could be the catalyst that initiates projects aimed at recovering value from old tailings. The Carrapateena, Nolans Bore and Toongi developments in Australia will each leave significant amounts of potentially valuable uranium in their respective tailings facilities. Each of the project proponents, for economic and political reasons, has chosen not to extract the uranium values at this stage. Should the political or market conditions for uranium improve in the future, the tailings repositories at Carrapateena, Nolans Bore and Toongi could represent significant potential commercial value for a project proponent. Geoscience Australia provides authoritative independent advice to the Australian Government and is supported by holdings of resource data over several decades. A record of potential resources, including those with altered physical characteristics, is maintained by Geoscience Australia, ensuring a complete picture of evolving circumstances is available to both government and the public.

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APPLICATION OF UNFC TO URANIUM RESOURCES DISCOVERED IN ALGERIA

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1. INTRODUCTION

The Algerian national mining sector is undergoing deep changes and fast evolution towards a market economy. The adequate and rigorous management of uranium resources discovered and evaluated in the Hoggar (southern Algeria) has been undertaken with a view to their development and integration into the national economy. A re-evaluation of these deposits and indices according to internationally accepted criteria, standards and models (OECD Nuclear Energy Agency/IAEA, United Nations Framework Classification for Resources (UNFC), CRIRSCO) is a necessary consequence of this.

In this perspective, and in order to contribute effectively to the preparation of this new stage, a first attempt to classify discovered and evaluated uranium occurrences in the Hoggar, according to generic specifications of the UNFC [1] is presented. It is developed with the aim of serving as a basis for the revival of the uranium resources exploration and development programme throughout Algeria.

2. EXPLORATION WORK CARRIED OUT AND MINING DEVELOPMENTS UNDERTAKEN

The first uranium mineralization found in the Hoggar (central Sahara) was discovered in 1958 in the Precambrian basement of the Timgaouine–Abankor region during the implementation of the first Hoggar mineral exploration programme undertaken by the Mining Research Bureau of Algeria (BRMA) between 1953 and 1960 [2, 3]. These first results were followed by the discovery of uraniferous showings around the granite of Aït Oklan–El Bema in the Tesnou region north of Timgaouine, by the Commissariat à l'Energie Atomique (CEA) between 1958 and 1960 [3]. These uranium occurrences were identified as intra-batholitic vein type mineralization. They all occur in the eastern branch of the Pan-African chain (western Hoggar).

In a second phase (1969–1974), one marked by a significant investment effort, detailed exploration work undertaken by the National Company for Research and Mining (SONAREM) with the assistance of a Romanian partner GEOMIN allowed the development of known uranium mineralization into two economically important uranium deposits (Timgaouine and Abankor) and the evaluation of the uraniferous resources of the Tinef deposit [4–6].

The extension of this exploration work to the sedimentary cover of basins on the outskirts of the Hoggar (Tassilis) resulted in the discovery of the Tahaggart deposit and the Timouzeline and Tamart-N-Iblis occurrences. These were discovered in the Precambrian basement–Palaeozoic cover interface and in continental sandstone horizons of the Lower Devonian of the Tin Séririne sedimentary basin (south-east of Hoggar) [7–9].

At the same time, with the continuation of regional uranium exploration in the Hoggar, development studies of the Timgaouine and Abankor deposits, which were initiated in 1976, were completed in successive phases with the assistance of several specialized companies. These companies sought to determine the technical, social and economic conditions determing the exploitation of these two deposits.

The main objectives of this first phase focused on:

a) The expertise of geological and hydrogeological work undertaken by SONAREM;

- b) The collection of ore samples for treatment trials;
- c) The identification of the main development variants.

This expertise, preceded by the work of the GTZ group (Germany), was entrusted to six operators: Davy McKee–Cotecna (United States of America–Switzerland), Kaiser (Germany), Kilborn (Canada), Tractionnel–Mining Union (Belgium), STEC (France) and Charter–CJB (United Kingdom) [10–13].

At the end of this first phase, SONAREM awarded (in December 1978) the second phase to two groups of companies from among the six of the first phase. The objectives were:

- Technical–economic optimization study;
- Preparation of preliminary project files.

The two groups of companies selected for the second phase were:

- The association Davy McKee (USA), Tractionnel (Belgium), Union Miniere (Belgium) and Cotecna (Switzerland);
- The French consortium composed of STEC, SOGEREM, MINATOME and SOFREMINES.

Results obtained at the end of the second phase are listed below [14–16]:

- Location: the two deposits, Timgaouine and Abankor, are 180 km south-west of Tamanrasset and 20 km apart;
- Geological reserves: 21 000 tU with an average in situ grade of 0.18% U;
- Recoverable reserves: approximately 14 000 tU (factory output;
- Production capacity: with the use of an alkaline treatment process, 600 000 t ore/year in all round products corresponding to 900 tU/year;
- Life expectancy: 15 years, based on recoverable reserves.

The Tinef deposit is situated 35 km from Timgaouine and is hosted in the same geological context and possesses the same type of uranium mineralization [4, 10]. Work carried out on an area of 21 km² consisted of recognition soundings spaced 2–3 km apart, and reduced to a 1 km spacing above the anomaly. Destructive soundings were conducted on a 200 m × 200 m spacing, which was reduced in the mineralized zones to 50 m × 60 m and to 25 m × 50 m to estimate the C2 category reserves. The estimation gives 374 000 t of ore at 0.1% U, i.e. 374 tU [4, 5].

To the north of this potential zone and situated in the same geological context, the El Bema–Aït Oklan– Tidjelamine occurrences in the Tesnou region have not been subject to detailed exploration sufficient to give a preliminary assessment.

Exploration work in the Tin Séririne sedimentary basin (south-east of Hoggar) consisted of an airborne geophysical survey (spectrometry and magnetism). The results after ground verification by soundings and ground survey works [7–9, 17] were as follows:

- Confirmation of the existence of the small Tahaggart deposit whose uranium reserve is estimated at 1677 tU with a grade of 0.217% U;
- Occurrences in the Tamart-N-Iblis and Timouzeline area of mineralized levels in the Lower Devonian sandstones suggest potential for these stratigraphic levels.

3. APPLICATION OF UNFC TO URANIUM RESOURCES DISCOVERED AND EVALUATED IN ALGERIA

The discovery and mining development of the Timgaouine, Abankor and Tinef deposits in the Precambrian basement of the Hoggar and the Tahaggart deposit in the Tin Séririne sedimentary basin have gone through several stages:

- 1) Discovery of Timgaouine, Abankor, Tinef and Tahaggart mineralization during regional exploration;
- 2) Confirmation of the Timgaouine, Abankor, Tinef and Tahaggart deposits through detailed exploration;
- 3) Technical–economic evaluation, mineral processing tests and mining works for the Timgaouine and Abankor deposits;
- 4) Evaluation of the uranium resources in the Tinef and Tahaggart deposits.

These detailed investigations have provided sufficiently detailed knowledge of these deposits to permit mining. On the basis of this information, UNFC categories E, F and G as well as the classes and sub-classes were determined for the Timgaouine, Abankor, Tinef and Tahaggart projects:

- E2: Probable economic viability of extraction and sale in the foreseeable future;
- F2.2: Need for further evaluation of extraction feasibility through a specified development project or mining operation;
- G1, 2, 3: Quantities associated with a known deposit that can be estimated with a high level of confidence.

The four projects are classified in the E2 F2.2 G1,2,3 Categories, Potentially Commercial Project class and Development on Hold sub-class.

After the discovery of the Aït Oklan–El Bema–Tidjelamine occurrences in the Tesnou region, north of Timgaouine, and the Timouzeline and Tamart-N-Iblis occurrences in the Tin Séririne sedimentary basin to the south of the Tahaggart region, only general exploration work was carried out in these two zones.

On the basis of all the collected information, categories E, F and G were determined as well as the classes and sub-classes of the Tesnou and Tin Séririne projects:

- E3: The assessment is at too early a stage to permit determination of economic viability;
- F3: There is a need to gather more data in order to confirm the existence of a deposit and characterize it;
- G4: Estimated quantities associated with a potential deposit, calculated in the first analysis on the basis of indirect evidence.

These two projects are classified in E3 F3 G4 categories and Exploration Project class.

4. CONCLUSION

The uranium resources discovered in the Hoggar (southern Algeria) have been evaluated according to the generic specifications of the UNFC. This example illustrates the application of multiple classification systems used by various groups involved in different phases of exploration and development of these resources. It is possible that this UNFC system can be a relevant tool for reviving the re-evaluation and development programme of uranium resources of Algeria's mining sector.
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URANIUM MINING IN THE UNITED REPUBLIC OF TANZANIA: CURRENT STATUS, CHALLENGES AND OPPORTUNITIES

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1. INTRODUCTION

The United Republic of Tanzania (Tanzania) is heading for a new dimension in large scale uranium mining. Significant uranium deposits have been identified in various parts of the country [1, 2]. More than 25 companies are conducting exploration for uranium in different geological environments in the country. These exploration activities are based on the results of radiometric surveys conducted in the 1970s, which pointed to uranium enrichment in various places. One of the major uranium development projects is the Mkuju River Project, which is located in southern Tanzania, about 470 km south-west of Dar es Salaam. The project operator is the Russian Federation's Uranium One Inc. Currently (2016), the project maintains an active status as research and preparatory operations are advancing. The mineral resource base of the project currently shows approximately 58 500 tU. The company has already acquired a prospecting mining licence from the Tanzanian Ministry of Energy and Minerals but mining has not started owing to the depressed uranium spot price.

2. CHALLENGES

Several challenges were encountered during the exploration phase. Similar challenges are anticipated during the mining and processing of the ore. An example of some of these challenges is provided below.

2.1. Public acceptance

There is a level of public concern, as the identified uranium-bearing deposits are located on the pastoral lands of local villages. Concern has been expressed in the areas around the Bahi and Manyoni deposits, which are located in the central zone of the country. In this region, there are wetland areas that are mostly utilized for agricultural activities as well as for rearing livestock. Most of the villagers, with the 'help' of non-governmental organizations, have been protesting against the Government's decision to permit the exploration projects in these areas. People within the Bahi and Manyoni districts are strongly opposed to uranium projects as they are afraid of losing their land to uranium mining companies without proper compensation. Apart from the fear of losing their land, there is a significant concern regarding the environmental impact in the Bahi and Manyoni districts. Most of the uranium exploration sites are within the agricultural districts and, therefore, the issue of contamination should be considered [3]. Most of the population in these areas depend on groundwater to serve as potable water.

2.2. Regulatory framework

Experience from historical uranium production sites globally have consistently shown that unregulated uranium mining practices have led to significant detrimental impact to water and soil, and also put the public at risk, resulting in the high cost of cleaning up the environment. In Tanzania, the primary legislation

controlling practices using ionizing radiation is the Atomic Energy Act 2003 [4] and associated regulations, namely, the Mining (Radioactive Minerals) Regulations of 2010 [5] and the Atomic Energy (Radiation Safety in the Mining and Processing of Radioactive Ores) Regulations of 2011 [6]. According to the Act, an ore is classed as radioactive if its total activity concentration exceeds 74 Bq/g [4]. In this context, those concentrations of economic uranium ores likely to exceed this activity are classed as radioactive ores and thus subject to stringent Federal regulatory control. The dose limits applicable in these regulations are those recommended by the ICRP (1977) for both occupational and public exposure to ionizing radiation [7]. The dose limits are as follows: maximum occupational dose of 50 mSv in any year with a mean of 20 mSv over any five-year period and a public dose limit of 1 mSv in any single year. In addition, the regulatory authority has a clear role in enforcing regulatory compliance with national and international standards.

Although the legal framework and relevant infrastructure for the management and control of occupational and public exposure, waste and the environment are in place, challenges nevertheless remain for the effective monitoring of the uranium mining industry in Tanzania [8]. A lack of financial and technical resources in Tanzania places significant limitations that may hinder the regulatory authority's ability to complete its primary responsibilities. Establishing baseline environmental data by the regulatory authority and the mining company prior to project development is of crucial importance and cannot be underestimated. A lack of comparable data could prevent the effective monitoring of changes in compliance with the environmental standards during and after the mining activities [8]. Environmental data that are established after mining activities commence cannot be used to relate the impact that uranium mining has on the environment and on public exposure. As the anticipated area in need of pre-mining data is extensive and the time available to establish impacts before actual uranium mining is required to establish environmental baseline data and build technical capability. This places a strain on government finances. Implicit, inadequate budget and technical capability could lead to impairment of the assessment and effective regulation of uranium mining in Tanzania.

2.3. Uranium spot price

The spot price for uranium has been declining for the past 11 years [9]. According to the source, the spot price was down more than 25% in 2016 with the U_xC broker average price sliding to US \$48.03/kgU. This spot price, according to the source, was the lowest it has been since 2 May 2005.

This decline in the uranium spot price has led Uranium One, an international mining company owned by the Russian Federation's Nuclear Energy Corporation to apply to suspend the Mkuju River Project [10]. This is a significant challenge for the country owing to the fact that the project is the first uranium mine to receive a licence from Tanzania's Ministry of Minerals (formerly the Ministry of Energy and Minerals). As of March 2013, the project had measured and indicated resources of 48 000 tU plus inferred resources of 10 600 tU at average grade of 0.026% U [10].

2.4. Wildlife conservation issues

The Uranium One project area has been classified as a UNESCO World Heritage since 1982. UNESCO agreed to change the boundary, therefore enabling uranium mining in this unique conservation area [11]. Selous, being the largest game reserve in Africa, is inhabited by the most important populations of the critically endangered wild hunting dogs as well as elephants. UNESCO describes the game reserve as an immense sanctuary of 50 000 km² which is relatively undisturbed by human activity and which is inhabited by large numbers of elephant, black rhinoceros, giraffe, hippopotamus and crocodile. The reserve has a variety of vegetation zones, ranging from dense thickets to open wooded grassland.

The planned mine is situated in an 'elephant corridor' between Tanzania and Mozambique, and will utilize an area of about 200 km². The mining methods preferred for this project after the exploration results and evaluation of the nature of the area was either open pit mining or in situ leaching (ISL) owing to the nature of the deposits in the area. Both methods will have environmental impacts in the mining area as well as in areas beyond the mining site. In the case of open pit mining, the environment will be affected by significant quantities of radioactive waste which may lead to the contamination of large areas of the project within and beyond the mining area if not managed properly [8]. Control of water from surface runoff and underground aquifers plays an essential role in an effective pit operation. If not well controlled, contaminated runoff will pose threats to the game reserve wildlife. In the case of ISL, the risk of spread of the ISL lixiviant outside the uranium deposits could impact groundwater quality for several generations following closure of the mine. Moreover, ISL has the potential to release considerable amounts of radon and in addition produces water slurries and wastewater during recovery of the uranium from the liquid.

3. BENEFITS

Despite the fact that uranium exploration and mining pose some serious challenges, there are opportunities during the exploration activities as well as expected benefits when the mining starts. The following sections give two examples of these benefits.

3.1. Employment

Uranium projects in Tanzania have created a number of employment opportunities during exploration and are also expected to create a number of jobs during the mining and milling of the ore. Some 1600 people are expected to be employed during construction and there will be about 750 permanent jobs when the mine starts operation [9]. At present, there are 120 employees who are involved in exploration activities.

Also, in order to ensure maximum implementation of the regulations which ensure maximum safety in the industry, regulatory authorities involved in uranium control process will need to increase the number of skilled staff. This will, in turn, increase the number of local job vacancies.

3.2. Export earnings

The Mkuju River Project is expected to attract Foreign Direct Investment (amounting to about US \$1 billion) [9]. This will boost the country's economy and thereby support the Government's desire to improve the overall quality of life.

Other benefits include government royalties, taxes and fees, as well as infrastructure development in the regions where the mining activities are conducted.

4. CONCLUSION

The uranium mining industry has been seen to improve the economy of the country where mining occurs through both direct and indirect investment. Currently, the price of the commodity is depressed. However, demand for uranium for use as nuclear fuel is expected to increase in the near future as the result of a number of expected new nuclear power plant construction projects in various countries. The expected rise in demand and subsequent uranium spot price increase will benefit the mining companies as well as the countries hosting the uranium deposits. However, despite benefits which may be expected, in certain countries, the challenges can outweigh the benefits.

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CONCENTRATION OF URANIUM FROM SOLUTIONS USING NANOMEMBRANES

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1. INTRODUCTION

Ensuring the effectiveness of the processes of natural uranium mining and processing is associated with the introduction of innovative methods and technologies that provide cost optimization and efficient use of resources, in particular lower specific consumption rates of chemical reagents.

Underground uranium leaching as practiced in Kazakhstan involves dissolving of the metal under the action of sulphuric acid at the site of the ore deposit and subsequent extraction through wells. Surface processing of the resultant solutions is carried out with the use of sorption technology. In the first stage, uranium has sorbed onto anion exchange sorbents after which a desorption process is undertaken with sulphuric solutions of ammonium nitrate. The obtained eluate is precipitated by hydrogen peroxide or sodium hydroxide solutions. For selective uranium precipitation, the preliminary neutralization of excess acid contained in eluate is required. This leads to a permanent loss of sulphuric acid and significant consumption of sodium hydroxide.

The purpose of the work described here is to describe efforts made to separate and return to the process circuit the sulphuric acid contained in the eluate prior to uranium precipitation. This problem can be solved by membrane separation and concentration processes.

Relative simplicity of instrumentation, no requirement for additional reagents and small volumes of liquid waste generated are the advantages of membrane processes. In addition, membrane processes have a number of undeniable advantages over other separation processes (rectification, extraction, adsorption, etc.):

- Continuity;
- Low energy costs;
- Convenience of combination with other technological processes;
- Soft technological conditions;
- Scalability.

There are many membrane separation processes based on different principles or mechanisms applicable to the separation of objects with different sizes, from heterophasic particles to molecules. The basis for separation during nanofiltration is the negative charge of the membrane surface. This makes it possible to retain multivalent anions as well as associated cations, thereby preserving electroneutrality. Positively charged ions, such as hydrogen, aluminium and sodium must pass through the membrane. Neutral molecules, as well as some large size cations, for example, uranium, will be retained by the membrane.

In this connection, prerequisites are created for the preliminary processing of eluate using membrane processes for the purposes of both separating sulphuric acid and concentrating uranium.

2. METHODS AND RESULTS

A baromembrane nanofiltration method was chosen to optimize the composition of eluate (acidity reduction and uranium content increase). In this method, the transfer of matter through the membrane occurs under the action of a pressure differential.

A pilot installation which works on the principle of tangential filtration was constructed. The main working elements of the installation are membrane modules consisting of enclosures capable of withstanding pressures of up to 70 bar and membranes directly connected to each other. As a result of the solution passing through the installation, two constant fluxes are created: a filtrate, also termed permeate, and a retentate or concentrate.

To perform the tests, semi-permeable (selective) membranes manufactured by the DOW company were chosen. In these membranes, during solution flow under pressure, a positive transmembrane pressure gradient is created across the surface of the membrane which causes the passage of protons and other components smaller than the pore size of the membrane to pass through the membrane.

To prevent nanomembranes clogging with suspended matter in the eluate, preliminary filtration through a fine filter with a pore size of 5 μ m was envisaged in the technological scheme.

Studies on the nanofiltration of eluate were carried out at an average pressure of 22 bar. The eluate, with a uranium content of 37.21 g/dm³ and a sulphuric acid content of 23.73 g/dm³, was used as the basic solution. The basic solution was pumped by a low-pressure pump through the fine filter, then by high pressure pump to the membrane module. Permeate and concentrate obtained by separation on the membrane module were piped from the installation to special tanks of the final product. The pressure at the outlet from the membrane module was 6 bar. The total capacity of the installation for permeate and concentrate was 250 L/h; the yield of permeate was 180 L/h and that of the concentrate 70 L/h. The installation was operated for 720 h in this mode.

The average uranium content in the permeate obtained during the entire operation of the installation was 2.32 g/dm^3 and the acid content was, on average, 21.66 g/dm^3 . The average content of uranium in the obtained concentrate was 126.93 g/dm^3 and the acid content was 29.11 g/dm^3 .

The experiment demonstrated that the maximum operating time of nanomembranes for the separation of the eluate of the test compound is 64 h. It was then necessary to rinse the membranes with process water for 10 min. After washing, the membranes were restored to their original throughput. The obtained concentrate was sent to peroxide precipitation. For comparison, uranium precipitation was also carried out from the initial eluate. Precipitation was carried out under the following conditions:

- Drainage time of reagents: 30 min;
- Volume of eluate: 0.5 dm^3 ;
- Excess of reagent–precipitator: ranges from 0 to 100%;
- Precipitation time: 60 min;
- Neutralizing reagent: NaOH solution.

It was found that the permissible content of uranium in the mother solution (no more than 30 mg/dm^3) could be achieved with a 20% excess of H₂O₂. The efficiency of peroxide precipitation is higher the lower the salt composition of the processed eluate. The amount of uranium recovery (with other equal things) is significantly affected by the initial concentration of uranium in the desorbate. With an increase in the content of the target metal, the recovery rate increases.

When uranium was precipitated from the concentrate obtained by nanofiltration, the specific rate of NaOH consumption for neutralization of excess acidity decreased by a factor of two. This corresponds to a total saving of 0.35 kg of sodium hydroxide per 1 kg of uranium.

3. CONCLUSION

The conducted experiments of eluate nanofiltration showed the theoretical feasibility of uranium and sulphuric acid separation. Nanofiltration of the eluate made it possible to achieve a fourfold increase the uranium concentration with a simultaneous decrease in the relative acid content by 63%. The extraction of uranium into the concentrate is 93.76%. The concentration of uranium with a simultaneous decrease in the efficiency of peroxide precipitation and to a decrease in the specific consumption of sodium hydroxide.

ALTERNATIVE DATABASE FOR DOMESTIC LOF NUCLEAR MATERIALS AND FUEL

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1. INTRODUCTION

As regards information on nuclear material, the location outside facilities (LOF) in Thailand total 93 and these forms the basis of a database created in 2016 via Microsoft Access 2010. The data input was compiled from Office of Atoms for Peace (OAP) licensing information on nuclear material. The nuclear material query template, both in Thai and English, was established to include more material details. This necessary information was intended to support law enforcement or regulatory investigations. The multimedia CourseLab demonstration module providing descriptions of how to complete OAP nuclear material licence forms was created to improve the understanding of the end users who have to fill the query template [1].

In 2017, the nuclear forensics database was created using Microsoft Access 2010 and was intended to be the prototype for developing the National Nuclear Forensics Library (NNFL). The NNFL was aimed to support National Nuclear Forensics Laboratory, which was established in 2013 under the project No. 30 on Network of Excellence for Nuclear Forensics in South East Asia Region (2013–2014), assisted by European Union chemical, biological, radiological and nuclear risk mitigation centre of excellence initiative [2]. Additional databases were developed via Microsoft Access 2010, such as: i) additional nuclear forensics information, including LOF database of year 2016 [1], and ii) OAP's Nuclear Forensics Laboratory inventory [3].

The library data were summarized for some domain expertise, i.e. fresh fuel and irradiated fuel in the nuclear fuel cycle stage, sealed sources and unsealed sources following the NNFL master index [4], as well as its Microsoft Word 2010 templates. The algorithms for comparative analysis are ongoing and have been developed for interpretation of the information on the seized materials and those existing in NNFL, to identify and report, for nuclear forensics purposes, conclusions on crime investigations in the events of a nuclear security alert.

2. METHODOLOGY

To implement nuclear forensics investigation, three step procedures are required [5]:

- 1) Collection, packaging and transport of seized nuclear/radioactive material from terrorists or smuggling detection in nuclear security event;
- 2) Laboratory analysis for cataloguing characteristics and signatures of these materials;
- 3) Data interpretation and analysis via the nuclear forensics database and comparative algorithms in NNFL.

To support the mission plan of the OAP nuclear forensics laboratory, the following tasks were performed to develop NNFL [6]:

- 1) Data collection relating to OAP conventional radioactive and nuclear material database of licensing systems;
- 2) Developing architecture as templates and databases cataloguing characteristics and signatures of material holdings under regulatory control;

- 3) Storage functions using Microsoft Access 2010 software;
- 4) Algorithm set-up for comparative analysis.

3. WORK PERFORMED

The architecture of this nuclear forensics database prototype was designed and was constructed initially as three main Microsoft Access 2010 databases. Comparative analysis is preliminary developed using Microsoft Excel 2010 for data interpretation and analysis to complete NNFL systems. All performed work is briefly explained as the following:

3.1. Nuclear and radioactive material information

The nuclear and radioactive material information was collected and based on the OAP conventional radioactive and nuclear material database of licensing systems. This information was sorted in relation to the material master index [4].

As there is only one domestic nuclear facility, a 2 MW research reactor, the domain expertise and fresh and spent/irradiated nuclear fuel are recorded together as nuclear fuel elements. Other domain expertise of nuclear or radioactive material include sealed and unsealed sources, which can be found in hospitals, industrial plants and research laboratories.

The templates for nuclear fuel element, and sealed and unsealed sources were created via Microsoft Word 2010 and Access 2010 [6] and are included in this nuclear and radioactive material database.

3.2. Additional nuclear forensics information, including LOF database (2016–2017) [1, 6]

It is planned to collect other nuclear forensics information, including the LOF database (2016–2017 or B.E. 2559-2560), with respect to relevant articles, IAEA publications, ISO material, legislative work, nuclear forensics analytical summary reports and templates.

3.3. OAP Nuclear Forensics Laboratory inventory [3]

The inventory database of the Nuclear Forensics Laboratory is planned to be complied and will include the following information:

- 1) General: List of buildings, floors and rooms;
- 2) Analytical equipment information: List of analytical instruments/equipment and details of the data parameters, i.e. identification data, physical data, hazardous materials, radiological data, etc.;
- 3) Technical support information: List of technological systems, inventory materials, laboratory materials, radionuclides, etc.

3.4. Comparative algorithm

The comparative analysis plan is set up to compare the obtained results with those existing in the NNFL [7-8], with respect to the following procedures:

- 1) Uploading nuclear forensics analytical results, sample information and all available signatures in the library system;
- 2) Interpretation via the algorithm for searching and findings:

Searching: Data comparison:

- Choose only some signatures which are relevant to the case in question;
- A flexible program but one which requires only relevant signatures for searching.

Findings: Agreement among samples:

- Based on numerical data and simple words;
- Requested and identified samples.

4. DISCUSSION AND CONCLUSIONS

The progress of this work is summarized as the following:

- 1) The architecture of the domestic forensic databases is set up and organized using Microsoft Access 2010 and Word 2010;
- 2) The preliminary algorithm for comparative analysis is set up via Microsoft Excel 2010 for data interpretation and analysis;
- 3) The collection of data/information on fresh/spent nuclear fuel, sealed sources and unsealed sources, will be performed over the long term for the whole country;
- 4) Accessibility and website links to other relevant domestic organizations may be addressed after the establishment of a national framework for nuclear forensics.

Current availability:

- It takes time to collect all data/information following nuclear forensics database from the whole of Thailand;
- The methods for determination of signatures are in research and development of the standard method to support the determination of nuclear and radioactive material by using inductively coupled plasma spectrometry (ICP-MS), scanning electron microscopy with energy dispersive (SEM/EDX) and gamma spectrometry in the OAP's Nuclear Forensics Laboratory;
- There are only a few domestic radiological incident and criminal cases, so there are not many seized samples to use for confirming trials in comparative analysis. Simulated scenarios are planned for test runs, as well as the examples of analytical results;
- However, a flexible program for searching is planned to be developed to help counter future acts of nuclear terrorism.

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ASSESSMENT OF THE IMPACT OF URANIUM PRODUCTION WASTE STORAGE FACILITIES ON THE ENVIRONMENT BASED ON THE RESULTS OF HYDROGEOLOGICAL MONITORING AND NUMERICAL MODELING

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1. INTRODUCTION

The largest uranium mining enterprise in the Russian Federation, Public Joint-Stock Company Priargunsky Industrial Mining and Chemical Union (Priargunsky) was established in 1968. Uranium mining is carried out by underground mining and ore processing is carried out at a hydrometallurgical plant [1], which began operating in 1976. Simultaneously with the commissioning of the hydrometallurgical plant, a sulphuric acid plant was started. Initially, sulphuric acid was produced from pyrite cinder but since 2009, the feed to the sulphuric acid plant has been switched to block sulphur.

Wastes with a residual radioactivity caused by processing uranium ore are deposited in a valley in two tailings dams and neutralized with calcareous water. A cinder storage facility for the wastes produced by the pyrite roasting process at the sulphuric acid plant is located in the same valley at the most downstream position. These cinder wastes are characterized by high sulphate ion concentration and a lack of radioactivity. All of these storage facilities are of the wet type, which in the landscape appears as a cascade of three lakes.

Leaks through earth dams within the limits of normative losses are intercepted by a system of drainage wells in the foot of the storage facility dam and are returned to the process. Dam leakage is monitored by 196 observation wells.

To inform the public about the state of the environment in the area where the enterprise is located, summarized results are published in annual environmental reports [2].

A wellfield situated near a river is located within the study area to provide water for a town with a population of 45 000. Water is obtained first from the aquifer of an intermontane artesian basin. The extraction wells are within 12 km of the waste storage facilities.

Over the more than 40 years' existence of the storage facilities, a contamination plume has formed in the aquifer from filtration through the earth dams. The plume does not exceed area of the sanitary protection zone of these three storages. As experience shows, the leaks through earth dams are very common for the wet type of tailings from old mines elsewhere [3].

The main objective of this study was to obtain a conservative forecast of the expected spread of the contamination plume towards the intake of the water supply wellfield. The forecast was made with two assumptions, namely that from 2015, the collection of waste into the storage facilities is stopped and that the interception of contaminated water by drainage wells below the cinder storage dam is also stopped. This conservative approach assumes that the concentration of pollutants in the sources remained at a constant level for the entire forecast period.

2. DESCRIPTION

The geological structure of the territory involves two structural layers. The lower layer is represented by Proterozoic and Early Palaeozoic metamorphic rocks, Riphean, Vendian and Palaeozoic granitoids.

The upper layer contains Mesozoic (Jurassic–Cretaceous) terrigenous strata of sedimentary and sedimentary–volcanic rocks that fill up depressions and calderas, small Upper Jurassic intrusions of the Kukulbei complex and subvolcanic rocks genetically related to Late Jurassic and Cretaceous volcanism.

The research area is located within an intermontane depression that hosts an artesian basin. This basin consists of a few aquifers which are hydraulically connected and form an aquifer system. The upper part of a cross-section consists of conglomerates, sandstones and siltstones (Lower Cretaceous rocks) that overlap with Quaternary sediments of alluvial and lacustrine origin, which are the main providers of the fresh groundwater used for the town's water supply.

For general purposes, all types of groundwater in this basin are considered to be part of a united aquifer system, but conditionally divided by the types of water-bearing rock and their filtration properties.

Systematic observations of the state of the environment on the territory of the Priargunsky operation began in 1973. Hydrogeological monitoring is currently carried out in 196 observation wells.

Data analysis of groundwater level dynamics shows that the longest observed stable period was the last 14 years. The groundwater average depth over this period is no deeper than 5 m over most of the research area, which leads to a high rate of the evapotranspiration. The wellfield situated near the river does not make a significant impact on groundwater level, because pumping wells obtain water that would otherwise be discharged by evapotranspiration and into the river.

Also, it is important to mention that an underground mine drainage outlet is located near to the tailings dump and this causes a local groundwater depression and prevents the spread of contaminated water.

3. METHODS

On the basis of the GIS project, digital elevation model, digitized geological maps, engineering geological well logs and hydrogeological monitoring data, a three-dimensional geological model was created in the Groundwater Modeling System software package by Aquaveo. The geological model was used as the basis for filtration and solute transport models. In the transport solute model, sulphate ion is selected as an indicator of groundwater contamination, since it has the greatest migration capacity compared with other contaminants in storage.

The analysis of the data of the geological site structure model was performed with four layers. The area of the model is 4283 km²; the boundaries of the model are determined by the boundaries of the catchment basins.

To verify the hydrodynamic and transport solute model, groundwater levels and concentration of sulphate ion from observation wells located in the valley were used. A good convergence of field and model data was obtained. The deviations of the model and measured concentrations of the sulphate ion are within the limits of error.

4. RESULTS AND DISCUSSION

The simulation results indicate that the contamination plume from the first tailings dam is stable and partially discharges in the mine drainage. The contamination plume from the second tailings dump is less influenced

by the mine drainage and is slowly spreading along the valley towards the river. The cinder storage facility, the last in the cascade of simulated lakes, has the main role in the groundwater contamination process. As mentioned above, the cinder storage facility is the main source of sulphate ion contamination, which is the reason why the sulphate ion is a very suitable indicator for this particular model.

The predictive modelling of remediation actions showed that in the case of complete elimination of the cascade of artificial lakes, the currently existing plume of pollution will migrate at a significantly lower rate and gradually degrade due to hydrodynamic dispersion. Reduction of the sulphate ion concentration to the values of the Russian maximum permitted concentration for drinking water (500 mg/L) will take about 300 years.

5. CONCLUSION

Facility focused monitoring allows the implementation of the concept of controlled pollution. This concept includes an information analysis system for facilities of the nuclear power industry based on a facility focused monitoring system of subsurface state, hydrodynamic and solute transport modelling and results in an informational geo-ecological report.

The conclusions of the project are:

- 1) The current state of groundwater in the area of waste storage shows that the groundwater contamination does not exceed the limits of the sanitary protection zone for all kinds of artificial pollutants;
- 2) The primary artificial contaminant of groundwater is the sulphate ion which originates from the cinder storage facility; uranium pollution is mainly intercepted by the mine drainage. Therefore, the sulphate ion was used in the solute transport model as an indicator of contamination spread;
- 3) A conservative forecast indicates that the spread of contamination in the groundwater from the tailing dumps does not reach the water supply wells even within the forecast period of 300 years.

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IMPACT OF GRAVITY EFFECT ON IN SITU LEACHING OF URANIUM

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Abstract

Gravity becomes an important factor that affects the hydrodynamics of the in situ leaching process, when the densities of leaching solution and groundwater are different. Consequently, leaching solution flows in the porous medium are noticeably at a lower rate than expected, which might introduce difficulties for recovering uranium concentrated in the upper parts of the geological layers. Current work investigates gravity effects on the flow regimes by including it in the Darcy equations [1]. Overall, the modelling consists of calculation of the pressure and density distribution and the filtration Darcy velocity with respect to the gravity effect. Increased resource demand when accounting for the gravity effect was managed by numerically solving the fully coupled differential equations using the CUDA (compute unified device architecture) parallel computing technology provided by nVidia. Results show a magnitude of gravity impact on uranium leaching depending on various concentrations of sulphuric acid in the leaching solution. Additionally, the pressure equation which was solved by CUDA on a graphics processing unit significantly accelerated simulation processes when compared with the central processing unit calculations.

1. INTRODUCTION

In situ leaching is a common method used to recover minerals in the mining industry, especially for uranium deposits. As the leaching agent density is slightly greater than groundwater, the density gravitational effect has to be accounted for as it may affect the flow direction. Owing to this gravitational effect, the denser fluid tends to flow downwards while the lighter fluid flows directly to the production well. The acid fluid–water interface (density of reagent + water compared with pure water) is more or less tabular near the injection well, but this density contrast produces a deepening of this interface near the production well. Thus, during the leaching process some regions (residual zones) are not leached because of this gravitational effect. Therefore, any hydrodynamic modelling of the in situ leaching process should take into consideration the gravity forces that exploit the difference between densities of injected solution and groundwater.

2. NUMERICAL MODEL

Numerical modelling of in situ leaching processes requires finding a solution for a system of partial differential equations and generally consists of two major steps: (i) calculating the pressure and velocity fields (by Mass Conservation Law and Darcy's Law) and (ii) solving mass transfer equations for chemical components (by Law of Mass Action) [2].

Iterative methods are commonly used in solving elliptic equations involved in finding pressure and velocity fields [3, 4]. Implicit and explicit approaches are used in calculating pressure, including the Jacobi Iteration Method, Point Gauss–Seidel Iteration Method, Line Gauss–Seidel Iteration Method and Point Successive Over-Relaxation Method. The main problem with these approaches lies in high resource demand which leads to longer solution times [4]. While high performance computing can be used to accelerate these calculations, modern parallel technologies such as CUDA can provide a significant improvement in calculation speed on ordinary desktop machines. Intel based central processing units and graphics processing units by nVidia were used to analyse the numerical model.

3. RESULTS

To determine the gravitational influence, three density ratios between initial groundwater and injected solution were considered with percentages of 1%, 5% and 10%, respectively. To provide a better comparison, streamlines [5] of solution flow from the injection wells to producing well were determined. In the case of increased density ratios, a higher gravity effect was observed, with solution flowing through lower parts of the stratum. In order to analyse the symmetry of the streamline, the authors calculated the average height between the streamlines along the wells for each density ratio. As a result, it was shown that when the density ratio is 5% or greater, the gravitational influence is significant, whereas with a 1% density ratio, the gravitational can be neglected.

4. CONCLUSION

Accounting for the gravity effect can significantly change the way a horizontal layer is being oxidized, and consequently leached during an in situ process. In the present study, this change has been demonstrated by conducting hydrodynamic calculations using a parallelized CUDA based numerical solver. When gravity effects are accounted for, consequent changes in the spatial distribution of the density (and so in acid concentration) around the injection wells are observed, which lead to a different pressure gradient field. As a consequence, the way that leaching solution flows in the stratum is changed. Resource intensive pressure calculations had to be solved on each density change, which leads to longer calculation times. Therefore, CUDA parallel technology was successfully used in each step to accelerate these calculations. Depending on the mesh size used, an acceleration of factor of 8–12 were thus obtained.

In many uranium deposits, sulphuric acid is used for as a leaching solution. The concentration of sulphuric acid used in Kazakhstan uranium deposits is about 20–25 g/L [6, 7]. Consequently, the density of the injected reagent will be about 1010 kg/m³, hence density ratios between initial groundwater and the injected solution will be 1%. Taking into account the results given above, the gravity effect with respect to the Darcy equation can be neglected.

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RADON MONITORING IN THE SOIL AIR WITH NUCLEAR TRACK DETECTORS: URANIUM EXPLORATION METHOD

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1. INTRODUCTION

The nuclear track detector uranium exploration method was presented and its limitations due to the effect of the moisture content in material that covers uranium mineralization as well as the thickness and uranium concentration of that overburden were considered. The radon survey was carried out over uranium anomalies that were confirmed by drilling. The radon results were used to optimize targets for future exploration drilling programmes.

2. METHODOLOGY DESCRIPTION

2.1. Radon in U orebodies and in their overburden

Radium-226 of the uranium decay series generates the inert radioactive gas radon (²²²Rn) that has a half-life of 3.8 d. Radon can 'migrate' relatively long distances towards the ground surface from uranium mineralization and/or a uranium anomaly. The principal mode of radon transport in soil/sediment that covers any uranium mineralization is diffusion. A less common but very important mode of radon transport is flow through geological cracks and voids. The radon gas diffusion process in any porous media can be almost inhibited by water saturation.

The radon activity concentration in air, RnAC (Bq/m^3), that is contained in the intergranular space in uranium can be calculated as according to Eq. (1) [1]:

$$RnAC(Bq/m^3) = a(^{226}Ra) \rho E$$

(1)

where the term 'a(²²⁶Ra)' is the specific radium activity of the ore, ρ (kg/m³) is the bulk density of uranium ore and E is the radon emanation coefficient. After the following values were substituted for a(²²⁶Ra) = 12 400 Bq/kg (the equilibrium specific activity of ²²⁶Ra of the 0.1% U ore is 12 400 Bq/kg), $\rho = 1500 \text{ kg/m}^3$ and E = 0.2, a equilibrium radon activity concentration in air of approximately 3 700 000 Bq/m³ was calculated for the uranium orebody.

The radon air activity concentration profile, RnAC(X), for a thick layer of porous non-radium bearing material can be approximately described by Eq. (2):

$$RnAC(X) = RnAC(0) \exp(-\lambda_{Rn-222}/D \times X)$$
(2)

where X is the distance from the surface of the uranium mineralization, RnAC(0) is the radon activity concentration at the orebody/cover layer boundary, D (m² s⁻¹) is the radon diffusion coefficient and λ_{Rn-222} (2.1 × 10⁻⁶ s⁻¹) is the radon decay constant [2].

The effect of the moisture content on the radon activity concentration of uranium ore in intergranular pores and in its covering material is well known and is mainly governed by the diffusion constant changes with the relative water content [3]. For example, if a 5 m wide body of uranium mineralization with a grade of 0.1% U is overlayed by a 5 m thick earth material layer with relative moisture contents of 4, 11, 15, 16 and 18%, the long term average radon activity concentration at a depth of 0.1 m below the surface of that layer could be calculated as 35 000, 24 000, 21 000, 1.9 and 0.01 Bq/m³, respectively [2].

Since the overburden of a uranium source also contains some uranium and radium, the measured radon activity concentration below the surface of the overlying material includes its radon activity concentration in addition to an incremental radon activity concentration caused by the radon diffusion from the mineralization. The radon air activity concentration in the 5 m thick porous overburden layer with 1 ppm U can be calculated from Eq. (3) [2]:

 $RnAC(X) = 12.4 \rho E \left[1 - \left[\cosh(\lambda_{Rn-222}/D X)/(\cosh(\lambda_{Rn-222}/D X_{L})\right]\right]$ (3)

where 12.4 Bq/kg is the equilibrium specific activity of 226 Ra of overlay material layer and X_L(m) = 5 m is the thickness of the layer. The radon air activity concentrations of 220, 330, 370, 950 and 2700 Bq/m³ were calculated for relative moisture contents of 4, 11, 15, 16 and 18%, respectively.

3. RADON MONITORING BY NUCLEAR TRACK DETECTORS

The short term radon air activity concentration near the surface of the material cover overlying a uranium orebody is affected by wind, ground temperature, rainwater, etc. In order to minimize these short term effects on the measured radon air activity concentration, it is necessary to use a radon monitoring technique that measures the long term average radon activity concentration and which is also able to measure the radon activity concentration within a range of about $50-1\ 000\ 000\ Bq/m^3$.

The most appropriate and 'robust' radon monitor suitable for large scale field application is a nuclear track detector. In the 1970s and 1980s, this method was used for uranium exploration [4]. However, it is not known if the method with its nuclear track detector arrangement was instrumental in any new uranium deposit discovery.

In 1980, the first author developed the nuclear track detection method for radon monitoring in the soil air and in water [5–7]. On the basis of the previously published work, the nuclear track uranium ore exploration tool (NTUOET) was developed. NTUOET includes the nuclear track detector Kodak LR-115 (type 2) that is situated inside a plastic 'cavity badge' (the passive radon monitor (PRM)). A moisture protector is also used and prevents the entry of thoron to the PRM. The PRM is inserted into a 17 cm long plastic conduit with its top opening sealed with a plastic cap (the PRM is held in place inside the plastic cap with a piece of foam). The NTUOET is inserted into a 20 cm deep hole with the top of the plastic cap at the surface. Slight compaction of the dirt around the conduit is also required during operation.

This robust design enables a large number of NTUOET units to be deployed over a day. The units are then collected after an exposure time of 2–3 weeks. As this method is relatively inexpensive, an exploration manager can use a number of units to obtain a more detailed radon activity concentration contour plan of the site that can be used to optimize the drilling programme and thus to carry out uranium exploration more cost effectively.

4. DevEx RESOURCES LIMITED URANIUM EXPLORATION AT NABARLEK

4.1. The history of the Nabarlek uranium mine

The deposit was delineated by diamond drilling in 1970 and 1971. Open cut mining took place between June and October 1979 with the ore stockpiled for milling. A total of 546 437 t of ore were mined at an average grade of 1.84% U₃O₈. The mill commenced operation in June 1980 and ran until 1988, during which time 11 084 t U₃O₈ were produced. The site was rehabilitated by 1995 [8]. As the geology around the old Nabarlek uranium deposit includes a number of outcrops with elevated uranium levels, DevEx Resources Limited ('DevEx') acquired exploration leases that include the old Nabarlek mining leases.

4.2. The Nabarlek uranium exploration programme

DevEx has carried out several exploration/drilling campaigns since acquiring the Nabarlek project. This presentation summarizes the most recent results of a radon survey that was carried out by the company in 2016. In order to improve the accuracy of radon monitoring, a scintillometer was also used to take a gamma count reading at radon sampling locations showing elevated radon levels.

The radon survey was carried out over three areas with NTUOET units positioned over a 100 m (W–E) by 200 m (N–S) grid. The first area served to test a largely unexplored region within a valley defined by sandstone escarpments located 12 km south-east of the Nabarlek mine site. The second area was to test a line of drilling from 2015 comprising four reverse circulation drill holes at the GC11 prospect. The third area was situated about 2 km west of the GC11 prospect to test for radon leakage over a gravity anomaly.

NTUOET units placed within the sandstone valley showed a distinct elevated radon anomaly trending southeast along a potential fault delineated by radon readings ranging from 3018 to 53 444 Bq/m³ within a background range of 95–2000 Bq/m³. Radon stations to the north and south of this trend are at background levels and sharply constrain the anomaly. This anomaly represents a strong exploration target and is recommended for test drilling.

Two reverse circulation drill holes at the GC11 prospect intersected elevated uranium concentrations within dolerite, with the best results including 2 m intersection at 2354 ppm U₃O₈ at a depth of 135 m (drill hole NAR7537) and a 5 m intersection at 1065ppm U₃O₈ at a depth of 169 m (drill hole NAR7535). Following this drilling programme, it was decided to place a number of NTUOET units within and near the area where the drill hole swere situated. The radon air activity concentrations that were measured within a 50 m radius of each drill hole lay within the range 2041–4043 Bq/m³, with a background range of 282–1339 Bq/m³. Comparison of these radon measurements was made with the results from the exploration drilling programme and confirmed a relationship between elevated radon and anomalous subsurface uranium concentrations.

The NTUOET readings west of the GC11 prospect showed elevated radon levels towards the east of the survey line, within the range 2955–7121 Bq/m³ with a background range of 282–1960 Bq/m³. These elevated readings are situated around a region of interpreted structural complexity based on gravity data and may represent a migration pathway for radon gas.

5. DISCUSSION AND CONCLUSIONS

Northern Australia, where the DevEx Nabarlek exploration leases are situated, has a sub-tropical climate with the majority of rainfall occurring during the 'wet season', i.e. between November and April. Therefore, the radon survey was carried out during September–October 2016, i.e. at the end of the 'dry season' when the ground is more likely to be 'dry'. Although some moisture content was detected inside some of the NTUOET units, the trends of measured radon air activity concentrations did not indicate that soil moisture content affected the survey outcomes. Scintillometer readings taken over radon stations of interest showed

counts per second measurements that were less than the defined upper background limit of 200 c/s. These results indicate the source of radon is not near surface and could represent a uranium source at depth.

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URANIUM MINE OPERATIONS IN INDONESIA

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1. INTRODUCTION

Mineral and coal mining in Indonesia is regulated by Act No. 4 Year 2009 [1]. In the Act, minerals are divided into four categories: rock, metal, non-metal and radioactive minerals. Implementation of the Act regulated in the Government Regulations from Act No. 4 Year 2009 include the arrangement of business, licensing and inspection activities. However, the arrangement for the radioactive minerals are excluded from Act No. 4 Year 2009 on Mineral and Coal Mining, but are included in Act No. 10 Year 1997 on Nuclear Energy [2]. The term nuclear material mining in the Nuclear Energy Act is compatible with term radioactive minerals in the Mineral and Coal Mining Act. Currently, Indonesia is in the development phase with respect to Government regulations, with implementation of Act No. 10 Year 1997 on Nuclear Energy for mining of uranium for nuclear material. The Act will regulate the detailed arrangement for business, licensing and inspection activities.

This paper describes the regulatory requirements for the mining of nuclear material, with uranium mining the main focus. These Government regulations are currently in draft form and still in the development phase.

2. DESCRIPTION

The Government of Indonesia is now opening up opportunities for parties to enter the uranium mining business in Indonesia. The interested party, known as the applicant, can be the National Nuclear Power Agency (BATAN), a State-owned enterprise, a cooperative, or a private business entity. The applicant to conduct activities related to uranium extraction and processing can apply for a nuclear material mining licence from the Nuclear Energy Regulator Agency (BAPETEN). BATAN is a Government institution having duties and functions as the nuclear promoting body, and BAPETEN is a Government institution that has the duties and functions of a nuclear regulatory body.

There are two major phases for the activities relating to undertaking a uranium mining business, which are:

1) *General investigation, exploration and exploitation phase:*

The initial phase of the uranium mining process is through feasibility study activities based on the results of general investigation and exploration activities. A State-owned enterprise, a cooperative, or a business entity interested in conducting such activities in this phase must cooperate with BATAN;

2) *Mining phase:*

Mining in this context is defined as the phase of activities that includes excavation, temporary storage, processing, transportation and sale of nuclear material derived from mining. The party interested in performing this phase of activity must meet administrative, technical and financial requirements. Satisfaction of these requirements proves to the State, in this case to BAPETEN, that the applicant has the ability to ensure the safety of the workers, the community and the environment as part of its uranium mining activities.

2.1. General investigation, exploration and exploitation phase

For the initial phase, before conducting any activities, the party must submit notification to the head of BAPETEN. The information submitted in the notification are:

- Map of the activity area;
- A State-owned enterprise, a cooperative, or a business entity must obtain a territorial designation and appointment to conduct uranium mining activities from BATAN;
- Documentation of the planning programme for general investigation, exploration and exploitation activities;
- Cooperation contracts;
- In the case of general investigation, all exploration and exploitation activities carried out by Stateowned enterprise, a cooperative, or a private business entity must cooperate with BATAN.

BAPETEN will complete verification after receiving the notification, which includes:

- Verification of documents;
- Field verification.

On the basis of the verification, BAPETEN will make technical recommendations regarding radiation safety during general investigation activities. Exploration and exploitation may then take place.

2.2. Mining phase

In the case of uranium mining carried out by a State-owned enterprise, a cooperative, or a business entity, the parties should request a letter of mining appointment (SPP) from BATAN. The SPP may be granted in the territorial designation of uranium mining (WPP) based on the results of general investigation, exploration and exploitation.

When granting a SPP, BATAN will give priority and take into account a State-owned enterprise, a cooperative or a private business entity cooperating with BATAN in conducting general investigations, exploration and exploitation. In the case that no State-owned enterprise, cooperative or private business entity expresses interest in continuing to the mining phase, the head of BATAN will offer selection to other business entities. The SPP is granted for a maximum period of 20 years and can be extended twice to give a maximum extension of 10 years.

The holder of an SPP may conduct uranium mining activities, which include: excavation, temporary storage and processing.

2.3. Nuclear mining licence requirement

The application for obtaining a nuclear mining licence must be submitted to BAPETEN and the applicant fulfil the administrative, technical and financial requirements.

For administrative requirements, applicants should provide evidence of having obtained an SPP from BATAN, evidence of incorporation of legal entities and proof of payment of an application fee for the nuclear mining licence.

As regards technical requirements, the applicant should provide evidence of its ability to ensure the safety of the workers, the community and the environment as a result of its uranium mining activities, such as:

- Have a qualified person to conduct activities and maintain safety as the top priority, particularly radiation protection;

- Tools or equipment required to monitor and ensure radiation safety;
- Documents that prove the applicant has a good understanding about the activities conducted, such as procedures relating to uranium mining activities and documentation on: the safety analysis report for uranium mining, the management system, the programme for protection and radiation safety, the physical protection plan, the safeguards system, and the emergency preparedness and response systems;
- A document that proves the applicant has taken into account environmental conservation, such as: documentation for handling of radioactive waste, having a documented closure plan after the end of the activities, a statement of ability to comply with laws and regulations in environmental protection and management, and approval of environmental documents in accordance with the provisions of legislation from the Ministry of Environment and Forestry;
- Local society participation should be taken into account for an SPP.

Regarding financial requirements, the applicant should provide evidence of its ability to finance all activities, including:

- Maintain operation in a safe condition;
- Conduct remediation at the end of mining and processing activities.

3. DISCUSSION AND CONCLUSION

Indonesia has received support from the IAEA in relation to uranium mining, including convening a Technical Meeting of the Uranium Mining and Remediation Exchange Group (UMREG) and a Workshop on Planning for Remediation of Legacy Sites under the International Working Forum on Regulatory Supervision of Legacy Sites (RSLS). The activities provided positive feedback and knowledge that supported the development of these regulations. Lessons learned from other countries and knowledge shared from IAEA experts provided constructive feedback. These can now be adopted and incorporated into Indonesian regulation, such as:

- Environmental decommissioning and remediation following the end of uranium mining and processing activities should be considered in the licence requirement;
- Even if a project were to be implemented by the Government, the responsibility to maintain safety, including environmental protection, during operation and after the end of activities should still be demonstrated.

The IAEA approach to regulate mining activities is described in the Nuclear Law Handbook [3] which was used for developing the required regulations. Well-developed regulations are required to maintain safety and ensure it is always implemented during all phases of the uranium mining activities, including the period following the cessation of uranium mining and processing activities.

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THE CHALLENGES TO EXPLORE AND DISCOVER AN UNCONFORMITY DEPOSIT AT DEPTH

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1. INTRODUCTION

Proterozoic unconformity uranium deposits are considered the highest-grade deposits in the world. The most recognized deposits occur in the Athabasca basin in Canada [1]. As indicated in the 2016 "Red Book", Proterozoic unconformity deposits account for about one-third of the world's uranium resources based upon reasonably assured resources [2]. In 2017, the only two producing uranium mines in Canada allowed for over 20% of the world supply utilizing underground mining methods [3]. One matrix using current research of active mining operations with publicly disclosed data involving ore reserves, calculated according to an international standard, has outlined Cameco's Cigar Lake and McArthur River operations as having the most valuable ore [4].

Expenditure spending in the search for deposits has diminished since a peak spot price of uranium in 2007 [5]. There are a number of well documented factors related to a decline in uranium prices that has led to a weak demand for the product. A few of the reasons for the lack of demand, but not limited to, include the events in Fukushima, Japan in 2011, economic challenges from fuel sources with cheaper capital costs for start-up, secondary supplies from government inventories as well as re-enrichment sales has also provided excess inventory.

Even with the previous described "headwinds" in the nuclear power industry there are reasons for optimism due to the new builds and forecasted growth in central and eastern Asia. The IAEA's high case projection has the global nuclear generating capacity increasing from 2016 levels by 42% in 2030, by 83% in 2040 and by 123% in 2050 [6].

Current statistics obtained from the Saskatchewan Mining Association indicate that exploration expenditures in the Athabasca Basin were \$CAD 44.8 million in 2016 [7]. Major uranium companies such as Orano Canada (previously AREVA Resources Canada Inc.) and Cameco Corporation have committed the majority of their annual exploration dollars to the Athabasca Basin. Other known uranium companies with publicly announced discoveries such as NexGen Energy Ltd (NexGen), Denison Mines (Denison) and Fission Uranium Corp. (Fission) continue to release promising results in defining new discoveries and provide optimism to investors with their exploration expenditures.

2. CURRENT LAND STATUS IN THE ATHABASCA BASIN

An internal review of the current land disposition in the Athabasca Basin (includes the provinces of Alberta and Saskatchewan) involving uranium exploration was conducted in February 2018. Upon review, it is estimated that 40% of the claims deemed for uranium exploration are located on the edge or outside of the sandstone cover of the Athabasca Basin. In terms of actual surface area within the confines of the basin itself, 53% of the land mass has been staked between the depths of 0 to 500 metres with the majority of the southern, central and eastern edges of the basin being claimed. The rational for the land disposition has to do with current and past mining operations in the eastern Athabasca; the Wollaston-Mudjatik transition zone hosts the Cigar Lake and McArthur River operations and the majority of economical and non-economical deposits. The staking along the southern and central edges of the basin has been driven in part by the discoveries by NexGen and Fission. As the unconformity becomes deeper there is less staked land and at a

known unconformity depth between 500 and 1000 metres only 25% of the land mass has been claimed. The acquired land at this depth is associated with the lateral extension of known fertile trends related to conductive corridors or regional fault systems. Within the deepest portions of the basin, greater than 1000 metres depth to the unconformity, less than 4% of the land mass is acquired.

There are numerous factors, mainly conjectural, that can be implied to interpret the current land status in the Athabasca Basin including a company's available funding for exploration, current exploration portfolio, company strategies, availability of favourable geological trends and access to a project area.

3. RATIONAL FOR LOOKING AND DISCOVERING NEW ECONOMIC DEPOSITS AT GREATER DEPTHS

Potential for discovering new economic deposits can be evaluated by ranking different projects according to multiple parameters among which the depth of the targets at the unconformity or in the basement can be considered as of most importance. Exploration maturity can be also judged on the basis of potential based on available conductor strike length following the traditional unconformity-type model [8]. Thus, the probability to find a new economic deposit at depth lower than 250m with the minimal footprint such as the Cigar Lake deposit is limited taking into account the existing spacing of drill holes along the main conductive trends. However, exploring high grade pods at shallow depth remains a short to medium term objective as these targets may be economic by small open pit means or if the possibilities of surface access borehole extraction methodology becomes cost effective.

In a long-term vision, the critical depth of exploration within the Athabasca Basin will likely evolve and it is probable that the deepest portions of the basin, will be considered for greenfield exploration. However, several economical and technical challenges will have to be faced. What type of mineral deposit and which size will have to be targeted to become economic? Can we expect some technical and scientific breakthrough that would improve significantly the resolution of the geophysical methods, the drilling technologies and our ability to vector our geological exploration?

This new frontier and challenges are discussed in relation to the present state of art and in reference to the Cigar Lake deposit. As a hypothesis, one considers that other world class deposits exist at the unconformity at depths greater than 500 metres. Although the geological conditions under which such a deposit can be formed are not fully understood [8], it is unlikely that these conditions were only met in a single locality over the whole extent of the Athabasca Basin. As a support to this hypothesis, other deposits like Shea Creek [9, 10] or Phoenix [11, 12] are formed under near identical mineral systems: association with long lived deeply penetrating and steeply dipping structures, enhanced permeability fault system within a compressive tectonic context, leaching of huge volume of sedimentary and metamorphic lithologies by oxidized basin, , formation of uranium deposits from highly concentrated uranium-bearing acidic brines [13], and deposition by reduced basement derived fluids.

An economic scenario for deep unconformity deposits is presently very difficult to define. Kerr and Wallis [14] consider that, if low grade deposits can be economically mined at depth lower than 200m, only purely basement hosted deposits and unconformity hosted giant deposits will possibly be qualified as reserves below 200 metres. A high-level study can be completed to determine the economics of a hypothetical mining and milling operation located in the centre portion of the basin. However, such calculation is very sensitive to the uranium price and capital cost and a detailed scenario is out of the scope of this discussion.

To follow up the discussion, one considers that the footprint of the targeted deposit should be an unconformity type deposit, comparable if not larger than the Cigar Lake deposit to be effectively economic at an uranium price of $US 40/lbs U_3O_8$ [15]. This deposit style is selected due to the alteration halo that reaches up to 200 metres in width and 250 metres in height and that is associated with mineralizing processes [15, 16]; likely to be identifiable under deep cover. Other styles such as basement mineralization were

considered, NexGen's Arrow deposit and Denison's Gryphon deposit, but ultimately rejected due to the potential limiting size of an alteration halo in the sandstone for a basement deposit with greater than 500 metres of sandstone cover.

4. THE CHALLENGE TO EXPLORE AND DISCOVER A GIANT UNCONFORMITY DEPOSIT AT DEPTH

There is no direct uranium detection for deposits buried at depth. Our present exploration technologies for depth greater than 500 metres are limited by several factors as the cost of drilling, in particular in remote sectors, and the decreasing resolution of geophysical modelling at increasing depth. However, some technical and scientific breakthrough in the coming years may improve our ability to vector our geological exploration.

Junior and major companies are investing millions of dollars every year for geophysical surveys, downhole geophysical probing and acquisition of complete petrophysical datasets including density, magnetic susceptibility and resistivity. Numerous case studies of ground and airborne electromagnetics (EM) and magnetics surveys, resistivity ground campaign, downhole geophysics are regularly presented and should enable the definition of best practices according to the different geological context if a complete return of experience could be achieved. Moreover, such analysis should guide the developments for the acquisition, processing and modelling. Thus, the principle of combined acquisition and joined inversion of EM, magnetotellurics (MT) and resistivity surveys is the current inherited way to explore at depth and to improve the resolution of the geophysical 2D and 3D models.

The main budget of exploration is oriented to drilling. One of the main problems faced today by the companies is the cost of drilling in purely greenfield terrain, the high risk of lost holes in zones of sandstone dissolution (that induces high cost and then limitation of the meterage to be drilled) and the low recovery of cores in fault zones that hampers the structural reconstruction of the architecture of the explored domains and a careful study of the mineralizations. Innovations should be deployed to use or test equipment in order to limit the risk of hole lost because of difficult geological environment, improve the drilling practices and for example generalize the use of directional drilling to explore large zones at depth from a pilot hole. The monitoring of the drilling parameters should also help to control the progress of the drilling in these zones and enhance the quality of coring. High resolution imagery of the structures of the hole and recording of the physical properties while drilling should also be an objective to be elaborated and tested by the drilling and exploration companies.

Exploring Cigar Lake analogs at the base of the unconformity can benefit of the geological knowledge that has been acquired since exploration and exploitation started. The Cigar Lake deposit is located 420-445 metres below the surface within the Athabasca Group's Manitou Falls Formation. The mineralization has a flat to tubular shaped lens approximately 2000 metres in length, ranges between 20 and 100 metres in width and with an average thickness of about 6 metres [17-19]. The mineralization has a crescent-shaped cross-sectional outline that closely reflects the topography of the unconformity. The alteration halo surrounding the Cigar Lake deposit is extensive and affects both sandstone and basement rocks, characterized by extensive development of Mg-Al rich clay minerals (illite and chlorite). It is presently possible to build a 3D earth model reconciling geological and geophysical data, based on extensive datasets including geological, geochemical and physical properties centered on the deposit but also extending along trend and other underexplored conductive trends. This type of modelling of the Cigar Lake domain could use recent developments performed on the application of Artificial Intelligence and learning machine [20, 21] to update the footprint of the deposit. It will also provide an excellent return of experience for defining appropriate acquisition parameters, processing and modelling of geophysical methods considered above as a first step to be accomplished for exploring at greater depth.

An earth model resulting of the updated footprint of Cigar Lake domain could be used to simulate the geological, geochemical and geophysical footprint that could be created by such a deposit in different localities at the base of the basin. Reprocessing and acquisition of complementary geological and geophysical datasets, linked to the measured, estimated or interpolated petrophysical datasets, should then provide a set of unconstrained and constrained inversions that will be compared with the simulated footprint. This modelling, both data and knowledge driven, could lead to a virtual exploration of Cigar lake analogs at the base of the Athabasca Basin.

Finally, as the exploration will provide new datasets from drilling, the new information could be used to refine constrained inversion and to evaluate the possibility to vector exploration towards new deposits.

In conclusion, this long-term vision can be put in perspective with the challenges that were faced by the oil and gas industry when exploration targeted deeper, more structured and remote reservoirs. Although the geology is much more complex than oil and gas reservoir, pre-competitive research and development programs could be set up in order to be on time when greenfield exploration will become open for defining a new critical depth for unconformity related uranium deposits.

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REGIONAL SIGNATURES AND METALLOGENIC MODELS OF SANDSTONE HOSTED URANIUM DEPOSITS IN NORTHERN CHINA

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1. INTRODUCTION

Since the beginning of the 21st century, uranium exploration in northern China has been focused on sandstone hosted uranium deposits. These represent a major deposit type in addition to granite and volcanic-related uranium deposits and their economic importance is increasing. Owing to progress made in metallogenic theoretical innovation and exploration, new deposits have been discovered and existing resources/reserves expanded in Mesozoic–Cenozoic basins. Examples are, moving west to east, Kujieertai in the Yili Basin; Zaohuohao, Nalinggou and Daying in the northern Ordos Basin; Basaiqi in the Erlian Basin and Qanjiadian in the Songliao Basin.

Sandstone hosted uranium deposits form in different geotectonic settings and have different mineralization and regional signatures which can be used to select targets and evaluate the uranium potential in exploration areas. Besides the traditional interlayered oxidation–reduction (redox) metallogenic model, some new models have been established for the sandstone hosted uranium deposits in northern China, such as the metallogenic superposition model and the tectonic activated metallogenic model, which have been of great importance to exploration and to the discovery of new uranium resources.

2. REGIONAL SIGNATURES

In northern China, the mineralization characteristics and regional signatures of these deposits are summarized below.

2.1. Diversity of metallogenic sedimentary basins

Sandstone hosted uranium deposits have been found in different types of basin. The northern China basins are generally subdivided into western, middle and eastern, based on their tectonic mechanisms. The western part is dominated by intermontane basins such as the Yili and Tuha basins within the Tianshan Mountains, where a number of sandstone hosted uranium deposits have been discovered. A middle foreland basin such as the Ordos Basin contains large uranium deposits and a continental margin rifted basin such as the Songliao Basin has deposits in its eastern part.

2.2. Diversity of the metallogenic sedimentary beds

Sandstone hosted uranium deposits can also be found in different sedimentary beds. The major mineralized host rocks are Early–Late Jurassic sediments to the west, Late Jurassic–Early Cretaceous sediments in the central area and Late Cretaceous sediments to the east. It is obvious that uranium rich sedimentary beds are younger moving from west to east, indicating a higher degree of erosion to the west due to stronger Himalayan neo-tectonism, especially in north-western China during the Cenozoic era.

2.3. Diversity and multiple stages of metallogenic age

Systematic geochronological studies have revealed that uranium mineralization usually exhibits multiple stages in one deposit and a younger age in the front of roll-front orebodies. Different uranium deposits often

have different ages in different areas, in spite of their predominantly Cenozoic age. However, obviously the uranium mineralization age is younger than the age of the host rocks, and in general, the mineralization ages are younger, from east to west, being associated with geotectonism and showing an opposite tendency to the age of the host rock. In addition, the age data of the uranium deposits indicate that they have been affected by several phases, further complicating the formation story in the middle region, such as in the Ordos Basin.

2.4. Diversity of metallogenic fluids and processes

Uranium mineralization processes are dominated by meteoric fluids which form typical redox zones controlling the orebodies to the west. These processes are related not only to meteoric fluids but also to oil–gas and hydrothermal fluids in the middle area to the east, which make the formation processes and signatures of the uranium deposits more complicated to decipher, such as alteration, variable compositions, e.g. pitchblende dominant in ores to the west and both pitchblende and coffinite in the middle and to the east [1].

The formation of these sandstone hosted uranium deposits and their regional metallogenic signatures in northern China are closely related to Himalayan geotectonic movements, which are due to the subduction of the Indian Plate towards the north-west and leads to continent–continent collision and the rise of the Qinghai–Tibetan Plateau. This process started around 55 Ma and is ongoing [2]. The collision resulted in the present signatures of the basins, especially in north-western China and central Asia, and has had a major impact on sedimentary formations, hydrogeological processes, palaeoclimate changes and movements of oil–gas fluids during the Cenozoic period. Furthermore, it has had a fundamental impact on the metallogeny of sandstone hosted uranium deposits in north-western China and central Asia, leading to the formation of world-class sandstone hosted uranium provinces.

The role and impacts of the collision and the Tibetan Rise on the metallogeny of sandstone hosted deposits can be summarized as follows.

(a) Deposition and erosion during the Cenozoic period:

Cenozoic sedimentary deposition provides possible new uranium-bearing beds and erosion or depositional hiatus facilitates ease of migration of oxidized uranium. In addition, the uplift of the provenance rocks could provide uranium sources and both of these are favourable to the formation of sandstone hosted uranium deposits;

(b) *Formation of tectonic slope:*

The tectonic slope formed by regional tectonic movements can provide a favourable hydrological condition for the formation of the deposits, i.e. oxidized uranium-bearing meteoric fluids can move into the permeable sandstone beds and meet the reductant materials needed for the redox process. The tectonism also formed faults in the discharge area which can improve the hydrological conditions and help channel the necessary reductants into the potential ore beds;

(c) Arid and semi-arid weather conditions:

This type of weather, which is favourable for uranium migration, developed during the rise of the Qinhai–Tibetan Plateau, especially in north-western China;

(d) Upward migration and escape of oil and gas:

During the rising process of oil- and gas-rich basins, the oil and gas can move upwards to the depressurized areas where they act as reductants and form redox zones for possible uranium deposition. In addition, secondary reduction processes related to oil and gas can protect the existing orebody and lead to secondary metallogenic processes [3].

3. METALLOGENIC MODELS

In northern China, several metallogenic models have been suggested for the formation of major sandstone hosted uranium deposits and these are summarized below.

3.1.1. Interlayered redox metallogenic model

The interlayered redox metallogenic model is a very popular roll-front type model and is exemplified by the Kujieertai deposit along the southern margins of the Yili Basin. The basement of the Yili Basin comprises two units, a Precambrian crystalline formation and a Late Palaeozoic clastic basement with a relatively high uranium content of 4–14 ppm representing a good potential source of mineralization. The sedimentary cover strata are dominated by Triassic–Jurassic strata, together with undeveloped Cretaceous and younger rocks. The uranium-bearing beds are mainly located in Jurassic coal-bearing clastic formations with frequent interbedded mudstone(coal)–sandstones and usually deposited as fluvio-deltaic sediments with a thickness of 25–40 m. The favourable host rock is a medium- to coarse-grained arkose with good permeability. Uranium mineralization can be found in 7 different ore-bearing horizons, extending over 10 km. The deposit shows complicated roll-front shapes with the ore grade varying in the range 0.01–0.2% U. Uranium exists predominantly as pitchblende, a little coffinite and also as absorbent forms; the associated elements are V, Se, Mo and Re. Mineralization formed during several phases dated at 19, 12, 5, 2 and 1 Ma.

3.1.2. Metallogenic superposition model

The metallogenic superposition model is represented by the Zaohuohao sandstone hosted uranium deposit in the north Ordos Basin. It is located at the southern margin of the Yimeng uplifted block and is adjacent to the Hetao Graben at the northern margin. Only Mesozoic sedimentary strata are exposed. The Upper Triassic Yanchang Formation is essentially composed of gravel-bearing sandstone interbedded with siltstone and mudstones, bearing oil and coal deposits. The Lower–Middle Jurassic Yanan Formation is mainly composed of arkose with coal beds, mudstone and siltstone. The Middle Jurassic Zhiluo Formation is the uranium-bearing bed and comprises grey, grey–green sandstone and mottled siltstone and mudstone, which is parallel to, or locally unconformably underlain by, the Yanan Formation. The Tertiary strata are absent. Sedimentary strata show that the study area underwent multiple tectonic events, which were closely related to uranium mineralization [2].

The large Zaohuohao deposit corresponds to a special type of sandstone hosted uranium deposit, different from other types of sandstone hosted deposit because of its unique signatures. It is generally controlled by a transitional zone between greenish and greyish sandstones, both sandstones indicating reduced geochemical environments. The greenish colour of the palaeo-oxidized sandstones results from chloritization and epidotization relating to hydrocarbon driven secondary reduction processes [3]. The deposit is genetically different from ordinary sandstone hosted deposits, being of more complex origin, undergoing not only a palaeo-oxidization mineralization process, but also circulating oil-gas fluids and hydrothermal reworking processes. The metallogenic superposition model for this type of uranium deposit has been established, i.e. the deposit underwent multiple mineralization processes and stages, such as tectonic multiphase 'dynamic-static' coupling movements, superposition of palaeo-phreatic oxidation and interlayer oxidation mineralization and composite transformation of oil-gas and hydrothermal fluids. The metallogenic stages can be identified as: (i) preliminary enrichment stage at 170 Ma, (ii) palaeo-phreatic oxidation stage at 160-135 Ma, (iii) palaeo-interlayer oxidation stage at 125-65 Ma, and (iv) oil-gas reduction and thermal modification at 20.8 Ma. Analytical data show that thermal modification of the deposit happened after the deposit formed. Coffinite, selenium and sulphide minerals formed under relatively high temperatures, leading to the preferential enrichment of elements such as P, Se, Si, Ti and REE over uranium [2].

3.1.3. Palaeochannel metallogenic model

The palaeochannel metallogenic model is represented by the Bayinwula deposit which is located in an Early Cretaceous palaeochannel in the Erlian Basin. The exposed crystalline rocks to the north of the mineralized area have a high uranium content of 8–11 ppm U and are thought to provide a good source of uranium for the deposit. The ore-bearing bed is characterized by braided palaeochannel sedimentary systems and the ore is controlled by both interlayer and phreatic oxidation processes. The favourable host rocks are debris sandstone and arkose, with some organic matter and sulphur materials. The orebody usually shows a roll-front or tabular shape and has an average thickness of 6.38 m and ore grades varying in the range 0.0113–0.2477% U. Uranium exists in predominantly absorbent form and also as pitchblende, and is associated with Re, Se, Mo, Sc and V. Three major metallogenic stages have been defined at: (i) 95 Ma with preliminary sedimentary enrichment, (ii) 65 Ma with dominant phreatic oxidation process, and (iii) 45 Ma with phreatic and interlayer oxidation process [4].

3.1.4. Tectonically activated metallogenic model

The tectonically activated metallogenic model is applied to the Qianjiadian sandstone hosted deposit in the south-western part of the Songliao Basin. It is located within the two wings of the anticline formed by a late activated tectonic event known Renjiang during the Late Cretaceous. The anticline structure which is also termed a 'window structure', plays a very important role in the formation of the uranium deposit. The host beds correspond to the Late Cretaceous Yaojia Formation with dominant fine-grained sandstones. Rocks such as Mesozoic granites and acidic volcanic rocks with a uranium content of 7–15 ppm could be potential sources of uranium. The late metallogenic processes are characterized by both oxidized infiltrating and reduced fluids due to oil–gas migration through deep faults to form a large tabular orebody. The Qianjiadian deposit is also affected by hydrothermal fluids related to basic dykes and dated to 53 Ma. Uranium mainly exists in an absorbent form and as pitchblende with an average ore grade of 0.0265%. Several metallogenic phases have been recorded at 96, 67, 53 and 40 Ma.

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PERSPECTIVES OF PHOSPHATE – URANIUM COMPREHENSIVE EXTRACTION PROJECTS IN ARGENTINA

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1. INTRODUCTION

Systematic prospecting studies of phosphates in sedimentary basins were carried out during the 1970s by the Argentine Geological Mining Survey (SEGEMAR). This program delineated eighteen areas in several marine basins with phosphate potential, occupying a total area of about 640,000 km² [1]. In the mid-80s, a research group of the Department of Geology of the University of Buenos Aires (UBA), faced the study of new areas for the prospection of phosphates, which currently continues, focused on the genesis and sedimentation environment of phosphate deposits in different basins. New data, together with published information about phosphates have been compiled, and principal phosphate occurrences and their correlation with the global phosphogenetic events have been defined (Cambrian, Ordovician, Jurassic-Cretaceous, Cretaceous-Paleocene, Miocene and Modern) [2].

At present, the National Atomic Energy Commission of Argentina (CNEA) and the UBA, in cooperation with the National University of Salta (UNSa), are carrying out the project "Assessment of the uranium potential of phosphate rocks and testing low-grade phosphate ores extraction" in the framework of the IAEA Coordinated Research Project (CRP), which is "Uranium-Thorium fuelled High-Temperature Gas-cooled Reactor (HTGR) applications for energy neutral sustainable comprehensive extraction and mineral product development". This paper briefly describes the specific objectives and activities in progress of this research project which has been underway since 2015 [3].

2. DESCRIPTION

In Argentina, all of the uranium identified and undiscovered resources belong to conventional sources, and the purpose of the aforementioned RC is to assess the unconventional uranium (Th, REE) resources related to phosphate rocks. The project also pursues the aim of better understanding how thermal extraction can be used to beneficiate and process low-grade phosphates from Argentinean sedimentary basins. This would help to increase the socio-economic viability and technical feasibility to set up productive projects in the long term.

The research project involves studies in three sedimentary basins (Ordovician North-Western Basin, Upper Jurassic – Lower Cretaceous Neuquen Basin, and Paleocene - Miocene Patagonia Basin), where low-grade phosphate mineralization and uranium anomalies (up to 135 ppm U) have been detected. Exploration and beneficiation/extraction studies are being conducted, which would allow an evaluation of the economic potential of the study areas.

During the first year of the project studies have focused on the geological and geochemical characterization of phosphate rocks of the Ordovician North-Western Basin. After completion of the evaluation of available information, Mojotoro Range (Salta Province) and Tilcara Range (Jujuy Province) sites, which are located approximately 1500 km away from Buenos Aires city, were selected for specific studies. Two field missions for geological characterization, sampling and ground gamma-ray spectrometry surveying have been carried out. In total, nine stations were set up, where geological studies and collection of 10-kg samples of phosphatic rocks, including all of the mineralized levels and the barren material as a background, were implemented.

These Ordovician phosphate deposits show a temporal and a spatial distribution of phosphate-bioclastic accumulations linked to the paleogeographic basin evolution and mineralization is made of discontinuous lenses from 10 to 60 cm thick of lingula-bearing coquinas outcropping in studied areas.

These phosphatic levels are intercalated in Tremadocian shales, Tremadocian-Floian shales and mudstones, Dapingian-Darriwilian quartz sandstones and Darriwilian-Sandbian shales, and limestones. Phosphatic inarticulate brachiopoda fragments are concentrated in the lower part of the laminated fine quartz sandstone, assigned these deposits to tempestites accumulated in lower to middle shoreface coastal marine environments. The grade varies between 5 to 7 per cent P_2O_5 . There is a positive correlation between phosphorus and U, Th and rare earth elements (REE). According to their P_2O_5 contents the analyzed samples are classified as: phosphorites (19 and 21 per cent P_2O_5), phosphate rock (8 – 18 per cent P_2O_5) and slightly phosphatic rocks (<8 per cent P_2O_5). By comparing data from mineralized and barren material, preliminary studies indicate that all samples exhibit significant enrichment in Y, Sr, La, Yb, U, Th, Pb, Zr and REE, which encourage further comprehensive extraction tests [4].

During the second year, tasks have been addressed to the Upper Jurassic - Lower Cretaceous Neuquen basin. After completion of the evaluation of geological, geochemical and gamma-ray spectrometry available information, two areas were selected for specific studies: "Cerro Salado" and "Vaca Muerta", which are located in the Neuquen province, approximately 1300 km away from Buenos Aires city. Therefore, at this basin, a field mission for sampling and ground gamma-ray spectrometry surveying has been carried out including a total of ten stations where geological studies and collection of 10-kg samples of phosphatic rocks for mineralogical, chemical and extraction studies were implemented. P_2O_5 content is between 3 to 4.5 per cent and U varies from 3.5 to 5.5 ppm [5].

The Quintuco Formation is 218 m thick and hosts phosphate mineralization. The phosphatic beds are wackestones, bioclastic rudstones and hybrid sandstones forming condensed beds with variable mechanical reworking and are grouped into four phosphatic intervals. Phosphatic particles are mainly nodules and subordinated, partially or totally phosphatized shells. It is though that the phosphogenesis took place during sea high stands and low clastic sedimentation rates, and then reworking by waves and currents and concentration of phosphatic particles occurred during periods of sea-level rise and fall [6].

During the third year of the RC, field work and laboratory studies were focused on Cenozoic marine section cropping out near Gaiman (Chubut Province, SE Argentina approximately 1400 km away from Buenos Aires city), which shows that most of the succession was deposited in a shallow, storm-dominated marine environment. Flat-lying Miocene rocks exhibit a 200-m thick column composed of a coarsening upwards succession of mudstones, fine tuffs, sandstones and coquinas, rich in phosphatic concretions, ray teeth, shark teeth and bones from marine vertebrates. Phosphatic strata are related to: a) in situ concretions developed within transgressive-early highstand system tracts, and b) reworked and winnowed lags associated with transgressive surfaces which display a concentration of phosphatic concretions, ooids, vertebrate bones, teeth and shells. P₂O₅ content in concretions is between 15.61 to 28.97 per cent and U varies from 46 to 135 ppm. Phosphogenesis would have taken place after cold and corrosive water, probably similar to the present Antarctic Intermediate Water (AAIW), flooded the continental shelf and mixed with warmer surficial waters. The development of the phosphorites would have occurred at times of global climatic transition and increased oceanic circulation, probably during the Late Oligocene–Early Miocene [7].

3. DISCUSSION AND CONCLUSION

It could be pointed out that to date economical phosphate deposits have not been found nor has production been carried out in Argentina. Phosphate identified resources, which belong to restricted sites of Northwest and Neuquen Basins, have been evaluated at 1 M t of P_2O_5 with grades ranging from 2.5 to 6.3 per cent P_2O_5 [8].

However, the existence of favorable basins and different mineralization models suggest promising conditions to set up new projects to develop the phosphate potential in the country, taking into consideration the perspective of uranium recovery from this unconventional source of nuclear raw material.

At the current level of knowledge, uranium quantities linked to phosphates are evaluated in the United Nations Framework Classification for Resources (UNFC) scheme as "Additional Quantities in Place Associated with Potential Deposits", where a portion of these quantities may become recoverable in the future [9].

The IAEA project CRP on neutral uses of HTGRs would allow accounting for a better understanding about heat processing of low-grade phosphates. This process would aid to increase the socio-economic viability and technical feasibility to set up productive projects in the long term by providing positive implications regarding food and energy security.

This contribution is a summary of several studies that were conducted by the National Atomic Energy Commission of Argentina, the University of Buenos Aires, the International Atomic Energy Agency, the National University of Salta and the Argentine Geological Mining Survey. The authors are grateful to many institutions for allowing the information to be assessed and presented here.

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URANIUM RESOURCES AND PERSPECTIVES FOR NUCLEAR SUPPLY IN ARGENTINA

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1. INTRODUCTION

In 1992, owing to the low prices in the international uranium market, the import of uranium concentrates began from South Africa, a situation that gradually led to the closure of local production in 1997. Since then, there has been no production of uranium in Argentina, while the uranium needs from operating nuclear power plants have been met with raw material imports (i.e. from Canada, Czech Republic, Kazakhstan and Uzbekistan).

However, despite the fact that international uranium market has been depressed in recent years, the free on board (FOB) prices that Argentina has paid for the purchase of yellowcake in the spot market have not necessarily been trivial, mainly due to the increases in transportation charges, insurance premiums and taxes [1].

This paper attempts to present a comprehensive vision of uranium projects, updated resources, project status and the perspective of local production of uranium oxide concentrate with respect to the foreseeable demand for nuclear energy generation in the country. In addition, raw material supply from the Latin American region is briefly discussed.

2. DESCRIPTION

Argentina has three heavy water reactors, namely Atucha I with a gross electrical power of 362 MW(e) that is fuelled with slightly enriched uranium (SEU) (0.85% U-235), Embalse (CANDU) and AtuchaII, both based on natural uranium fuel with generation capacities of 648 MW(e) and 745 MW(e), respectively. At present, Atucha I and Atucha II, both located in Buenos Aires Province, are in commercial operation, while Embalse, located in Córdoba Province, has been out of the generation system since January 2016 for refurbishment. This is required to extend its useful life for a term of 30 years and also to increase its power by an additional 35 MW(e) [2]. With an approximate installed capacity of 1.7 GW(e), nuclear power sources have a 10% share in the national electricity matrix, with natural uranium requirements representing about 220–250 tU/year.

In addition, at the Atucha site, the Argentine prototype small modular reactor CAREM (27 MW(e) net/32 MW(e) gross) is under construction and is forecast to come into operation in 2020–2022. Future plans are to increase the scale of the unit, possibly to 120 MW(e).

As part of the nuclear development in Argentina, China and Argentina signed an agreement for the installation of a fourth (CANDU pressurized heavy water reactor) and fifth (Hualong-1pressurized water reactor) nuclear power plant, with construction planned to start in 2019 and 2021, respectively.

On the basis of various nuclear growth scenarios, it is estimated that by 2030 there will be a generation capacity of some 3470 GW(e) for the low case and about 4070 GW(e) for the high case. Therefore, the requirement for uranium would amount to 525 tU and 620 tU in the respective scenarios, which is about double the current consumption.

In 2017, CNEA reported about 19000 tU as identified domestic resources (reasonably assured resources + inferred resources) for the production cost category <US \$130 US/kgU in the OECDNuclear Energy Agency–IAEA classification scheme [3]. Approximately 11000 tU of Canadian National Instrument 43-101 (NI 43-101) certified domestic resources have been reported in recent years by U3O8 Corporation, the public mining company [4] and the private mining company UrAmerica Limited [5]. The total uranium resources of Argentina are therefore 30 010tU in the aforementioned identified resources category. It can be highlighted that if the higher production cost category of <US \$260/kgU is considered, there is no substantial variation and identified resources amount to 31060 tU.

In the Cerro Solo deposit (Chubut Province), the tonnage and grade estimated are expected to ensure sustained uranium production in the future. The identified resources are 9230 tU with a grade of approximately 0.1–0.2% U, which are included in the <US\$260/kgU production cost category. The reported resources correspond to the most studied mineralized bodies, and available geological knowledge indicates excellent potential to develop new uranium resources at this mining property. In connection with pre-feasibility studies, in 1997 CNEA retained NAC International to complete a preliminary economic assessment of the Cerro Solo uranium deposit [6]. Recently, a programme to complete a technical feasibility study of the deposit has been formulated and started. Also, the social–environmental baseline is being surveyed in cooperation with national universities and research councils.

In the Laguna Salada project (Chubut Province), uranium identified resources have been evaluated at 3880 tU at grades ranging between 55 and 72 ppm U, while identified vanadium resources have been assessed at 21330 t at grades ranging from 308 to 330 ppm V. Recently, following the NI 43-101 preliminary economic assessment, a comprehensive U–V recovery concept is reinforced. Uranium and vanadium would be extracted (by alkaline leach) from the fine material after screening. The alkaline leach reagents are sodium carbonate (washing soda) and sodium bicarbonate (baking soda) at an optimal leach process temperature of $80^{\circ}C$ [7].

Sierra Pintada uranium deposit (Mendoza Province) [8] has been the focus of the most significant uranium production in the country, with a total of 1600 tU produced from 1975 to 1997, after which, the mining-milling facility was put on standby status for economic reasons. The level of uncertainty in the estimation of remaining resources is medium to high, which are evaluated to be 10010 tU of recoverable identified resources at a production cost of <US \$130/kgU. Therefore, feasibility has been partially demonstrated by the fact that this deposit was previously in operation, using an acid heap leaching mining method. Given the possibility of the reopening of the mining-milling complex, all available data have been processed to redefine the geological model and formulate a more suitable mining design.

Meseta Central project (Chubut Province) is located in the vicinity of Cerro Solo and comprises the Graben, Plateau West and Plateau East deposits. The total inferred resources for the project are 7350 tU at an average grade of 260 ppm U. As reported by UrAmerica Ltd, about 75% of the uranium resources evaluated occur in confined aquifer layers [5]. Therefore, further geological and hydrological studies will be undertaken to determine amenability to in situ leaching. The results of these studies could play a relevant role regarding the socioeconomic viability of this project. It should be noted that in January 2018, the Ministry of Science, Technology and Productive Innovation of Argentina, Uranium One Group, subsidiary of State Atomic Energy Corporation of the Russian Federation (ROSATOM), and UrAmerica Argentina S.A. signed a memorandum of understanding whose main purpose is to promote cooperation and joint development with respect to uranium exploration and production focused on in situ leaching. Planned investment in this project amounts to US \$250 million [9].

The Don Otto (Salta Province) uranium deposit was in operation from 1963 to 1981 and produced 201 tU at a grade of 0.1–0.2% U [10, 11]. The remaining identified resources are estimated at 430 tU and current exploration/evaluation studies have yielded very encouraging results. Additionally, enlargement of the mining property and resource augmentation are considered key factors to ensure the project's feasibility. A comprehensive study that includes updating environmental impact assessment reports, block leaching

research and development studies, feasibility of underground extraction, use of a mobile ionic exchange plant, hydrogeological studies to define in situ leaching amenability, vanadium resource evaluation and extraction feasibility, and uranium recovery from the former heaps and remediation of the site, are all factors that could combine to increase project viability [12].

Laguna Colorada is located in the Chubut Province and has evaluated resources of 160 tU at 660 ppm U [13]. The limited resources of the project make it difficult to envisage extraction at present unless the characteristics of the ore will allow treatment in a plant that may, in the future, be located in the area of Cerro Solo.

At the exploration level, there are several projects under way, such as Golfo San Jorge, Amarillo Grande, Alipan, Mina Franca and Laguna Sirven. These are of great interest in the country and exploration activities are currently being carried out by both the private sector and the government. Initially, it will be necessary to advance the delineation of resources and raise their level of confidence through preliminary economic assessments of these projects, taking into account that, as general rule, the integral exploration at the basin level has not been carried out and the resources have generally been evaluated with a low level of confidence. In sedimentary environments, particular attention should be given to those sandstone type deposits that are amenable to in situ leaching as a means of recovering uranium.

Also, there are some unconventional sources of uranium that could provide sustainable alternatives for nuclear supply in the foreseeable future, such as rare earth projects, phosphates, and lake and sea waters.

3. DISCUSSION AND CONCLUSION

Despite the apparent growth prospects for the use of nuclear energy to generate electricity in Argentina, which would lead to a doubling of the uranium requirements by 2030, there are no immediate prospects for the provision of nuclear raw material for fuel fabrication from the local production of uranium oxide concentrates from domestic deposits. This has implications for supply and energy security [14].

One main concern is that the identified uranium resources in Argentina are mostly located in the provinces of Chubut and Mendoza. These are areas where no metallic mineral mining projects are in operation, and also, the provincial legislations markedly restrict uranium production. These factors need to be taken into account when studying the socioeconomic viability of the projects. However, it could also be assumed that the mining laws could be amended as necessary if a requirement for uranium and other critical materials for clean energy projects becomes very important to Argentina.

Also, projects with a higher degree of maturity must complete technical feasibility studies for the recovery of uranium. In the case of possible future production of U, other valuable materials such as V and Mo can be assumed to be produced as a by- or co-product, contributing to the mineral sector development in Argentina. While U is used for nuclear fuel, V and Mo have critical applications, especially in the renewable energy and steel industry sectors.

In the Latin America region, both Brazil and Paraguay could be considered as potential uranium suppliers for Argentina. In Brazil, in the short to medium term, domestic needs would be covered and even significant uranium surpluses could be produced that could contribute to nuclear supply for Argentina. On the one hand, with expansion, the Lagoa Real deposit could produce up to 670 tU/year; on the other hand, some 1700 tU/year could be obtained as a by-product of the extraction of phosphates in the Santa Quitéria deposit. Production is scheduled to start between 2020–2022. As a recent precedent, in 2016 Industrias Nucleares de Brasil and Combustibles Nucleares Argentinos signed an agreement for the provision of four tonnes of low enriched uranium (1.9–3.2% U-235) produced at the Rio de Janeiro facility in Brazil and to be used as the fuel for the initial load of the CAREM reactor which is under construction at the Lima site in Argentina [15].

In Paraguay, there are two projects of interest found in the eastern part of the country, which are related to sandstones in the western flank of the Parana Basin: the Yuty project, which possesses about 4290 tU of NI 43-101 certified resources, and the Coronel Oviedo project, which constitutes a NI 43-101 exploration target in the range 8900–21500 tU. In both projects, hydrogeological testing indicates that the uranium-bearing unit has aquifer characteristics that would support operational rates for in situ mining. These projects are awaiting better market conditions before commencing operation. Paraguay has no prospects for developing nuclear power so these resources could potentially contribute to the supply of nuclear fuel resources for Argentina. On this basis, it should be noted that Argentina is constructing a new uranium purification plant located about 200 km from the Paraguayan uranium deposits. Therefore, transportation of pregnant resins or eluants could be considered as the best economic and technical option, rather than yellowcake to be precipitated at a Paraguay in situ leach facility and to be dissolved at the uranium purification plant in Argentina [16].

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THORIUM AND RARE EARTH ELEMENT COMPREHENSIVE RECOVERY PROJECTS IN ARGENTINA: ASSESSMENT USING THE UNITED NATIONS FRAMEWORK CLASSIFICATION FOR RESOURCES (UNFC)

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1. INTRODUCTION

This case study looks explicitly into how integrated thorium and associated rare earth element (REE) projects could contribute to the development of the minerals sector in Argentina [1, 2].

Thorium could be used as fuel for low carbon nuclear power generation, while REEs are widely accepted as critical materials required for renewable energy technologies, among other uses [3].

For the accurate assessment and for planning the progression of resources, the United Nations Framework Classification for Resources (UNFC) is used in the case study summarized here [4]. In particular, the specific guidelines for uranium and thorium resources in comprehensive recovery projects were used in this case study. In general, UNFC uses a three-dimensional classification system with: (i) socioeconomic viability (E), (ii) technical feasibility (F), and (iii) geological knowledge (G) as the three major criteria for assessment.

Thorium resources in Argentina, as in most other countries, have not been subjected to systematic studies. Most of the existing anomalies, showings and deposits were discovered as a result of uranium exploration, where airborne radiometric surveys played a relevant role as a prospecting technique [5, 6]. Additionally, the REE potential was also estimated as part of the examination of high Th radiometric records and field geological characterization.

More recently, and due to the renewed worldwide interest in REEs and other critical materials, exploration companies have initiated different projects in Argentina, which have shown encouraging geological potential for thorium and REEs. Additionally, thorium resources have been evaluated and reported.

In 2013, the CNEA (Comisión Nacional de Energía Atómica) carried out a plan for the expeditious reexamination of the radiometric anomalies related to Th and U in the Ambargasta and Sumampa Ranges in Santiago del Estero Province. This study allowed the definition of sites with the most mining potential, where high radioactivity areas were mostly related to carbonatites [7].

The only reported production of REE–Th minerals in Argentina was the recovery of 1010 kg of monazite, without recovery of REEs and Th, from the Teodesia mine (Valle Fertil Range) during 1954–1956.

2. DESCRIPTION

The REE interest covers vast areas of the country in the Puna, Cordillera Oriental and Pampean Ranges regions, and is focused mainly on Upper Jurassic–Cretaceous carbonatite rocks intruded in extensional geotectonic settings. The geological types of REE–Th deposit that have been found in Argentina are carbonatites, pegmatites and placers. The main projects of interest and their status in the UNFC scheme can be summarized as follows.

2.1. Rodeo de los Molles REE (Th, U) deposit/Project

This deposit was discovered by the CNEA in the early 1980s while mapping and prospecting the area identified by regional airborne radiometric anomalies. The deposit is hosted in 'fenitized' alkaline igneous rocks (Jurassic) of the Las Chacras igneous complex and it is LREE dominant. Rodeo de los Molles is the most significant undeveloped REE project in Argentina, with a historical geological resource of 5.6 Mt of mineral ore, containing an estimated 117 600 tREO (rare earth oxides) and 950 tU. About 10 000 tTh are estimated with a lesser degree of confidence. The first resource estimate was prepared in 1992, including metallurgical testwork that demonstrated the amenability of bastnaesite to REE recovery. This estimate was based on approximately 6000 m of rotary air blast drilling [8]. Significant quantities of uranium could be produced as by- or co-product from this project. About 15 tU in G2 and 950 tU in G3 resource categories are estimated for this project. The Th resources of the Rodeo de losMolles project are also considered as a potential by- or co-product of the project, but the resources are estimated with a lower level of confidence and hence are assigned to a G4 category. In San Luis Province, where this project is located, Law 634/2008 prohibits the use of chemicals in all forms and stages of metalliferous mining and processing. Under the UNFC, the Rodeo de los Molles REE-U project is considered as a 'potentially commercial project' within the subclass 'development on hold' with categories E2, F2.2, G2-G3. The Th resources are at present classified separately as an 'exploration project'. With additional data availability, these quantities can be progressed to higher G categories and merged with the REE-U project.

2.2. Puna and Cordillera Oriental thorium (REE) deposits

These deposits are located in the Salta and Jujuy Provinces of north-western Argentina. The deposits have a complex mineralogical composition and are linked to Jurassic–Cretaceous alkaline magmatism that took place in an extensional geotectonic setting. Identified resources of 23 900 tTh at a grade of 0.37% Th and 35 300 tREO + Y (yttrium) at a grade of 0.58% REO + Y derive from nine mineral deposits [9, 10]. The resources associated with these deposits have been estimated with a low level of confidence. In the case of REO + Y resources, it is considered that economic viability of recovery cannot yet be determined owing to insufficient information and the justification as a commercial development may be subject to significant delay. Thorium resources, even though currently considered as having no reasonable prospects for economic recovery, can be produced as a by- or co-product along with the primary REE production. Hence, Puna and the Cordillera Oriental projects are classified as 'non-commercial projects' with sub-class 'development unclarified' (E3.2, F2.2, G3).

2.3. III River and V River Surveys

In the 1950s and 1980s, the CNEA addressed some specific thorium recognition studies on the detrital deposits along the III River (Cordoba Province) and V River (San Luis Province) [11, 12]. Thorium resources at both sites and Th and REO resources at the III River site were evaluated, based on raw material and monazite tonnages and monazite chemical compositions. The areas involved are densely cultivated and any mining may impact access to large tracts of agricultural land. Owing to these constraints, the projects became unattractive and no project was identified with the potential to recover the resources. Resources of 850 tTh and 15 500 tREO in III River and 260 tTh estimated in V River projects are assumed to be currently

unrecoverable, as no development project has been identified. The quantities fall in the UNFC class of 'additional quantities in place', with UNFC criteria of E3.3, F4 and G4.

2.4. Exploration projects

Several new REE (Th) projects are currently active in Argentina, such as Jasimampa, Susques, Cachi and Cueva del Chacho [13, 14]. In these projects, economic viability and feasibility of recovery cannot yet be assessed owing to insufficient information and limited technical data. Eventual reported resources associated with these mineralizations would be considered as belonging to the undiscovered category. Therefore, in the UNFC scheme these projects are qualified as 'exploration projects' (E3.2, F3, G4).

3. DISCUSSION AND CONCLUSIONS

Although the potential for mineral resources is very high in Argentina, the mining sector plays only a minor role in the socioeconomic development of the country. Most of the mineral potential of the country is underdeveloped, which therefore offers a possible opportunity for future investments. The REE potential of the country is significant and its potential development in the future is one that may be worthy of serious consideration. This case study specifically examined how integrated REE and associated thorium and other valuable material projects could contribute to solidifying mineral sector development in Argentina.

Argentina has no current plans to use Th as a nuclear fuel. However, it can be pointed out that all three existing HWR nuclear power plants offer potential capabilities for large scale irradiation of natural Th-232 to produce U-233. More recently, owing to renewed interest in REE worldwide, the private sector has set up different exploration projects, underscoring the geological potential. As a result, thorium resources are started to be evaluated and reported. In the case of possible future production of REEs, Th and some other materials such as U, it can be assumed that these will be produced as by- or co-products. While REEs have crucial applications, especially in the renewable energy sector, the Th produced can be stored for future use.

Thorium resource assessment in the country is far from complete, and most thorium resource estimations correspond to undiscovered resources because specific exploration and comprehensive resource estimation of REEs and thorium deposits have only been conducted at a very preliminary level.

When mapping REEs and thorium resources in the UNFC scheme, the Argentine projects currently have neither the economic potential nor technical feasibility for commercial recovery and sale in the foreseeable future. Except for the Rodeo de los Molles project, which has been classified as a 'potentially commercial project' no other project has matured well enough for commercial recovery to be viable in the near future. However, when considered as comprehensive recovery projects, there are projects with significant potential for future development. In this case, thorium and other valuable materials also become significant and could be produced without major additional investment as by- or co-products. This case study demonstrates the potential for assessing REEs and Th as an integrated project, thereby increasing the potential of the combined project.

The application of the UNFC scheme contributes to a better understanding of the availability of reliable nuclear and associated critical material resources, especially for development of green energies in Argentina, and this helps in gaining an understanding of where the focus should be in future. The role of REEs in contributing to Argentina's gross domestic product could be reassessed with this in view.

This contribution is a summary of several studies that were conducted by the CNEA, the Argentine Geological Mining Survey and different exploration companies. The authors are grateful to many companies and institutions for allowing the information to be assessed and presented here.

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EFFECTIVE AND ENVIRONMENTALLY COMPLIANT IN SITU RECOVERY OF SEDIMENTARY HOSTED URANIUM

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1. INTRODUCTION

Heathgate Resources Pty Ltd (Heathgate) operates the Beverley uranium mine, which is located in the Frome Basin close to the northern Flinders Ranges, South Australia, about 550 km north of Adelaide. After exploiting the original Beverley deposit, which is hosted within the Miocene Namba Formation (summarized in Ref. [1]), Heathgate explored and developed additional sedimentary U deposits amenable to in situ recovery (ISR). These, however, are located in the Eocene Eyre [2] and in Cretaceous diamictite host formations under quite different petrophysical, geochemical and mineralogical conditions, which required an adjustment of ISR technology for optimized performance. This paper reviews advanced methodologies including exploration/delineation, laboratory and field testing, ISR wellfield planning/optimization/control, and post-mining measures for ISR aquifer restoration, altogether providing the preconditions for the recent significant increase in production (≥ 4 Mlbs/year U₃O₈ or ~1800 tU/year) in an environmentally responsible manner. This paper is focused on acid ISR as used by Heathgate, but the general principles outlined here apply to alkaline ISR accordingly.

2. EXPLORATION AND DELINEATION

State of the art exploration/delineation methodology is applied to comprehensively characterize sedimentary U deposits within the regional hydrogeological framework. In addition to standard geophysical surveying techniques, advanced high resolution seismics (trend from 2-D to 3-D) adjusted to the depth range of interest (in general, less than 500 m) have been optimized. Heathgate considers hybrid seismics, combining reflective and refractory responses and, most recently, the implementation of the innovative Acoustic Zoom® (non-specular seismic imaging) at substantially improved resolution. The results from geophysical surveying with a focus on seismic data are used to develop the hydrogeological framework in general and the structural 3-D model, including the sedimentary stratigraphy as well as any (tectonic) irregularities. Together with hydrological surveying data (including hydraulic pressure profiles, pumping test data, groundwater sampling and analysis), this forms the basis for creating a regional hydrological 3-D model considered to be the framework of ISR, with wellfields embedded therein, when developing the ISR mine project.

Whereas exploration drilling at larger spacing delineates the approximate outline of the sedimentary, in most cases roll-front type uranium orebodies (however, sufficient for resource estimates), closer spacing in delineation drilling is applied to quantify the reserve figures and to digitize the orebodies in detail for developing a 3-D deposit model, including U grade distribution, petrophysical, geochemical and mineralogical data. Heathgate has fully implemented the <u>A</u>dvanced <u>P</u>rompt <u>F</u>ission <u>N</u>eutron (APFN⁺) logging tools, thus, substituting most conventional logging tools and reducing core drilling and core assaying significantly. APFN⁺ is based on a pulsed neutron generator technique in combination with

multiple time resolving neutron counting and high performance γ -spectroscopy to measure pU₃O₈⁵ and eU₃O₈⁶ accurately (and the disequilibrium between both), to determine several geophysical parameters (density, porosity, permeability, etc.) and to log main elemental/mineral abundances. All this is achieved by one tool [3]. Subject to verification, borehole based Acoustic Zoom® could support delineation data evaluation, if acoustic response from ore is distinctive enough against the surrounding rock.

3. LABORATORY AND FIELD TESTING

Laboratory testing, typically using representative core samples, and field leach trials are essential activities (i) to verify ISR feasibility criteria and (ii) to adjust/optimize ISR performance in dependence on the mostly specific conditions in particular wellfield zones. Quite often, particularly in the case of leach tests or dedicated mineralogical studies, it is most important that sampling, sample handling and preparation is performed under inert (i.e. non-oxidative) conditions to keep the original oxidation state(s) of U within the mineral texture unchanged, i.e. to avoid any pre-oxidation that might drastically interfere with the test (i.e. by using N_2 filled gloveboxes). Appropriate conventional laboratory methods include:

- Geophysical: pycnometry (density), porometry, permeametry, NMR⁷ spectroscopy (pore size distribution), BET N₂ adsorption (specific inner surface) and others;
- Geochemical/mineralogical: elemental analysis methods, SEM⁸, XRD⁹, QEMSCAN or MLA (SEM combined with EDS¹⁰ for quantitative evaluation of minerals, grain size distribution and other parameters).

In addition to these conventional laboratory techniques, Heathgate/UIT have been investigating new core test techniques, including:

- 3-D X ray computer tomography (to characterize pore distributions and simulate permeability and fluid flow dynamics in 4-D) in cooperation with LIAG¹¹ Hannover;
- GeoPET, 4-D positron emission tomography to image fluid flow through core samples in space and time (in cooperation with HZDR Dresden–Rossendorf/Leipzig), in particular to identify conditions for preferential flow on an intermediate spatial scale (decimetre),
- XRLFS¹² and other methods to characterize and quantify the U minerals and their oxidation states (U^{IV} versus U^{VI}).

Batch tests to study and quantify the basic chemistry of leachate–rock interactions, including reactions interfering with ISR (acid–base or redox, adsorptive effects and surface complexation) and microbial effects are also used to characterize leach kinetics versus multicomponent kinetic models. Uranium leaching kinetics (as well as the kinetics of competing redox reactions) is usually described in terms of a reaction rate r (mol/s) within the model cell according to H⁺ concentration [H⁺] or pH, concentration of electron acceptors [A] or oxidation potential (concentration of Fe³⁺ or O₂ or others as applicable), concentration of complexing ions [C], temperature (Arrhenius term with activation energy, E_a), optionally a microbial term, M, and others are shown in Eq. (1):

⁵ The term pU₃O₈ refers to the actual uranium grade deduced from prompt fission neutron (PFN) response.

⁶ eU₃O₈: Approximate uranium grade deduced from natural γ ray counting (more accurate spectroscopic response used in APFN⁺); actually representing the abundance of progenies, including ²²⁶Ra.

⁷ NMR: nuclear magnetic resonance.

⁸ SEM: scanning electron microscopy.

⁹ XRD: X ray diffractometry.

¹⁰ EDS: energy dispersive X ray spectroscopy.

¹¹ Leibniz-Instituts für Angewandte Geophysik.

¹² TRLFS: Time resolved laser fluorescence spectroscopy.

$$\mathbf{r} = \mathbf{r}_0 \cdot \mathbf{S} \cdot [\mathbf{H}^+]^a \cdot [\mathbf{A}]^b \cdot [\mathbf{C}]^c \cdot \exp\{-\mathbf{E}_a/(\mathbf{R} \cdot \mathbf{T})\} \cdot \mathbf{M}$$
(1)

S is the effective mineral contact surface. The rate r_0 is given in units of mol·s⁻¹·m⁻² or equivalent units. Knowledge of the above parameters a, b, c and (r_0 ·S) for U mineral(s) and interfering sulphidic minerals (e.g. pyrite) and organic matter is most important in optimizing the leach chemistry for a given deposit (i.e. adjusting the leach regime to the specific mineralogy of the orebody) by applying reactive transport models (see below). This methodology, based on the quantification of kinetics in accordance with the above variables, was an important precondition to achieving Heathgate's current production rates in real ISR practice.

As an integrative test approach to combine leach kinetics with pore volume exchange kinetics, advanced (pressure, temperature, chemistry) controlled, automated column test facilities provide the data basis for reactive transport simulations on a laboratory scale (versus test data) and upscaling to 3-D reactive transport conditions in real wellfields. Typically, the U recovery curves (leachate grade c_U as a function of leaching time, t, or pore volume exchange) measured by the use of (nearly 1-D linear) column become folded by the diversity of flow path lines when upscaling to 3-D wellfields (i.e. flattening the 3-D recovery curve $c_U(t)$ with reference to the ideal 1-D case to a certain degree in accordance with wellfield geometry and heterogeneity of permeability).

The recent field leach trials performed in a high grade, clayey Cretaceous ore formation has been combined with 4-D electro-resistivity tomography to image the leachate (lixiviant) distribution in one wellfield test pattern, thus, providing an excellent reference for validating/adjusting the 3-D hydrological (permeability, flow rates, contact with the ore) and reactive transport (breakthrough and leaching chemistry, recovery curve modelling and overall recovery) models.

4. ISR WELLFIELD PLANNING, OPTIMIZATION AND CONTROL

ISR wellfield design and performance planning comprises both (i) the hydrologically optimized set-up of injection/extraction well patterns to realize the best dynamic contact of leachate to U mineralization and (ii) the definition of leachate chemistry (optionally in phases) to maximize selective U leaching (leach efficiency and economics) as well as to minimize interfering reactions and environmental impact. The ISR wellfield operation is closely monitored and controlled with regard to:

- Wellfield hydrology (flow rates and pressures to carefully balance the operation for achieving ISR efficiency and environmental compliance);
- Wellfield chemistry (chemical dosage control, in-line monitoring of uranium/pH/redox potential, sampling and analysis);
- Environmental monitoring (multilevel well ring) to measure hydrological and chemical parameters in the mining aquifer, as well as in adjacent formations, in comparison to the excursion control limits defined within the regulatory approval.

Conventionally, ISR wellfields are designed by applying regular patterns of injection/extraction wells (including 5-spot, 7-spot and line drives) with reference to the grade-thickness contours of the orebody and adjusting the well screen intervals accordingly. Heathgate developed the model based, optimized 3-D wellfield design by applying a more 'relaxed' (less stringent) geometry that is more efficient and cost effective. On the basis of the monitoring of wellfield operation and the regular, careful assessment as opposed to model predictions, the wellfield design can be adjusted to improve ISR recovery and economics, in particular, by injector/extractor role reversals, in-fill wells, re-screening (depth interval adjustment) and to prove environmental compliance of the operation.

Heathgate/UIT's reactive transport software tools are suitable to resolving the ISR redox puzzle by adjusting the oxidant concentration and other chemical parameters, including pH, to clearly favour the leach of U^{IV}

minerals against the interfering dissolution of sulphidic minerals such as pyrite (FeS₂) or organic matter (xCH_2O) becoming degraded under oxidative conditions. The quantification of the kinetic rate parameters (see Eq. (1)) for the main reductants was an essential precondition for this optimization method, one that is practically realized by the chemicals' dosage control.

5. POST-MINING MEASURES FOR ISR AQUIFER RESTORATION

The chemical attenuation of the leachate during its passage through the orebody (verified and quantified daily by controlling the leachate refortification) continues after wellfield shutdown over the long term and leads to its neutralization and chemical reduction (thus, immobilizing U) in a timescale that is considered tolerable in view of Heathgate's ISR application in aquifers of the 'no-use' category. This effect, termed natural attenuation could be enhanced, if required, by remediation measures Heathgate is prepared for, such as enhanced natural attenuation [4].

After wellfield shutdown, the post-mining solution becomes a localized component of the natural groundwater system, i.e. it moves at the characteristic flow velocity (ranging from 0 to a maximum 20 m/year in the relevant mining aquifers) on a regional scale within an attenuation zone, thus interacting with sedimentary minerals outside the original (hydraulically constrained) mining zone. The post-mining natural attenuation is simulated by 3-D reactive transport software tools extended to an appropriate regional scale. The chemical ensemble for the simulation reflects a wider range of chemical parameters reliably (pH from acid to neutral, redox potential to strongly reducing conditions), again quantified by dedicated test work and geochemical assessment. Whereas the chemical neutralization (pH>6) and reduction (dependent on original formation conditions) is achieved within a few decades (typically about 50 years for the relevant formations), uranium is immobilized over the shorter term at an intermediate pH already (effectively a 10–30-year timescale, according to conservative simulations). The in-field effects of natural attenuation are closely monitored to verify the model predictions presented in the approval documents.

6. SUMMARY

ISR technology is highly complex and requires the application of a versatile, comprehensive methodological basis to optimize recovery economics under the primary condition of environmental compliance. Heathgate has developed advanced means and tools to face this challenge under varying deposit conditions, i.e. to gather all required data before, during and after ISR operation ('data mining'), and to use this comprehensive database for model based ISR planning, performance and after-care ('move theory to practice'), particularly for (remote) process control and automation, towards a next generation ISR technology.

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LABORATORY AND ION EXCHANGE PILOT PLANT STUDIES SUPPORTING THE FIELD LEACH TRIAL AT THE HONEYMOON URANIUM PROJECT

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1. INTRODUCTION

The Honeymoon Uranium Project is an acid in situ recovery (ISR) mine in South Australia. The project contains three deposits: Honeymoon, Jasons and Goulds Dam. The measured resource consists of a total of 29 000 tU (6.5 M lb) U_3O_8 at an average grade of 1720 ppm U_3O_8 (1460 ppm U), with total resources (measured + indicated + inferred) of 28 800 tU (63.3 M lb) U_3O_8 at 660 ppm U_3O_8 .

The mine was previously operated by Uranium One for approximately 18 months, producing \sim 335 t of U₃O₈, before being placed on care and maintenance in 2014 as a result of the persistently low uranium price and production issues. Boss Resources acquired the project in December 2015. As part of the plan for restarting the mine, Boss performed a successful field leach trial (FLT) on an area of the deposit between August and December 2017.

In support of the FLT, ANSTO Minerals undertook a comprehensive laboratory testwork programme. This included a study to optimize the leaching conditions, as well as column leaching of samples taken from the FLT area. The laboratory studies also identified an ion exchange (IX) resin capable of achieving significantly higher uranium loading than conventional resins under the elevated chloride concentrations in the Honeymoon leach liquor. As a result, ANSTO Minerals constructed and commissioned an IX pilot plant that operated over a 10-week period during the FLT. The success of this pilot plant means that IX could potentially be used as an alternative to the existing solvent extraction facility.

This paper presents the results from the laboratory programme, as well as highlighting the success of the FLT campaign and associated IX pilot plant operation.

2. LABORATORY LEACHING PROGRAMME

A laboratory leaching programme was performed using samples taken from the Jasons deposit, as well as samples taken from the FLT area. The programme comprised two main parts: (i) a leach optimization study to determine the conditions for maximizing uranium extraction while minimizing acid and oxidant consumption and (ii) a series of column leaches simulating ISR conditions to confirm the results from the optimization study and assess the leachability of the uranium in the FLT area.

The leach optimization study, investigating the effect of pH, oxidation–reduction potential (ORP) and Fe addition, was performed in 2 L stirred tank reactors at a solids density of 50 wt% and a temperature of 30°C for a period of 24 h. The pH and ORP set-points were maintained by the automated addition of concentrated sulphuric acid and sodium permanganate. The results from the optimization study demonstrated that uranium extraction was strongly influenced by pH, with a pH of approximately 1.5 required for maximum

extraction. This pH is considerably lower than that employed by the previous operators at Honeymoon, and indicates that the uranium recovery could potentially be significantly higher or the kinetics significantly faster than that historically achieved.

Tests at varying ORP set-points also demonstrated increased uranium extraction with ORP, although the effect was generally not as significant as for pH. Significantly, if the ORP was maintained at \geq 475 mV (relative to a Ag/AgCl reference electrode filled with 3 mol/L KCl), then extensive oxidation of any pyrite present in the sample occurred, resulting in excessively high oxidant consumption. This demonstrates the impact that the presence of sulphide could potentially have in practice, with any ferric iron injected potentially being reduced upon contact with the sulphide. This could result in the rate of uranium extraction being retarded until the sulphide phase is significantly oxidized, with the ferric being consumed by the sulphide before reaching the uranium mineralogy. It is also possible that solubilized uranium could be subsequently precipitated by reducing conditions upon contact with the sulphide and would not be redissolved until the sulphide is consumed and/or liquor of sufficiently high ORP reaches the precipitate.

As a result of the leach programme, the optimum conditions identified for leaching of the supplied ore samples were pH 1.5 and ORP 450 mV. In practice, it is likely that in order to minimize sulphide oxidation, it would be necessary to keep the ORP as low as possible while still being sufficiently high to achieve an effective rate of uranium leaching. This could be potentially achieved by increasing the total iron concentration while maintaining the injection ORP at 400–450 mV, meaning that uranium leaching would occur while sulphide oxidation would be minimal.

Uranium extractions of >90% were consistently achieved in leaches under optimized conditions. The gangue acid consumption in all tests was very low, less than 11 kg H₂SO₄/kg U₃O₈, indicating the acid costs in operation would also likely be low. As noted above, oxidant consumptions were high in tests at high ORP set-points, but under optimum conditions, consumptions were typically less than 4 kg equivalent H₂O₂/lb U₃O₈, or <22 kg Fe³⁺/kg U₃O₈.

3. COLUMN LEACHING

A series of column tests were also performed on samples taken from both the Jasons deposit and the FLT area. These tests utilized horizontal columns of 1 m length, with ore samples crushed to -2 mm and packed tightly into the columns. The packed ore was irrigated by leach liquor, gravity fed into the column to achieve a target liquor flow rate of 2 m/d through the bed.

The column tests investigated the impact of increasing uranium concentration in the feed on the rate of uranium extraction, simulating the effect of solution recycle (also known as solution stacking). Tests were also performed to confirm the effects of pH and ORP observed in the stirred tank tests and also to confirm the optimum leaching conditions.

The column tests utilizing feed liquors with varying uranium concentration (between 0 and 200 g/L U) showed a small decrease in the rate of uranium extraction with increasing concentration. The impact of pH and ORP on uranium extraction in the column leaches was variable, although extractions of >90% were consistently achieved throughout the tests, again demonstrating the amenability of the uranium mineralogy to leaching. Significantly, the calcium contents of the ore samples were very low, and there was no evidence of the precipitation of gypsum or any other calcium salts in the column tests.

4. FIELD LEACH TRIAL

The FLT was performed on-site from mid-August until early December 2017 and utilized a wellfield approximately 1:10 the size of a typical production wellfield. This comprised two well patterns with a total of 8 production wells and 2 extraction wells. The primary objectives of the FLT were to determine the

necessary conditions required for effective uranium leaching (pH, ORP, Fe³⁺ concentration), to determine the resultant reagent consumptions and to evaluate the effect of solution recycle in order to increase uranium tenor feeding IX.

The wellfields were initially injected with liquor at pH1.6 with 1.2 g/L Fe³⁺ added as FeCl₃, resulting in an injection ORP of approximately 650 mV. Owing to the unusually high pyrite content of the FLT area, the oxidant consumption was high, resulting in the Fe³⁺ addition being increased to approximately 2.5 g/L and an ORP of approximately 700 mV. This resulted in an increased rate of pyrite oxidation, allowing the uranium leaching rate to also increase. After the increase in Fe³⁺ addition, a stable U₃O₈ tenor of 75–85 mg/L was achieved as leaching continued at a steady rate for the remainder of the trial. Towards the end of the campaign, a role reversal was performed (where the injection and extraction wells were reversed), resulting in a maximum U tenor of 375 mg/L, the highest recorded at Honeymoon.

Following the initial injection of liquor into the wells when the readily available acid consuming phases reacted, the pH of the liquor from the extraction wells stabilized at approximately pH1.5. This confirmed the low acid consumption observed in the testwork programme and also demonstrated the effectiveness of uranium leaching at this pH. Similarly, calcium concentrations remained low in all extraction liquors throughout the campaign and no issues were observed with gypsum precipitation throughout the operation.

The successful FLT supported the observations and conclusions from the ANSTO Minerals leaching testwork. In addition to confirming the requirement for a lower pH than previously utilized, as noted above, the FLT also showed that localized regions of high sulphide content can impact the consumption of $Fe^{3+}/oxidant$ and subsequently the rate of uranium extraction. Increasing the rate of uranium extraction was achieved by increasing the Fe^{3+} added.

5. ION EXCHANGE PILOT PLANT

Laboratory testwork performed at ANSTO Minerals identified and tested a commercially available resin capable of high uranium loadings from liquors at the elevated chloride concentrations in Honeymoon groundwater. The successful results from this study allowed Boss Resources to evaluate the use of IX for the concentration of uranium from ISR liquors by operating an IX pilot plant campaign over a 10-week period during the FLT. The pilot plant was designed, constructed and commissioned by ANSTO Minerals personnel and subsequently operated by Inception Consulting Engineers for Boss Resources.

The pilot plant consisted of 21 fluidized column contactors divided between 3 modules of 7 contactors each. The function of each contactor (feed, wash or elution) was changed by relocation of feed and outlet hoses, resulting in the resin effectively flowing incrementally in the opposite direction of the liquor. The 21 contactors were divided into 14 loading and 7 elution contactors, representing this number of stages for each. Elution was performed using NaCl/HCl solution. A total number of 312 cycles were performed over the 10-week operating period.

The adsorption circuit yielded excellent results, achieving 97% extraction from the pregnant liquor solution, with resin loadings under base case conditions averaging 26 g/L_{wsr} (wet settled resin) U₃O₈, with feed and barren concentrations of 50 and 1 mg/L U₃O₈, respectively. The elution circuit also produced good results, with eluted resin consistently below the target of 2 g/L_{wsr} U₃O₈, corresponding to 95–99% elution, during stable periods of operation. The maximum eluate concentration achieved was 2.4 g/L U₃O₈, corresponding to a resin loading of 28 g/L_{wsr} U₃O₈.

The IX pilot plant performance overall was in agreement with the bench scale testwork carried out on synthetic liquors, for the pregnant liquor solution's chloride concentration and acidities that were tested in the laboratory. Modelling of the IX circuit, on the basis of the laboratory results, was validated by the uranium concentrations measured in both the barren and loaded resins.

The success of the IX pilot plant campaign means that in future operation the existing solvent extraction facilities at Honeymoon could be replaced or supplemented by IX. The use of IX for uranium in elevated chloride liquors is a significant new development in the industry.

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GEOCHEMICAL PROSPECTING STUDY OF THE VANADIUM–URANIUM MINERALIZATION OF PUYANGO, ECUADOR

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1. INTRODUCTION

A geochemical prospecting study was carried out in the Puyango sector, Loja Province, Ecuador, to determine uranium and vanadium anomalies and identify the main mineral phases that make up the mineralized rocks, through a combination of chemical analysis using portable X ray fluorescence (pXRF), gamma spectrometry, petrographic analysis and X ray diffraction (XRD). Maximum values of 136 ppm were detected, in situ, by gamma spectrometry and maximum values of V_2O_5 of 1.60% by pXRF. The mineralization is hosted mainly in black bituminous limestones of Cretaceous age which belong to the Ciano and Puyango Formations of the Alamor–Lancones marine basin [1]. These rocks are composed mainly of calcite, quartz, illite, apatite, uranospathite and minor amounts of phyllosilicates and vanadium minerals such as sherwoodite, rossite and ronneburgite. The hypothesis for the formation of this mineralization is that both vanadium and uranium were deposited in a reducing environment, in marine waters under euxinic, anoxic to sub-oxic conditions, as evidenced by V:Cr and V:V + Ni ratios and by the presence of organic matter in the samples, in which these elements can be linked in compounds such as porphyrins, where V can be complexed.

2. METHODS AND RESULTS

2.1. Mineralogical analysis

Petrographic and mineralogical analyses by XRD permitted the determination of the main rock forming minerals: calcite (CaCO₃: 61–88%), quartz (SiO₂: 6–22%), fluorapatite (Ca₅(PO₄)₃(F), uranospathite (Al₁. $xx[(UO_2)(PO_4)]_2(H_2O)_{20+3x}F_{1-3x}$: 1–3%), sherwoodite (Ca₉Al₂V⁵⁺₄V⁵⁺₂₄O₈₀·56(H₂O)) and smaller amounts of rossite (CaV₂O₆), ronneburgite (K₂MnV₄O₁₂), illite ((K,H₃O)(Al,Mg,Fe)₂(Si,Al)₄O₁₀[(OH)₂,(H₂O)]), biotite (K(Mg,Fe)₃[AlSi₃O₁₀(OH,F)₂), kaolinite (Al₂Si₂O₅(OH)₄), chloritoid ((Fe,Mg,Mn)₂Al₄Si₂O₁₀(OH)₄), chamosite ((Fe,Mg,Fe)₅Al(Si₃Al)O₁₀(OH,O)₈) and glauconite ((K,Na)(Fe,Al,Mg)₂(Si,Al)₄O₁₀(OH)₂).

2.2. Chemical analysis

Chemical analyses by pXRF give background concentration of 49 ppm U and a maximum value of 153 ppm U in black bituminous limestones. The background value of vanadium was statically determined to lie in the region 1500 ppm V_2O_5 , with a maximum value of 23 100 ppm.

Anomalous values were determined statistically for P_2O_5 (4.52%), Zn (3340 ppm), Mo (219 ppm), Cu (165 ppm), Cd (131 ppm) and Se (21 ppm). High concentrations of other uranium pathfinder elements and geochemically associated to it and to vanadium were also detected and included sub-anomalous values of As (95 ppm), Bi (68 ppm), Ni (337 ppm) and Pb (72 ppm).

2.3. In situ gamma spectrometry

In situ gamma spectrometry analyses were made with a portable gamma spectrometer and led to the determination of anomalous eU values (86 ppm) and a maximum eU value of 136 ppm. This evidence U mineralization associated with the in black bituminous Cretaceous limestones [2].

3. DISCUSSION AND CONCLUSION

3.1. Mineralogical analysis

According to the geochemical prospection carried out, the majority of the rocks correspond to bituminous limestones of Cretaceous Puyango Formation. Most of the samples are composed of calcite (CaCO₃: 61–88%) and, to a lesser extent, quartz, phosphates and phyllosilicates (clays and micas).

Petrographic analysis showed that the majority of the samples correspond to micritic limestones and sparritic limestones with foraminiferous fossils. The mineralogical studies show that the uranium and vanadium are present in the following proportions:

- Fluorapatite: 28–75%;
- Uranospathite: 2–3%;
- Sherwoodite: 1-2%;
- Rossite and ronneburgite: <1%.

Uranospathite may have been formed by weathering and chemical alteration of the primary phosphate (uraniferous apatite) [3].

The minerals that contain vanadium (sherwoodite, rossite and ronneburgite) are vanadates with V^{5+} and V^{4+} in their crystalline structures, in addition, possibly, to V^{3+} in the clay minerals such as illite, since it can replace Al^{3+} during diagenesis [4]. This occurs similarly in vanadium deposits in black shales and in vanadium accumulations in carbonaceous rocks in general [5, 6].

The samples contain organic material of marine origin according to the sedimentary environment, so it is likely that vanadium is also linked to organic matter, in compounds such as porphyrins [7, 8].

3.2. Chemical analysis and statistics

The statistical treatment of the chemical analyses shows that U and Ca correlate with P, indicating that the minerals that host U are apatite and uranospathite. There are also strong correlations between V–Ni, V–U, V–Mo and V–Zn, which are probably associated with organic matter and, more specifically, with porphyrins [7, 8].

By calculating V:Cr and V:V + Ni ratios, it can be deduced that the sediments were deposited under euxinic, anoxic to sub-oxic conditions [9]. Thus, the following hypothesis for the formation of this mineralization can be proposed: both vanadium and uranium were deposited in marine waters, in a reducing environment with the presence of organic matter to which these elements were linked in compounds such as porphyrins and where V can be complexed [7, 8].

Several authors [10] have indicated that the sediments of the Puyango Formation were deposited in a marginal marine basin, formed between the Celica volcanic arc to the east and the Amotape–Tahuin Massif in the west, which corroborates the results obtained.

3.3. Gamma analysis interpretation

According to in situ gamma spectrometry, anomalous values of eU (86 ppm) and a maximum value of eU (136 ppm) were detected in bituminous limestones. The values of eTh reached a maximum of 31 ppm in the shales, with a background value of 5 ppm, which evidences the low mobility of Th under the conditions of formation of the mineralization resulting from its geochemical properties. The eU:eTh ratio was calculated

for the analysed samples fluctuated between 0.06 and 18.80, with the high values of the ratio in the mineralized areas.

4. CONCLUSIONS

The geochemical prospection study of the Puyango sector using chemical, mineralogical and gamma spectrometry analyses, determined the presence of a V–U mineralization associated with black bituminous limestones, which form part of the Cretaceous Puyango Formation.

There are anomalous values of P_2O_5 (4.52%), Zn (3340 ppm), Mo (219 ppm), Cu (165 ppm), Cd (131 ppm) and Se (21 ppm), in addition to sub-anomalous values of uranium pathfinder elements: As (95 ppm), Bi (68 ppm), Ni (337 ppm) and Pb (72 ppm).

The host minerals of uranium are apatite and uranospathite. The last mineral is formed by the weathering and chemical alteration of the primary phosphate.

The minerals that contain vanadium are sherwoodite and, in a smaller proportion, rossite and ronneburgite, which are vanadates with V^{5+} and V^{4+} in their structures. There may, in addition, be V^{3+} in clay minerals such as the illite, since this can replace Al^{3+} during diagenesis.

Mineralogical and geochemical analysis should be done through scanning electron microscopy to identify with greater precision the mineral phases that contain vanadium, as well as its precise association with organic matter.

According to the calculation of the eU:eTh ratio for the samples analysed by in situ gamma spectrometry, these fluctuated in the range 0.06–18.80, with the highest ratios corresponding to the mineralized areas.

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GEOCHEMICAL AND MINERALOGICAL CHARACTERIZATION OF THE URANIFEROUS PHOSPHATE ROCKS OF THE NAVAY FORMATION, TÁCHIRA STATE, VENEZUELA

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1. INTRODUCTION

Through the IAEA's CRP T11007, a geochemical and mineralogical characterization study was undertaken on the uraniferous phosphate rocks of the Navay Formation, Táchira State, Venezuela. A phosphate deposit associated with sandstones in the upper levels of the Navay Formation (Upper Cretaceous) in southwest Táchira State, Venezuela, was discovered in early 1978 by radiometric surveys conducted by The National Commission of Nuclear Affairs (CONAN) of the Ministry of Energy and Mines. This deposit consists of siliceous shales, calcareous shales, uraniferous phosphatic sandstones and cherts (phtanites) [1]. To date, there have been studies on the feasibility of their exploitation to produce phosphate fertilizers. There has been no study focused on uranium mining.

2. METHODS AND RESULTS

2.1. Mineralogical analysis

From petrographic examination and mineralogical analysis by X ray diffraction (XRD), it was determined that the main rock forming minerals are fluorapatite/chlorapatite ($Ca_5(PO_4)_3(F,Cl)$, collophane or carbonate fluorapatite ($Ca_5(PO_4,CO_3)F$), uranospathite ($Al_{1-x}[]x[(UO_2)(PO_4)]_2(H_2O)_{20+3x}F_{1-3x}$), quartz (SiO₂: 4–88%), calcite (CaCO₃: 10–35%), montmorillonite ((Na,Ca)_{0,3}(Al,Mg)₂Si₄O₁₀(OH)₂) (maximum 6%) and microcline (KAlSi₃O₈) (maximum 1.43%).

The mineralogical studies show that uranium is present in the following forms:

- Fluorapatite and carbonate fluorapatite: 28–75%;
- Uranospathite: 2–3%.

2.2. Chemical analysis

Chemical analysis was achieved by several techniques: portable X ray fluorescence (pXRF), total reflection X ray fluorescence (TRXRF) and inductively coupled plasma — atomic emission spectroscopy (ICP AES). According to these techniques, the background concentration of U is 102 ppm, reaching a maximum value of 160 ppm in a calcareous phosphatic sandstone. These values are within the average range of U concentrations in marine phosphate rocks (50–300 ppm) [2].

Sub-anomalous values were determined statistically to give: Cd (82 ppm), Cu (261 ppm), Zn (268 ppm), Sr (1832 ppm) and Zr (510 ppm), as well as anomalous values of Cr (1653 ppm). In addition, maximum values of major, minor and trace elements were determined: MgO (12.40%), Al₂O₃ (9.60%), K₂O (3.07%), Fe₂O₃ (1.25%), MnO (0.05%), TiO₂ (0.35%), S (1.31%), Cl (1.07%), V (82 ppm), Ni (2083 ppm), Pb (86 ppm), Co (199 ppm) and Rb (91 ppm).

According to the chemical composition of the samples, most correspond to phosphatic rocks (median 17.25% and maximum 24.81% P_2O_5), quartz sandstones (median 25.60% and maximum 88.70% of SiO₂) and phosphatic limestones (median 27.88% and maximum 70.40% of CaO) [3].

2.3. Gamma spectrometry

Gamma spectrometric analyses were also undertaken in the laboratory on several samples from the deposit which detected the presence of 226 Ra, which may be present in the apatite either by replacing the Ca²⁺ (geochemical affinity) or in the radioactive decay series of 238 U. Other isotopes of this decay series were also detected (214 Pb and 214 Bi).

3. DISCUSSION AND CONCLUSION

3.1. Mineralogical composition

Fluorapatite has been identified as the main phosphate mineral, which in some cases contains carbonate in its structure ($CO_3^{2^-}$), which is common in this group of minerals where carbonate ions can replace phosphate ions ($PO_4^{3^-}$) [4]. The U is hosted in the apatite because the U⁴⁺ (ionic radius 1.00 Å) can replace the Ca²⁺ (ionic radius 1.12 Å for the same octahedral coodination as U) [5]. The presence of uranospathite has been detected by XRD, which is a secondary phosphate of Al and U and belongs to the autunite group formed as a result of the weathering of primary phosphates in humid environments [6]. The presence of autunite and wavelite is not ruled out, as these have been identified in samples from La Lucha River, also in Táchira State [1].

The mineralogy is typical of marine phosphatic deposits. From petrographic observation of thin sections it was possible to identify phosphatic sandstones, phosphatic limestones and micritization of peloids.

The presence of the foraminiferan fossil *Orthokarstenia ewaldi* of Upper Cretaceous age (Maastrichtian), identified by petrographic analysis, indicates a shallow marine environment for the deposition of the sediments [7, 8]. The Navay deposit is a sandy phosphorite type, formed during the Lower Cretaceous, probably by upwelling currents which promoted phosphate deposition within the sediments. This deposit represents a lithological facies deposited in shallow waters and is locally of Campanian–Maastrichtian age [9].

The Navay Formation is a lateral equivalent of the La Luna Formation in western Venezuela, which contains black phosphorites and hydrocarbon-bearing black shales [10].

3.2. Chemical composition

The chemical analyses indicate that U and Ca are correlated with P, indicating that the mineral hosting uranium is apatite. There are strong correlations between P and Y (0.72) which may indicate the presence of yttrium in the phosphatic minerals, Ca–Mg (calcite), Ca–Sr (substitution of Sr²⁺ by Ca²⁺), Si with Al and K (silicates such as microcline and clays such as montmorillonite), Fe–S (possibly forming sulphides), Fe–V (associated in detrital oxides and/or in organic matter), S–V (possibly in organic matter), U with V and Ni (probably associated with organic matter, as well as the strong V–Ni correlation, which may be geochemically associated with porphyrins [11, 12].

In several samples, yttrium was detected. Yttrium is associated with phosphates and this may be due to the substitutions of Y^{3+} (ionic radius 0.93 Å) in the structure of the apatite by Ca^{2+} (ionic radius 1.12 Å). It is recommended that REE analysis using ICP-MS be undertaken or another analytical technique, since REEs cannot be detected using the techniques used in the present investigations. The REEs can be incorporated into the structure of the phosphate minerals owing to their geochemical affinity [2].

The V:Cr, V:V+Ni and V:Ni ratios, indicate that the Navay sediments were deposited under oxic conditions, without replacement. The Ni:Co ratios of several samples indicate that these sediments were deposited under sub-oxic to anoxic conditions [13, 14]. This difference may be due to the evolution of redox conditions during sedimentation as a result of upwelling currents that brought oxygen-poor water from the bottom to the surface. Another interpretation could be a remobilization, or a secondary dispersion of several of these redox sensitive elements under oxidative conditions during weathering.

3.3. Gamma spectrometry analysis

According to gamma spectrometric analysis of surface samples and cores, an average activity of 2100 Bq/kg produced by ²²⁶Ra was detected, in addition to other isotopes of the decay series of ²³⁸U. The ²²⁶Ra activity was measured (by measuring ²¹⁴Pb and ²¹⁴Bi activities) and ²³⁴Th activity directly through the emission at 63 keV. Owing to their low activites, the isotopes of the ²³²Th series and ⁴⁰K were not detected by this technique.

This implies that the concentrations of thorium in the deposit are low, in accordance with geochemical environments of this type, in which the U is mobilized as U^{6+} (uranyl ion UO_2^{2+}) and fixed in the apatite crystal structure as U^{4+} under reducing conditions, while Th^{4+} remains immobile in superficial environments and thus stays at low concentration in this type of deposit.

4. CONCLUSIONS

The mineralogy of Navay Formation is typical of marine phosphatic deposits with fluorapatite/chlorapatite, collophane or carbonate fluorapatite (Ca₅(PO₄,CO₃)F), uranospathite, quartz and calcite as the major phases.

The presence of autunite and wavelite is not ruled out, as these have been identified in samples from La Lucha River in Táchira State, which is an outcrop of the Navay Formation.

The mineralogical studies show that the uranium is present in the following forms: apatite (28-75%) and uranospathite (2-3%).

The fossil Orthokarstenia ewaldi of Upper Cretaceous age (Maastrichtian) indicates a shallow marine environment.

According to chemical analysis, the background concentration of U is 102 ppm, reaching a maximum value of 160 ppm in a calcareous phosphatic sandstone, so this occurrence can be considered as an unconventional uranium deposit type according to its U grade.

Statistically sub-anomalous values of Cd (82 ppm), Cu (261 ppm), Zn (268 ppm), Sr (1832 ppm) and Zr (510 ppm) and anomalous values of Cr (1653 ppm) were determined. These elements are interesting because of their geochemical association with uranium and phosphates and some of these may represent potential by- or co-products. In several samples, yttrium was detected (maximum of 144 ppm), which is associated with phosphates. It is recommended that REE analysis be undertaken using ICP-MS or another analytical technique, since REEs cannot be detected using the techniques used in this research.

The V:Cr, V:V+Ni and V:Ni ratios indicate that the Navay sediments were deposited under oxic conditions, but the Ni:Co ratio of several samples indicates that some of these sediments were deposited under sub-oxic to anoxic conditions and this difference may result from redox changes during sedimentation, produced by upwelling currents that brought oxygen-poor water to the surface regions.

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AN ESTIMATE OF URANIUM RECOVERY FROM PHOSPHORITE ORES

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1. INTRODUCTION

The bulk of the unconventional uranium resources worldwide are associated with phosphorite ores. Despite the ongoing depression in the global uranium market, intense research activity is under way in various countries with the objective of developing cost effective ways of uranium recovery from non-conventional resources. Annual global production of phosphorous pentoxide (P₂O₅) is about 50 Mt, including 9.5 Mt in North America, 9.4 Mt in Africa and 19.2 Mt in Asia. Up to 15 400 tU is contained in phosphorite ores mined worldwide each year, while practically no uranium production has been reported. The value of uranium produced as a minor by-product during phosphate fertilizer production is negligible when compared with value of the main product (phosphate fertilizer). Hence, the phosphate fertilizer market acts as a determining factor of how much uranium contained in the phosphate resources can be produced, and of its production cost parameters, which are closely tied to fertilizer production economics.

2. DESCRIPTION

According to the traditional technology, uranium is recovered from wet process phosphoric acid using solvent extraction (SX) based flowcharts, with octylpyrophosphoric acid (OPPA), di(2-ethylhexyl)phosphoric acid coupled with trioctylphosphinic oxide (DHEPA–TOPO) and octylphenylphosphoric acid (OPAP) used as extractants. The preliminary reduction of U(VI) to U(IV) is traditionally performed by adding iron powder (specific consumption of the iron powder being 8 kg/m³ of the source solution).

In 2009, Urtek LLC developed an alternative uranium recovery technology from phosphorites known as PhosEnergy and successively piloted it in Australia and the United States of America. The novel technology features ordinary ion exchange (IX) sorption of uranium from the wet process phosphoric acid followed by its desorption and yellowcake production using traditional methods.

Wet process phosphoric acid $(20-40\% H_3PO_4)$ coming directly from the phosphorite sulphuric acid treatment is used as the uranium source for the PhosEnergy process. The uranium sorption is combined with its oxidation from U(IV) to U(VI). The phosphoric acid, thus purified of uranium, is then returned to the main process stream. The PhosEnergy process can be essentially described as the decontamination of the wet process phosphoric acid of U and V without any waste or refuse forming.

In the former USSR, low grade, complex phosphate type ores of the Melovoye and Tasmurun deposits (northern Caspian Sea in western Kazakhstan) were mined for uranium. The ores of these deposits are represented by exotic assemblages of uranium, rare metal and phosphate occurring as bone detritus hosted by Maikop (Oligocene–Early Miocene) clays of deep marine origin which were deposited in the extensive marine palaeobasin of eastern Parathetys. Skeletal detritus of various marine palaeofauna in which the original bone tissue has been replaced by francolite, a phosphate mineral, is uniformly distributed throughout the ore mass. Both U and rare earth elements (REEs) are contained in the crystalline structure of francolite, partially replacing calcium ions in the lattice, with other valuable elements concentrated in pyrite which also occurs in the ores.

The yttrium group REE grade in the ores is uniquely high, totalling about 30-35% of the overall REE grade. The uranium reserves of Melovoye deposit, the largest ore deposit of the Transcaspian uranium region (Kazakhstan), have been estimated at 44 000 tU. The uranium recovery from the low grade ores (<0.05% U) was conducted by means of the hydraulic separation of the bone concentrate and the subsequent production of phosphate fertilizers from it during which uranium and valuable minor by-products were recovered (thorium, REEs, scandium, sulphur).

The francolite concentrate produced by the hydraulic separation and pre-concentration process consisted mainly of francolite with minor admixtures of residual clay minerals and pyrite. On average, the concentrate contained $\sim 25\%$ P₂O₅, up to 1% Ln₂O₃, 0.2% U and up to 0.04 % Sc. The dissolution of the concentrate was performed by using sulphuric acid or a sulphuric acid–nitric acid mix taken stoichiometrically against the calcium oxide contents in the concentrate [1].

The recovery of uranium from the resulting acid digestion solutions was conducted via SX with the final product being U_3O_8 . During the SX process, iron and scandium are co-extracted into the organic phase while both phosphorus and REE remained in the raffinate. Following the stripping of uranium from the organic phase, the stripping of scandium was made with 99.9% Sc₂O₃ finally produced as a by-product [1, 2].

Following the recovery of uranium and the valuable by-products, the acid technology solutions containing both phosphate and the residual sulphuric acid were further treated to produce a granulated complex 'ammophos' type fertilizer containing in excess of 50% N and P_2O_5 . The fertilizer production process consisted of the ammonization of the source solution followed by further concentration for which a countercurrent multiple effect evaporation scheme was employed. The resulting concentrated slurry was then granulated, dried, chipped and classified before packaging and shipping [1].

The final products of the ore processing, along with the fertilizers, were U_3O_8 , REE oxides and Sc_2O_3 . The total percentage recovery of the target elements was: U (93%), REE (54%), Sc (70%), P₂O₅ (85.5%) from the respective ore grades.

The technology described above was implemented in 1969 at Almaz Production Association (Lermontov town) and had been used with some minor adjustments until 1991. The processing of the ore concentrates sourced from the Melovoye deposit had been conducted at a plant in Dneprodzerzhinsk until 1989.

The Yergeninsky uranium ore district is situated in the Republic of Kalmykia and is a Russian Federation analogue of the Melovoye deposit. It comprises 13 uranium deposits hosted in Oligocene–Early Miocene clayey sediments of the Maikop Series, featuring the same complex uranium–phosphate–REE ores. The resource estimate for these, from the author's calculations, is 59 000 tU, 8 462 000 t P and 296 000 t REEs. The Shargadyk deposit is the most extensively studied one in the Yergeninsky uranium ore district.

The commercial resources of the deposit are uranium, phosphates and REEs. The main ore constituent is fossilized bone detritus (comprising 15–45% of the bulk ore) which contains the uranium and the REE resources. The detritus is associated with varying proportions of minor ferric sulphide, clay and carbonate constituents. It is essentially a calcium phosphate based mineral, mineralogically very similar to hydroxylized carbonated fluorapatite and containing some minor organic impurities.

In 2015–2016, a pilot plant run was conducted at the Shargadyk deposit to test the possibility of metal recovery from the ores by heap leaching. The sulphuric acid solution leaching of the agglomerated ore was successfully tested. The source ore was crushed to 100% -20 mm and then agglomerated before the leaching. The resulting ore agglomerate was placed into percolation columns measuring 1 m in diameter and 5 m in height. During the ensuing sulphuric acid percolation leaching, U, REEs, Ni and Co, along with P_2O_5 , went into solution for subsequent separation and recovery of individual products using IX sorption and selective precipitation. The results obtained during the pilot plant run were sufficiently successful to recommend the

heap leach processing of Shargadyk deposit ores occurring at a depth of up to 120 m, which can easily be mined using the open pit method.

The prospective process flowchart, which was tested and streamlined during pilot plant operation comprises the following stages and operations:

- (i) Ore preparation (mining, crushing, agglomeration, heap stacking):
 - Ore delivery to the heap leach site using dump trucks combined with the simultaneous transporting of the leached ore for disposal in old excavated parts of the open pit (up to 1500 t/d.
 - The ore crushing to 100% -20 mm (up to 100 t/h).
 - The agglomeration of the crushed ore with concentrated sulphuric acid and sodium silicate to be added into the process. The agglomerate is to be produced in a pipe type agglomerator. The ore throughput rate is up to 100t/h.
 - The stacking and formation of the ore heaps using a heap stacker with the subsequent pipelining at the rate of one heap (84 000 t of the agglomerated ore) every 2 months (up to 1500 t/d).
- (ii) The heap leaching of the ore heaps comprising the following operations:
 - Three-stage heap leaching at the rate of 6 ore heaps annually (84 000 t of agglomerated ore per heap). Two ore heaps are to be leached at a time to produce the heap leach solutions at the mean rate of 230 m³/h, draining into collector ponds.
 - The heap leach solutions are to be collected into 5 collector ponds as follows:
 - Two individual collector ponds Nos 1 and 2 (volume = 25 000 m³ each) are to receive stage 1 heap leach solutions (one to serve as a drainage reception unit, the other as an evaporation pond).
 - Collector pond No. 3 (volume = 5000 m^3) is to receive stage 2 heap leach solutions.
 - Collector pond No. 4 (volume = 5000 m^3) is to receive stage 3 heap leach solutions.
 - One collector pond (volume = 10 000 m³) is to be used for collecting the barren solutions to be pumped back and used for irrigation.
- (iii) The pregnant solution processing:
 - The IX sorption of nickel and cobalt to Lewatit TP 207 ionite to produce a Ni-Co concentrate.
 - The IX sorption of uranium to Lewatit K 1000 ionite to produce a U concentrate.
 - Adding magnesia (MgO) to the pregnant solution from the above operation to produce three separate phosphate precipitates of Fe, REE and Mg.
 - The sintering of iron and REE phosphate products (10 t/h) with sodium carbonate (5 t/h) in a natural gas heated tube kiln at 700°C.
 - Hot water leaching of sodium phosphate from the sintering product followed by the precipitation of secondary magnesium phosphate with sodium sulphate solution as a by-product.
 - The addition of sulphuric acid solution to the precipitates of the primary and secondary magnesium phosphate to produce a solution containing phosphoric acid and magnesium sulphate.
 - Adding lime to the above solution to produce a superphosphate precipitate and a magnesium sulphate solution. The rinsed residue of the hot water leaching of sodium phosphate from

the sintering product is to be leached with 50 g/L H_2SO_4 for REEs. The solution is to be treated with oxalic acid to produce the REE oxalate concentrate containing ~50% REEs (3 kg of concentrate/t ore). The oxalic acid leaching residue is then to be calcined to produce ferric cake (43 kg of cake/t ore), containing 180 g/t Sc and 45% Fe₂O₃.

• The evaporation of the post-precipitation solutions to produce magnesium sulphate and sodium sulphate products (5 t/h each) by crystallization.

The marketable products of the project are: superphosphate (P_2O_5 grade 27%, according to Russian Federation technical specifications (TV 2182-003-56937109-2002), uranium concentrate (ammonium polyuranate, grade no less than 60% U according to Russian Federation technical specifications TV 95.2822.2002), a 50% nickel–cobalt hydroxide mix concentrate (Ni: 37%, Co: 13%), a mixed hydroxide–oxalate REE concentrate containing ~50% REEs + Y. Marketable by-products obtained during the utilization of the leaching chemicals are sodium sulphate technical grade (grade 2 according to Russian Federation State standard GOST 6318-77), magnesium sulphate heptahydrate (GOST 4523-77) and construction grade sand (GOST 8736-2014).

The summary recovery rates for the key elements have been confirmed to be as follows: U: 84%, Ni: 76%, Co: 61%, $\Sigma REEs + Y$: 63%, P₂O₅: 77%, with the respective average content values in the dewatered source ore: U: 0.035%, Ni: 0.05%, Co: 0.02%, $\Sigma REEs + Y$: 0.28%, P₂O₅: 11%.

The solid wastes produced are ore processing tailings (mainly phosphogypsum), which is to be used as a backfill for the open pit upon depletion, and the ferric residue containing 180 g/t Sc to be stored on-site for the future recovery of scandium.

The value breakdown for the final products of the proposed heap leach plant is as follows: superphosphate (53%), uranium concentrate (17.6%), sodium sulphate (10.8%) and the REE concentrates (9.6%).

3. DISCUSSION AND CONCLUSIONS

The feasibility analysis was calculated on the basis of discount rates set at 10% and 15%. The ore resources of the projected plant are sufficient for 39 years of operation. The planning horizon used was assumed to equal 17 years.

The feasibility analysis conducted backs up the potential commercial profitability of the development and exploitation of the Shargadyk deposit resources. In the case where the discount rate is set at 10%, the net present value totals RUR 2661.4 million, the yield index is -1.2, the internal rate of return is 14.4%, the discounted payback period is 9.5 years while the discounted budget efficiency totals RUR 4607.1 million.

The main conclusions from the above pilot plant test results are:

- In the market scenario, the recovery of uranium and the associated metals from the Shargadyk complex phosphate ore deposit will be considered only when it becomes economically viable to do so.
- The development of the Shargadyk deposit of complex uranium–phosphate–REE ores appears to be commercially profitable.

The development project displays a reasonably high commercial and internal financial efficiency values in the case where the discount rate stands at 10%, although the efficiency appears to be problematic in the case where a discount rate of 15% is adopted.

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ACTION LEVELS FOR AIRBORNE NATURAL URANIUM IN THE WORKPLACE: CHEMICAL AND RADIOLOGICAL ASSESSMENTS

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1. INTRODUCTION

Intakes of natural uranium (U) present two hazards to workers, namely chemical and radiological. The consequence of too much intake can be chemically induced damage for which kidney is the primary target tissue, or radiogenic cancer for which lung appears to be the primary target tissue. The chemical damage to the kidneys depends on the concentration of U in the kidneys. Nephrotoxicity is thought to be the greater risk for inhalation of relatively soluble forms of natural U due to a high fractional absorption of U to blood and uptake and retention by the kidneys. The radiological risk of lung cancer depends on the radiation dose to the lungs. Lung cancer is thought to be the greater risk for inhalation of relatively insoluble forms of natural U due to extended retention of the inhaled material in the lungs. Neither the concentration of U in the kidneys nor the cumulative irradiation of the lungs can be directly measured, but both quantities can be assessed using biokinetic models.

2. DESCRIPTION

In the workplace the primary and most significant intake of U typically is from inhalation. Continuous measurements of the concentration of U in air at work locations can be used together with the most recent, internationally accepted models to estimate the concentration of U in the kidneys and the dose to the lungs from inhalation.

We reviewed the scientific literature to evaluate the relation of the concentration of U in the kidneys to various levels of levels of damage to the kidneys and to propose a limiting kidney concentration (called primary chemical guidance in the following) for U as a chemical hazard [1-9]. We used primary guidance of the International Commission on Radiological Protection (ICRP) as a limit on intake of U as a radiological hazard [10]. These primary guidance levels for U as chemical and radiological hazards were used, together with best available biokinetic and dosimetric models [11-13], to derive 'action levels' for U exposure in the workplace as represented by the concentration of airborne U.

Two levels of primary guidance are proposed for the purposes of avoiding chemical effects of U and limiting its potential radiological effects to ICRP's recommended levels defined in terms of effective dose. The lower level of primary guidance is used as the basis for determination of an investigation level (IL) of airborne U. An IL indicates the need to confirm the validity of moderately elevated measurements and adequacy of confinement controls and determining an immediate action level (IAL). An IAL indicates that safety measures should be put into place immediately, including removal of workers from further exposure until conditions are acceptable. An action level is reached if model predictions based on current air monitoring data, together with best available information on the form of U in air, that either the limiting chemical

guidance or the limiting radiological guidance could eventually be exceeded if the air concentration is not reduced. The lower level of primary guidance is 0.3 μ g U / g kidney for avoidance of chemical effects and 2.0 mSv y⁻¹ for limitation of radiological effects. The higher level of primary guidance is 1.0 μ g U / g kidney for avoidance of chemical effects and 5.0 mSv y⁻¹ for limitation of radiological effects.

For each of several different levels of solubility of airborne U, ranging from highly soluble to highly insoluble forms, models were used to predict the lowest concentration of U in air that would eventually yield the limiting U concentration in the kidneys of a chronically exposed worker. For each solubility level, a similar calculation was performed to predict the lowest concentration of airborne U that would eventually yield the limiting annual effective dose to a chronically exposed worker. The biokinetic models (and dosimetric models in the case of radiological considerations) used in these calculations were those recommended in ICRP Publication 137 [13].

For intake of a given concentration of U in air, both the effective dose and the peak kidney concentration depend on the solubility of the U compound, so that the IL and IAL both vary with the solubility of airborne U. ILs and IALs were derived for each of the Absorption Types (solubility classes) for U addressed in ICRP Publication 137 [13]. That report defines five Absorption Types for U, representing a range of dissolution levels. In order of decreasing solubility the five levels are as follows: Type F (fast dissolution, e.g., UF₆), Type F/M (somewhat slower dissolution than Type F, e.g., UO₂(NO₃)₂), Type M (moderately soluble, e.g., UF₄), Type M/S (somewhat slower dissolution than Type M, e.g., U₃O₈), and Type S (very slow dissolution; no examples are given in Publication 137 but presumably Type S would include high-fired oxides).

3. DISCUSSION AND CONCLUSION

To derive radiologically based action levels, we assumed that U contains 0.0057% 234 U, 0.72% 235 U, and 99.27% 238 U by mass. Despite its small percentage of mass, 234 U contributes significantly to the total dose, because its specific activity is on the order of 10,000 times greater than that of each of the other two nuclides. Effective dose coefficients for the assumed mixture of natural U isotopes were based on effective dose coefficients given in ICRP Publication 137 [13] for the individual isotopes. It was assumed that 234 U, 235 U, and 238 U represent 50.45% 2.2%, and 47.35%, respectively, of inhaled U, based on their relative masses and specific activities of 2.32 × 10⁸, 8.01 × 10⁴, and 1.25 × 10⁴, respectively [5].

The solubility of airborne U is a key variable regarding both the chemical and radiological risk to an exposed worker. If inhaled U is highly soluble, it is removed quickly from the lungs with a sizable portion being absorbed to blood and the remainder entering the alimentary tract. The absorbed U yields some radiation dose to systemic tissues, but most of the absorbed activity is removed in urine over a period of days. The main hazard from the absorbed U is thought to be its relatively high accumulation in the kidneys and its subsequent chemical effects on kidney tissue. If inhaled U is highly insoluble, much of it will be retained in the deep lungs for an extended period, possibly decades, and little will reach the systemic circulation. In this case, the main hazard from the inhaled U is expected to be its prolonged alpha irradiation of lung tissue, potentially leading to lung cancer. Thus, chemical toxicity to the kidneys is presumably the dominant risk from relatively soluble U in air, and radiological toxicity is presumably the dominant risk from relatively of airborne U. In terms of the Absorption Types defined in ICRP Publication 137, the chemical risk decreases in the order Type F > Type F/M > Type M > Type M/S > Type S, and the radiological risk decreases in the order Type S > Type M > Type F/M > Type F/M > Type F.

The radiological risk depends on the isotopic composition of U in air, as 234 U has a much higher specific activity than 235 U or 238 U. Calculations of chemical toxicity are simpler than those for radiological risk, because the chemical processes depend on the total mass of U in the kidneys and are independent of the isotopic distribution. Thus, for evaluation of chemical risk from a given concentration of U in air, it suffices to use a biokinetic model to predict the time-dependent mass of U in the kidneys. The biokinetic models

applied are taken from ICRP Publication 137 and are the same as those used to predict the distribution of inhaled radioactivity.

For a worker to be protected from both the chemical and radiological hazards of a given form of U, the lower of the limiting values based on chemical and radiological considerations should be applied.

Chemically and radiologically based ILs and IALS were derived using the biokinetic models, dosimetric models, and Absorption Types for U defined in ICRP Publication 137 [13]. A particle size of 5 μ m AMAD was assumed. This is the ICRP's default particle size for inhalation of radionuclides in the workplace.

The derived radiological IL in μ g m⁻³ for F is 1350; for F/M is 824; for M is 244; for M/S is 61.6; for S is 25.4. The derived chemical IL in μ g m⁻³ for F is 30; for F/M is 56; for M is 81; for M/S is 167; for S is 253. For example, for Type M the chemically based IL is 81 μ g m⁻³ and the radiologically based IL is 244 μ g m⁻³, so the chemically based value of 81 μ g m⁻³ is used as the IL.

The derived radiological IAL in μ g m⁻³ for F is 3376; for F/M is 2060; for M is 610; for M/S is 154; for S is 63.5. The derived chemical IAL in μ g m⁻³ for F is 101; for F/M is 188; for M is 272; for M/S is 563; for S is 845. The more restrictive is shown in boldface. For example, for Type M/S the chemically based IAL is 563 μ g m⁻³ and the radiologically based IAL is 154 μ g m⁻³, so the radiologically based value of 154 μ g m⁻³ is used as the IAL.

If the solubility is unknown, the most limiting action level should be used. Based on the above values, the most limiting IAL value is the chemically based limit of $30 \ \mu g \ m^{-3}$, assuming a particle size of $5 \ \mu m$ AMAD. Ideally the limiting air concentration would be based on site-specific information on the particle size as well as the solubility of airborne U.

There are several work environments where U may be inhaled in relatively high quantities. These include underground mining, surface mining, in situ leaching, phosphate processing, and heavy metal processing. Each of these has different characteristics of the solubility of the aerosols and the particle size. These characteristics must be identified and used to assess the applicability of models for the protection of the workers. In addition to U, there are other radionuclides that must be assessed and controlled. Radon and its progeny are particularly important for control in the workplace.

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REMEDIATION OF FORMER URANIUM MILL TAILINGS FACILITIES: CONCEPTS AND LESSONS LEARNED

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1. INTRODUCTION

Between 1946 and 1990 a total of 216 300 tU were produced by mining and milling facilities in the eastern part of the former German Democratic Republic [1]. A former Soviet and later Soviet–German (former German Democratic Republic) joint stock company was responsible for uranium production in the former German Democratic Republic prior to the German unification when uranium production was stopped for economic and political reasons. As successor of the uranium mining company Wismut GmbH is responsible for the remediation of the legacies of these former activities in the densely populated areas of the German Federal states of Thuringia and Saxony. The remediation activities are funded by the Federal Budget due to a decision of the German Parliament made in 1991 allocating a total budget of ϵ 6.2 billion for this purpose [1].

The remediation of the four largest mill tailings facilities, Helmsdorf, Dänkritz 1, Trünzig and Culmitzsch, with a total of approximately 160 Mm³ of tailings stored in an area of 570 ha, is part of this remediation project. Generally, the design of these tailings facilities was implemented without consideration of base sealing. Mill residues were dumped in former open pits or valley structures where up to 57 m high dams were erected to create additional storage volume. The processing sludge was transported through pipelines to the tailings facilities and discharged, predominantly from the outer rim of the ponds, resulting in a separation of the material by grain size, with fine particles mostly found in the centre of the ponds which lead to variable geotechnical and geochemical conditions occurring within the tailings facilities.

At the Seelingstädt site, as one of the two main milling sites, processing was done using either an acidic or alkaline processing scheme according to the ore composition. The residues of these schemes were dumped separately, resulting in two ponds within the two separate tailings facilities, Trünzig and Culmitzsch, located at the Seelingstädt site. Tailings from acidic processing were neutralized before being discharged. At the time of writing, while the works at the tailings facilities in Helmsdorf, Dänkritz 1 and Trünzig are nearly complete, contouring and covering works at Culmitzsch are still ongoing.

2. GENERAL REMEDIAL SOLUTION

The remediation of the former tailings facilities follows the same general strategy, while the particular technical solutions are adapted to the site specific conditions. Apart from the long term geotechnical stabilization of the tailings facilities, remediation activities have to ensure that the additional equivalent dose rate to the general public from all pathways has to be below 1 mSv/year [2].

The first securing measures against acute risks were implemented in 1991 when the beach areas were covered with an interim cover to stop deflation of fine radioactive particles. In parallel, additional effort was put into collection and treatment of contaminated waters. The mining and milling facilities are sited in a densely populated area, posing a high risk to the general public.

On the basis of a cost benefit analysis made in the mid-1990s, the dry in situ remediation concept was chosen as the general technical approach for stabilization and final closure. The analysis was made based on the
conditions of the Helmsdorf site, where it was found that dry in situ remediation is the most appropriate in terms of total costs among the potential remediation scenarios [3]. The dry in situ remediation of tailings facilities requires a set of technological steps. Expelling supernatant water and initiating interim covering and geotechnical stabilization of the dams and the tailings are preconditions for safe access to the site, but which also require an extended time frame. With sufficient capacity, contouring earthworks can proceed to gain a long term stable morphology, ensuring the safe discharge of surface waters and protecting the facility from erosion. A final cover on top of the contoured facility is required to control the infiltration of precipitation water and to ensure the correct conditions for the development and maintenance of a stable vegetative cover. This approach was generally adopted at all tailings management sites under the responsibility of Wismut. The necessary activities, as well as the status achieved, for example at the Seelingstädt site, are documented in more detail in Ref. [4].

An important aspect at all sites is the collection and treatment of seepage as well as contaminated surface water and groundwater. An extensive technical system, including treatment plants, utilizing lime treatment is available at all sites. This water collection and treatment system is also expected to be necessary in the long term to ensure the capture of contaminated waters, irrespective of the individual remediation solution adopted.

3. SITE SPECIFIC APPROACH

While the general remediation approach is implemented at all sites, a number of differences can be found locally owing to site specific conditions. The differences mainly consider the requirements for reduction of the infiltration of precipitation into the deposited tailings material, which are defined specifically for each site. At the Thuringian site in Seelingstädt, the covering concepts were intensively discussed between Wismut and the permitting authorities, which were supported by the services of a consultant in providing an extensive peer assessment. Throughout this time consuming process, the basic requirements for the planning of the covering and the final contours of the tailings facilities were established. This has led not only to differences in the cover concepts followed at the different sites but also at the individual facilities themselves.

The main focus in determining the site specific cover concept was the control of the expected long term contaminant release along with seepage water from the sites. It was found that this release very much depends on the properties of the tailings material itself and therefore varies widely over the facility. Another important factor was the availability of appropriate contouring and cover materials at the individual sites. Preference was given to locally available materials. Mine waste rock and process residues resulting from former mining activities were used for contouring and partly as cover material, depending on the radiological composition and technical requirements. This allowed reduction of the mining induced footprint at the sites and the importation of material from other sources. On the other hand, it required specific logistics to supply the materials with the required geotechnical and radiological characteristics, depending on respective remediation progress. At the Seelingstädt site, tailings were disposed of in former uranium open pits. Part of the waste rock material from the overburden at this location is classified as radioactive material. Material with elevated ²²⁶Ra activity concentration is used for contouring, while the cover has to be constructed using waste rock material with a specific activity of less than 0.2 Bq/g ²²⁶Ra or, as an alternative, with material from external sources.

At the Seelingstädt site, the reduction of infiltration rate received special focus. In contrast to the implementation of the evaporative cover concept at other Wismut tailings management sites, with a storage layer as the main functional layer, the cover system at the Culmitzsch tailings facility is more complex. By adopting steeper final contours, allowing shorter slopes, and providing an additional sealing and drainage layer, the predicted infiltration rate was reduced by more than 75% compared with the original, simpler, mainly evaporative cover concept. In addition to more specific material requirements for the various functional layers, the effort needed for implementation of such a cover system was considerably increased.

Therefore, this cover system is implemented only on top of the sandier tailings beaches that have a higher hydraulic conductivity. The areas with finer tailings will have significantly lower hydraulic conductivities over the long term, when compaction and pore water release will be finished, even if a different, simpler, cover approach is adopted. These processes of compaction and pore water release are enforced by additional drainage measures and by applying an additional load to ensure contouring generates a long term stable tailings surface and thereby exploits the inherent sealing properties of these layers. As a consequence of this self-sealing, the seepage rates are reduced more significantly over the long term than could have been achieved by a highly engineered cover system. This allows, while constructing the final cover for these parts, a design incorporating less stringent requirements as regards the long term infiltration rates to be achieved in the cover itself.

4. PRESENT AND FUTURE CHALLENGES

With construction works coming to an end, the benign nature of surface water runoff has to be ensured in the long term. Thus, the quality and quantity of the waters released from the former tailings facilities must be considered. Sufficient retention of heavy rainfall events is an important design criterion for the contouring, together with additional measures for temporary storage of runoff waters. On the other hand, compliance with the requirements for water quality has to be proven for the discharged surface waters which are to be released without additional treatment into the receiving streams.

Management of newly developed landscapes at the sites is required which extends beyond the end of the construction period. A landscape development concept is also one of the requirements for the necessary permits covering nature conservation aspects. This concept defines the final use, while allocating areas as open grassland or as forestry. The implementation of the landscape development concept is a lengthy process and requires effort for the necessary management and maintenance. This is essential, even with the main remediation concept, and foresees the development of the site to natural conditions where no further technical intervention measures are needed. However, predefined nature conservation prospects have to be achieved according to the permitting documentation.

Water collection, treatment and the storage of treatment residues is a task extending beyond the end of the construction period. Irrespective of a successful implementation of the remediation activities at the site, the necessity for water treatment is clearly expected owing to the long term release of pore water from static sources in the tailings facility as well as the remaining infiltration and throughflow of rainwater deposited on the tailings material. In addition, groundwater with elevated concentrations of contaminants is found in aquifers downstream of the tailings and influenced by seepage waters during the uranium production period. These concentrations will decrease slowly due to limited inflow from the covered tailings facility and its immediate surroundings.

Uranium has been in the main focus concerning the contaminants released by seepage waters since remediation works started. At present and over the longer term, salt load becomes more of a concern. While treatment of seepage and surface waters for uranium is state of the art and can be implemented, effective reduction of salt content faces technological and economic challenges, especially in terms of long term stable storage of the residues. It is thought that there is no feasible technological alternative available under the present site conditions. Owing to the continuous tightening of environmental standards and requirements, additional long term efforts will be needed beyond the time frame of the remediation works at the site itself.

After finishing the construction work, environmental monitoring and maintenance are required under the provisions of the permitting process. Firstly, the success of remediation has to be demonstrated. Further, the achieved status has to be ensured after remediation by regular maintenance of the constructed elements. While simple cover systems based solely on a sealing and evaporative cover concept should show natural behaviour by adjusting to specific site conditions, for other engineered elements with specific functions such

as drainage or water discharge, any potential deterioration has to be avoided and maintenance will be required over the very long term.

5. DISCUSSION AND CONCLUSIONS

The operation of uranium mill tailings storage facilities impacts not only the radiological conditions at the site but also other environmental media. Remediation faces complex requirements aimed at reduction of potential risks and current impacts, in combination with the need to stimulate the long term use of the site under strict economic constraints. As the examples of the legacies of former mining and milling sites demonstrate, a sound closure concept defining the status to be achieved after operation is not just necessary for mining permits but also an essential requirement for the operator. However, the time frame of remediation activities clearly extends beyond the period of construction work and has to be considered, in terms of effort and costs, at an early stage in the planning procedure. These long term activities in most cases comprise monitoring and maintenance, especially at sites with radiological hazards, but can also require costly water management and treatment facilities. A sound funding for these activities has to be ensured so as not to undo the good work of the initial remediation work.

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QUANTITATIVE MINERAL RESOURCE ASSESSMENTS OF ROLL-FRONT AND CALCRETE URANIUM IN SOUTHERN TEXAS AND THE SOUTHERN HIGH PLAINS PROVINCE OF THE UNITED STATES OF AMERICA: RESULTS AND SIMPLE ECONOMIC FILTER ANALYSIS

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1. INTRODUCTION

The US Geological Survey (USGS) recently completed two uranium mineral resource assessments in the south-central United States of America as part of a re-evaluation of domestic resources previously considered by the 1980 National Uranium Resource Evaluation Program [1]. These new assessments include: (i) in 2015, an assessment of undiscovered roll-front uranium resources in Tertiary coastal plain sediments of southern Texas [2], and (ii) in 2017, an assessment of undiscovered calcrete uranium resources in Pliocene and Pleistocene carbonate-rich sediments of the Southern High Plains region of Texas, New Mexico and Oklahoma [3]. Roll-front uranium in southern Texas has been recognized since the mid-1950s. Calcrete uranium, however, a deposit style known elsewhere around the world but previously unreported in the USA, was only brought to the attention of the USGS in 2015 after two small deposits (Buzzard Draw and Sulphur Springs Draw) and several prospects were recognized in northern Texas in the mid-1970s [4].

2. METHODS AND RESULTS

The roll-front assessment was conducted using a combination 3-part quantitative [5] and weights-ofevidence qualitative mineral potential modelling [6] methods, and identified 54 000 tU, with 85 000 tU estimated mean undiscovered. The calcrete assessment was conducted using the 3-part quantitative method, and identified 1000 tU, with 15 000 tU estimated mean undiscovered. Collectively, they total about 155 000 tU.

3. DISCUSSION AND CONCLUSIONS

If these identified and estimated undiscovered uranium resources are economic, and if the identified resources are mined and undiscovered resources found and produced, this represents nearly 8 years of US civilian nuclear power reactor fuel requirements (based on an annual requirement of approximately 19 500 tU [7]). A simple economic filter was used to investigate whether the undiscovered uranium resources could be economic in relation to known and/or produced regional and global uranium resources. The filter is based on the Pareto principle, and uses uranium resource data from the IAEA global UDEPO database [8] and a USGS database for southern Texas [9]. Given the uranium resource endowment (size) of deposits regionally and globally, and the current market prices for uranium (approximate price of US 20/pound U₃O₈ or US 52/kgU, as of October 2017), the results suggest that: (i) the undiscovered calcrete uranium resources are not likely to be currently economic, and (ii) the undiscovered roll-front resources are economic in the context of regional (southern Texas) uranium production considerations and setting, but marginal to sub-economic when regarded in a larger, global context.

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URANIUM PROVINCES OF THE WORLD

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1. INTRODUCTION

Uranium deposits in continental blocks of the Earth are distributed rather randomly and form uranium provinces and districts. The expression "uranium ore province" is used to denote a block of the earth's crust, characterized by the occurrence of uranium deposits of a certain type (or types), the main features of which result from the specifics of the ore-forming process and the peculiar geotectonic position.

When systematizing uranium targets, great importance was attached to the ore hosting environment and geotectonic conditions of ore formation during the early stages of crustal evolution, and for particular areas, their relation to the main typomorphic structures (arcogenic, taphrogenic, orogenic, epeirogenic) and derivatives of their activation of different ages was considered to be the controlling factor. The analysis of extensive material is aimed at the identification of new patterns and prognostic criteria for commercial uranium mineralization identification in various regions of the world.

2. METHODOLOGY AND RESULTS

The research described in this abstract is based on a historical–geological approach, which makes possible the systematization of the data on uranium geology, geochemistry, geophysics and metallogeny in various countries and continents and in order to develop a unified research base. Most of known uranium ore deposits and numerous (95) ore areas ranked as provinces and regions on five continents were analysed as part of the study [1–3].

Results of original palaeotectonic and palinspastic reconstructions were used for analysing uraniferous areas. It is shown that geological structures of arcogenic (dome) and taphrogenic (rift) origin played a leading role in uranium metallogeny since the Early Precambrian. Two global generations of major orebearing dome structures of different age have been identified: the Archaean (3.2–2.5 Ma) generation of domes and the Palaeoproterozoic (2.5–1.6 Ma) generation of granite–gneiss domes. The identified generations of dome structures differ in internal structure and metallogeny mainly as a result of the structure and evolution of the granitized substrate. The metallogenic uranium zoning of the continents made it possible to identify transcontinental marginal and intracontinental ore-bearing megabelts and extensive ore clusters in areas of megabelt telescoping [1].

Totally, 12 global megabelts have been identified on the continents, including marginal continental: 1 – East Pacific with Cordilleran and Andean fragments, II – West Pacific; and inland: III – East African, IV – Damara-Katanga, V – Karpinsky, VI – Baltic–Carpathian, VII – West Siberian–Central Asian, VIII – East Siberian–Gobi, IX – Chara–Aldan, X – Central Australian, XI –Wollaston, XII – Grenvillian. In areas of megabelt telescoping (Middle European, Middle Asian, Mongolian–Transbaikalian), uranium resources are up to 500 000–1 500 000 tU, but similar amounts are sometimes also typical of some provinces inside the megabelts (Athabasca, Colorado–Wyoming, Arnhem Land, Olympic Dam).

Two large groups, distinguished on the basis of the degree of lithification of the uranium-bearing rock complex, corresponding to main geological structures and genetic classes of uranium deposits are high order elements used to categorize uranium areas.

The first group consists of ore provinces and regions with ore deposits hosted in lithified rock complexes in the basement of old and young platforms, median massifs, fold areas, ancient epicratonic depressions and in areas of continental volcanism and granitoid magmatism (endogenic and polygenic classes of deposits). Among them, ore provinces are distinguished in typomorphic proto-structures of domes and activation structures of different age.

Commercial uranium concentrations in domes appear at the final orogenic stage and are often clastic formations resulting from the accumulation in placers of accessory uranium-bearing minerals from Late Archaean potassium granite and pegmatite. Such metamorphosed placers in quartz-pebble conglomerate are typical of proto-orogenic depressions, occurring as 'spots' along the periphery of domes of mainly antiform (uninverted) type, e.g. Superior, East Brazilian, South African and other megaprovinces. With some epochs of dome activation, a number of provinces and regions with deposits of various types are associated: carbonatite in alkaline ring structures of different age (Ilimaussaq, Palabora, Khibiny, etc.); black shale type in superimposed foreland basins (South China, Carpathian and other provinces); leucogranite type in fault zones among the Mesozoic highly radioactive rocks in association with rare metal mineralization (Gan–Hang, Kerulen–Argun ore belts) [1–3].

Uranium mineralization accompanies all stages of the formation and transformation of dome structures of second generation (dome uplift stages). The formation of typomorphic structures of domes of this generation started at the stage of destruction, subsidence and collapse of the roof. Provinces in the fault contact alaskite (Rössing), albitite (Kirovograd) and glimmerite (Padma) types are associated with similar structures.

Ore provinces in proto-structures of Riphean granite–gneiss domes near zones of structural–stratigraphic unconformities at the base of basins belong to polygenic ones (Canadian and Australian subtypes). In the Riphean–Phanerozoic, in some provinces (Franceville, Czech Republic, Katanga), regeneration of ore deposits occurred near the unconformity surfaces with a change in their morphology and scale of mineralization [3].

The second group includes ore provinces and areas with deposits in weakly lithified or unlithified rock complexes, in sedimentary basins of covers and young platforms (exogenous class of deposits).

This group includes provinces with syngenetic concentrations of uranium (surficial, with carbonized residues, phosphate, black shale types) and provinces with epigenetic sandstone type hydrogenous deposits represented by stratabound, roll-front and palaeovalley types. Ore provinces were formed in sedimentary basins in the central (destroyed) parts of dome structures and in the inter-dome space within rift structures.

Syngenetic type provinces are characterized by the constant relationship between uranium and phosphorous and carbonaceous matter (Phosphoria, Chattanooga and other provinces) [3]. For most of the epigenetic provinces possessing hydrogenous deposits in suborogenic depressions and platform covers, overlapping ancient dome structures, the role of linear, linear–arcuate faults in sedimentary basin deposits (cis-Tian Shan Province, Colorado Plateau, etc.) is emphasized. Faults play an important role in the localization of hydrogenous uranium mineralization in or near the flanks of petroliferous areas, which are sources of gas–liquid reducing agents (south Texas, central Kyzyl–Kum province) [1, 3].

The identified patterns and spatial position of ore districts and provinces allow drawing several conclusions concerning the prediction of the ore grade within their limits. The relation of uranium ore districts to similar geological structures does not always mean a similar level of ore grade. The authors suggest that the parameter termed the 'maturity' of the crust can serve as a regional criterion for predicting rich endogenous ores. This level of maturity clearly correlates with the level of average uranium concentrations in the granitoid formations of dome structures.

In addition, there are ore formation types of uranium mineralization which differ significantly in ore grade. Therefore, there is a group of ore deposits characterized by low grade ores but with immense reserves: Archaean (3.1–2.7 Ga) quartz-pebble conglomerate (Witwatersrand, South Africa), uranium-bearing black shale (south-western Sweden), phosphorite (Morocco), pegmatite (Charlebois, Canada), nepheline syenite (Ilimaussaq, Greenland), anatectic alaskite granite (Rössing, Namibia), carbonatite (Palabora, South Africa), calcrete (Yeelirrie, Australia) and uranium–coal deposits (Nizhneiliyskoe, Kazakhstan). However, the formation type of mineralization does not guarantee that the ore grade will be similar.

The characteristics of ore hosting rocks do not always affect significantly the degree of concentration of uranium mineralization. The role of lithological factors as well as structural factors in the localization of rich mineralization cannot be considered separately from the nature of metasomatic transformation. Extensive areas of pre-ore metasomatism testify to the relative open system behaviour of hydrodynamic systems and is evidence of the dilution of ore forming solutions. Closed hydrodynamic systems that ensure the presence of high metal concentrations in solution and local, contrasting zones of wall-rock alteration are more conducive to the formation of rich ores. Probably, the alkaline solution containing H₂, H₂S, S⁻², CH₄, hydrocarbons, Fe⁺² and other reducing agents is initially most suitable for the formation of a large volume of rich ores. Highly concentrated brine with salt complexes is one of the sources of heated waters. The ore grade of 'hydrogen' deposits is also controlled by several ways of ore deposition. If the reduction barrier contains only syngenetic reducing agents (with a primary grey colour), the ores are usually poor. The epigenetic preparation of the barrier to ore deposition can be a result of the action of ascending reducing thermal waters and lateral migration of hydrocarbons from neighbouring oil and gas basins.

3. CONCLUSIONS

When analysing the large volume of factual material, a number of important factors of uranium geology and metallogeny were discovered: linear–geoblock divisibility of the continental crust as the basis of metallogenic zoning on global and regional scales; factor of geological time in ore genesis; factor of tectono-physical correspondence of global and local geotectonic settings.

Many of the discussed problems are beyond the scope of uranium metallogeny but allow discussion of a number of basic factors of uranium metallogeny from a new perspective.

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URANIUM MINERALIZATION IN THE KHETRI SUB-BASIN, NORTH DELHI FOLD BELT, INDIA

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1. INTRODUCTION

The Palaeo-Mesoproterozoic North Delhi Fold Belt (NDFB) [1, 2] of the Aravalli craton is trending NE– SW, extends from Delhi in the north to Ajmer in the south and covers parts of Rajasthan and Haryana states. The NDFB is characterized by the presence of syn-kinematically emplaced granites that have been dated to 1.73–1.70 Ga (combined zircon U–Pb ages and Lu–Hf isotope data) [3–5]. From west to east, the belt comprises three sub-parallel volcano-sedimentary sub-basins, namely, Khetri, Alwar and Lalsot-Bayana. Among them, the Khetri sub-basin is identified as an important host for copper [6], uranium [7–12], molybdenum, iron and fluorite mineralization. This paper deals with the uranium mineralization of the Khetri sub-basin and summarizes its geological attributes and potential for hosting uranium deposits.

2. GEOLOGICAL SETTING

The folded sequences of the Palaeo-Mesoproterozoic Delhi Supergroup form a narrow belt extending from Haryana in the north to Gujarat in the south. The belt is further subdivided into the older NDFB and younger South Delhi Fold Belt (SDFB) [2]. This subdivision is based largely on the Rb–Sr whole rock isochron data from syn-kinematically emplaced granites in the NDFB and SDFB, which have been dated to 1.65–1.45 Ga and ~0.85 Ga, respectively [4, 5]. These belts are separated by a migmatitic gneiss tract around Ajmer [2].

The Mangalwar Complex of banded gneiss forms the basement and comprises high grade metamorphic and migmatized rocks in the southern parts of the Alwar sub-basin. The grade of the regional metamorphism recorded in the rocks of the Delhi Supergroup is up to amphibolites facies.

The Khetri Sub-basin (KSB) exposes rocks of the Delhi Supergroup over a basement comprising gneiss, paragneiss and mica schist of the Mangalwar Complex. The Delhi Supergroup in this sub-basin is further subdivided into the Alwar Group, followed by the Ajabgarh Group with gradational contact. The Alwar Group comprises mainly arenaceous units and the Ajabgarh Group is predominantly argillaceous and calcareous. Occurrence of felsic tuff has been recorded in quartzite in the upper part of the Ajabgarh Group, which has been dated at 1830 Ma [3]. The KSB lithological units have experienced three phases of deformation related to the Delhi orogenic cycle [13, 14]. The first and second phases of folding are coaxial and trending in a NE–SW direction. F1 folds are isoclinal and F2 folds are normal, upright to inclined with a moderate northerly plunge. F3 folds have their axial plane trending along a WNW–ESE direction. The Delhi Supergroup rock units have experienced two major events of regional metamorphism. The first phase of metamorphism is prograde up to amphibolite facies while the second phase of metamorphism is retrograde to greenschist facies. Several phases of acidic and basic igneous activity, including emplacement of granites and pegmatites, have been recorded in the sub-basin.

This sub-basin is characterized by the presence of broad zones of albitization [15–17], including a 20-km linear zone in the Khandela–Kerpura–Guhala sector of the southern Khetri copper belt [12]. Two other zones in the Maonda–Sior sector of the northern Khetri copper belt and in the Sakun Ladera sector of the NDFB define a narrow zone of approximately 170 km length trending in a NNE–SSW direction. Ray [15] describes this zone as the 'albitite line', indicated by linearly arranged albitite and albitized and alkali metasomatized rocks along deep-seated fracture zones. The majority of the lithological units in the vicinity of the albitite zones have been affected by albitization. These albitite zones follow a NNE–SSW trend which is also the trend of the Kaliguman and Khetri lineaments. A few other albitite occurrences have been subsequently reported by other researchers. These form a linear zone about 130 km in length and 5–12 km in width from Neorana in the north to Nayagaon in the south. This zone has a regional NE–SW trend and forms another albitite line about 20–40 km east of the known albitite line [17]. The Narda polymetallic occurrence is reported along this albitite zone. Thus, different episodes of albitization have been observed in this sub-basin.

3. URANIUM MINERALIZATION

Uranium exploration, including 'heliborne' geophysical, ground radiometric, hydro-geochemical, lithogeochemical and pedo-geochemical surveys carried out in this sub-basin by the Atomic Minerals Directorate for Exploration and Research helped in delineating several potential zones for uranium mineralization [18– 22]. Multi-parametric, high resolution heliborne geophysical surveys, including aeromagnetic, frequency domain electromagnetic and time domain electromagnetic surveys and gamma ray spectrometry identified potential zones for U mineralization within the Ajabgarh Group in soil covered areas. Ground geophysical surveys in selected blocks helped in delineating low magnetic, high chargeability trends and low resistivity zones for further exploration. Radiometric surveys undertaken during the past six decades have discovered more than 400 radioactive anomalies. These anomalies are predominantly confined to lithological units of the Ajabgarh Group and are associated with structurally weaker and altered zones.

The KSB can be sub-divided into three blocks: southern, central and northern. The central block, extending from Rohil, to the south of the Kantli lineament, is characterized by intensive albitization and other types of alteration and contains most of the uranium occurrences and polymetallic mineralization. The Rohil and Jahaz uranium deposits are located in this block. The southern block extends from Rohil to Khatundra in a NE–SW direction and is characterized by weaker albitization and fewer uranium occurrences compared with the central block. The northern block, extending from the north-east of Kantli lineament to Narnaul, is characterized by the presence of extensive copper mineralization, fewer uranium occurrences and less albitization. Uranium occurrences in the KSB are broadly associated with two NE–SW trending (eastern and western) albitite zones. Rohil, Guman Singh Ki Dhani, Narsinghpuri, Maota, Jahaz, Bagholi uranium occurrences are associated with the western albitite zone, while Buchara, Ladi Ka Bas, Geratiyon Ki Dhani, Kalatopri, Rela–Ghasipura are associated with the eastern albitite zone.

4. DISCUSSION AND CONCLUSION

Uranium exploration in the Khetri sub-basin resulted in the discovery of a low grade, medium tonnage metasomatite type uranium deposit at Rohil and significant uranium occurrences in the contiguous area, i.e. Jahaz–Maota–Bagholi, Narsinghpuri, Guman Singh Ki Dhani, Hurra Ki Dhani, Ladi Ka Bas, Geratiyon Ki Dhani in Rajasthan state and Rambas–Gorir in Haryana state. They are undergoing further exploration and evaluation. Uranium mineralization in the KSB is mainly associated with deep seated fractures/shears and F2 folds affected by intense hydrothermal activities and is preferentially hosted by sheared/fractured, albitized and altered metasediments, i.e. quartz–biotite–chlorite schist, quartzite, carbonaceous/graphitic phyllite, quartz–amphibole schist and calc-silicate of the Ajabgarh Group. Alterations recorded in this area correspond to albitization, chloritization, silicification, sericitization, calcitization and sulphidization [22]. Uraninite is the dominant uranium mineral, in addition to minor brannerite and coffinite. Uraninite occurs in clusters, as disseminations of subhedral grains and in veins. The geochemistry of the mineralized rocks

indicates polymetallic (U–Cu–Mo) mineralization associated with sulphides such as chalcopyrite, molybdenite, pyrite and pyrrhotite. The uranium mineralization of the KSB is similar to the metasomatite type deposit [23], especially with the Na-metasomatite subtype of Australia, Brazil, Canada, Guyana and Ukraine, as indicated by its close association with the albitite zone, high Na₂O content and high Na₂O/K₂O ratio. The presence of coarse-sized dispersed uraninite in the albitite veins also supports a close relation between albitization and uranium mineralization. The uranium mineralization ages at Rohil and Jahaz are 830 ± 5 Ma and 841 ± 26 Ma, respectively [24].

Currently, heliborne geophysical data are being utilized in conjunction with detailed surface and sub-surface geological, geochemical and geophysical investigations for prioritizing potential target areas for uranium mineralization in other parts of the Khetri sub-basin and for follow-up exploration. High chargeability zones with low magnetic anomalies have emerged as a geophysical guide to exploration for concealed uranium mineralization in the Khetri sub-basin.

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HYDROMETALLURGICAL CONTROLS ON ARSENIC, MOLYBDENUM AND SELENIUM IN URANIUM MILL EFFLUENT AND TAILINGS

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1. INTRODUCTION

Contamination of groundwater and surface water by arsenic, molybdenum and selenium derived from both natural and anthropogenic sources is an issue of global concern. Uranium-bearing ore material often contains all three of these elements and sulphuric acid leaching of these ores results in the liberation of all three. In the hydrometallurgical process for uranium purification and concentration, these elements must be separated from uranium either via solvent extraction or ion exchange processes to achieve the required product quality for uranium ore concentrate. Often, these elements are of little or no economic value to the operator. As a result, arsenic, molybdenum and selenium are treated with the waste streams and must be removed prior to reusing the water in the process (to avoid a circulating load) or release of treated effluent to the receiving environment.

The arsenic, molybdenum and selenium (among other elements and radionuclides) removed from the uranium mill process wastewater are often combined with the mill tailings, and the final mill tailings are ultimately emplaced in engineered tailings management facilities. For best practice, the precipitated arsenic, molybdenum and selenium should be geochemically stable and should not dissolve in the tailings management facility, since transport of arsenic, molybdenum and selenium from the tailings facility to the local groundwater or surface water system has the potential to negatively impact the regional biota. It is therefore important for uranium processors to have well-defined and effective effluent treatment processes. In addition, the operational process must ensure geochemical stability of the elements emplaced in the engineered tailings management facility.

2. DESCRIPTION

The Key Lake uranium mill is located approximately 650 km north of Saskatoon, Saskatchewan, Canada. The climate is sub-arctic with a mean annual temperature of 4°C (ranging from -45° to 25°C) [1]. The mill is located within the Athabasca Basin which contains the world's richest uranium deposits. The Key Lake mill began production in 1983 and two open pit mines were in operation from 1983 to 1997. Stockpiled ore continued to feed the mill from 1997 to 1999 and in 1999 the Key Lake mill began to receive ore from the McArthur River mine located approximately 80 km to the north [2].

The Key Lake mill blends the high-grade ore from the McArthur River mine ($\sim 18\% U_3O_8$ wt%) with low grade ($\sim 0.2\% U_3O_8$ wt%) material already stockpiled at the Key Lake uranium mill. The resulting leach feed slurry head grade is about 5% U₃O₈. Leaching of the leach feed slurry takes place in agitated leach tanks where sulphuric acid and oxygen are added along with steam. Retention time is approximately 24 h and the resulting uranium recovery averages 99.2%.

Following the leaching process, the undissolved sandstone material is separated from the leach aqueous solution in a series of eight thickeners. Acidic wash water is introduced in a counter current fashion to wash

adsorbed uranium from the leach residue solids. This occurs at each stage of thickening. The resulting leach aqueous solution is then fed to the solvent extraction circuit where the uranium is purified and concentrated. The resulting purified and concentrated uranium-bearing loaded strip solution is then forwarded to the yellowcake precipitation circuit where the uranium is precipitated as ammonium diuranate. The ammonium diuranate precipitate is thickened, washed, dewatered and then calcined at 850°C to produce a jet-black free flowing uranium oxide powder.

The uranium-free waste aqueous solution from the solvent exchange process (raffinate) contains the dissolved metals (including arsenic, molybdenum and selenium) and radionuclides liberated in the leaching process. This solution is forwarded to the effluent treatment process and mixed with other process wastewaters. The mixture of waters is progressively neutralized with lime in a series of four pachucas with target pH of 1.2, 3.5, 6.5 and 9.5 [3]. Barium chloride is also added at the second stage of neutralization to co-precipitate ²²⁶Ra as (Ba/Ra)SO₄. The chemical precipitates formed in this neutralization series are settled in a thickener. The overflow solution is pH adjusted with dilute acid to a target pH of 6.2. The solution is forwarded to a final clarifier before being transferred to monitoring ponds for analysis and certification before being released to the environment. 'Off-spec' treated effluent is redirected to a contaminated water reservoir and reintroduced to the effluent treatment circuit for reprocessing.

This effluent treatment scenario resulted in removal efficiencies for arsenic, molybdenum and selenium of 99.8%, 21% and 19%, respectively. Correspondingly, the average daily concentration of arsenic, molybdenum and selenium in the Key Lake mill final effluent was 0.006 mg/L (n = 81; range = 0.003–0.017 mg/L; standard deviation = 0.002), 0.74 mg/L (n = 81; range = 0.27–1.8 mg/L; standard deviation = 0.27) and 0.073 mg/L (n = 81; range = 0.052–0.094 mg/L; standard deviation = 0.010), respectively. This resulted in average annual loadings of arsenic, molybdenum and selenium of 9 kg/year, 1110 kg/year and 110 kg/year, respectively, to the downstream receiving environment.

Environmental studies in the downstream receiving environment of the Key Lake mill effluent concluded that Mo and Se could have an impact if loading of these elements to the lake sediments was not reduced. Arsenic, at the annual current loading, was determined as not having an impact on the downstream receptors. The environmental studies further concluded that if annual loadings of Mo and Se remained below 600 kg and 40 kg respectively, the long-term impact would be reduced to a level that was in keeping with the original environmental impact statement for the Key Lake mill. Therefore, technical and operations personnel were required to enhance the current effluent treatment process to increase the removal efficiency of Mo and Se while at the same time not increasing the loading of As (or other elements of concern) to the environment.

In an effort to increase the removal efficiency of Mo and Se and subsequently reduce the concentrations of the elements in the mill's final effluent, several treatment options were evaluated and tested. These options included:

- Reverse osmosis;
- Ion exchange;
- Co-precipitation of oxyanions with ettringite;
- Reduction and adsorption with zero valent iron;
- Microbial reduction;
- Photocatalytic reduction using UV light and TiO₂;
- Adsorption of oxyanions to ferrihydrite followed by gypsum encapsulation.

The criteria for testing and ultimately selecting a treatment option included the following:

- The selected option must integrate well with the current processing infrastructure;
- The selected option must be capable of achieving the desired targets on a consistent basis;

- The selected option must not increase the concentration of any other regulated/non-regulated element in the mill's final effluent;
- The selected option must be robust and circuit availability (uptime) must not be affected (currently was at 95% uptime);
- Capital and operating costs must be considered when selecting a final option.

3. DISCUSSION

The above noted seven treatment options were evaluated and tested on the basis of the identified criteria. A brief summary of the results of each treatment option is summarized:

1) Reverse osmosis:

Reverse osmosis was considered as a processing option to remove arsenic, molybdenum and selenium from the mill effluent. Results showed that the high concentration of Ca and SO₄ in the effluent (near saturation) feeding the RO system resulted in significant scaling and rapid fouling of the RO membranes. As a result, this technology was not considered further.

2) Ion exchange:

Ion exchange resins were tested for their affinity for arsenic, molybdenum and selenium. In all cases, the high ionic strength of the mill effluent (saturation with respect to Ca and SO_4) resulted in scaling of the column and resin beads and also resulted in excessive back pressure on the column. This caused flow restrictions in the ion exchange columns in all resins tested. As a result, this technology was not considered further.

3) Co-precipitation of oxyanions with ettringite:

Ettringite (Ca₆Al₂(OH)₁₂(SO₄)₃) precipitates from solutions containing Al, Ca and SO₄ at high pH levels (pH >11) [4]. Selenium (as selenite or selenate), arsenic (as arsenite or arsenate) and molybdenum (as molybdate) can substitute for SO₄ in the ettringite lattice, thereby removing these elements of concern from solution. Results from testwork showed that Se was removed solution but not to the level required. Removal efficiencies for As and Mo were not improved with this chemical treatment process. Finally, to effectively precipitate ettringite the addition of aluminium was required at stoichiometric levels and this resulted in an increase in the concentration of aluminium in the mill's final effluent. This was not acceptable as Al in the effluent can have a negative impact on downstream receptors. As a result, this technology was not considered further.

4) Reduction and adsorption with ferrous iron or zero valent iron:

Testwork results showed that selenium removal improved when ferrous sulphate ('green rust') was added to the water stream at $pH \sim 4$. However, this option was not pursued further owing to excessive sludge levels to tailings and high reagent costs when compared with marginal improvement in process performance. The zero-valent iron in the form of iron filings was also tested on a bench scale, again yielding marginal improvement, and was observed to be prone to surface passivation.

5) Microbial reduction:

The use of microbes to electrochemically reduce arsenic, molybdenum and selenium to their elemental form thereby significantly reducing the concentration of these elements of concern in the final effluent, combined with a geochemically stable species in the mill tailings was evaluated. Results showed that it was difficult to sustain the biomass as it was sensitive to changes in

temperature and redox conditions. Further, traces of solvent extraction organic carry over into the raffinate also had a detrimental effect on the biomass. Results further showed that these aspects would cause a rapid deterioration in the biomass and it took several days for the biomass to recover. Should this happen at the plant scale, if the process were to be implemented, the resulting mill's final effluent has the potential to be 'off-spec' with respect to Mo and Se for several days while the biomass stabilizes. This was unacceptable from a process perspective. As a result, this technology was not considered further.

6) Photocatalytic reduction using UV light and TiO_{2:}

Photo-assisted electrochemical reduction of oxyanions (e.g. As, Mo and Se) using semiconductor particles as catalysts was investigated. Of all semiconductors, titanium dioxide is suited for photocatalytic processes [5–7]. Titanium dioxide is highly stable, non-toxic and has the potential to be reused following its recovery from the treated effluent stream. The ability of titanium dioxide to function as a photocatalyst arises from its semiconducting properties. Illumination of semiconductor particles with electromagnetic radiation (e.g. UV light) of energy greater than their band-gap results in the promotion of an electron from the valence band to the conduction band. This process generates pairs of electrons (e⁻) and holes (h⁺) in the conduction band and valence band, respectively. The conduction band becomes electron-rich, and hence possesses a reducing ability, while the valence band hole is deficient of electrons, thereby possessing an oxidizing ability. Titanium dioxide has an adsorption affinity for oxidized oxyanions. In the context of Se(IV) or Se(VI) reduction, the conduction band electrons produced by electromagnetic radiation are transferred to either the adsorbed Se(IV) or Se(VI) species, reducing them to elemental Se. The same mechanism was hypothesized for As and Mo oxyanions in solution.

Results on clean distilled water spiked with arsenic, molybdenum and selenium (as AsO_4^{3-} , SeO_4^{2-} and MoO_4^{2-}) and showed excellent results for Se removal with >99% of the Se converted to elemental Se. Removal efficiencies for As and Mo were lower (10% and 15%). This was attributed to a lower adsorption affinity of TiO₂ for As and Mo oxyanions. The application of photocatalytic reduction using UV light and TiO₂ was also tested on Key Lake mill effluent. Results showed significantly reduced removal efficiencies for arsenic, molybdenum and selenium compared with results achieved with spiked clean distilled water. Removal efficiencies of 48%, 5% and 7% were observed for Se, As and Mo, respectively. The difference was the reduced photon flux from the UV light in the mill effluent sample due to the higher total dissolved solids concentration. On the basis of these results and limited commercial plant scale applications, this technology was not considered further.

7) Adsorption of oxyanions to ferrihydrite followed by gypsum encapsulation:

Dissolved iron in solution forms two-line ferrihydrite at pH3.2 and has a strong adsorption affinity for arsenic, molybdenum and selenium oxyanions in solution owing to the net positive surface charge of ferrihydrite at this pH [8–9]. Test work completed on mill effluent showed very good removal efficiency of arsenic, molybdenum and selenium over the pH range 3.5–4.5. The target pH of the mill final tailings is pH11 and the surface charge of ferrihydrite changes from net positive to net negative above pH 8.1, thereby desorbing arsenic, molybdenum and selenium. Pre-neutralizing the adsorbed Fe–As/Mo/Se complex from pH4.5 to pH7.5 using lime increased the geochemical stability of this complex when it was mixed with the final tailings at pH11. Ageing studies confirmed that this adsorption complex combined with gypsum encapsulation at pH7.5 resulted in a stable complex within the tailings management facility. On the basis of these positive results, the Key Lake mill effluent treatment circuit was modified to include enhanced Eh control, a low pH (pH4.5) thickener and a gypsum encapsulation tank.

4. RESULTS ACHIEVED

The selected ferrihydrite precipitation hydrometallurgical treatment method achieved excellent results at full plant scale. Prior to the installation of the required process equipment and subsequent process changes, the daily concentrations of arsenic, molybdenum and selenium in the mill's final effluent were as follows: As average concentration = 0.006 mg/L (n = 81; range = 0.003–0.017 mg/L; standard deviation = 0.002). Mo average concentration = 0.74 mg/L (n = 81; range = 0.27–1.8 mg/L; standard deviation = 0.27). Se average concentration = 0.073 mg/L (n = 81; range = 0.052–0.094 mg/L; standard deviation = 0.010).

After the installation of the thickener, the average daily concentrations of arsenic, molybdenum and selenium were as follows: As average concentration = 0.005 mg/L (n = 145; range = 0.001-0.019 mg/L; standard deviation = 0.003). Mo average concentration = 0.10 mg/L (n = 145; range = 0.005-0.70 mg/L; standard deviation = 0.086). Se average concentration = 0.018 mg/L (n = 145; range = 0.004-0.031 mg/L; standard deviation = 0.004).

As a result of these changes to the effluent treatment circuit, the removal efficiency for As remained high and was 99.8% before process changes and 99.9% following the changes. Significant improvement was observed for Mo and Se, where the removal efficiencies increased from 21% to 90% for Mo, and from 19% to 80% for Se. Finally, the annual loading to the environment decreased from 1110 kg/year to 100 kg/year for Mo (on average) and from 110 kg/year to 18 kg/year (on average) for Se. Finally, following implementation of the effluent treatment process improvements, the Key Lake mill met environmental performance expectations (as per the environmental impact statement) with respect to effluent quality. The annual loadings for Mo and Se after process improvements were below the limit of 600 kg/year for Mo and 40 kg/year for Se.

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THE FLUID FLOWS AND URANIUM MINERALIZATION IN THE NORTHERN ORDOS BASIN, NORTH CHINA*

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1. INTRODUCTION

An extensive quantity of uranium reserves discovered in the northern part of the Ordos Basin in northern China is interesting increasing numbers uranium geologists. The uranium mineral belt, including a series of deposits such as those at Dongsheng, Nalinggou, Daying and West Daying, extends from east to west over more than 100 km. Moreover, new deposits are still being discovered. Current exploration shows a great potential for additional discoveries to the west and south of the belt.

1.1. Evolution of an exploration strategy

Exploration work in the Ordos Basin has an unusual history. During the 1990s, the uranium geologists thought the Ordos Basin was unfavourable for the occurrence of significant uranium reserves because of the young groundwater discharging from the basin into the surrounding Yellow River. It was speculated that uranium could not accumulate in the case of discharging water. However, this hypothesis was soon overturned by the discovery of the Dongsheng deposit in 2000. Reconsideration of the tectonic evolution of the Ordos Basin demonstrates that the water discharge condition has occurred because the Yellow River's faulted sub-basin has separated the northern part of the basin from the uplifted mountainous area since the Cenozoic. Prior to the Cenozoic, the uranium–oxygen-bearing fluids sourced from the northern uplifted mountains were able to flow into the basin and form uranium ore deposits. The breakthrough of the Dongsheng deposit discovery encouraged uranium explorers to look for more deposits in the basin.

1.2. Characteristics of orebodies

The burial depth of orebodies varies from 200–300 m to the east to 700–800 m to the west of the northern part of the basin. The uranium mineralization is hosted only in the upper part of the Zhiluo Formation I to the east and in both the upper and lower parts of the Zhiluo Formation II to the west. In general, the whole uranium mineral belt is globally controlled by a palaeo-oxidation front which is sinuous and trending E–W. A single orebody is always tabular, lenticular and crescent shaped in all deposits. None of the typical roll-front bodies have been found up to now. Some lenticular orebodies are controlled by deep seated faulting, such as the Bojianghaizi Fault in the Nalinggou deposit. On average, the mineralized zone is 9000 m long, 500–2000 m wide and 3–4 m thick in Nalinggou and 2000–8000 m long and 5.26 m thick in Daying.

1.3. An atypical interlayered oxidized zone

It is worth noting that the primarily oxidized sandstone in all deposits is not yellow or red but has been turned into green in colour. Usually, the orebodies lie on the boundary between the green and grey sandstones, both horizontally and vertically, i.e. the sandstone is green to the north and grey to the south of the mineralized zone belt. The upper part of the sandstone is green and the lower part is grey. Hence, the

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interlayered oxidized zone seems to be atypical compared with the typical oxidized zone in a roll-front sandstone type uranium deposit.

2. GEOLOGICAL SETTINGS

2.1. Tectonic evolution

The tectonic evolution of the northern part of the Ordos Basin is synchronous with the Yin Shan tectonic event. The coupling of the mountain and basin determines the relationship between uplift and subsidence. At the end of the Permian, the North China Plate collision with the Siberian Plate caused the closure of the palaeo-Asian ocean [1–6]. During the Triassic, a strong compression resulted in the uplift of Yin Shan and the formation of large scale folds and thrust faults associated with strong magmatism [7–9]. From the Early to Middle Jurassic, widespread coal-bearing strata were deposited within the depression area of both uplift and sub-basin. The target layer hosting uranium was deposited as a large scale fluvial to delta system [10]. During the Late Jurassic, the Yin Shan area was uplifted and thrusted again due to the regional shortening [11–13]. Accordingly, the Anding and Fenfanghe Formations were deposited in fluvio-lacustrine environments. During the Cretaceous, the basin underwent an early extension with deposition of the Dongsheng Formations, then late uplifting and erosion resulted from a new compressive event [14, 15] with eruption of basaltic magma by the end of the Mesozoic [16]. Since the Cenozoic, especially during the Oligocene, rapid subsidence occurred around the basin in response to normal faulting and caused the formation of the Hetao, Yinchuan and Fenwei faulted basins, with regional eruption of basaltic magma and earthquake activity [17, 18]. The northern part of Ordos Basin has been gradually separated from Yin Shan.

2.2. Target horizons and depositional facies

Currently, three rock series have been verified as target layers for sandstone type uranium deposits in the Ordos Basin. These are the Yan'an Formation (J_2y) , the lower Zhiluo Formation $I(J_2z^{1-1})$ and the upper Zhiluo Formation $I(J_2z^{1-2})$. The Yan'an Formation is composed of thick coal beds intercalated with thin sandstone and mudstone beds, which were deposited in swamp and lacustrine environments in a damp climate. The Zhiluo Formation unconformably overlays the Yan'an Formation with a weathered crust rich in kaolinite. The Zhiluo Formation consists of thick layered sandstone and thin to thick layered mudstone, which were deposited in braided (J_2z^{1-1}) and meandering (J_2z^{1-2}) fluvial systems [10]. The Zhiluo Formation I is rich in organic matter and is partially interbedded with thin coal beds which indicates a damp climatic setting.

3. METHOD AND RESULTS

In order to study uranium–oxygen-bearing fluid flow and the mineralizing processes, researchers have sampled both the uplifted area (Yin Shan) and drill core taken from the basin deposits.

3.1. Heavy minerals

The authors took 32 samples from 18 boreholes in Nalinggou, Xinsheng and west Daying deposits. Firstly, the samples are crushed, then acidified and washed with water and baked. All heavy minerals were separated with heavy solutions. After separation, the 0.063–0.5 mm mineral fraction was separated from the heavy solution and all minerals identified under a binocular microscope. Statistics shows the heavy minerals to be garnet (41.78%), zircon (6.41%), titanite (1.93%), hornblende (1.54%), tourmaline (1.34%), rutile (1.31%) and so on. It is deduced from these results, combined with thin section observations, that the uplift source rocks for the target layer (J₂z) were mainly metamorphic rocks and intermediate to acidic igneous rocks.

3.2. SEM and XRD

A total of 37 samples were selected for XRD and 18 samples for SEM from the Nalinggou deposit. XRD analysis was performed with a D/max-2500 and TTR at the laboratory of Research Institute of Petroleum Exploration and Development. SEM analysis was done using a NovaSEM450 and X-Max equipment at the Key Laboratory of Nuclear Resources and Environment of the Ministry of Education, East China University of Technology. Clay minerals in target sandstone include smectite, kaolinite, chlorite and illite. The average content of clay minerals in sandstone is about 15.6%. Smectite abundance in grey sandstone ranges from 44% to 76% (average 59.4%), in grey–green sandstone from 28% to 60% (average 50.1%), and in green sandstone from 12% to 62% with (average 42.5%). Kaolinite abundance ranges from 15% to 34% (average 24.9%) in grey sandstone. Chlorite ranges from 6% to 17% (average 10.8%) in grey sandstone, 12% to 41% (average 19.5%) in grey–green sandstone and 13% to 48% (average 27%) in green sandstone. Morphologically, smectite is semi-euhedral to anhedral. It forms cotton-like coatings to the grains of feldspar and quartz, sometimes 'honeybee nest-like' in pores. Kaolinite is usually booklet-like and vermiform in pores of sandstone. Chlorite is light green and foliated, sometimes flower-like and spheroidal, coexisting with pyrite. Overall, illite is in a lower proportion and difficult to identify under SEM.

3.3. EMPA (U minerals and chlorite)

In this study by electron probe microanalysis (EPMA) was accomplished at the Key Laboratory of Nuclear Resources and Environment of Ministry of Education, East China University of Technology using the following equipment/parameters: (i) a JXA-8100 electronic microprobe, (ii) an IncaEnery energy dispersed spectroscope, (iii) an acceleration voltage of 15.0 kV and (iv) a beam diameter of 1 μ m of 2.00 × 10-8 A. First, a rough qualitative analysis was conducted using the IncaEnery energy dispersed spectroscope and then quantitative analysis on several uranium minerals selected from uranium-bearing ores by means of observation and analysis of the mineral grains shown in the back-scattered electron images. Coffinite is the most important uranium mineral in all the deposits. Its grain size varies from several micrometres to several tens of micrometres, with $50-70 \text{ wt}\% \text{ UO}_2$ and $10-20 \text{ wt}\% \text{ SiO}_2$ and occurs as coatings to grains or filling the pores between the grains or in the cleavage plane of detrital biotite. Coffinite sometimes replaces the blocky matrix in sandstone. Coffinite usually co-exists with pyrite and ilmenite. The second important uranium mineral is pitchblende. It is 3–15 μm in size with >80 wt% UO₂, ≈4 wt% CaO and <2 wt% SiO₂. Generally, pitchblende is well crystallized and fills the pores between the grains in sandstone. Brannerite and titanium-bearing uranium minerals are frequent in sandstone type uranium deposit because they are formed under higher temperature. They vary in grain size from several micrometres to about 100 μ m, with UO₂ 46-53 wt%, SiO₂ 6-16 wt% and TiO₂ 8-15 wt% and coexisting with calcium cement between sandstone grains. It is worth mentioning that there are some low temperature hydrothermal sulphide minerals such as galena, clausthalite and brookite in the mineralized sandstone. The composition of chlorite is as follows: SiO₂ 24.02-31.87 wt% (average 28.45 wt%), Al₂O₃ 17.16-1.31 wt% (average 18.63 wt%), FeO^T 21.80–36.39 wt% (average 27.31 wt%) and MgO 5.80–16.35 wt% (average 12.42 wt. The inverse relationship of iron with magnesium means they have replaced each other in the chlorite crystal lattice. The gradual decease of silicon from green to grey-green to grey sandstone implies that the solution precipitating chlorite would be less acidic.

4. DISCUSSION AND CONCLUSION

4.1. Structural inversion

Structural inversion occurred during the Early Cenozoic in the tectonic evolution of the Ordos Basin. During the Late Mesozoic, the west and north area of the basin were under compression. The slope between the Yin Shan Uplift and Yimeng Uplift (in basin) is favourable for facilitating uranium ore fluid flow into the basin. A large quantity of uranium transported in solution was brought into the target layers (Zhiluo Formation).

However, this metallogenic process ceased because the Yinchuan faulted sub-basin and Hetao faulted subbasin began to form at about 40 Ma (Middle Eocene). The strong faulting occurred at about 20 Ma (Miocene) with rapid subsidence and thick layered sediments in sub-basins. This extensional tectonic process is favourable for the upward migration of deep seated hydrothermal solutions.

4.2. Target sandstone petrology

The clastic grains in the target sandstone in the Ordos Basin amount to 76–92%. They mainly consist of quartz, feldspars and lithic fragments. Quartz, sub-angular to sub-rounded and clean on the surface, ranges from 33% (in volume) to 76% (average of 50%). Feldspars, including plagioclase, microcline and perthite, range from 10% to 50% (average of 30%). Argillization, epidotization and zoisitization are common within feldspars. Feldspars are sometimes replaced and cut by carbonate minerals. Lithic fragments range from 5% to 50% (average of 30%). The metamorphic rock dominates lithic fragments. The others are quartzite, siliceous rock and granite. On the basis of the ternary diagram shown in Ref. [19], the target sandstones are mainly lithic arkose and partially arkose and feldspathic lithic sandstones.

4.3. Uranium source

The study by Jiao et al. [20] shows that there are three kinds of uranium sources, metamorphic rocks, igneous rocks and sandstone. As stated above, the sediment source of the target sandstone is the strata of the Yin Shan Uplift. The metamorphic gneiss contains 2.54×10^{-6} uranium with $-\Delta U$ 43.7% (lost uranium). The igneous rock (acidic intrusions) contains 9.29×10^{-6} uranium with $-\Delta U$ 36.9%. Sandstone itself may have contributed as a source of uranium for the deposits. The uranium content in grey sandstone lies in the range $0.01-47.63 \times 10^{-6}$ (average of 5.75×10^{-6}). The grey–green sandstone has a uranium concentration of $0.01-9.56 \times 10^{-6}$ (average of 2.16×10^{-6}). Red sandstone contains uranium at concentrations of $0.01-9.39 \times 10^{-6}$ (average of 2.63×10^{-6}). Both green and red sandstone (residual) have lost more uranium than other types of coloured sandstone. Hence, uranium in the deposits may derive from multiple source rocks.

4.4. Genetic model and hydrothermal reworking

The extensive uranium enrichment in the Ordos Basin has undergone three stages as follows:

- 1) *Pre-enrichment stage*. This stage is where sediments sourced from uranium-bearing metamorphic and igneous rocks were transported by surface water via fluvial systems into the basin during the Middle Jurassic. Uranium initially present in sandstone grains and in the matrix, may have been dissolved later. Consequently, the depositional process plays a pre-enrichment role in the mineralization process;
- 2) Interlayered oxidation stage. Large volumes of uranium–oxygen-bearing fluids leaching both the uplifted provenance rocks and along the fluid pathway through the sandstones into the underground target in the basin during the Late Jurassic–Cretaceous. Uranium ore fluids can be reduced at the redox zone created by organic matter to form tabular and/or roll-front uranium orebodies;
- 3) Hydrothermal and petroleum reworking stage. The Yimeng Uplift area in the northern part of the basin was separated from the Yin Shan Uplift by the Yinchuan and Hetao faulted sub-basins under a regional extensional stress regime since the Miocene. The hydrothermal fluids have migrated through normal faults into the uranium orebodies and redistributed the original mineralization. During this process, a large amount of pitchblende was turned into coffinite because of the addition of silica released from feldspar alteration to uranium in pitchblende which occurred simultaneously with the formation of hydrothermal sulphide minerals. At the same time, tabular/roll-front orebodies changed into tabular and/or lenticular shapes. This is the reason why no roll-front shaped orebody has been found in all deposits. Moreover, large scale migration of hydrocarbons from deeper source rocks turns the red and/or yellow oxidized sandstones into a green colour. Exploration geologists may use this model to predict the uranium orebodies and drill exploration boreholes to test it.

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THE EXTRACTION OF URANIUM FROM SALT LAKES IN CHINA

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1. INTRODUCTION

Uranium is the primary fuel source for nuclear power generation, making it an element of considerable technological importance. The energy produced by 1 kg of uranium is equivalent to that of 2500 t of coal. With increasing environmental concerns, priority will be given to nuclear energy over other energies because of its cleanliness and high efficiency. Uranium resources are finite and relatively few countries around the world have large resources. According to the 2016 'Red Book' [1], it is reported that world uranium identified resources recoverable at a cost of <US \$130/kgU were 5 718 400 tU as of 2015. In the highest cost category (<US \$260/kgU), total identified resources amount to 7 641 600 tU. Economic uranium reserves will be exhausted within in near future, according to current levels of consumption and development.

Uranium resources are broadly classified as either conventional or non-conventional. Non-conventional resources are very low-grade resources and those from which uranium is only recoverable as a minor by-product [1]. Uranium is therefore a secondary product and its recovery is, in most cases, not dependent on extraction costs. The exploitation of non-conventional resources is an inevitable choice for long term development. The high salt and low uranium aqueous systems such as seawater or salt lakes are amongst the most important non-conventional resources. The total amount of uranium in seawater is about 4.5 billion t. In this study, it is planned to extract uranium from seawater, taking the extraction of uranium from salt lakes as a starting point. Data obtained during studies on salt lakes will be used to develop extraction of uranium from seawater.

2. DESCRIPTION

2.1. Uranium resources in salt lakes from China

There are many salt lakes in the west provinces of China and some of these salt lakes are uraniferous. The uranium-bearing salt lakes are distributed within five regions, which are, from south-west to north-east Tibet region, Qinghai region, Sinkiang region, Inner Mongolia region, and East Halite region. Boundaries between the different regions correspond to mountain chains ranging from the Himalayas and Kunlun Mountains, to the Altun–Qilian–Liupan mountains and to the north-east Helan and Taihang mountains, ending with the Greater Khingan mountains [2].

Uranium resources of salt lakes are estimated by measuring water volumes. On the basis of the uranium amount of the salt lakes in China, the potential uranium resource was estimated to be about 80 000 tU. Considering the number of salt lakes without available uranium data, total uranium resources are probably much larger.

2.2. A single specific uranium-bearing salt lake in Tibet

A single specific uranium-bearing salt lake is present to the north of Tibet province where the climate is characterized by low precipitation, high evaporation and drought areas. The water of the salt lake is limpid,

salty and weakly basic. The salt lake is located to the north-west of the Gandise tectonic belt. The altitude of the lake is 4500 m and it covers an area of 252 km^2 . The deepest part of the lake is 36 m, the pH value of the water is 9.52 and all the elements present is 20.35 g/L.

Uranium concentrations in the salt lake are around 260–324 μ gU/L and the average value is 289 μ gU/L. Uranium concentrations near the shores are higher than those of the river supplies and higher at depth than in the upper parts of the lake. Uranium concentrations at the surface of the lake are variable, in the range 264–324 μ gU/L because of river supplies. The average uranium value at the surface is 285 μ gU/L.

2.3. Synthesis of functional materials for uranium extraction from salt lakes

Different methods such as solvent extraction, ion exchange, flotation, biomass collection, adsorption and precipitation, etc., can be used to extract uranium from seawater or from salt lake water. Among them, adsorption is considered the best technique to develop and to apply. To choose which type of material can be the key to the adsorption method, approprite materials have to be selected and tested to extract uranium from salt lakes.

According to the literature [3], salophen (SLP, an organic compound with the chemical formula $C_{15}H_{13}NO_4$) can be fixed onto the surface of silica gel particles and used as the solid phase receptor for quantitative uranium analysis. Under optimal conditions, the range for the detection of uranium is 0.5–30.0 ngU/mL with a detection limit of 0.2 ngU/mL. It was concluded that SLP has a selective interaction with uranium to form complexes in the strongly diluted solution. SLP was grafted to styrene–divinylbenzene (ST-DVB) copolymer microspheres. Experimental procedures were followed:

- a) Characterization: The infrared spectra of SLP functional material and intermediate amic microspheres were recorded with the KBr pellet method. The elemental analysis of SLP functional material and amic microspheres were recorded by an EL-2 type analyzer;
- b) Uranium capacity: For the experiment, 1.0 g of SLP functional material was added into 100 L simulated salt lake solution (multiple ion solution) containing uranyl ions as well as other ions (U 0.34 mg/L, K⁺ 0.55 g/L, Na⁺ 7.98 g/L, Mg²⁺ 0.13 g/L, Ca²⁺ 3.40 mg/L, Cl⁻ 1.26 g/L, SO₄²⁻ 6.28 g/L, CO₃²⁻ 5.03 g/L, HCO₃⁻ 1.02 g/L, pH9.5). After 30 d, the uranium capacity of the material was calculated to 1.17 mgU/g by reducing to ash and lixiviation.

3. URANIUM SORPTION EXPERIMENTS OF MATERIALS

Uranium sorption experiments of materials were tested at the above-mentioned salt lake. The materials comprised simple equipment which was set underwater in the centre of the lake. After 3 months, the equipment was removed. Thick yellow matter was found to be adhering to the equipment, in addition to a little mud.

4. MELIORATION OF FUNCTIONAL MATERIALS

The thick yellow matter found adhering to the equipment and the materials was identified by polarizing microscope. The images of single organisms were presented in the photographs and the presence of diatom fronds was confirmed through investigation and contrast techniques.

Isothiazolinone (MIT) compounds are germicides used widely, which can restrain effectively the growths of bacteria, mildew and algae. The route was by which MIT was grafted to ST-DVB copolymer microspheres was reconstructed. The infrared spectra of the SLP functional material and amic microspheres were recorded the same as above. Experimental procedures were:

a) Uranium capacity: In the experiment, 1.0 g of MIT functional material was added into 100 L

simulated salt lake solution, as above;

b) Anti-bio-adhering ability of MIT functional material: The living environments of algae are similar to that of bacteria, which can grow and propagate in salt solutions. The anti-bio-adhering ability of MIT functional material was tested with germ cultures in indoor experimentation and SLP functional material was used in contrast techniques.

MIT and SLP functional materials were put into incubators at 30°C for germiculture:

- a) The bacteria was thiobacillus ferrooxidans and the substrate composition was 3.0 g (NH₄)₂SO₄, 0.5 g K₂HPO₄, 0.1 g KCl, 1.0 g MgSO₄·7H₂O, 44.4 g FeSO₄·7H₂O, 1000 mL deionized water, pH2.0;
- b) The bacteria was sulphate reducing and the substrate composition was including 5mL sodium lactate, 1 mL yeast extract, 0.2 g (NH₄)₂Fe(SO₄)₂·6H₂O, 0.01 g KH₂PO₄, 0.2 g MgSO₄·7H₂O, 2.0 g NaCl, 7.2 g Na₂SO₄, 1000 mL deionized water, pH7.0. After 7 days, the materials were taken out and observed with a microscope.

5. DISCUSSION AND CONCLUSION

In summary, the uranium is present in the salt lakes in China and the regions of the lakes with the highest uranium concentrations are near the south and north-west shores; the uranium concentration in the centre of the lakes remains constant. The uranium content of the lake surface below 18 m change little. Some uranium-bearing salt lakes in Tibet are of the carbonate type and their estimated water volume is at least 5.0 billion m^3 .

As part of the characterization process and batch sorption experiments of SLP functional material, the infrared spectrum of SLP functional materials shows that the new frequencies appearing at 1618 cm⁻¹ belong to C=N stretching vibrations in the SLP. The C, H and N contents of SLP functional material decreases, while the O and Cl contents increase accordingly compared with those of amic microspheres. The result indicates that SLP was successfully grafted onto ST-DVB copolymer. The SLP calculated functional content was 2.23 mmol/g. The result suggests that the graft reaction was successful. Also, the sorption amount increases drastically with the increase of pH values, indicating that SLP functional material has high capacities in alkaline solutions. The uranium desorption rate of SLP functional material is \geq isterialu20 g/L Na₂CO₃ + 60 g/L NaHCO₃ were used as desorption agents.

In the uranium sorption experiments of SLP materials, the materials were retrieved then washed by distilled water. The uranium adsorption capacities of materials were calculated by reduction to ashes and lixiviation. SLP functional material exhibits more selective adsorption of uranium, whose uranium capacity is up to 2.53 mgU/g. In addition, the uranium adsorption capacities of several materials in simulated solutions were higher than those in the salt lakes. The reason possibly is, on the one hand, the simulated solutions are not balance states, considering kinetic and thermodynamic factors. On the other hand, the MgUO₂(CO₃)₃²⁻ and Ca₂UO₂(CO₃)₃ complexes interfere with adsorption courses of materials in solution [4].

The bio-adhering phenomena happened during experiments. This is similar to what is observed during uranium extraction from seawater in China, Japan and the United States of America. It is a difficult problem overcoming bio-adherance in order to extract uranium from seawater or salt lakes. The concept of anti-bio-adhering materials to aid the extraction of uranium was investigated. Anti-bio-adhering material for the extraction of uranium is defined as a functional material that can adsorb and enrich uranium selectively, and which reduces or avoids bio-adherance in natural uraniferous water [2].

As part of the characterization process and batch sorption experiments of anti-bio-adhering materials, the infrared spectrum of MIT functional materials shows that the new frequencies appearing at 1646 cm⁻¹ belong to C=N stretching vibration in MIT. This result suggests that the graft reaction was successful. After 30 d of uranium sorption experiments, the uranium capacity of the material was calculated to be 1.36 mgU/g by

reduction to ashes and lixiviation methods, which was higher than that of SLP functional material. It was found that MIT functional material has remarkable anti-bio-adhering properties.

Anti-bio-adhering mechanism of MIT functional material was present. MIT functional groups interfere partially with the phosphorylation of adhesion kinases. Certain bonds of the adhesion kinase are the most sensitive part, where cells begin to cease breathing. The microbes cannot attach themselves to anything and continue to breed.

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INNOVATIVE INTELLECTUAL MANAGEMENT TECHNOLOGY OF URANIUM MINING BY THE ISL METHOD

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1. INTRODUCTION

In recent decades, there has been an intensive expansion of the information technology application in mining. From the tool of geometrical modelling of deposits and calculation of reserves they have turned into a tool of mining optimization and enterprise management. This is due to the multidimensionality and multivariance of the mining tasks and the need to make the correct investment, design and management decisions under numerous constraints, risks and uncertainties. At present, information technologies are applied to problems of geological and hydrogeological modelling, design of mining enterprises and their feasibility studies, production scheduling, assessment of geo-ecological consequences, transportation, etc. Mining companies implement complex information systems that are constantly used by engineering and technical services for monitoring mining operations, preparing reports, analysing and optimizing deposit development, and for operational and strategic management of a mining company.

However, the use of information systems designed for traditional mining methods is difficult to apply to the development of infiltration uranium deposits by the in-situ leaching (ISL) process. Since the ISL process does not involve ore extraction, it is based on a useful component transfer to a solution and then retrieval from production horizon by means of an engineered well system. In connection with this, the Seversk Technological Institute of the National Research Nuclear University (MEPhI) has developed a specialized software package for informational support of uranium mining by the ISL method [1–6]. The coordinated work of the information systems of the software package makes it possible to implement the intellectual technology for managing the uranium deposit development by the ISL process. The intellectual technology is based on a comprehensive analysis of geological and geotechnological data at all stages of the operating procedures and application of intelligent expert systems for decision support. The present report is devoted to the systems of the software package and its application for increasing the uranium mining efficiency by the ISL method.

2. METHODS AND RESULTS

The software package consists of seven interconnected information systems: mining–geological, technological, geotechnological modelling, geo-information expert–analytical (GEAS), techno-economic, computer aided design and mining planning. In addition, the software package includes a data warehouse that provides consistent storage of the information of any information system. The program code is developed in the programming language C++ using an object-oriented approach. The operation of the software package is based on client–server technology. The interaction of client programs with the data store is performed by means of SQL queries.

The mining and geological information system (MGIS) allows collection and processing of primary geological data and generation of 2-D and 3-D geological and mathematical models of the productive horizon to facilitate calculation of uranium reserves and other geotechnological indicators of geological and operational units in various ways, and also visualization of information on the production horizon condition by means of geological columns, sections, maps, etc. [2]. The entire cache of geological information received during the MGIS operation is stored in the geological database included in the data warehouse of

the software package. In addition to storage, the geological database ensures the integrity and consistency of various information types.

The technological information system is designed to form a model of the structure of the geotechnological enterprise mining complex, to collect and handle technological data on the operation process and to coordinate data and prepare reports on the mining complex operation [3, 4]. The model of the mining complex structure includes a set of technological object models and incorporates the relations between them. The technological information system allows: importing geological data related to engineered wells and production units from the geological database; generating and editing the process object models; defining their relationships; carrying out expert assessment of the data to identify any contradictions and logical errors; and visualizing the model in the form of plans, structured lists and tables. Collection of primary actual data on the process parameters and the condition of mining complex structure model and the agreed data coordinated, the values of geotechnological indicators of the operational units are determined, and shifts and daily and monthly technical reports are formed. The initial data and the mining complex structure model are stored in the technological database, taking into account all the interrelations, which ensures their integrity and consistency.

The geotechnological modelling system makes it possible to carry out simulation of the underground uranium ISL process and pollutant migration within groundwater [5]. The calculations are performed on the basis of the geological and mathematical model of the productive horizon and the digital model of the mining complex imported from geological and technological databases. Geotechnological simulation is based on a mathematical model of a multicomponent non-equilibrium filtration of reacting solutions. The hydrodynamic part of the model includes calculating the distribution of underground water heads, filtration velocity, convective mass transfer and hydrodynamic dispersion. In the physicochemical part, homogeneous and heterogeneous processes occurring during ISL between the lixiviant solution–groundwater–host rock (acid base and redox processes, complexation, etc.) are considered.

GEAS is used to optimize the operating modes of technological objects and to evaluate and analyse the efficiency of the geotechnological process. GEAS allows visualization of the entire pool of information on the mining complex operation, which is stored in the data warehouse. All mining complex objects are displayed on the interactive plan for the date specified by the user. For any mining complex object, it is possible to obtain all the information available from the data warehouse in the form of graphs, tables, maps of geological columns, sections, etc. In addition, the simulation results of the productive horizon condition can be shown on the plan. The system has built-in tools for investigating correlations between geological, geotechnological parameters and indicators for different objects. With the help of the GEAS, it is possible to analyse the hydrodynamic flows in the productive horizon and optimize them, in order to improve the quality of the productive solutions and reduce the reagent expenditures during the ISL process.

The techno-economic system includes an economic–mathematical model for calculating the economic performance of the operation units. The model describes capital costs and operating costs for the construction and development of units. On the basis of the economic–mathematical model, the uranium mining unit base cost and other economic indicators of unit development can be calculated.

The computer aided design system is used to design and optimize the system of uranium deposit development [6]. The initial datum for the design is the geological and mathematical model of the deposit. The design of the mining development pattern can be carried out in either automatic or manual mode. In automatic mode, the pattern of holes is designed using the specially developed algorithms. Algorithms make it possible to create linear and cellular mesh patterns adapted to the deposit morphology.

The optimization of the hole patterns is carried out by searching for the extremum of objective functions by the gradient descent method. The objective functions are: time, liquid:solid ratio (the ratio of the volume of lixiviant solutions to the solid rock mass) for a given degree of unit development, formation exposure degree, uranium mining unit cost and also combinations of these.

The mining planning system is used to predict the performance of existing and planned operational units and to formulate the mining plans of an enterprise on the basis of the predicted data, which guarantee the planned production level of uranium mining. The system operation is based on multifactorial statistical models of the operational units' productivity. The input data for making mining plans are the geological and technological parameters of the planned operation units and the geotechnological retrospective data of the operating units.

3. DISCUSSION AND CONCLUSIONS

The software package is applied practically at all stages of the mining enterprise life cycle. At the stage of exploration work, the geological data obtained during the core survey and geophysical studies of the wells are collected with the help of MGIS. On the basis of the information received, a digital model of the productive horizon is constructed and the geotechnological parameters of the geological units are calculated. The deposit estimation and the feasibility study are carried out on the basis of the digital model of the deposit created at the previous stage. The optimal parameters of the field development system (the distances between the engineered wells, the distances between the row wells, etc.) are determined by carrying out a series of geotechnological modelling exercises using the geotechnological modelling system. The modelling parameters are determined on the basis of the results of laboratory studies, geotechnological investigation and pilot-industrial geotechnological testwork at the field. With the help of the mining planning system, the prediction of geotechnological indicators of operation unit development is carried out (production rate, uranium content in pregnant solutions, specific acid consumption, etc.) based on a certain set of geological and geotechnological parameters (ore mass, metal content in the rock, well production, acid concentration in lixiviant solutions, etc.). On the basis of medium and long-term predictions, the mining plans of the enterprise, which provide a planned production level, are carried out. On the basis of the results obtained using the techno-economic system, the analysis and evaluation of the technical and economic performance of the enterprise are carried out, which are used to prepare the feasibility study for enterprise construction.

Design of operational units is carried out using computer aided design, the geotechnological modelling system and GEAS. On the basis of the geological-mathematical model of the productive horizon, an adapted well pattern is created and a unit design formed. For the proposed draft operational units, multivariate geotechnological modelling is carried out and the cost price of uranium mining and other economic indicators for different variants of the unit development are calculated. From the results obtained, the best unit design is selected, which is the most appropriate for the tasks facing the enterprise.

At the stage of field development and with the aid of the technological information system, a digital mining complex model is created and maintained, the coordinated values of the geotechnological indicators are calculated, and shift, daily and monthly reports on the enterprise work are prepared. The geotechnological modelling system is used for diagnostic and predictive simulations to determine the current state of the productive horizon, to optimize ISL processing of well units, for short term planning of deposit development and to predict the propagation of the lixiviant solutions within the aquifer. The modelling parameters are constantly adjusted by comparing data of the mining complex control and the productive horizon state monitoring with the results of diagnostic geotechnological simulations. From the results of the diagnostic simulations, the unit parts are identified where the ISL process is not effective enough and proposals are being prepared to change the operating modes of the engineered wells. The verification of proposal effectiveness is determined by multivariate modelling. With the help of the GEAS, the analysis and assessment of the efficiency of individual operational units and the enterprise as a whole requires that preparation of proposals for uranium extraction intensification and reduction of reagent consumption be carried out. The analysis of geological data for wells and sections is carried out using the MGIS. The mining

planning system is used for multifactor analysis and prediction of geotechnological indicators of unit development. The techno-economic system is used for calculating the economic performance of the mining complex (the cost of operational uranium mining, capital and operating costs, the cost change dynamics over time, etc.) and the selection of the most effective operating modes for the operational units.

At the completion stage of field development, the software package is used to determine the optimal procedure for decommissioning engineered cells and units, to prepare activities for the additional recovery of uranium, to forecast and assess the geo-ecological consequences of the ISL process, to determine the duration and depth of groundwater self-purification, and to prepare the aquifer remediation plan.

The advantages of the developed software package are: modular architecture, scalability and the possibility of development; optimal database structure, thereby ensuring the integrity and consistency of information; availability of mechanisms for integration with existing information systems at the enterprise; the inclusion of new modern decision support tools and compliance with information security requirements. The use of the software package for managing field development makes it possible to create an integrated information and production environment for a mining enterprise. It also provides consolidation of information for the purposes of operational management, production accounting, planning and forecasting; increases the productivity of technical, engineering and administrative personnel (automation of data processing and preparation of report documents, efficiency and availability of any information at various levels, etc.) and improves the quality of management decisions (completeness, accuracy, reliability and relevance of data, automated analysis of sizable data, support for decision making, etc.). All these factors contribute to enhancing the field development efficiency and reducing the cost of uranium mining by selection of the optimal development systems and monitoring regimes, which aid in the ISL optimization process.

An important factor in the effectiveness of the software package application is the completeness of the line of software products that provide solutions for the enterprise covering the entire life cycle, from exploration to completion. Joint application of various systems of the software package has a synergetic effect and envisages development of an intelligent technology for geotechnological enterprise management based on a comprehensive analysis of geological and geotechnological data, multi-variant modelling of the geotechnological process and the use of intelligent systems to support decision making.

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GROUNDWATER CONTAMINATION AND SELF-PURIFICATION AT URANIUM PRODUCTION BY THE IN-SITU LEACHING PROCESS

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1. INTRODUCTION

An important condition of uranium mining industry development is environmental monitoring and ecological security of field development. The in situ leaching (ISL) method of uranium mining has less impact on the environment than traditional underground and open pit mining methods. The uranium extraction is carried out by the engineered well system that accesses a productive horizon containing the orebody. Injection wells are supplied with leaching solutions capable of selectively dissolving uraniferous minerals. The sulphuric acid ISL method is the most widespread in the world. The pregnant solution is returned to the surface by pumping wells and is discharged into the processing complex for uranium sorption extraction. Thus, mining is carried out without lifting ore to the surface through selective dissolution of uranium minerals directly within the mineralized host strata. At the same time, deposit development is not accompanied by the formation of overburden and tailings dumps, drainage of underground aquifers, formation of wastewaters from hydrometallurgical plants, etc. However, during field development of the ISL method there is some contamination of underground waters with petrogenic and technogenic substances due to the leach solution injection and its interaction with the host rock [1–3].

To monitor the productive horizon state and assess the geo-ecological effects of ISL, it is wise to use mathematical modelling methods. This is due to the process complexity occurring during ISL and the lack of information on the productive horizon state and the high cost of observation well construction. The report presents a mathematical model of uranium sulphuric acid leaching and software for forecasting the groundwater state during deposit development by the ISL method. The results of the epigenetic and predictive modelling of the change in the productive horizon state during the development of the Khokhlovsk uranium deposit by the ISL method are presented.

2. METHODS AND RESULTS

In sulphuric acid ISL, sulphuric acid is injected into the productive aquifer together with the working solution. An oxidizer can also be added to the working solution. As a result of the interaction of the leaching solutions with uranium-bearing and rock forming minerals, a sufficiently large number of different chemical elements pass into lixiviant solution. According to their characteristics and ecological significance, all polluting components can be divided into three groups. The first group includes the radionuclides of both the uranium and thorium series (U-234, U-235, U-238, Th-230, Th-232, Th-228, Ra-228, Ra-226). The second group involves items passing into processing solutions in amounts exceeding permissible limits (Be, Al, Fe, V, Cd, Zn, Pb, Ti, Tl, Ni (1–3 orders of magnitude), and Na, Ca, Mg (several multiples)). The third group consists of elements whose concentration in the lixiviant solution does not exceed the acceptable

limits (Co, Mo, Sr, Se, Hg, Ag, Sb, Te, Cu). From the point of view of groundwater pollution monitoring, only the elements in the first two groups are of interest. The movement of pollutants in the aquifer occurs as a result of convective mass transfer, hydrodynamic dispersion and molecular diffusion. In solutions, pollutants migrate in the form of ions, neutral molecules and complex compounds. The form in which there is a polluting component in the liquid phase is conditioned by the geochemical conditions. The geochemical situation is determined by the following main factors: hydrogen index (pH), oxidation-reduction potential (Eh), solution ionic strength and the presence of a large number of complex agents [4]. In the ISL process, the geochemical state of the productive horizon within the well units varies significantly. In sulphuric acid ISL, the pH values within the well unit decreases and Eh increases compared with the reservoir waters. This can change the oxidation degree of polyvalent elements, such as iron and uranium, and as a result, their migration properties are changed. Contaminants can also be in the form of complex compounds. The main ligand in sulphuric acid leaching is the sulphate ion. In the form of complex compounds, the components can increase their migratory ability or form sulphate insoluble compounds. It is not possible to describe the migration of all components of the ISL process in detail. Therefore, when creating a model, it is necessary to determine the main physical and chemical processes in order to choose a limited number of minerals and components, the descriptions of which are sufficient for adequate modelling of pollutant migration.

This paper presents a model describing the main hydrodynamic and physicochemical processes that determine pollutant behaviour in uranium sulphuric acid ISL [5]. The hydrodynamic processes include filtration of solutions within porous media and hydrodynamic dispersion. Physicochemical processes include complexation, diffusion, and single phase and multi-phase oxidation–reduction and acid base processes, sorption, mineral precipitation–dissolution and coprecipitation. The following components are contained in lixiviant solutions in significant quantities and determine the geochemical environment: Fe³⁺, Fe²⁺, Al³⁺, Ca²⁺, H⁺, OH⁻, K⁺, Na⁺, Mg²⁺, S²⁻ and SO₄²⁻. These are considered in the model as well as radioactive contaminants (U⁴⁺, UO₂²⁺, Ra²⁺, Th⁴⁺). The model does not examine the components of the third group (Co, Mo, etc.) as these are present in the ISL process in only small amounts and do not affect the geochemical situation. Also, some of the elements of the second group present in small amounts in technological solutions are not taken into consideration. This is due to the fact that they precipitate in the form of hydroxides during acid neutralization as a result of interaction with the host rock and therefore do not extend beyond well units.

On the basis of the mathematical model generated, problem oriented software was developed to predict the migration of pollutants within underground water and to evaluate the effect on the environment as a result of uranium mining by the ISL method [6]. The software performs calculations, taking into account actual operating modes of injection and extraction wells, working solution compositions, hydrogeological structure of the productive horizon and regional groundwater flow. The software is developed in C++ programming language and intended for the use on personal computers with Microsoft Window XP-10 operating systems. Interaction with geological and technological databases is carried out through SQL enquiry.

3. DISCUSSION AND CONCLUSIONS

Groundwater contamination and self-purification of the productive horizon after uranium mining is considered in the example of the central part of the Khokhlovsk uranium deposit, which is located in the Zauralsk uranium ore district. Deposit development is carried out by Dalur, which is a part of the ARMZ uranium holding company. The simulation was carried out on the basis of the deposit's hydrogeological model, which was constructed with the help of a mining and geological information system, in turn based on data from exploration and geophysical investigations [7]. The information on working solution compositions, injection and extraction well operating modes was imported from the technological database of the mining complex's information system [7]. Simulations have been carried out since the beginning of operation up to the present-day but forecast calculations are for a twenty-year period after the cessation of uranium mining.

The simulation results show that, from the commencement of operations, the acid content in the lixiviant solutions within the operating unit region increases. After attaining a value of several grams per litre less than the acid concentration in the leaching solutions themselves, the acid content growth diminishes. The oxidation and reduction potential, Eh, which increases from 100-200 mV to 350-450 mV during the ISL process, behaves similarly, returning towards the original values. The total iron content also increases during the ISL process, reaching values about of 1 g/L. The uranium content in the lixiviant solutions increases, reaches a maximum value, and then decreases as the orebody is worked out. The sulphate content in the process solutions of the operating unit reaches values of 15–20 g/L up to mining completion. In addition, the contents of aluminium, potassium, sodium and magnesium are increased. Thus, the total mineralization of lixiviant solutions increases to 30–40 g/L. During the ISL process, most of the lixiviant solutions remain within the operating unit region. This is due to the balanced rates of working solution injection and extraction, both for separate operational units and for the entire field. When the process solutions leave the operating unit region, acid neutralization and the formation of insoluble compounds of uranium and other pollutants takes place. As a result, the area of uranium distribution extends beyond the well units for distances of up to 20–30 m. The sulphate ion, having the highest migration capacity, extends beyond the block outline by distances of up to 80–100 m. To confirm the adequacy of the ISL process description by the generated model, the simulated and actual time dependences of the uranium concentration, bi- and trivalent iron, sulphuric acid and sulphate ion in productive solutions were compared. The comparison was carried out both for individual pumping and observation wells, and for the operational unit and the entire field. A good agreement of simulation results with real data confirms the adequacy of the proposed model and the correctness of the software operation.

Neutralization of the lixiviant acid and the subsequent increase in the pH of the residual process solutions have occurred for several years due to the chemical interaction with the host rock. As a result, insoluble hydroxides of uranium, iron and aluminium formed and their dissolved concentration in the residual solution decreased. At the same time, insoluble sulphate-containing minerals (gypsum, alunite, jarosite, etc.) formed. Over 20 years, the total mineralization of residual lixiviant solutions decreased from 30–40 g/L to 7–10 g/L. Having completed the operation, the stratigraphic lens of residual solutions remains within the operating unit region as a result of the very low rate of regional groundwater movement within the productive horizon of the Khokhlovsk uranium deposit.

The simulation results show that, in the case of uranium ISL, the region of groundwater contamination is local and situated mainly within the boundaries of the operational units. The main indicator of pollution is the sulphate ion because its content in processing solutions with sulphuric acid ISL greatly exceeds the concentrations of other components and it also has a high migration capability. Using its distribution in the underground waters, it is possible to evaluate the area of productive horizon pollution. Having completed uranium mining, there is self-cleaning of the productive horizon over a period of several decades. The reduction in pollutant concentration occurs as the result of the interaction of residual lixiviant solutions with rock forming minerals, formation of new minerals and dilution with groundwaters. The self-cleaning process speed depends on the mineralogical composition of the ore-bearing rocks in the productive horizon and the intensity of water exchange. In the case of low groundwater movement speed, the self-cleaning process takes place within a region extending a little beyond the boundaries of the well units.

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DEVELOPMENT OF HANDHELD X-RAY FLUORESCENCE (hXRF)SPECTROMETRY FOR MAJOR AND MINOR ELEMENTS ANALYSIS IN GEOLOGICAL SAMPLES FROM PHUKET PROVINCE, THAILAND

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1. INTRODUCTION

Soils and rocks have a complex matrix composition and their chemical analysis is interesting from geochemical and environmental studies perspectives. A well-established and common technique for obtaining the chemical composition of a geological sample is X ray fluorescence (XRF) spectroscopy [1]. The XRF technique has been used to minimise matrix effects and sample heterogeneity but analytical precision and the ultimate accuracy of the results depend on several factors. These factors include instrument setting and stability, the calibration procedure, mineralogical and matrix effects, the reference materials used to calibrate the instrument, sample preparation and the strategy adopted to maintain the results within accepted limits [2]. For providing the highest possible quality of data, the measurements can be costly, require intensive sample preparation and significant analytical time [1].

Hand-held field instruments can be a new application for use both within and out of standard laboratory settings [1]. The hXRF has a precision comparable to benchtop models. Moreover, it allows for direct substrate measurements without the need to collect samples or the use of special containers for the analyses. The hXRF is also less expensive than benchtop models [3, 4]. In recent years, the hXRF has been used to analyse major and minor elements in different materials (rocks, soil, sediment, wood and archaeological specimens) [5].

However, the hXRF analysis has some limitations with respect to efficient application which constrain its reliable uses for optimal element analysis of different types of material. The hXRF limitations are: (i) calibration of the analysis of a small number of element, (ii) measurement is based on the instrument's internal calibration, (iii) an a priori measurement time determination is based on the relative deviation as a determinant factor and (iv) the absence of criteria to establish the minimum amount of sample that can be measured and its container material [3].

In this study, handheld XRF (hXRF) was developed to determine major and minor elements in soil and rock samples at different levels along soil profiles. The effect of the type of film used during the measurements on chemical compositions of samples was investigated. The accuracy of the methods was measured by using geological reference materials.

2. MATERIALS AND METHODS

2.1. Sample preparation

Ten samples were taken per horizon which varied in thickness according to the profile characteristics: O horizon (0–0.1 m), A horizon (0.1–0.3 m), B1 horizon (0.3–1.0 m), B2 horizon (1.0–2.0 m), C1 (2.0–3.0), C2A (3.0–5.0), C2B (5.0–8.0), C3 (8.0–12.0), D (12.0–20.0) and RK (>20.0 m). The sample locations were Tambon Chalong, Amphoe Meuang, Phuket province, Thailand (latitude 7°51'24.22" N, longitude $98^{\circ}19'19.49"$ E).

Each sample was manually homogenized and passed through a 250 µm sieve. The sample was dried to constant weight at 110°C before the element analyses were performed.

2.2. Wavelength dispersive X-ray fluorescence spectrometry (WD-XRF) analysis

The sample was prepared by the following two methods:

- 1) *Fused bead method*: The dried sample and flux were weighed in an exact ratio into the platinum crucible (0.62 g of sample, 1.24 g of lithium metaborate, 4.96 g of lithium tetraborate and 0.08 g of ammonium iodide). The fusion was performed at 1000°C for 2.30 min in a furnace.;
- 2) Loose powder method: Two types of film were used in this study including (i) 4 µm Prolene® thin film and (ii) 6 µm Mylar® polyester film. Each cup was covered with thin film. The fine powder sample was then filled into the cup.

2.3. Hand-held X-ray fluorescence spectrometry)hXRF(analysis

The sample was prepared by the loose powder method with two film types. A Delta Professional hXRF Analyzer, DPO 2000 (Olympus Scientific Solutions Americas, Inc.) equipped with an instrument's Prolene® window of 8 mm², a 4W miniature X ray tube (200 μ A maximum current), and a silicon drift detector was used to measure all samples using Geochem mode with two beams. The first beam (40 kV) measured the elements V, Cr, Fe, Co, Ni, Cu, Zn, W, Hg, As, Se, Pb, Bi, Rb, U, Sr, Y, Zr, Th, Nb, Mo, Ag, Cd, Sn and Sb, and also Ti and Mn. The second (10 kV) was used to determine the light elements Mg, Al, Si, P, S, Cl, K, Ca, Ti and Mn. The measuring time for an individual beam was set at 120 s. The internal hXRF stability was monitored by measuring Fe K- α count on a 316-stainless steel coin every day of use. Each sample was analysed three times.

The hXRF was calibrated after measuring intensities in the following seven geological reference materials: JA-1, JG-1a, JG-2, JSy-1 (andesite, granodiorite, granite, syenite, GSJ, Japan); BCR-2, COQ-1, GSP-2 (basalt, carbonatite, granodiorite, USGS, Reston). Each reference material was analysed ten times.

3. RESULTS AND DISCUSSION

3.1. Calibration curves

From the collected data on the reference materials, linear calibration curves were constructed for each element. It was found that the calibration curves of Ag, As, Cd, Cr, Hg, Mg, Mo, Ni, S, Sb, Se, Sn, U, V and W measured using hXRF were poor owing to their restricted range of concentration in the standard materials for both film types. In contrast, those of Al, Ca, Fe, K, Si, Ti, Mn, Nb, Pb, Sr, Th and Zn were acceptable, with $R^2 \ge 0.95$ except for Cu, P and Y. The calibration curves of Nb and Rb analysed using 4 µm Prolene® thin film ($R^2 \ge 0.95$). The slopes of the regression line for each element were integrated into the hXRF analyser software for automatic correction of the measurements, if the difference between the hXRF analysed value and the CRM recommend value was more than 10%. When 4 µm Prolene® thin film
was used for the analysis, the recalibration factors for Al, Fe, K, Si, Ti, Rb and Th were 1.0649, 0.8487, 0.9140, 0.9615, 0.9810, 0.9892 and 0.9167, respectively. In the case of 6 µm Mylar® polyester film, these elements, including Al, Fe, K, Si, Ti and Th were recalibrated with 1.8805, 0.8969, 1.0251, 1.4803, 1.1013 and 0.8689, respectively.

Neither P nor Na could be detected by hXRF spectrometer. For P, this is due to its very low concentration in the geological reference materials. In case of Na, it was too light to be detected by the hXRF model [1]. Hunt and Speakman [6] suggested that Na X rays were extremely low energy, with a K α line at 1.041 keV, and re-absorbed into the sample matrix and scattered as Bremsstrahlung radiation. There was a much higher degree of scatter between the hXRF analysis and the results at low concentration [7].

3.2. Measurement of major and minor elements in soil and rock samples by hXRF and WD-XRF techniques

The major elements, including Si (20–27 wt%), Al (13–17 wt%), Fe (1–4 wt%) and K (1-3 wt%) could be detected. The minor elements comprised Mn (135–793 g/kg), Th (128–188 g/kg), Zr (65–89 g/kg) and Sr (25–63 g/kg). It was also noted that the concentrations of Th found in the studied samples were very high and over the calibrated range (>105 ppm Th). There was variation of each element in different soil and rock horizons.

For the hXRF analysis using the 6 μ m Mylar® polyester film without recalibration, Al and Si concentrations were the lowest values, but these values could be improved by the recalibration method. However, the recalibration was not required for the hXRF analysis using the 4 μ m Prolene® thin film. Therefore, efficiency of element analysis by hXRF depended on film type and film thickness. Some elements, i.e. Al, Fe, Ti, Pb, Sr, Th and Zr, were reliable when compared with WD-XRF results (fused bead and loose powder techniques) but other elements (such as K, Si and Mn) were different from the laboratory values (>20%). The concentrations of K, Si and Mn obtained using the hXRF tend to be significantly underestimated. The variance in Pb, Sr, Th and Zr were related directly to their small concentrations in these samples. Although the hXRF was able to measure some geologically important elements (such as Al, Fe, Ti, Pb, Sr, Th and Zr), the instrument was unable to detect reliably other important elements (i.e. Ca and Mg). This was due to the particle size, mineralogy and the coexisting component effects (matrix effect) when the hXRF spectrometer was used for these geological samples even using the recalibration method. These effects were increased when the sample contains abundant sheet silicate minerals, quartz and accessory minerals [8].

4. CONCLUSION

The results demonstrated that the hXRF can provide data consistent with laboratory reported values. The hXRF measurement of geological reference materials by both film types were in satisfactory agreement with certified values for all elements except for Cu, Nb, Ni, P, U, V, W, Y and Zn. The recalibration was required for 6 µm Mylar film analysis. The accuracy and precision of the elements present in geological reference materials by hXRF after recalibration were acceptable. Elements such as Al, Ca, Fe, K, Mn, Si, Sr, Th and Zn in geological samples were detected by the pXRF technique. Good agreement between the result values obtained by the pXRF and by WD-XRF was found for some elements, including Al, Fe, Ti, Pb, Sr, Th and Zn. The study showed that the hXRF had significant potential as a geochemical tool. For the future work, the effect of particle size, sample preparation and moisture content will be investigated for reliable quantitative analysis.

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MACUSANI URANIUM DEPOSITS, PUNO, PERU: PRODUCTS OF EPISODIC LATE PLEISTOCENE PERIGLACIAL FLOODING

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1 INTRODUCTION

The swarm of near-surface uranium orebodies of the Macusani district, southern Peru, controlled by Plateau Uranium Inc., contain mineral resources of 51.9 Mlbs at 248 ppm U₃O₈ (20.0 ktU at 210 ppm U - Measured & Indicated) and 72.1 Mlbs at 251 ppm U₃O₈ (27.8 ktU at 212 ppm U - Inferred) using 75 ppm U economic cut-off [1]. This Preliminary Economic Assessment study has shown the easily leachable, near surface mineralization constitutes a major, potential low-cost uranium source capable of producing uranium at cash costs of US\$17.28/lb U₃O₈ (US\$44.5/kgU). The deposits are genetically anomalous: although the predominant host-rocks are rhyolitic volcanics and hypabyssal intrusions with geochemical affinities with the U-rich Hercynian S-type granites, the hexavalent uranium mineralogy, comprising meta-autunite and weeksite, is akin to that of other surficial systems [2], and differs fundamentally from all recognized high-and low-temperature uranium deposit clans [3]. The uniqueness of the district is also highlighted by the exceptional, inherent, lithium endowment of the host volcanics. Both the Miocene bedrock geology and the Plio-Pleistocene geomorphology and climatic history of the district are critical to an understanding of the origin of these unique uranium deposits. This unique origin is key to the excellent potential economics of these near surface, low-grade uranium deposits.

2 GEOLOGICAL SETTING

The Macusani uranium district is located at Lat. 13° 57' S; Long. 70° 37' W in northern Puno Department, southern Peru, and is essentially cospatial with the Quenamari Meseta at an elevation ranging from ca. 4400 to 5000 m a.s.l. The Quenemari meseta separates the WNW-trending Carabaya-Apolobamba and Vilcanota segments of the Cordillera Oriental (Eastern Cordillera). The high plateau is underlain by an Upper Miocene (10.1-6.7 Ma) succession of subaerial glass-rich and unwelded rhyolitic flows assigned [4] to the Macusani Formation, which attains thicknesses in excess of 500 m and covers an area approaching 1500 km². The Macusani Formation is the youngest unit of the Quenamari Group, locally the youngest major magmatic unit of the Central Andean Inner Arc Domain [5], and represents the sole important host for uranium mineralization. The rhyolites are dominated by lapilli-crystal-ash tuffs and pumice flows, extremely rich in broken phenocrysts, and lacking fabrics ascribable to ignimbritic, ash-flow processes. No early Plinian explosive stage occurred, and eruption of extremely viscous magma into an actively-subsiding tectonic basin is envisaged as occurring as frothy debris-flows [6] from vents around the southern margin of the field.

Subsidence and volcanism were nucleated by a series of NNW-striking, sinistral, transcurrent, crustal-scale faults which accommodated the initial rotation of the Bolivian Orocline in the latest-Oligocene, representing the beginning of the ongoing Quechua Orogeny [7].

The rhyolites are strongly-peraluminous (A/CNK, including Li = 1.19-1.35; normative corundum exceeding 2), exemplified by phenocrystic muscovite, and alusite, tournaline, sillimanite and cordierite/osumulite, but are also enriched in alkalis (K, Na, Li, Rb, Cs), as well as lithophile metals (Sn, Nb, Be), HFSE (Ta, W, U), and "volatile" elements (B, F, P). Magmas were generated at moderate temperatures (max. 800° C) and high

pressures through vapour-undersaturated, low-degree of partial melting of batches of mature, pelitic metasediments, probably induced by mantle melt incursion into thickening continental crust [7, 8, 9]. Magmatism occurred in a transpressional tectonic regime accompanying antithetic subduction and delamination of Brazilian Shield lithosphere. The uranium content of unaltered rhyolites, hosted by accessory monazite and apatite, but predominantly by pumiceous and matrix glasses, averages 10-30 ppm, and the rhyolites display geochemical affinities to the uraniferous, post-collisional SP, S-type, two-mica Hercynian granites [7,8].

The lithium potential of the district is entirely represented by the inherent magmatic endowment of the main succession of rhyolites. These average 400-600 ppm Li (8,9), hosted in part by phenocrystic biotite, muscovite and sodic plagioclase, but predominantly in volcanic glass, making 70% of the Li easily leached in dilute sulphuric acid at moderate temperatures of 85°C.

3 GEOMORPHOLOGICAL SETTING

The Macusani Formation flows dip at ca. 3° NE, but the surface of the meseta is defined by a more gently, NE-dipping, sub-planar, erosional pediment, generated through uplift under semi-arid climatic conditions at ca. 5 Ma. To the west, the meseta surface exhibits an abrupt backscarp rising to the 5645 m a.s.l. Quelccaya temperate mountain ice-cap. Although Quelccaya is fast receding, it remains the world's largest tropical ice mass [10], with a firn-line at 5250 m and surrounded by steeply-plunging outlet glaciers. Quelccaya formed part of a continuous ice-cap extending from northern Bolivia to southern Peru in the Early Pleistocene, but had become isolated by the Late Pleistocene. It has expanded and contracted radically and abruptly over the past ca. 700 ka [11,12]. The meseta, now stripped of glacial/fluvioglacial sediments, is traversed by a series of ENE-trending fluvial canyons, converging on the valleys of the Macusani and San Gaban rivers which, in the austral summers channel warm, humid Atlantic air from the contiguous Amazonian lowlands. Annual precipitation, largely as rain, averages 3000 mm.

4 URANIUM MINERALIZATION

The major uranium mineral in the Macusani district is finely acicular-to- platy, yellow-orange meta-autunite $(Ca[(UO_2)(PO_4)]_2(H_2O)_{6-8})$ [13,14] with subordinate weeksite $(K_2(UO_2)_2(Si_5O_{13})(H_2O)_4)$ [3]. Despite previous descriptions [15], no uraninite or pitchblende has been observed. Meta-autunite and weeksite occur as disseminations in rhyolitic tuff, replacing apatite phenocrysts and infilling original volcanic cavities, and as stockworks of 1-3 cm-wide veins, controlled by subvertical cooling joints and steeply-dipping, NE-striking faults, as well by flat-lying structures sub-parallel to volcanic stratigraphy.

Deposition of the uranyl minerals is sometimes associated with powdery to crudely botryoidal, black oxide mineraloids, largely Mn-rich, but locally dominated by Fe and Si. White, clay-like moraesite $(Be_2(PO_4)(OH) \cdot 4H_2O)$ occurs erratically with the uranium minerals, or forms separate veinlets. Over 95 percent of the strictly primary uranium mineralization is hosted in rhyolitic tuff flows and hypabyssal stocks, but high-grade mineralization occurs locally in coarse terrigenous clastic and epiclastic interbeds along the eastern margin of the volcanic field.

With the exception of radiation-induced smokiness in quartz phenocrysts, no hydrothermal alteration is associated with the deposits, and there is no evidence of uranium depletion surrounding mineralization, implying that the uranium was not largely locally derived. Although the rhyolites are enriched in lithophile metals, only beryllium appears to have been mobilised with uranium. Earlier hydrothermal activity, ranging from post-magmatic F-rich (topaz-muscovite-quartz) greisening, in the vicinity of intrusive bodies, to more widespread intermediate-argillization (F-rich illite and Ca-montmorillonite/ nontronite) was similarly ineffective in concentrating Sn, Nb, Ta, W and U. Barren, advanced-argillic (kaolinite-quartz) alteration is intense both in the vicinity of the faulted Rio Macusani trough and along contiguous interflow contacts, but predated uranium mineralization.

The uranium orebodies are focused in at least two 15-60 m-thick *mantos*, sub-parallel to the surface of the meseta, but discordant to volcanic stratigraphy. Mineralization is concentrated within ca. 200 m of surface, in the upper, 7 ± 1 Ma flow sequence [4]. Here, the majority of the deposits occur adjacent to the upper slopes of the canyons dissecting the plateau, with a striking areal concentration in the vicinity of their confluence with the main Macusani River valley. However, high-grade mineralization with higher weeksite content occurs locally within and at the base of the 10 ± 1 Ma flows, beneath the floor of the valley.

5 URANIUM DEPOSITION CONDITIONS

Fluid inclusions have not been observed in either meta-autunite or weeksite, but a low temperature and/or unusually brief duration of ore formation may be inferred from the preservation of the magmatic high-sanidine, disordered crystal structure of translucent K-feldspar phenocrysts in immediate contact with uranium mineralization. Investigation of the nature of the ore-forming aqueous fluids through light-stable isotopic chemistry is inhibited by the absence of mineral-water oxygen and hydrogen fractionation data for uranyl minerals, but the structural affinities of meta-autunite and smectite suggests that the latter may serve as a proxy. The δ^{18} O and δ^{2} H compositions of the meta-autunite, respectively are 5.2-14.7 and -141 to -83 per mil, and fall well outside the "magmatic box", implying that meteoric waters were responsible for uranium mineralization. Application of the fractionation factors determined for smectite [16,17], and assuming that ore deposition took place at ca. 15°C, ambient near-surface temperatures on the meseta, yields oxygen and hydrogen isotopic water compositions of -21.7 to -12.2 per mil and -181 to -123 per mil, respectively [3], defining a field overlapping extensively with that of the Quelccaya ice-cap [18]. Similar water oxygen isotopic compositions are estimated [3] by applying the incremental fractionation calculation proposed for hydroxyl-bearing silicates by Zheng [19] to meta-autunite.

6 AGE OF MINERALIZATION

Application of U-Pb geochronology to the Macusani deposits [20] is precluded by the high content of common lead and minimal radiogenic lead in meta-autunite, evidence for youthful crystallization but defining only very imprecise ages in the approximate range 350 ka to 1.06 Ma. In contrast, U-series (U-Th-Pa) geochronology [21,22] applied using LA-ICP-MC (Multicollector)-MS analysis of natural and cut surfaces of meta-autunite and weeksite vein-fill from six prospects at the eastern/northeastern margin of the meseta, yields acceptable dates for crystallization or re-crystallization, all extremely young. The technique utilizes the gradual increase in ²³⁰Th and ²³¹Pa through, respectively, ²³⁴U and ²³⁵U decay, until secular equilibrium is attained at, respectively, ca. 500 and 300 ka. Isotopic ratios for multiple sites in small volumes of mineral are plotted on Concordia diagrams with calculated ²³¹Pa/²³⁵U activity ratios as the ordinate and 230 Th/ 234 U ratios as the abscissa. Four samples yielded concordant or near-concordant data, with ages of +500, 335, 130 and 75-65 ka, while five defined discordia extending from the origin to Concordia, with upper intercepts of +500, 397, 218-207 and 113-103 ka. Other samples gave discordant compositions with no meaningful intercepts with Concordia. The data are evidence for open-system behaviour, most probably involving variable, and in cases mutually differing, gains and losses of ²³⁰Th and ²³¹Pa, a process extending over at least the past 500 ka, i.e., through much of the Late Pleistocene. Several samples, including one comprising both meta-autunite and weeksite, reveal multiple episodic mineralization events.

7 ORE-GENETIC MODELLING

The Macusani uranium mineralization has been widely assigned [e.g., 23] to the IAEA clan of "volcanicrelated" deposits, exemplified by, Strel'tsovskoe, Sierra Pena Blanca and BaiYangHe. However, although uranium was certainly derived from strongly-peraluminous silicic magmas, the Macusani deposits lack U^{+4} minerals – the U^{+6} minerals, meta-autunite and weeksite are primary, not supergene. In addition, although post-magmatic and lower-temperature activity was widespread, this caused no mobilization or concentration of either uranium or lithophile metals. Instead, the uranyl minerals were directly precipitated at low temperatures from entirely meteoric waters at least 4 Ma after the local cessation of magmatic activity. Mineralization does locally occur in terrigenous sediments at the eastern margin of the basin, but, uranium precipitation is not associated with reductants as in traditional sandstone-hosted systems: in contrast, the close association with Mn-Fe oxide mineraloids is inferred to reflect their highly-absorbing nature, promoting meta-autunite precipitation even in undersaturated conditions [24]. Although the environment of mineralization is largely near-surface, it extends locally to depths of several hundreds of metres, precluding analogies with other "surficial" uranium deposit clans [e.g., 2, 23].

A critical constraint on ore-genetic modelling is the age of mineralization. The Macusani uranium deposits are undoubtedly extremely young, but the U-Th-Pa geochronology does not unambiguously discriminate between original deposition and subsequent modification of the dominant uranium mineral, meta-autunite. Nonetheless, the radiogenic isotope relationships show clearly that the ore assemblages were subject to multiple reconstitution since ca. 500 ka, demonstrating that surficial conditions in the Late Pleistocene were favourable for uranium transport and precipitation. A major consideration here is the enormous volume of meteoric water which was repeatedly required, both for leaching, largely from volcanic glass, and the rapid transport of several hundreds of millions of lbs. of uranium. The inherently porous rhyolitic tuffs clearly acted as permeable aquifers, the through-going channels represented by flat-lying flow-contacts and faults, and steeply-dipping joints (hydrologically, "pipes") and faults (collectively, "macropores"), being interconnected by the cavity-rich ashy matrix of the tuffs. This hydrological environment, continuously opened up by ongoing orogenic surface uplift, would have permitted extensive mixing of overland and infiltrating shallow waters with "old" resident water stored in the volcanics, the latter providing an effective leaching agent for glass-bound uranium. Deep penetration of shallow waters would be optimized during flood run-off, channelled along pre-existing and actively deepening fluvial canyons, feeding the baseline drainage along the Macusani-San Gaban river valley. In this model, mineralization would be precipitated in riparian environments during episodes of sub-surface storm- flow.

The abrupt and radical shrinkage of the Quelccaya ice cap during the Tarantian (late-Late Pleistocene) and early Holocene revealed by terminal moraine dating [10,11], as well as the vastly more extensive glacial cover documented for the preceding Plio-Pleistocene [25], provides a rigorous geomorphological and climatic context for the inferred flooding events: the mineralization episodes documented by U-series dating correspond strikingly with climatic. The δ^{18} O values and low ice volume (high sea-level) in the low-latitude oceanic, foramanifera-derived, time -scale [e.g., 26]. Concordant dates for mineralization coincide with events at 315 ka, 120 ka and 69-79 ka, while the upper-intercept dates match events at 397 ka, 210-217 ka and 103-113 ka, which accounts for all of the major warming interglacial events of the Late Pleistocene.

The Macusani mineralization represents the final episode in the evolution of the major Carabaya polymetallic (Sn, Au, Pb, Zn, Ag, W) metallogenetic sub-province of northern Puno Department [5], with uranium deposits generated in an unparalleled periglacial environment resulting from catastrophic episodic flooding during Late Pleistocene global interglacial periods. The Macusani Uranium district truly hosts a unique class of uranium deposit, but with aspects of both surficial and sandstone systems.

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A NEW IAEA SAFETY REPORT ON OCCUPATIONAL RADIATION PROTECTION IN THE URANIUM MINING AND PROCESSING INDUSTRY

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1. INTRODUCTION

The Fundamental Safety Principles IAEA Safety Standards Series No. SF-1, together with Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards IAEA Safety Standards Series No. GSR Part 3, set out the principles and basic requirements for radiation protection and safety applicable to all activities involving radiation exposure, including exposure to natural sources of radiation and bring challenges to the regulators, operators and workers in implementing the occupational radiation protection requirements [1, 2]. There have been more than 40 years of experience in applying international radiation safety regulations at uranium mines worldwide. Even though radiation safety regulations are among the most comprehensive and stringent in many uranium producing countries, there is still scope to enhance protection of occupationally exposed workers in terms of improving mechanisms to reduce occupational exposure, achieving informed personal behaviours, applying best engineering controls and other aspects.

While many uranium mining companies generally take active steps to reduce radiation doses and control exposures wherever and whenever they can, and often voluntarily adopt the most recent international recommendations on dose limits and necessary occupational radiation protection requirements before they become part of the regulations, consideration needs to be given to enhancing radiation protection of workers on an industry-wide and global basis. This is important as it supports the implementation of internationally consist standards and approaches regarding the protection of workers.

In the last 60 years uranium has become the world's most important nuclear fuel. It is mined and concentrated similar to many other metals. Uranium is a naturally occurring element with an average concentration of 2.8 ppm in the Earth's crust [3]. Traces of it occur almost everywhere. It is more abundant than gold, silver or mercury, about the same as tin and slightly less abundant than cobalt, lead or molybdenum. Natural uranium being the basic fuel for its first phase of nuclear power programme, an increase in the momentum of prospecting, mining and processing of uranium is inevitable.

There are three main methods of producing uranium - underground mines, open pit mines, and in–situ-leach (ISL) (sometimes referred to as in situ recovery or ISR). Conventional mines, either underground or open pit mines have usually associated with a mill where the ore is crushed, ground and then leached to dissolve the uranium and separate it from the host ore [4]. At the mill of a conventional mine or the treatment plant of an ISL operation, the uranium which is now in solution is then separated by ion exchange before being precipitated, dried and packed [4,5]. This product, uranium ore concentrate (UOC) is also referred to as yellowcake and mixed uranium oxides – U3O8 and/or UO4.

In addition, uranium can be recovered as a by-product from phosphate fertilizer production and from mining of other minerals including copper and gold where the ores contain economically exploitable quantities of uranium. In such situations, the treatment process to recover uranium may be more complex.

World annual uranium production is 55 975 tU as of 1 January 2015. This uranium production occurred in nearly 20 countries at approximately 50 different mining and processing facilities. During uranium mining and processing, workers may be exposed externally to gamma rays emitted from the ores, process materials,

products and tailings, and internally exposed from the inhalation of long lived radioactive dust (LLRD), radon and radon progeny, and through ingestion, injection and absorption of contamination.

2. OBJECTIVES OF THE NEW SAFETY REPORT ON OCCUPATIONAL RADIATION PROTECTION IN THE URANIUM MINING AND PROCESSING INDUSTRY

The objective of the new Safety Report is to provide detailed information that will assist regulatory bodies and industry operators in implementing a graded approach to the protection of workers against exposures associated with the uranium mining and processing. This information will also serve as the basis for creating a common understanding, based on common knowledge, between the various stakeholders — such as regulators, operators, workers and their representatives, and health, safety and environmental professionals — of the radiological aspects of the various processes involved and the ways in which these aspects can be addressed appropriately and effectively.

3. SCOPE OF THE REPORT

The new Safety Report describes the various methods of production used by the uranium industry and provides practical information on the radiological risks to workers in the exploration, mining and processing of uranium, on exposure assessment, and on management of exposure based on the application of the appropriate standards and good working practices. This information has been compiled from published literature, from unpublished data provided by contributors to the report and from numerous experts with extensive experience, notably in the various sectors of the uranium mining and processing industry.

4. STRUCTURE

The new Safety Report comprises six sections. Following the introductory section, Section 2 gives an overview of the uranium industry and the general radiation protection aspects of uranium mining and processing stages and techniques. Section 3 summarizes the radiation protection considerations that apply to the uranium mining and processing industry in general and application of the international standards in particular, including the basic radiation protection principles, the graded approach to regulation and specific aspects of radionuclides in the uranium decay series. Section 4 addresses the general methodology for control with the introduction of occupational health and safety considerations, the hierarchy of control, the radiation protection principles and exposure pathways. Section 5 deals with the requirements and dose assessment, with discussion on general dose considerations for different types of exposure pathways. Section 6 introduces the essentials of radiation protection programmes to adequately protect the workers, illustrating the process, design and operation, principal exposure pathways, control mechanisms and monitoring and dose assessment for different uranium mining and processing stages and techniques. The report is supplemented by appendices describing the findings of the International System on Uranium Mining Exposures (UMEX) survey, and the technical details of various exposure pathways.

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UMEX PROJECT, AN IAEA SURVEY OF GLOBAL URANIUM MINING AND PROCESSING OCCUPATIONAL DOSES

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1. INTRODUCTION

With the current level of interest in nuclear power, there is ongoing interest in uranium exploration and in the development of new uranium production facilities in many countries. Such facilities include in situ leaching operations and facilities for the mining and processing of uranium ore. Workers engaged in uranium production receive external exposure to gamma radiation emitted from uranium ore, process materials, uranium products, tailings and other process residues. In addition, they receive internal exposure from the inhalation of airborne dust particles containing long-lived alpha activity and from the inhalation of radon and its short-lived decay progeny [1,2]. The number of uranium production workers may increase substantially over the next few years.

Against this background, the IAEA has established the Uranium Mining Exposure (UMEX) project. The general aim of the project is to strengthen and enhance the radiation protection of uranium production workers, while more specific aims are to increase the opportunities for optimization of protection and to support quality assurance programmes across the industry. Within the framework of the project, the following key activities have been initiated with respect to uranium production workers worldwide:

- (a) Development of an information system for occupational exposure;
- (b) Evaluation of the current occupational radiation protection situation;
- (c) Identification of instances of good practice, opportunities for improvement and, where appropriate, actions to be implemented for assisting employers, workers, regulatory bodies and other stakeholders in implementing the principle of optimization of protection and safety.

In 2012, the IAEA developed a questionnaire which was distributed to uranium producing countries. In 2013, responses to the questionnaire were received from 36 operating facilities which, between them, accounted for about 85% of worldwide uranium production. This paper presents:

- (a) A summary of the results of the information survey and a preliminary analysis thereof;
- (b) A summary of current practices for monitoring and reporting of occupational exposure;
- (c) A summary of occupational exposures reported for 2012.

2. ANALYSIS OF RESULTS

Total annual effective dose:

- (a) For mining and processing facilities at sites using underground extraction, the overall dose was heavily influenced by one operator owing to the large number of occupationally exposed workers recorded for this particular facility.
- (b) Among the mining and processing facilities at sites using opencast extraction, two operators had by far the highest numbers of occupationally exposed workers and therefore had a major influence on the overall dose.

(c) For facilities using in situ recovery, one operator had the highest number of occupationally exposed workers. However, because this was an amalgamation of 15 facilities which were treated separately in the weighted averaging process, the overall dose was not unduly influenced and was therefore considered representative of in situ recovery facilities in general.

Contributions from the three exposure pathways:

- (a) In underground mines, the contributions from external gamma exposure and internal exposure to inhaled short-lived radon decay progeny were similar (47% and 43%, respectively), while the contribution from the inhalation of long-lived radionuclides in airborne dust was much smaller (10%). This reflects the approach taken in modern underground mines, namely, a combination of dust suppression, good ventilation and shielding against gamma radiation.
- (b) In the processing of ore derived from underground mining, the contributions from external gamma exposure and internal exposure to inhaled long-lived radionuclides in airborne dust were similar (44% and 34%, respectively), while the contribution from internal exposure to inhaled short-lived radon decay progeny was smaller but still significant (22%). However, since background subtraction was not generally used for exposure to radon decay progeny, a significant proportion of this contribution may not have been related to the ore processing operation.
- (c) In opencast mining operations, the main contribution was from external gamma exposure, as would be expected for modern mining methods. Gamma shielding is not generally possible beyond that provided by the heavy earthmoving equipment that many workers operate. The next most significant contribution was that from the inhalation of long-lived radionuclides in airborne dust this was dominated by some operators which were both in semi-arid regions where airborne dust was likely to be more prevalent because of less water being available for dust suppression and more rapid drying of material. The inhalation of short-lived radon decay progeny was the least significant exposure pathway, as would be expected given the natural dispersal of radon within large open pits.
- (d) In the processing of ore derived from opencast mining, the relative contributions to the total dose were, as expected, similar to those in facilities processing ore from underground mining.
- (e) In operations involving in situ recovery, the main contributor to the total dose was external exposure to gamma radiation. It should be noted, however, that this result is almost totally related to one operator which is an amalgamation of 15 separate facilities, none of which applied a correction for background gamma radiation, leading to the likelihood of a significant overestimation of occupational exposure from this pathway.
- (f) Facilities categorized as 'other' included facilities for uranium recovery from rehabilitation, waste water treatment and a form of contract processing known as 'toll milling'. The relative contributions from the three exposure pathways varied widely. One of the operator provided only gamma exposure data and this pathway was therefore recorded as the only contributor to the total dose. In the case of one operator, a contract processing operation which had the largest number of occupationally exposed workers, external gamma exposure was the largest contributor to the total dose this was expected given the nature of a purely contract processing operation.

3. MAIN OBSERVATIONS AND CONCLUSIONS

A worldwide survey of occupational radiation exposure in the production of uranium was performed in 2013. Responses were received from 36 operating facilities covering nearly 85% of global uranium production. A review of information from the responses to the UMEX questionnaire has identified several observations of a general nature as well as more specific observations on assessments related to individual exposure pathways.

These are summarized as follows:

- (a) General observations:
 - (i) Although several methods have been adopted for the production of uranium, the most widely used method is in situ leaching, followed by underground and opencast mining of uranium ore;
 - (ii) The most widely used technique for the processing of uranium ore is acid leaching, followed by alkaline leaching;
- (b) Assessment of external exposure to gamma radiation:
 - (i) Most facilities use thermoluminescent dosimeter (TLD) for the assessment of individual doses;
 - (ii) The most widely used assessment strategy is the monitoring of all occupationally exposed workers, followed by the monitoring of average exposures of selected groups and the monitoring of selected individuals;
 - (iii) Approximately 50% of facilities do not use background subtraction, leading to an overestimation of the doses received by workers;
- (c) Assessment of internal exposure from the inhalation of long-lived radionuclides in airborne dust:
 - (i) Approximately 50% of facilities use workplace dust sampling and 50% use personal dust sampling;
 - (ii) Most facilities use gross alpha counting methods for assessing the alpha activity in dust samples;
 - (iii) Most facilities use periodic monitoring for the assessment of exposure;
 - (iv) Most facilities do not routinely use bioassay monitoring techniques, although some facilities are using urine analysis;
- (d) Assessment of internal exposure from the inhalation of short-lived radon decay progeny:
 - (i) The most widely used monitoring technique is active workplace monitoring of radon progeny in conjunction with the use of timesheets, followed by active monitoring of radon progeny using personal dosimeters;
 - (ii) The most widely used monitoring strategy is work group averaging, followed by individual monitoring;
 - (iii) Most facilities do not use background subtraction, which may lead to some overestimation of the dose;
- (e) Dose assessment:
 - (i) The most widely used method for the determination of occupancy time is the timesheet method, followed by the use electronic devices;
 - (ii) While various dose conversion factors are being used, most facilities use factors specified by the regulatory body or by international recommendations or standards;
 - (iii) There is a need for global harmonization with respect to the selection of dose conversion factors in order to provide a common basis for comparison;
 - (iv) In order to obtain a more reliable estimate of the dose from inhalation of radionuclides in airborne dust, parameters such as particle size, solubility and radionuclide composition should be included in the dose calculation.

Overall findings showed an industry in compliance with international standards on radiation protection and a strong commitment to optimisation of protection. A new IAEA Safety Report on Occupational Radiation Protection in the Uranium Mining and Processing Industry, which includes the results and findings of the survey, is in publication. A new survey has been proposed and will be introduced within the framework of IAEA's occupational radiation protection programme in 2019.

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REGIONAL FORECASTING OF SANDSTONE TYPE URANIUM DEPOSITS

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1. INTRODUCTION

The Neogene–Quaternary collision of the African, Arabian and Indian Plates from the south and the Mesozoic–Cenozoic subduction of the Pacific Plate from the east led to the formation of large orogenic belts in the regional parts of the Eurasian Plate. Each of these is characterized by its unique metallogeny. The analysis of the spatial distribution of endogenous and exogenous uranium deposits within the limits of separate orogenic areas creates preconditions for the occurrence of metallogenic zonation in every large geological block. It allows reconstruction of the formation of uraniferous sandstone deposits during the formation of sedimentary basins. The leading ore localizing factors, groundwater and interlayer oxidation zones controlling uranium mineralization, have been established for all sandstone hosted type deposits. The sources of uranium are frequently the areas adjacent to mountain structures and this source has been proposed for the overwhelming number of deposits [1]. The metallogeny of uranium has been fully studied within the limits of the Alpine–Himalayan tectonic belt.

2. THE METALLOGENY OF URANIUM OF THE ALPINE–HIMALAYAN BELT

A number of major segments spanning different orogenic regions and adjacent to suborogenic sections of activated platform were considered.

2.1. The Mediterranean segment

The subduction of the African Plate below the western end of the Eurasian continent began during the Miocene–Pliocene. The Mediterranean segment is subdivided into orogenic and suborogenic regions. The orogenic area 300–700 km in extent is located in the extreme south of the folded belt. Typically, a foreland zone is situated within the orogeny boundary and is characterized by thrusts and overthrust sheets and is frequently capped with red coloured molasse at the frontier. In this segment, the notion of suborogen is seen as the slightly reactivated part of the Western European platform. The French Massif Central and the Bohemian Massif are included in it.

The metallogenic sequence is quite clearly outlined within the limits of the segment. Here, the Permian uranium ore epoch is widely displayed, which was the time of formation of the stratiform uranium deposits around Bikhor. Its genesis is still widely debated [2]. Small, rarely medium-sized, deposits (Pb, Zn, As, CaF₂, etc.) were formed in the Mesozoic–Cenozoic period (elementary stage of subduction) and are not infrequently conjugated with small granitoid intrusions. Small sandstone deposits (Grézieux le Fromental, Saint-Pierre and others) were later revealed in areas of France's Massif Central, within the limits of suborogen. The deposits of Gamr and Königstein are closely connected with effusions of the Bohemian Massif in the regional part of suborogen and these completed the metallogenic evolution of the European section of the West European platform. In general, the Mediterranean segment represents a full metallogenic picture.

2.2. The Arabian segment

The subduction of the Arabian Plate at the southern part of the Eurasian Plate determined the formation of the 500-km wide orogenic belt spanning the territories of the Islamic Republic of Iran, Turkey and the

Caucasus region. This belt is divided it into three sectors – Anatolian, Caucasian and Kopet Dagh. The Oligocene dates the beginning of intensive orogenesis. The first point of analysis within this segment is the development of volcanic activity. The second is the presence in the Early Miocene of the trough instead of the present Caucasian ridge. The last appeared in place of the trough in the Late Miocene, at the time of the young volcanoes (Elbrus, Kazbek). The third and final peculiarity of the Caucasian region is its oil resources.

As a result, the following, incomplete, metallogenic series was formed:

- 1) Large accumulations of hydrocarbons within the limits of the Persian Gulf, the Islamic Republic of Iran, Iraq and the North Caucasian Basin;
- 2) Endogenous deposits of Cu, Mo, Co, Au, Mn and others, as well as hydrothermal uranium deposits (Byk, Beshtau) located on the external front;
- 3) The area of the suborogen in the Ciscaucasia with titanium–zirconium placers and accumulations of hydrocarbons (the North Caucasian Basin), and at the eastern slope of the Stavropol arch, weakly developed groundwater oxidation zones (Balkovskoe) were discovered in the young sediments of the palaeo-Don [3].

2.3. The Indian segment

The most productive uranium region in the extended Tethys belt is the Indian segment. As regards intensity of orogenesis, the Indian segment has surpassed all else. The collision of the Indian Plate subducted over 1500 km below the Eurasian Plate and differentiated the orogenic area with vertical uplifts of up to more than 9000 m and subsiding basins down to below 5000 m. It is divided into the Pamir and the Himalayan sectors. They differ in structural peculiarities and the scale of their ore content.

Three types of metallogenic zone controlling the roll-front type uranium deposits in the Pamir sector. Each zone has unique charcteristics, but they have in common the evidence for the largest and most unique deposits, which are located in the suborogen area and also in areas remote from orogeny.

The Pamir 'wedge' is the result of the protracted collision between the Indian Plate and the Eurasian Plate. All deposits, major examples of roll-front type, are located within the limits of the suborogenic (reactivated) part adjacent to the Turan platform and the southern edge of Kazakh 'shield'. It has been demonstrated that the main 'conveyer' of uranium for the major roll-front type deposits were initially only surface and groundwaters, and only later infiltration (interlayer) waters originating in the north and the central Tien-Shan, at the zone of maximum collisional stress [4]. Installed tight spatial and paragenetic connection of the inflow of uranium waters, forming extensive roll-front type uranium deposits with the most actively advanced site located on the north part of Indian Plate – the Pamir 'wedge'. The most productive metallogenic zones originate at supposed sites of mantle uranium accumulation [5].

The Himalayan sector is characterized by a more complicated geological structure in comparison with Pamir. One of the unsolved problems of the Himalayan sector is the reason for such a minor uranium content, compared with the Pamir sector. The absence of large deposits of uranium within the limits of the Himalayan sector is explained by intensive movement to the north-east of the orogenic area border during the Neogene–Quaternary period. This impacted frequent recharge area fluctuations, active migration of hydrocarbons and an absence of regional stable centres of unloading and hampered the broad development of ore forming interlayer oxidation zones [4].

It should be noted, that major deposits of uranium in the area of the hinterland were revealed only in the northern edge of the Indian subcontinent. Here, the preconditions were created for the formation in the Neogene–Quaternary uraniferous sedimentary basins.

2.4. The metallogeny of uranium of the Pacific belt

The high metallogenic potential of meridional part of the Pacific ore belt is determined by the Mesozoic– Cenozoic subduction of the Pacific Plate. This process affected the tectonic blocks of the Eurasia continent over distances 500–1500 km.

It should be noted that insignificant deposits of uranium (Ningyo–Toge, Tono and others) and located in the small grabens within coarse-grained bed and lake sediments of Cretaceous and Miocene–Pliocene age were discovered within the limits of the islands of Japan and the southern Korean peninsula in the rear (eastern) part of the belt. The ores were formed by groundwaters [2].

It is emphasized that the eastern part of the Eurasia Plate has undergone significant changes in the course of subduction. Within the limits of the activated part, the areas with intracontinental rifting and passive margins have escaped. Endogenous deposits of caldera type are connected with volcano-tectonic structures of Mesozoic age. On the external part of the belt, sandstone type uranium deposits of Cenozoic age occur. Young basalts do not carry uranium mineralization. However, they do possess spatially connected epigenetic uranium deposits. This cover marks the western extension of the subduction in the east of the Eurasian continent and confirms the western meridional border of the Baikal–South China uranium ore belt [1]. The above model implies a tight spatial connection between abyssal geodynamical processes during the Mesozoic and Cenozoic with the formation of uranium deposits. Separation of the metals is established in the transverse section of the belt outlined. In its internal part, uranium is associated with Au (Aldan caldera); Mo, Pb–Zn and CaF₂ (Streltsovskaya caldera); Pb, Zn, W, Mo, Au, CaF₂ (Dornod caldera) and with Mo, Ti, CaF₂ (Xiangshan caldera) [6–8]. The uranium is often separated from the other metals on the external front of uranium ore belt, a feature which is evidently explained by its high mobility.

To the west, basalt magmatism was intense in the area of tectonic damping at the passive margin of the continental block. Basalt magmatism was intense in the field of attenuation of the passive margin of the continental block. Sandstone type uranium deposits in the Transbaikalia (Vitim district), in Mongolia (Sul and others) and at the western end of the South China platform (Yunnan) are spatially closely connected with this magmatism. All of these are covered by Quaternary basalts. The infiltration deposits of uranium not correlated with young volcanism (outpourings of basalts) were revealed within the limits of the sedimentary cover of the Sino-Korean Craton, such as in the Ordos Basin and Erlian Depression in China. Possibly the greatest proportion of these were discovered within the limits of these structures and were formed from domestic synsedimentary sources [1].

The subduction process of the Pacific Plate has generated a full set of natural metallogenic zones spanning from the rear of the subduction zone and along its external damped front.

3. CONCLUSION

The marginal part of the Eurasian continent was divided into a number of segments, each of which is characterized with its own metallogenic specialization caused by the collision and subduction processes. The sandstone type uranium deposits are located on the external weakening collision front and situated within the limits of suborogenic areas in three structures, namely, the Mediterranean and the Indian segments, and the Pacific belt. Different metallogenic specialization and differing scales of hydrogenic ore processes have occurred within the limits of the Pacific belt and the Indian segment of the Alpine–Himalayan belt, the formation of which is caused by similar Mesozoic–Cenozoic global geodynamical processes. The uranium on the external front of the weakening geodynamic processes (within the limits of a sub-orogen) occurs in different structural, lithological and hydrogeological environments. Within the limits of the Baikal–South China belt, it was localized in areas restricted by palaeo-valley basins and depressions. The deposits are often spatially and temporally sealed by younger basalt covers. Large

endogenic deposits of uranium occurring in local structural blocks (calderas) are localized in the rear parts of the belt. The resources of sandstone type deposits within the limits of the Baikal–South China uranium belt do not exceed the average. The deposits of uranium within the limits of the Indian segment (Pamir sector) are localized in vast basins of suborogen type and in major extensive palaeo-valleys in the artesian basins.

This area is characterized by the weak expression of young volcanic activity in the district, insignificant compared with the scale of endogenic uranium deposits in the rear parts of province (Tien Shan mountains). Considering the southern part of the Eurasian continent (area of collision of the Indian Plate), a similarity is drawn in the location of infiltration type uranium deposits of the Tien Shan megaprovince and the Baikal–South China uranium ore belt, which are both components of the Pacific metallogenic belt. Both gravitate towards area of attenuation of geodynamical processes. The endogenous uranium deposition takes places near the area of contact of collision plates. Their size, both endogenous and exogenous, is noticeably different in the south and the east of the Eurasian Plate. The size of infiltration type deposits of the Tien Shan megaprovince is one order of magnitude above the deposits of the Baikal–South China belt. This is due to the wide areas of transit and the numerous geochemical barriers favourable for localization of uranium from the oxygenated uranium-bearing waters, moving through the Cretaceous and the Palaeogene deposits of the Turan Plate and the major basins of south Kazakhstan. However, endogenous uranium deposits of the Tien Shan are significantly of smaller size compared with major uranium deposits of Mesozoic age in the Pacific ore belt.

The reasons for such phenomena require further study. A tight spatial relationship between infiltration uranium deposits and endogenous uranium deposits confined to volcano-tectonic structures is presumed. Moreover, these and other types of uranium deposit are confined to a single metallogenic zone. This is entirely due to global geodynamical processes occurring in the crust and mantle in the marginal parts of the Eurasian Plate.

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FREE THERMAL CONVECTION MODEL FOR FORMATION OF THE LARGEST URANIUM OREFIELD IN THE STRELTSOVKA CALDERA, TRANSBAIKALIA, RUSSIAN FEDERATION

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1. INTRODUCTION

The Streltsovka collapse caldera hosts the largest U orefield associated with volcanism in the world. Its total ore resource of more than 250000 tU is distributed throughout 19 deposits. The dominant hypotheses with respect to the origin of these Mo–U deposits, as proposed by exploration geologists, suggest that uranium was transported to the sites of ore deposition by ascending flow of magmatic fluids separated from a deepseated intracrustal or subcrustal magmatic source [1]. According to this concept, the origin of the deposits is only paragenetically related to the volcanic process of caldera formation, since such a distinctive feature of volcanic collapse calderas as the shallow source magma chamber was not taken into consideration in the deep source hypotheses. However, from the standpoint of general ideas about the relationship of uranium ore deposits with continental volcanism, an alternative hypothesis suggesting a genetic relationship between caldera volcanism and Mo-U ore formation was already proposed in the Russian scientific literature more than 40 years ago, "magmatic chambers, at an early stage of their development supplying volcanic material, at the consolidation stage were a source of uranium, fluorine, molybdenum and other associated components of molybdenum-uranium deposits" [2]. The authors of this early caldera related genetic concept envisaged palaeo-hydrodynamic conditions of ore formation "thermo-artesian systems of volcanic depressions that determined the conditions for mobilization of dispersed ore components, their migration and position of the sites for discharge of productive hydrotherms" [2]. In a more modern formulation, the caldera related concept of the uranium deposits formation implies "the existence of a relatively shallow magmatic chamber inducing convective hydrothermal fluid circulation lasting over a long period of time allowing an important alteration of rocks and thus remobilization of the U from the volcanic rocks" [3]. This abstract provides a summary of the preliminary results of numerical simulation of the process of free thermal convection of fluids specifying this hypothesis, with reference to the formation conditions of the deposits at Streltsovka and Antei. Brief details about the simulation results obtained are found in Ref. [4].

2. PROBLEM FORMULATION

The Streltsovka deposit is localized in the volcanic-sedimentary cover of the caldera. The Antei deposit comprises the lower continuation of the central section of the Streltsovka deposit in granitoid rocks of the caldera basement. Thus, the structurally conjugate deposits at Streltsovka and Antei, with combined total uranium reserves of about 90000 tU, can be regarded as the product of a single Antei–Streltsovka oreforming system. According to the geochronological data given in Ref. [5] and the results of the thermophysical calculation given in Ref. [6], the magma chamber under the caldera must have been fully crystallized by the beginning of the ore formation process, but a residual locally elevated geothermal gradient should still be preserved. The authors developed a 2-D computer simulation model for the Antei–Streltsovka oreforming system assuming a geothermal gradient of 60°C/km.

The total thickness of the volcanic-sedimentary sequence of the Streltsovka caldera infill is up to 1200 m. The orebodies of the Streltsovka deposit are localized within it mainly in the depth interval above the caldera

bottom and to within 150–300 m of the present-day surface. The morphology of the 'blind' ore deposits and the mineralogical and geochemical zoning of the hydrothermal rock alteration haloes [7] allow the suggestion that the upper horizons of the caldera rock section played the role of a hydraulic screen that prevented the outflow of ascending ore-bearing fluids to the caldera palaeosurface. With this assumption, the authors adopted in the simulation model a two-layer structure of the caldera filling, with the thickness of the top screening horizon, including its eroded part, equal to 500 m, and the thickness of the lower, ore-bearing horizon, being 1000 m. The total thickness of the two-horizon volcanic-sedimentary rock sequence therefore is equal to 1.5 km.

The Streltsovka collapse caldera is rimmed by a system of ring faults that have a vertical displacement of up to 700 m. On the basis of the results of tectonophysical (thermomechanical) modelling of the collapse caldera structure [8], the caldera ring faults are specified in the model as vertical zones extending from the magma chamber roof to the caldera palaeosurface or to the bottom of the screening horizon of the caldera filling. The fault zone of the Antei deposit is represented as a vertical fault extending from the magma chamber roof to the caldera base in the middle, between the ring faults. The zone of the Antei fault traces the vertical line of the model symmetry that permits consideration in the simulation as a modeling domain comprising only a half of the caldera cross-section with the one ring fault and the half-width of the Antei fault zone and the half-width of the Antei fault zone are taken to be 100 m, as in the Antei deposit [1].

The boundaries of the consolidated magma chamber are traced by the caldera ring faults. The critical value of the dimensions of the magma chamber at which the caldera ring faults are formed is D/d > 5, where D is the chamber diameter and d is the depth of the chamber roof [8]. Taking the value D of ~12 km for the Streltsovka caldera, the authors obtained an estimate of the depth of the magma chamber under the caldera bottom of $d \sim 2.5$ km. Taking into account these data and the 1.5 km of the caldera volcanic-sedimentary filling, the depth of the magmatic chamber under the paleosurface of the caldera can be estimated as being approximately 4 km. This estimate corresponds to the results of gravimetric studies, according to which the magmatic chamber was located at a depth of about 5 km [1].

The diameter and vertical thickness of the caldera magma chamber were assumed to be 12 km and 4 km, respectively, which accounts for its volume of about 450 km³. This estimate is consistent with the extruded volume of rhyolitic ignimbrite estimated to be not less than 50 km³ [9]. According to the estimate obtained in the analysis of US geothermal resources, from 3 km³ to 9 km³ of molten rock remain in the feeding centre for each cubic kilometre of erupted volcanic material in the process of caldera formation [10]. Taking this estimate into account, the volume of 50 km³ of the erupted ignimbrite corresponds to the residual volume of rhyolitic magma in the caldera chamber of 150–450 km³, the higher value corresponding to a magma chamber vertical thickness of 4 km. The structural scheme with the above geometric parameters from the modelling domain is given in Ref. [4].

3. RESULTS

In the numerical simulation, the structure of the fluid flow and the distribution of temperature in the modelling domain were determined. In addition, the velocity value of the fluid upwards flow along the Antei fault at the depth of its top termination in contact with the volcanic-sedimentary rocks of the caldera filling was calculated. To determine the main features of convective fluid heat and mass transfer, the following simplified approach was implemented. On the basis of the results of test calculations, the basic model was formulated, after which the authors examined what influence variations in permeability values of the main structural elements of the model exert on calculation results.

In the basic model, the following permeability values were adopted: for the caldera basement rocks 10^{-15} m², for the ore-bearing lower horizon of the caldera filling 10^{-14} m², for the top screening horizon 10^{-16} m², for the ring fault 10^{-14} m², for the Antei fault 10^{-13} m². The simulated fluid flow self-organizes into a

convective cell with a descending branch along the ring fault and an ascending branch along the Antei fault. The heat input by fluids of the ascending branch leads to an increase in temperature in the range of $340-400^{\circ}$ C in the zone of the Antei fault and in the range of $200-340^{\circ}$ C in the caldera filling rocks. The calculated value of the fluid flow velocity along the Antei fault is 7.5 m/year. The descending branch of the fluid convection cell penetrates deeply into the caldera basement rocks, thus providing the conditions for mobilization of uranium from both the host granitoids in the caldera basement and the consolidated magma chamber rocks. The representative pattern of the fluid flow configuration in the basic model is given in Ref. [4].

The numerical simulation experiments with variation in the permeability values of the structural elements of the basic model were carried out for checking what influence is exerted by permeability contrast between the caldera ore-bearing and screening horizons and the changes in permeability values of the ring fault zone and of the Antei fault zone on fluid circulation. The results obtained permit the authors to conclude that the favorable conditions for ore formation in the Antei–Streltsovka thermoconvective system could be realized only under a certain, and narrow, range of permeability values of its main structural elements. This limiting factor, as the authors believe, is one of the distinctive palaeo-hydrodynamic conditions that predetermined the uniqueness, among the volcanic-related uranium deposits, of the exceptional uranium reserves of the Streltsovka orefield.

4. DISCUSSION AND CONCLUSIONS

The potential oreproducing capacity of the Antei–Streltsovka thermoconvective system can be estimated from data on the rate of oreforming solution discharge from the Antei fault zone into the volcanic-sedimentary sequence of the caldera filling. With the calculated value of fluid flow rate along the Antei fault of 7.5 m/year, a strike extent of about 1000 m [11] and fault zone thickness of 100 m, the rate of fluid discharge from the fault zone to the caldera filling is 7.5×10^5 m³/year. The equilibrium concentration of the oreforming fluids, as estimated by the results of thermodynamic modelling, in the process of medium temperature leaching of uranium from leucocratic rocks is between 1×10^{-6} and 2×10^{-5} mol U [12]. With this range of uranium concentration, the time period needed for the formation of total uranium reserves of about 90000 tU in the Streltsovka and Antei deposits is from 500000 years to 25 000 years, respectively. At an exceptionally high uranium concentration of 1×10^{-4} mol U [13], established in the fluid inclusions of Canadian unconformity-related uranium deposits, the assessment of the duration of the ore deposition process is reduced to 5000 years.

A distinctive feature of thermoconvective systems with a closed circuit of convective circulation is the absence of restrictions on the quantity of fluids. However, since ore loading of fluids should be extracted from the enclosing rocks, the limitation on the resources of the ore material within the contour of the convective cell is maintained. As noted above, the convective circulation of fluids penetrates deeply into the rocks of the Streltsovka caldera basement, thus providing the conditions for mobilization of uranium from the both available sources: the host granitoids and the anomalously enriched rocks of the consolidated magma chamber. According to the data on differences in the uranium content between the rhyolite magma [14] and the geochemically similar granite massifs in the southern Transbaikal region [15], the possible scale of uranium extraction from the rocks of the consolidated magma chamber by thermoconvective circulation of post-magmatic fluids can be estimated at U content of ~13–14 g/t rock or, at a granite density of 2.6 t/m³, as ~35000 t/km³. Assuming that the volume of the magma chamber under the caldera to be 450 km³, an estimate of the total amount of uranium mobilization from the consolidated magma chamber will be ~ 16 million tU, which is approximately 60 times greater than the total reserves of the uranium deposits of the Streltsovka orefield. This extensive uranium source can be considered to have originated from uranium leached from the caldera basement, the potential amount of which, as evaluated in Ref. [14], can also exceed by several times the uranium resources of the Streltsosvka orefield.

Thus, the proposed thermoconvective model of the Antei–Streltsovka oreforming system ensures the formation of the significantly large uranium reserves without restrictions on both the required quantity of oretransporting fluids and on the quantity of the accessible uranium needed for its leaching, transport and deposition by fluid convection. According to the general geological–genetic classification, such a model of the oreforming system is close to the conceptual models of oreforming systems of epithermal deposits.

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URANIUM EXTRACTION TECHNOLOGY IN THE PHILIPPINES: THE NEXT STEP

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The phosphate fertilizer industry is one of the key players in sustaining the development of the important agricultural Philippines economy. Since 2002, phosphate based fertilizers have become one of the most important and consumed fertilizers next to nitrogen based fertilizers [1]. About 60% of produced and imported fertilizers are consumed by major and staple food crops such as rice (38%) and corn (21%), fruits and vegetables (19%), sugar (7%) and other crops (15%) [1]. Currently, domestic fertilizer production is being sourced from five fertilizer companies. The Philippines Phosphate Fertilizer Corporation (PHILPHOS), located at the Leyte Industrial Development Estate, Isabel, Leyte, is the largest and the leading fertilizer production company in the country and has been in operation for the past 28 years.

Phosphate rocks are also potential sources of uranium (66–145 ppm), thorium (1–20 ppm), rare earth elements (108–1085 ppm) and several other elements in the periodic table [2]. Annually, more than 1.97 Mt of imported phosphate rock is being used as raw material and is being processed, producing 1.17 Mt of diammonium phosphate fertilizers at PHILPHOS. During the digestion of phosphate rocks with sulphuric acid, most of the uranium and other trace elements are transferred into the phosphoric acid and, ultimately, produce uranium contaminated fertilizers. Around 44.97 Mt of uranium per year are lost into agricultural fields as a result of fertilizer application, with potential risks for humans and for environmental safety [3].

The Philippines Nuclear Research Institute (PNRI) has pioneered the uranium extraction from wet phosphoric acid (UxP) technology in the country to recover uranium and critical elements from phosphate processing, thereby translating these problems into opportunities.

1. URANIUM RECOVERY USING THE D2EHPA–TOPO METHOD

In 1987, PNRI initiated uranium recovery from phosphoric acid utilizing the liquid–liquid extraction method which uses the synergistic mixture of di-2-ethylhexyl phosphoric acid and trioctyl phosphine oxide (D2EHPA–TOPO). Although this method is already established and widely used, it had to be optimized to suit Philippine phosphoric acid, which is a mixture of different phosphate rock imported from several countries such as Israel, Egypt, Morocco, Jordan, etc. Tests were conducted only up to the first cycle solvent extraction and first cycle acid stripping, which had recovery rates ranging from 64% to 75% [4]. However, this initiative was discontinued due to the downtrend of nuclear energy and the slump in the global price of uranium.

In 2011, there was a renewed interest to continue the UxP project through the IAEA TC Project PHI/2/010 entitled Enhancing National Capacity for Extraction of Uranium and other Valuable Elements from Phosphoric Acid. It was funded by the National Research Council of the Philippines through the project entitled Comprehensive Extraction of Uranium, REE and Other Valuable Resources from Wet Phosphoric Acid. This time, PNRI had successfully developed and built its capacity to conduct static laboratory scale extraction of uranium through training, fellowships and expert missions and through the upgrade in laboratory infrastructure, including the use of a wavelength dispersive X ray fluorescence spectrometer (WDXRF), fluorometer and portable gamma ray spectrometer. The process parameters on uranium recovery by D2EHPA–TOPO method from pretreatment of raw phosphoric acid (absorbent materials, optical density, mixing time and mixing intensity), to extraction (optical density, organic/aqueous ratio, P₂O₅ concentration and contact time), to stripping (aqueous/organic ratio, amount of Fe, temperature) and to precipitation of

uranium yellowcake were optimized during the three-year implementation of the project. The project ended in 2017 and demonstrated a feasible laboratory scale UxP technology.

2. THE NEXT STEP

The UxP research and development undertakings, which started from basic research, will enhance indigenous capabilities and competence to build the first industrial scale UxP facility in the country. As a next step, a newly approved IAEA TC Project PHI/2/013 entitled Enhancing Bench-scale Simulation for the Development of Continuous Extraction Technology of Uranium and Other Valuable Elements from Phosphates — Phase II, will be implemented over three years (2018–2020), in cooperation with PHILPHOS. The project will develop a comprehensive and environmentally acceptable continuous uranium extraction process, which specifically aims to: (i) perform tests from static laboratory scale into continuous recovery of uranium, (ii) provide engineering design parameters for pilot plant or commercial scale operations, and (iii) determine waste minimization technologies. A bench scale continuous laboratory scale extraction system will be installed to validate the results from phase I of the project and to obtain more reliable and realistic process parameters that would better simulate conditions in an industrial/commercial set-up. Financial assistance from a local funding institution, the Philippines Council for Industry Energy and Emerging Technology Research and Development, through the project Laboratory/micro-scale Continuous Extraction System for the Recovery of Uranium from Philippines Wet Phosphoric Acid: Phase I, is already in the pipeline. This will sustain other requirements of the project.

With the dedication of the PNRI team to developing a comprehensive extraction technology from phosphate resources, a phosphogypsum research project entitled Extraction of Radionuclides, Rare Earths and Other Valuable Industrial Elements from Philippines Phosphogypsum Tailings — Phase I is conceived as a spin-off project. The long-term goal of the project is to develop a technology to recover radionuclides, rare earths and other valuable industrial elements in phosphogypsum resources from phosphate fertilizer plants. This project is also in the pipeline and will also be financially supported by the Philippines Council for Industry Energy and Emerging Technology Research and Development.

The growing capacity of the PNRI in this area will have a long-term impact in terms of a more sustainable and environmentally friendly method of mining and extraction in the country. Uranium recovery from phosphates is a prime example of this safe and balanced sustainable management and use of natural resources promoting sustainable socioeconomic and environmental development to address the country's needs in regard to food, energy and water security. This will lead to: (i) minimal environmental impacts and to protection of human health by producing cleaner fertilizers with greatly reduced uranium content, (ii) zero waste and maximized resource utilization, (iii) additional revenue in the phosphate processing industry, and (iv) an opportunity to utilize uranium in the nuclear fuel cycle were the Philippines to decide to proceed with the nuclear option.

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EXPLORATION SUCCESSES IN THE TIM MERSOI BASIN (NIGER) – A CASE STUDY

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1. INTRODUCTION

The Madaouela Uranium Project consists of a string of seven deposits located within the Tim Mersoi Basin, near the town of Arlit. Since 2008, GoviEx Uranium Inc. (GoviEx) has been exploring for, and defining, the mineral resources at the Madaouela Uranium Project. GoviEx has to date delineated a total resource of 117 Mlbs (62800t) of U (46 Mt of ore at a grade of 0.115% eU) in the measured, indicated and inferred categories [1]. On 25 January 2017, GoviEx received its Madaouela I mining permit, after completing an environmental, social impact assessment and a feasibility study, as required by Niger regulation. After GoviEx acquired the licences, there was an intense period of delineation and validation of the previous work, followed by exploration along a perceived redox front towards the south. This led to the discovery and the delineation of a number of deposits to the south, culminating with the Miriam deposit, broadly along the same trend [2–5].

2. HISTORY

The CEA (Commissariat à l'Energie Atomique) conducted drilling operations using drilling grids of 800 m over large areas, and down to 100 m over two contiguous mineralized zones named Marianne and Marilyn. After its discovery, the Marilyn deposit was drilled locally at 50 m and <50 m spacing, and an underground mining test was implemented for detailed sampling prior to mineralogical studies, processing tests and investigations into the global rock quality from a mining perspective. CEA had also previously discovered the other deposits that are the current active mines in the area (the SOMAÏR and COMINAK operations), and subsequently ceased exploration work on Madaouela in 1967 [1].

The Japanese Power and Nuclear Fuel Development Corporation (PNC) conducted additional uranium exploration work up to 1992 and produced a report on the feasibility of the Madaouela deposit in 1993, which was later updated in 1999. Historical mineral resources/reserves were stated at 5-15 Mlb U₃O₈, depending upon the cut-off used [1]. A total of 5 exploration licences were granted in 2007 to GoviEx and exploration and development activities have been ongoing since 2008.

3. GEOLOGY

The Tim Mersoi Basin is defined by fluvio-deltaic sedimentary packages that host significant uranium mineralisation. A combination of structural, palaeo-geographical, palaeo-hydrological and sedimentary factors controlled the location of these deposits [6]. The main deposits, namely Marianne, Marilyn, Maryvonne, MSNE and Miriam, occur within the Carboniferous Guezouman Formation and are differentiated on their gross morphology which consists of a thin carpet type (basal deposit) which occurs at the base of the Guezouman Formation. The mineralisation is controlled by sedimentological factors, such

as organic accumulation at cross-bed foresets and sulfide accumulation. It is also found within the basal conglomerate (the Teleflak), which consists of pebbles from the Air basement, clay and phosphatic nodules. Another deposit type is described as having a Christmas tree morphology (roll-front) with mineralized accumulations up to 25 m thick and appears to be controlled by fractures.

Geological control is a combination of structurally controlled palaeochannels trending in a N 70° direction, with the associated development of the UA Formation (feldspathic sandstone) within some of these channels and thickening of the Guezouman Formation. The mineralisation occurs at the contact between the reduced Talak Formation (dark mudstone) and the Guezouman Formation, a fluvio-deltaic sandstone and siltstone [6].

The Miriam deposit is different to the others as it can be considered as a more of a classic roll-front with Christmas tree-like structures believed to be controlled by N 140° trending expansion fractures, as opposed to the carpet-like morphology of the other deposits. These fractures can be seen on aerial photographs and aeromagnetic data and are significant features in the search for other Miriam type roll-front deposits. Proximity to the N 40° trending Madaouela Fault may be an essential control as the N 140° trending fractures are more like Riedel type fractures, located between the Izeretagen and Madaoulea Faults.

Another type of deposit occurs further up the stratigraphic column, within the Madaouela Formation, near or at the contact with the Permian Tarat Formation, host to the nearby SOMAÏR mine. This is more of a classic roll-front, associated with thin mudstone layers, which occur as stacked lenses.

Uranium mineralisation typically comprises coffinite and uraninite associated with molybdenum-rich and titanium-rich coffinite occurring as interstitial grains within a kaolinite–illite–chlorite–carbon–calcite cement within the quartz–feldspar matrix of the sandstone. Sulfide minerals are associated with the uranium minerals, typically pyrite, nickeline, molybdenite and gersdorffite. Radiogenic galena is also present and associated with early phase uranium paragenesis.

Some surficial oxidation has occurred at the La Banane deposit and other localities with near surface carnotite, unhoite and tyuyamunite occurring in fractures within calcite cemented shale.

4. CURRENT STATUS OF EXPLORATION

The discovery of the Miriam deposit represents the continuity of exploration which started with the Marianne–Marilyn deposit and which have been rediscovered by reopening some old holes drilled by CEA–COGEMA. The GoviEx geologists suggested that at a certain stage it should be possible to encounter the redox front of the Akouta model (COMINAK). Therefore, a grid of 400 m × 400 m has been defined on the basis of redox observation from surface geological formations and structure. Unfortunately, no rich intercepts were recorded, but the scintillometric logs and chip colours clearly show the possibility of a local redox front, albeit at low grade. These results encouraged the GoviEx team to define the 200 m × 200 m grid and this defined important mineralisation at a 200 ppm U cut-off, showing interesting continuities at an average depth of less than 100 m and some rich intercepts, suggesting the possibility of a low grade deposit possibly exploitable by open pit. Following this, the Miriam deposit was then drilled out on a 25 m $\times 25$ m grid to define the known resource [5].

For the La Banane deposit, this was purely a greenfield discovery following a step out from the main trend to test the hypothesis that parallel redox fronts exist to the east of the one that runs through the Marianne–Miriam deposits and hosted within the Guezouman Formation. The work started by regional strip mapping along 800 m lines to identify the geological structure and favourable redox zone in the eastern part of Madaouela Fault. This was followed with the reopening of a few historic holes to verify the radiometric data, which was followed up by drilling on an initial 3200 m spacing grid with 1600 m infill along sections, followed by further infill as anomalies were identified. The redox interpretation was conducted mainly on

rock chip observations (grain coatings, colours of matrix, clay, organic matter, hematite, limonite) and scintillometer anomalies [3].

Further additional anomalies have been identified within the Guezouman Formation (Marianne–Marilyn), although the largest number of mineralized intercepts occur in the Madaouela arkosic channels. The geological continuity of mineralisation within the Madaouela was confirmed by reducing the drill spacing, which resulted in several elongated mineralized bodies 300–400 m being delineated. GoviEx finally conducted infill drilling at 100 m spacing to control extension and to carry out the correct sequential correlation and sustain the geological model [1, 2].

5. CONCLUSIONS

This case study demonstrates that the geology of the Tim Mersoi Basin is still largely unknown. The basin is large and has a complex geology, but is similar to other sedimentary basins elsewhere in the world known to host uranium. Current discoveries and exploration activity indicates potential for further development in the region.

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FALEA: AN UNCONFORMITY-TYPE POLYMETALLIC DEPOSIT, MALI, WEST AFRICA

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1. INTRODUCTION

The Falea project contains a polymetallic orebody hosted within the Neoproterozoic portion of the lower Taoudeni Basin, where it overlies a heavily deformed Birimian basement composed of schists and metasediments. The project is located in western Mali, approximately 350 km west of the capital, Bamako, and consists of three exploration permits covering 225 km². Of these, the Falea permit covers 75 km² and hosts several orebodies with an indicated mineral resource of 6.88 Mt at 0.115% U₃O₈ (0.098% U(6694t U), 0.161% Cu and 73 g/t Ag, and an inferred mineral resource of 8.78 Mt at 0.07% U₃O₈ (0.059% U (5155t U), 0.20% Cu and 17 g/t Ag, using a cut-off grade of 0.03% U₃O₈ (0.025%U)[1].

2. HISTORY

Uranium mineralization was discovered by COGEMA in 1977, having identified the area of southern Mali and adjoining Senegal and Burkina Faso as having potential as early as 1957. COGEMA drilled 86 holes on a nominal 800 m grid over the Falea permit, and a more concentrated 200 m grid on the Central deposit. COGEMA abandoned the project in 1982, at a time of low uranium prices [1]. Delta Exploration obtained the permit in 2006 from the Government of Mali, with Rockgate Capital, a Canadian company, funding the exploration as of 2007 during the uranium resurgence. Delta acquired Rockgate Capital in 2008.

The exploration carried out by Delta/Rockgate started at the known Central deposit and progressed northwards to define the north zone and, ultimately, define the current resource. The companies also carried out hydrological, environmental and social studies [1]. Denison Mines Corporation acquired the project in 2014 and initiated an airborne geophysical survey as well as soil and termite mound sampling. The Falea project was acquired by GoviEx Uranium Inc. (GoviEx) from Denison Mines Corp. on 13 June 2016.

3. GEOLOGY

The project is situated in the Falea–North Guinea–Senegal sedimentary basin, on the southern edge of the western province of the Taoudeni Basin. The Taoudeni Basin is a Neoproterozoic (750 Ma) to Carboniferous, intracratonic basin. The Falea–North Guinea–Senegal basin consists mostly of the sedimentary rocks of 'Supergroup 1', which is the lowermost sequence. This group comprises a basal, predominantly fluvial package grading upwards into a series of shallow shelf sandstones and mid-shelf mudstones (total thickness 500–550 m). The Falea–North Guinea–Senegal basin is situated within the West African Craton between the Archaean rocks to the south-east and the Birimian rocks to the north, east and west.

In the Falea region, this lowermost sequence sits unconformably on the Birimian basement. The basal package (approximately 10-30 m thick) consists of conglomerates (VC), the Kania Mudstone with stromatolites (KI), the Kania Sandstone (KS) and the ASK mudstones. The ASK is marine but the VC and KS represent a fluvial sequence of channel and inter-channel sedimentation with a minor marine incursion (KI mudstone plus thin stromatolites). The sedimentary rocks are largely unfolded and sub-horizontal, with a very shallow dip to the west ($<10^\circ$). The sequence is intruded by Carboniferous dolerite sills up to 80 m thick in places which form cliffs in the area.

The North and Central zones are bisected by a N–S trending reverse fault, the Road Fault. The Road Fault verges to the west and repeats the stratigraphy and the mineralization in the zone proximal to it. The vertical throw is 70 m. The main deposits are spatially associated with this fault. The eastern portions of the Central and North zones have depths of 180–280 m below the plateau, whereas the western blocks lie at depths of 250–350 m. The Bodi Zone is NW of the North zone, but hosts only sporadic U mineralization. The East Zone is located 4 km from the main deposits and is a small area of Cu–U–Ag mineralization, also spatially associated with N–S faulting [1, 2].

4. MINERALIZATION

The Falea deposits consist of four separate zones known as Bodi, Central, North, and East. The North and Central deposits have been intercepted at depths of 180 to 300 m below surface and are the principal deposits. The Bodi, Central, and North zones occur along a 3 km-long, north-south trending mineralized corridor. The East Zone is located approximately 4 km to the east of the Central and North zones. The Falea deposit is interpreted as an unconformity associated polymetallic deposit with associations of uranium, silver and copper.

The mineralization is mainly located within the KS unit and averages 3.6 m in width. It is also present in the VC, KI and at the base of the ASK. Mineralization can be distributed throughout the KS when it is thin (<4 m), but is most commonly seen at the contacts of the KS with VC or KI or at the lower contact with the ASK. The main gangue minerals detected by XRD in the Falea ore are quartz and muscovite/illite. Chamosite, clinochlore, dolomite, calcite and albite are less abundant. Sulfide mineralization consists of argentite (Ag₂S), tennantite (Cu, Ag, Zn, Fe)₁₂As₄S₁₃, galena (PbS), sphalerite (ZnS), cobaltite (CoAsS), arsenopyrite (FeAsS) and covellite (CuS), and their presence was confirmed by SEM/EDS analysis. The main uranium mineral is uraninite (pitchblende), but also includes coffinite and brannerite [3]. Uranium is spatially associated with silver in the North deposit, where native silver can be seen in drill core. The copper is low grade but ubiquitous and present in almost every hole drilled. Uraninite often forms rims around chalcopyrite. Copper mineralization is also present at the base of the ASK formation for widths of 1–4 m.

5. DEPOSIT TYPE

The Falea deposit has been previously postulated to represent a combination of two mineralization events. The first event was similar to a sedimentary exhalative (SEDEX) event and the second event was interpreted to be formation of a roll-front deposit, that is, an epigenetic uranium deposit at a redox interface occurring on top of a SEDEX deposit [2].

In 2011, Rockgate reinterpreted the Falea deposit as an unconformity associated uranium deposit, using a polymetallic egress model as the geological model. The unconformity at Falea lies between the Birimian basement and overlying sedimentary sequences. The egress model was applied due to the presence of the Road Fault, which could have introduced fluids into the sandstones. Unconformity associated deposits are high grade concentrations of uranium that are located at or near the unconformity between relatively undeformed quartz-rich sandstone basins and underlying metamorphic basement rocks. The compositional spectrum of unconformity associated uranium deposits can be described in terms of monometallic (simple) and polymetallic (complex) end members on the basis of associated metals. Polymetallic deposits are

typically hosted by sandstone and conglomerate, situated at the basement unconformity. Polymetallic ores are characterized by anomalous concentrations of sulfide and arsenide minerals containing significant amounts of nickel, cobalt, lead, zinc and molybdenum. Some deposits also contain elevated concentrations of gold, silver, selenium, and platinum group elements. Deposits with egress halos include both basement hosted and sandstone hosted types, and the alteration ranges between two distinctive end member types: (i) quartz dissolution + illite and (ii) silicified (Q1 + Q2) + later illite–kaolinite–chlorite + dravite [1, 4, 5].

6. WORK COMPLETED AND DISCUSSIONS

A total of 944 drill holes, representing 231 887 m, have been completed over the Falea deposits. Most holes were diamond cored from the surface, with a small amount of reverse circulation pre-collars. Drilling was completed to define the resources, which leaves significant exploration potential outside the main deposit area. Other work completed over the area includes soil surveys for gold over sub-cropping Birimian, as well as soil and termite mound surveys over the Falea deposits. Radon cup surveys and geological mapping along the range fronts, which included scintillometer surveys, were also completed.

Helicopter-borne geophysical data were collected by Rockgate in 2012 and by Denison in 2015. The data included airborne magnetics, TEM and radiometrics. These data were recently remodelled. The structural complexity of the area becomes evident as a series of N–S and conjugate NE–SW and NW–SE trending fault patterns divide the area into what appears to be horsts and grabens, bringing target horizons of the lower Taoudeni and particularly the KS closer to the surface. The thick dolerite unit unfortunately tends to 'blind' the EM and deeper magnetic signatures. In some areas, however, the analytical signal strength of the magnetic data, the EM conductivity and the higher U values from the radiometrics can be correlated [6].

Isopach analysis was undertaken in-house on the main deposit and concentrated on the sequence between the base of the ASK unit to the top of Birimian (the unconformity surface) and the thicknesses of KS, VC and KI. The Birimian surface forms a N–S trending palaeochannel just east of the Road Fault. The VC unit is thicker in this channel whereas the KI unit (thin shale) is only well developed east of the channel. Similarly, the KS unit attains greater thicknesses (>6 m) east of the channel. This suggests that the Road Fault was probably a hinge line or small scarp during sedimentation and created a channel for conglomerate deposition whereas channel edge and interchannel areas were dominated by sand and shale during the brief marine incursion of KI. The channel and interchannel areas formed a sedimentary trap for the focus and the precipitation of metals from saline, metal-bearing brines at a later stage. Similarly, the Eastern zone is also spatially associated with a N–S trending structure and has variable VC thickness. The following points are evident from the isopach work:

- There is a clear relationship between the Road Fault and the distribution of the VC conglomerate supporting the fault scarp hypothesis. Using the base of ASK to the top of Birimian, this is the thicker accumulation, just east of the fault (a paleo-low area). In the field, conglomerates next to the fault had some boulder sized rocks;
- The KS sandstone is better developed (thicker) to the east of the fault zone in the palaeo-high area. The VC and KS may represent facies changes, i.e. channel versus interchannel areas;
- The channel relationship is not so clear if sea level is used as a datum. The base of ASK is considered a better datum because it represents the first major marine incursion;
- Grade accumulation spans both high and low areas, with U and Ag mirroring each other and Cu showing higher concentrations to the east;
- Closer examination of the northern zone highlights the strong relationship between a thin KI unit (mudstone and stromatolites) and higher grades of Ag and U. Again, Cu shows a preference for a thicker KI as a preferred trap. The KI unit represents a marine incursion which was clearly only thinly developed once it encountered the paleo-high;
- The relationships in the Central zone are not as clear, although if the KS is too thin then mineralization seems to reduce in tenor and quantity;

The isopach work highlights the importance of the sedimentology in creating a suitable trap for
precipitation of metals from metalliferous brines which were mobilized after basin formation and
relate to fluid movement triggered by a later deformation event.

Whereas there has not been any proper analysis of alteration patterns of the hanging wall and footwall rocks at Falea, visual inspection of drill core reveals that the sandstones contain primary quartz, muscovite and minor feldspars. Alteration includes chlorite, sericite/illite and carbonates (calcite and dolomite). Albite and riebeckite have been observed. Apatite, rutile, zircon and anhydrite have also been noted. Hematite staining is common. In the East fault zone, there is abundant hematite staining and silicification which has pervaded both basement and hanging wall units. Bleached zones and hematite staining was observed in the hanging wall package. Chlorite and sometimes hematite were noted in the basement rocks.

The further delineation of the deposits and comparison with large, rich, historic districts overseas may point to considerably larger resources occurring in the area.

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THE KAROO SANDSTONE-HOSTED URANIUM DEPOSIT AT DIBWE EAST, MUTANGA, ZAMBIA

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1. INTRODUCTION

The late Carboniferous – early Jurassic Karoo rift basins of southern Africa are an important emerging uranium province. A number of sandstone-hosted deposits have been identified, although only Paladin Energy's Kayelekera deposit in Malawi is currently being mined. The deposits are typically tabular, with variable proportions of primary and secondary uranium minerals. They generally occur at "energy drops" in fluvial sandstone successions, where organic material accumulated and subsequently acted as a reductant for uranium dissolved in basin waters (G.Yeo, 2011).

The Dibwe-East is part of GoviEx Uranium Zambia Limited, Mutanga Project licenses (13880-HQ-LML and 13881-HQ-LML) encompassing 457.3 square kilometers. The mining licenses have a term of 25 years to April 2035. The mining licenses are located in Siavonga district in southern Zambia, approximately 180km south of the nation's capital Lusaka and 36km from Siavonga town.

Dibwe-East geologically, lies in the Mid-Zambezi Rift Basin of southern Zambia; the fluvial Escarpment Grit sandstones unconformably overlie the late Permian lacustrine Madumabisa Mudstone and are conformably overlain by the early Triassic fluvial Interbedded Sandstone and Mudstone Formation.

2. GEOLOGY

In the Mid-Zambezi Rift Basin of southern Zambia, the fluvial Escarpment Grit sandstones unconformably overlie the late Permian lacustrine Madumabisa Mudstone and are conformably overlain by the early Triassic fluvial Interbedded Sandstone and Mudstone Formation (Nyambe and Utting, 1997). The Dibwe-Mutanga Corridor uranium deposits are located within the Zambezi Rift Valley which is hilly with large fault bounded valleys filled with Permian, Triassic and possibly Cretaceous sediments of the Karoo Supergroup. The Mid-Zambezi Valley is characterized by a series of NE-trending, fault-bounded cuestas or fault blocks, uplifted to the NW and dipping to the SE. Rocks of the Karoo Supergroup (late Carboniferous to Jurassic) occupy the rift trough of the Zambezi Valley (Money and Prasad, 1977).

Dibwe-East is predominantly composed of Escarpment Grit Formation (EGF). The surface geology is characterised by a few scattered sandstone outcrops. Two major units can be distinguished, the "Braided facies" member (EGF_{b-f}) of the lower EGF and the "Meandering facies" member (EGB_{m-f}) of the upper EGF In core, the two units appear to be transitional from one another. The "Braided Facies" which covers mostly half of the northern prospect is distinguished in outcrop as gritstones, very-coarse-grained to coarse grained sandstones and pebbly sandstones. Ripple lamination is common and mudstone beds are laterally continuous.

The absence of any marker beds is typical of braided river successions. Broad lithologic features, however, including zones of largest average and maximum grain size, relatively abundant pebbles, mudstone beds and mudclasts can be matched from hole to hole. On the basis of these features, three subdivisions have been distinguished within the EGF (Lusambo, V., 2011):

The "Braided Facies", which is at least 120 m thick at Mutanga, was subdivided into three subunits:

- Unit A, bounded by the underlying Madumabisa mudstone and the lowest EGF conglomerate bed, is characterized by cross-bedded, low-angle cross-bedded and ripple-laminated, coarse- to medium-grained sandstones with local mudchips, interbedded with mudstones and very fine-grained sandstones. Thickness variations in Unit A probably reflect deposition on an irregular paleotopographic surface. Whereas there is no apparent unconformity between Units A and B, that contact is the best datum to use in any stratigraphic reconstruction.
- Unit B is characterized by the presence of conglomerates, gritstones, very-coarse-grained to coarse grained sandstones and pebbly sandstones, locally with mudclasts derived from interbedded mudstones. The upper boundary of unit B can be defined by the last appearance of mudstone or mudclasts associated with pebbly sandstone. Whereas, the historic AGIP graphic logs did not distinguish mudclasts, on this profile the B/C boundary was taken as the highest mudstone bed. Unit B appears to thicken toward the southeast, presumably reflecting increased syndepositional subsidence in that direction, as noted above.
- Unit C is dominated by gritstones and coarse-grained, rarely pebbly sandstones. Mudstones are rare; hence mudclasts are uncommon in this unit. The scarcity of mudstones and mudclasts suggests that Unit C should be more permeable than Unit B. This may be a factor in localization of mineralization near the contact between these units.

The southern part for the prospect is mostly "Meandering Facies" reaching in excess of 8m and is distinguished in outcrop as massive, or trough and tabular planar cross-bedded, fine- to medium-grained sandstone, locally with scattered small pebbles. In core, the "Meandering Facies" sandstones show ripple lamination as well as cross-bedding. Sandstone beds typically grade up from coarse-grained bases to medium grained or fine grained tops (Lusambo, V., 2011). Mudclasts and pebble lag layers are common. The "Meandering Facies" is distinguished from the braided facies by scarcity of pebbly sandstones and conglomerates and by the presence of extensive mudstone beds.

3. MINERALISATION

The uranium mineralization identified to date appears to be restricted to the Escarpment Grit Formation of the Karoo Supergroup. Within the tenement area, the Karoo sediments are in a northeast trending rift valley. They have a shallow dip and are displaced by a series of normal faults, which, in general, trend parallel to the axis of the valley. The Madumabisa Mudstones form an impermeable unit and are thought to have prevented uranium mineralization from moving further down through stratigraphy. Mineralization is associated with iron-rich areas (goethite), and secondary uranium is distributed within mud flakes and mud balls as well in pore spaces, joints, and other fractures.

Mineralization at Dibwe East is similar to that at the Mutanga deposit in that it is composed of coarse Autunite in fracture zones within an upper oxidized horizon overlying finer grained disseminated mineralization within a pyritic reduced zone. Coffinite is dominant at depth (70 - 100m zone) whilst Phurcalite (similar chemical formula as Autunite) is dominant in the 0 - 40m and 40 - 70m zones. Thus it appears thet primary mineralization is at depth qnd gives the high grade zones with secondary mineralization in the 0 - 70m zone. Mutanga lies 40 km via all-weather road from a major paved highway and only 35 km from the Kariba hydro dam. There is strong local community and government support for the project.

4. EXPLORATION STATUS

Exploration for uranium in the Middle Zambezi valley during the early 1970's revealed the existence of several uranium deposits. The most interesting occur in the vicinity of Siavonga and are currently held by GoviEx Uranium Zambia Limited.

In 2006 a detailed aeromagnetic and radiometric survey (Symons & Sigfrid, Report on the Interpretation of Aeromagnetic and Radiometric data, 2006) was completed over the areas of interest which were revealed during an earlier pre-digital airborne survey. The 2006 survey has confirmed the position and tenor of the existing targets and identified additional, targets.

- 1. The EGF appears to have two clear radiometric signatures;
 - a. A reddish brown ternary radiometric signature indicates the presence of K in the Formation, consistent with description of the EGF as feldspathic sandstone. This part of the EGF was mapped and designated as D1
 - b. The areas marked as D2 appear to have a similar K response but with additional uranium producing a white ternary radiometric signature.
- 2. The structures identified indicate an extensional half-graben regime with normal faults trending in a generally NE direction. The movement on these faults appears to down throw blocks to the NW. Later faulting in a NW, WNW and NNE direction crosscutting the Karoo stratigraphy is also noted.
- 5. CONCLUSIONS
 - Exploration data suggest that the likely environments of uranium mineralization are meandering stream depositional systems within paleochannels, with fine- to coarse-grained sands and silts containing some organic and pyrite material, which could serve as reductant for the precipitation of uranium.
 - At least three mineralized zones ("sand packages") have been identified.
 - A stacked series of three mineralized horizons extend from near surface down to nearly 150m along nearly a 4km NE-SW strike, with their thickness ranging from 2m to 14m.
 - Coffinite is dominant at depth (70 100m zone) whilst Phurcalite (similar chemical formula as Autunite) is dominant (0 40m zone and 40 70m zone). Thus it appears primary mineralization is at depth giving the high grade zones with secondary mineralization at surface 0 70m zone.

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URANIFEROUS POTENTIAL AND OCCURRENCES OF MADAGASCAR: AN OVERVIEW

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1. INTRODUCTION

Geologically, Madagascar is divided in two parts. The larger, eastern region comprises Precambrian crystalline basement [1] which can be divided into six domains; from north to south these are the Bemarivo, Antongil–Masora, Antananarivo, Ikalamavony, Androyen–Anosyen and Vohibory, respectively. The western region is covered by three important basins: Diego Basin, Mahajanga Basin and Morondava Basin. A small basin on the eastern coast is also present. Additionally, there exists the Lake Basin in the central part of the country.

Uranium occurrences have been found within two domains in crystalline bedrock, the Antananarivo and Anosyen Domains, and these are believed to have potential. There are also two deposits in the Morondava Basin and in the Lake Basin.

Two types of uranium deposit occur in crystalline basement and two other types in sedimentary cover. The present work delineates the occurrences already known and assesses the uranium potential of Madagascar, including details of a new potential uranium deposit.

2. DESCRIPTION OF OCCURRENCES AND URANIFEROUS POTENTIAL

2.1. Uranium in sedimentary cover

There are two types of deposit in sedimentary cover: i) sandstone hosted type, and ii) surficial lacustrine type.

2.1.1. Sandstone hosted uranium deposits

The Makay and Folakara deposits are located in the north-western part of Madagascar, within the Morondava Basin. Makay is located in the southern part and Folakara in the northern part of the Basin. From south to north in the Morondava Basin, uranium occurrences have been found at Sakoa, Sakamena, Isalo I and Isalo II. Carnotite mineralization has been found at Isalo II, which is hosted within sandstone and fine clays.

After geological prospecting, geophysical airborne survey and geochemical studies undertaken by the Commissariat à l'Energie Atomiques (CEA) and the Office Militaire National pour les Industries Strategiques (OMNIS) in partnership with Programme des Nations Unies pour le developpement, the IAEA continued to undertake geological, geochemical and drilling work in 1979–1982. The IAEA evaluated the economic potential and estimated 272 000 tU of reserves [2].

2.1.2. Surficial lacustrine deposit

Geographically, the Vinaninkarena deposit is situated in central Madagascar, south of Antsirabe. The deposit can be classified as a surficial type. Uranium occurrences formed by uranocircite are located within the Lake Basin.

The uraniferous zone is located at the contact with crystalline basement at southern part of the lake. This deposit is considered to be a secondary deposit, derived via alteration, erosion and transport from from crystalline basement mineralization.

Starting in 1910, the CEA spent over 30 years evaluating the Vinaninkarena deposit and concluded that it held reserves of 140 000 tU [2].

2.2. Uranium in crystalline basement

The crystalline basement hosts both metasomatite and intrusive type deposits.

2.2.1. Metasomatite deposit

The Tranomaro uranium deposit is classified as a metasomatite deposit [1]. Geographically, this deposit is located in southern Madagascar and geologically it forms part of theAndroyen–Anosyen domain and Anosyen subdomain. The Anosyan subdomain consists of metagabbros and granitic orthogneiss interpreted as Palaeoproterozoic in age.

This deposit is hosted in Tranomaro group, which consists of calc-magnesian paragnesis, werneritites, cipolin, leptynite (with uranium and thorium mineralization) and quartzite. This formation is cross-cut by three igneous suites: i) Dabolava Suite (1000 Ma), ii) Imorona–Itsindro Suit (820–760 Ma), and iii) Ambalavao Suit (570–550 Ma) [1].

Uranothorianite mineralization is associated with pyroxenites in granulite facies. Both CEA and OMNIS conducted exploration work in this area (detailed mapping, excavation of prospecting trenches and pits, and airborne geophysics) during 1947–1969.

Between 1953 and 1967, OMNIS, in partnership with IAEA, estimated the reserves of uranothorianite in the Tranomaro deposit at 5 000 t containing 1 000 tU [2].

2.2.2. Intrusive deposit

Two deposits are classified as being of the intrusive type: Antsirabe and Ankazob–Vohimbohitra. Both deposits are located in the Antananarivo domain, which comprises Neoarchaean greenschist to granulite facies orthogneiss and paragneiss. This domain includes three greenstones belts, which, from west to east, are the Bekodoka–Maevatanana Belt, Andriamena Belt and Beforona Belt [1]. Collectively, these three greenstone belts constitute the Tsaratanana complex. These formations are cross-cut by the ultrabasic to acid Imorona–Itsindro suite (860–720 Ma) [1].

2.2.2.1. Antsirabe uranium deposit

Geographically, the Antsirabe uranium deposit is situated in eastern part of Antsirabe, in central Madagascar, near the town of Betafo. The uranium mineral, betafite, is named after Betafo town.

Three types of potassic pegmatites are present in this area and are differentiated according to their stratigraphic relationship:

- 1) Pegmatite cross-cutting granites contains betafite, euxenite, columbite, pyrite and garnet;
- 2) Pegmatite cross-cutting gabbros appears as veins filling fractures and contains magnetite, euxenite, betafite and beryl;
- 3) Pegmatite cross-cutting crystalline basement fills fractures in a migmatite gneissic complex.

Some exploration work has been carried out in this area. Initial exploration by CEA was conducted by airborne survey between 1947 and 1969. OMNIS, in partnership with the United Nations Development Programme, continued this work between 1976 and 2000 [2].

Thirty pegmatites were investigated in this area and 50 t of ore grade material were collected at an average ore grade $12-15\% \text{ U}_3\text{O}_8$ [1]. Pegmatite cross-cutting the Vavato Granite (860–720 Ma) was the main host lithology [1].

2.2.2.2. Ankazobe–Vohimbohitra uranium deposit

This deposit is located in the Andriamena Belt in central Madagascar, which is associated with uraninitebearing pegmatite hosted within various formations of different metamorphic grade, although generally, the gneissic complex in this area is of a high metamorphic high grade [1]. This area is geologically very similar to the greenstone belts of Zimbabwe. The 2014 Red Book states resources as 1400 tU in the reasonable assured resources category and in the US \$130–260/kg cost category. Speculative resources are estimated at 25 000 tU [3].

Zimbabwe is believed to have uranium reserves of around 45 000 t [4]. Bacher and Morgenthau stated that "The pegmatites in Madagascar are the only one that have indicated appreciable tonnages of uranium minerals. Records indicate the sale of over 100 t of autunite and uranociricite ores" [5].

3. DISCUSSION AND CONCLUSION

After investigations by various international and national entities and following comparison of the Andriamena Belt with the greenstone belts of Zimbabwe, it is concluded that pegmatites in Madagascar host significant uranium mineralization. The Ankazobe–Vohimbohitra uranium deposit hosted in pegmatite could prove to be significant and further detailed exploration is warranted.

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STATUS OF ACTIVITIES ON UNCONVENTIONAL URANIUM RESOURCES IN THE PHILIPPINES

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While the initial search for uranium in the Philippines dates back to as early as 1954, it was only in 1977 that a systematic exploration approach for uranium was started under the IAEA's Technical Cooperation project PHI/3/04 on Uranium Geochemical Prospection [1]. This was tied up with the decision of the Government of the Philippines at that time to establish the Philippines nuclear power programme and build the first nuclear power plant in the country. Unfortunately, owing to the Chernobyl accident that happened 26 April 1986, the first power plant was suspended and later on mothballed by the then government, although it was almost 100% complete. Thus, the quest for indigenous uranium mineral deposits was discontinued.

However, in May 1995, Executive Order No. 243 was issued, which created the Nuclear Power Steering Committee that provided the policies, direction, monitoring, evaluation and other functions necessary and appropriate to attain the objectives of the overall nuclear power programme. It states, in part, that, "the Philippines Nuclear Research Institute (PNRI) shall also conduct research and development programs on the various facets of the nuclear fuel cycle, including the resumption of activities on uranium exploration" [2].

A reconnaissance approach using combined radiometric and geochemical exploration methods was launched that resulted in covering, to date, almost 70% of the entire Philippines archipelago. Results, however, were disappointing, since, except for a few minor showings of mineralization, no major uranium deposits were discovered. Hence, the strategy was shifted to sourcing uranium from unconventional resources and thus PNRI was included in 2015 in the IAEA (CRP 18759) on Geochemical and Radiometric Characterization of the Cu–Mo–U Occurrences in the Larap–Paracale Mineralized District, Camarines Norte, Philippines.

It is in this district that the mineral uraninite was discovered for the first time by Frost [3] in 1959 and an indicated resource of about 200 t U₃O₈ contained in 500000 t of ore with a grade of 0.04% U₃O₈ was reported in 1965 by Dr. J. Cameron, IAEA expert [4] at the Bessemer pit that was being operated by the Philippines Iron Mines. Efforts at that time to locate other uranium mineralized areas were not encouraging, although some copper-molybdenum showings with associated uranium were noted. These areas are now under investigation by the current IAEA investigation (CRP 18759). Surveys conducted within the Nakalaya locality delineated an area with field gamma ray spectrometric measurements varying in the range104-138ppm U using a RS230 gamma ray spectrometer. Fluorimetric analysis of rock and soil samples gave 39-193ppm U, while atomic absorption spectrometric analysis gave 209–588ppm Cu and 53–363 ppm Mo. Interestingly, ICP-MS analysis showed 173–544ppm rare earth elements (REEs). Recently, a more detailed gamma ray spectrometric survey pinpointed an area about 100 m south of the Nakalaya area with 76-236ppm U. Analyses of rock and soil samples are still pending. This anomalous area is underlain by the Tumbaga/Universal Formation of Eocene age. It is part of a sedimentary rock sequence consisting of limestone, marl and shale that was subjected to thermal metamorphism, which resulted in the formation of skarns, hornfels and marble that acted as hosts to iron deposits and minor base metal mineralization with associated uranium. It is therefore aimed that uranium will be produced as a by-product or co-product if this area is shown to be economically viable to mine with the combined production of Cu, Mo and REEs.

Under the IAEA TC project PHI2010 on Enhancing National Capacity for Extraction of Uranium, Rare Earth Elements and Other Useful Commodities from Phosphoric Acid, a study on uranium recovery from phosphoric acid is being carried out. This project is undertaken in collaboration with the Philippines Phosphate Fertilizer Corporation (PHILPHOS) and with financial assistance from the National Research Council of the Philippines (Department of Science and Technology). PHILPHOS imports around 1.97 Mt of raw phosphate ores annually from different countries for the production of fertilizers. Samples of phosphate ores, phosphoric acid and fertilizer products were analysed using ICP-MS to determine the elemental contents. Analysis showed that the phosphate ores contain as much as 139 ppm U along with 20.5 ppm Th and up to 828 ppm REEs. Analysis of phosphoric acid samples using ICP-MS gave uranium values varying in the range 66-189 ppm. Phosphatic fertilizer products, particularly nitrogen-phosphoruspotassium (NPK) fertilizers, contain radionuclide and REE values reaching up to 223.8 ppm U, 0.8 ppm Th and 36.8 ppm REEs and when dispersed, these fertilizers are contaminating the environment. However, uranium levels in the fertilizers is well above the global average uranium content in soils, which is 0.3–11 ppm [5]. Laboratory scale solvent extraction of uranium using a synergistic mixture of diethylhexyl phosphoric acid (D2EHPA) and trioctyl phosphine oxide (TOPO) from phosphoric acid was conducted. Static laboratory testing achieved a 92% recovery rate of uranium from phosphoric acid. This experiment thus led to the precipitation of the first yellowcake from phosphates in the country. The goal of this study is to produce cleaner fertilizers, mitigating the risk of environmental contamination, promoting maximization of resources and opening up the opportunity to utilize uranium if the Philippines decides to continue with the nuclear option.

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A REVIEW OF THE GEOCHEMICAL CONTROLS ON ELEMENTS OF CONCERN IN URANIUM MILL TAILINGS, ATHABASCA BASIN, CANADA

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1. INTRODUCTION

The Athabasca Basin of northern Saskatchewan (and a small part of Alberta), Canada, is a major source of global uranium (U) supply. Uranium mined from the Basin comprised 22% of the world's supply in 2015, and, as of 2016, there are 225 000 tU of known economically mineable U in reserves in the Basin [1, 2].

There are three U mills currently operating in the Basin: Rabbit Lake, Key Lake and McClean Lake. Uranium production began at Rabbit Lake in 1975. Key Lake was commissioned in 1983. The McClean Lake mill began operation in 1999. A fourth mill, Cluff Lake, was commissioned in 1980 and decommissioned in 2003 [3]. Conventional U milling processing in the Basin follows the pathways: comminution (crushing and grinding); leaching (using sulphuric acid under oxic conditions and resulting in a solution rich in Fe, Al, Mg, Si, As, Ni, Se, Mo, SO_4^{2-} and U (among other elements)); solid–liquid separation; purification; precipitation of uranium; precipitation of other dissolved metal(loid)s (as secondary minerals as the solution pH is neutralized to neutral–alkaline pH with slaked lime); and packaging.

Tailings slurries from the mill process can contain elevated concentrations of elements of concern (EOCs) including As, Ni, Se, Mo and ²²⁶Ra. Above ground tailings management facilities (TMF) were first used to store tailings [4]. Subsequently, above ground TMFs were replaced with in-pit TMFs located in mined-out open pits [5]. These in-pit TMFs were engineered to optimize tailings consolidation and, after decommissioning, minimize groundwater flow through the tailings and ensure EOC transport is dominated by diffusion. The first in-pit TMF was constructed at Rabbit Lake in 1984 (termed the RLITMF) [5]. The second in-pit TMF was constructed at Key Lake in 1996 (termed the DTMF) [6]. The third TMF was constructed at McClean Lake in 1999 (termed the JEB TMF) [7]. All three mills discharge tailings sub-aqueously to the TMFs to prevent transportation of contaminated dust and to spread the tailings more evenly across the TMF [8].

This study summarizes the extensive existing literature on the mineralogical controls on the EOCs in tailings in in-pit TMFs in the Athabasca Basin compiled over the past two decades.

2. METHODS

Many methods have been used to study the geochemical controls on EOCs in Athabasca Basin tailings. These include solids and aqueous sampling during the neutralization steps at individual mills, analysis of decades-old porewater and solids samples from TMFs, and batch and continuous mode laboratory experiments to generate precipitates of synthetic raffinate solutions. The aqueous and solid phase chemical compositions were measured and used in geochemical models and to study spatial and temporal trends in the tailings. Generally, solid samples were subjected to complementary characterization techniques including sequential extractions, X ray diffraction, electron microscopy and X ray absorption spectroscopy.

3. RESULTS, DISCUSSION AND CONCLUSIONS

3.1. Uranium ores

The U ores in the Basin are dominated by uraninite and pitchblende [9]. A strong association exists between U minerals and sulphide- and arsenide-rich mineralization including gersdorffite, niccolite, rammelsbergite, pyrite, chalcopyrite and arsenopyrite.

3.2. Mineralogy of tailings

The precipitates in the neutralization processes from the three mills studied are highly dependent on the process pathway, which differs between mills. Different pH set points at each stage in each mill affects the saturation state of minerals and influences the final mineralogy of the precipitates. The initial concentrations of the major raffinate elements (which determine the mass of the minerals that precipitate) and the pH set points of the neutralization steps determine the solubility controls of EOCs driven by surface complexation or co-precipitation. Secondary minerals constitute 10–20% of the total tailings mass, with the remaining being leach residues. With the exception of gypsum, these precipitates are generally amorphous or nanocrystalline because of the rapid neutralization at high saturation conditions and ambient temperature and pressure inhibiting crystallization [10].

Differences exist in raffinate compositions between mills and between samples collected from the same mill at different times. These differences are attributed to the variability of ore deposits and the heterogeneity of ores from the same deposit. These variations render it difficult to generalize with respect to which secondary minerals will precipitate from the neutralization processes, although general trends exist.

The dominant Fe mineralogy of the final mill precipitates in all three neutralization processes is ferrihydrite. The lower terminal pH at McClean Lake is, however, more favourable for increased concentrations of ferric arsenate. Raffinates processed at Key Lake contain much greater concentrations of Al compared with raffinates processed at McClean Lake and Rabbit Lake owing to the ores used. Aluminium and Mg comprise 1–5% of the secondary precipitates by mass in Key Lake tailings [11, 12]. Calcium comprises 10–20% of the final neutralized precipitates and is precipitated mostly as gypsum [12, 13].

3.3. Mineralogical controls on elements of concern in mill tailings

Research shows that Fe and Al secondary minerals provide the dominant mineralogical controls of EOCs in the precipitates from raffinates [7, 14–20]. Most studies of Ca mineralogical controls on As and Mo show that Ca minerals provide a minor control compared with Fe and Al minerals [5, 16, 21–24]. Co-precipitation with baryte (barium chloride is added to the neutralization processes to precipitate ²²⁶Ra) is an important mineralogical control on ²²⁶Ra [25, 26]. However, adsorption of ²²⁶Ra to ferrihydrite appears to be the dominant sequestration mechanism [26].

Co-precipitation of ferric arsenate and the adsorption of arsenate to ferrihydrite are major mechanisms of As sequestration [14, 17, 19]. Molybdenum is primarily removed from raffinate by outer-sphere complexation with ferrihydrite at low pH neutralization stages [21, 23, 27, 28]. Studies of mineralogical controls of dissolved Ni are less prominent than As and much of the data are only qualitative or semi-quantitative [5, 6, 15, 17, 18, 24, 28, 29]. There is a lack of literature on the removal of Se during the neutralization processes.

Arsenic remaining in solution after the low pH stage forms bidentate adsorption complexes with amorphous $Al(OH)_3$ and hydrotalcite at pH9.5. Between 41% and 71% of adsorbed As in pH 9.5 precipitates is associated with these Al phases [13, 29]. In a final tailings slurry samples collected at pH 10.9, 59% of solid

phase As was associated with Al phases (amorphous Al(OH)₃ and hydrotalcite) and the remainder associated with Fe phases [29]. This distribution may be attributed the higher point of zero charge of Al hydroxides relative to Fe hydroxides, resulting in As desorbing from the ferrihydrite surface and re-adsorbing onto the Al phases during the pH adjustment [30]. The dissolution of ferric arsenate could also be a source of As adsorption onto Al phases.

Most studies of EOC controls by Al and Mg minerals were determined on Key Lake samples [13, 28, 29]. As an example, Al was measured to control 5–25% of As at low pH stages (pH 4) through adsorption with amorphous AlOHSO₄ (bidentate-binuclear bonds) [13, 28]. In a final tailings slurry sample collected at pH 10.9, 59% of solid phase As was associated with Al phases (amorphous Al(OH)₃ and hydrotalcite) and the remainder with Fe phases [29]. Robertson et al. (2017) determined that Ni is controlled by amorphous Al(OH)₃ and Ni–Al layered double hydroxide that forms surface precipitates onto the surface of hydrotalcite. This observation contrasts with results from other studies of laboratory and in situ tailings that suggest Ni is predominantly controlled by adsorption onto ferrihydrite or precipitation of theophrastite, annabergite, or cabrerite [15, 17, 18].

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PERSPECTIVES ON SOCIAL COMMUNICATION IN THE BRAZILIAN NUCLEAR LICENSING PROCESS AND CHALLENGES ON STAKEHOLDER ENGAGEMENT: CAETITÉ URANIUM MINING CASE

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1. INTRODUCTION

According to the Brazilian system of laws and regulations, uranium and thorium mining and milling facilities are considered as nuclear installations, being subject to both licensing processes: (i) a nuclear licensing process performed by the Brazilian Nuclear Energy Commission (CNEN) and (ii) an environmental licensing process performed by the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), with the participation of State and local environmental agencies. The nuclear licensing process is performed in steps (starting with setting up the decommissioning phase), which encompasses the submission of reports/documents and, in the case of subsequent approval, the granting of specific authorizations for each step. Proactive stakeholder engagement activities are taken into account, such as the holding of public hearings, which are considered an aspect of environmental licensing.

In the nuclear licensing process, the main activities of the regulatory body are the safety assessment of the applicant's documentation and the conduct of regulatory inspections. It is worth mentioning that nuclear regulation establishes that no nuclear installation can operate without a licence, as well the necessary review and assessment process, including the specification of the documentation to be submitted to the nuclear regulatory body at each phase of licensing. Additionally, there is a system of regulatory inspections and the corresponding enforcement mechanisms that include the authority to modify, suspend or revoke the licence. Nuclear installations will also have an authorized radiation protection supervisor certified by the nuclear regulatory body.

In the town of Caetité (State of Bahia) is located the only uranium mine in operation in Brazil and named the Uranium Concentrate Unit, the activities of which are developed by the Brazilian State-owned company, Brazilian Nuclear Industries (INB), including the development of environmental and radiological protection monitoring programmes [1]. During the uranium mining and milling operations, some events had occurred and their impacts on social media reflect the concerns, demands and challenges with respect to perspectives on social communication and accountability. Also, in the event presented in this paper, it is possible to perceive that despite the environmental monitoring programme conducted by the operator demonstrating a lack of contamination, the local community nonetheless did not feel confident about the operation of the uranium mining facility.

2. NUCLEAR REGULATORY BODY ACTIONS ON COMMUNICATION AND TRANSPARENCY

Over the past few decades, Brazil has been developing initial actions in terms of opening and transparency of information, using the 1988 Constitution as a framework. However, even before a legal mechanism concerning information access, some measures were taken to facilitate public access to data [2]:

- Files Law (No. 8.159 (1991));
- Habeas Data Law (No. 9.504 (1997));
- Fiscal Responsibility Law (Complementary Law No. 101 (2000)) on financial data;

- Transparency Portal (activated in 2004) made available on the internet the budget and expenditure data of the Executive;
- Transparency Portal for States and Towns (2006);
- Agreements System of the Federal Government (SINCOV (2007));
- Providers Registration System (SICAF (2008)).

Law No. 10.650 [3] was enacted in 2003 and the concerns, specifically, public access to environmental information data that are available in public and member institutions of the National System of the Environment (SISNAMA) [4]. However, nuclear licensing information was not included. Significant progress has been made in recent years with the enactment of the Information Access Law, No. 12.527/11 [5] and its regulation by Decree 7.724 [6], where all public institutions must provide specific information on their web sites and must also create an 'information service to citizens' (ISC), in order to answer any questions proposed by the general public, promoting a significant change in the conception of public information and in transparency culture [2]. Similarly, legal advances were also made in relation to the rights to information and the availability and publishing of open data, establishing a new concept of open data policy for governmental institutions (Normative Instruction No. 4/2012, Decrees No. 8.638/2016 and No. 8.777/2016) [7].

Despite the majority of the documentation relating to the nuclear licensing process being considered as 'classified' [8], the nuclear regulatory body provides information concerning environmental, effluent and waste monitoring, inspections, reports and allegations, among others, when requested by the ISC and 'Talk to Us', officially or through 'courts'.

3. CAETITÉ URANIUM MINE CASE

Some events have occurred on Caetité uranium mining and milling site and their impacts on social media reflect the concerns and challenges surrounding the perspectives on social communication and accountability. The historical occurrence of allegations by non-governmental organizations (NGOs) and the population, and their publication in regional and national media, allows the development of factors that may lead to stigmatization of the inhabitants that live close to the uranium mining facility, manifestations of public concern, increase in allegations and rejection of mining activities.

The last event occurred in August of 2015 and was related to an article published in a national newspaper under the headline "Uranium Contaminates Water in Bahia" [9], which reported a finding of uranium, iron and manganese contents above the potability level limit (Resolution No. 396 CONAMA/2008 and Order MS No. 2914/2011) in groundwater samples. On that specific event, a local farmer had requested that INB/URA sample and carry out chemical analysis of a groundwater well located inside of his own property. A first sample was collected by the operator in October 2014 and a second one in March 2015. However, the results exhibiting uranium, iron and manganese contents above the potability level limit were just officially informed to the local farmer and the local mayor in May 2015, seven months after the first sampling.

In the case of that specific event, despite the environmental monitoring programme conducted by the operator, it was not demonstrated that any contamination related with the mining operation in the locality. Despite the location of the well being outside the mining watershed and that the information supplied by the operator stated that the uranium concentration was linked to natural processes (a region with 38 uranium anomalies) [10, 11], the environmental regulatory body ordered the immediate suspension of water consumption in the region's wells [12]. As a result, the local community especially did not feel confident about the operation of this uranium mining facility.

4. DISCUSSION AND CONCLUSION

The regulatory licensing process comprises a formal authorization relating to specific legislative and regulatory requirements and procedural conditions that are usually clearly defined in scope and received at a specific time by a recognized government authority. Nevertheless, such an instrument requires sustained investment by proponents to acquire and maintain social capital within the context of trust based relationships.

In view of past events, the concerns and demands in terms of stakeholder engagement and social communication, some aspects will be included in further discussions, mainly about:

- Credibility (as a social licence perspective) is a continuous process of engagement and effort;
- A 'licence' does not imply universal acceptance by the community, thus the opposition and questioning will be used as experiences for improvement and to stimulate new ideas within licensing process management;
- Despite the mining operations implementing their social responsibility and communication programmes, it is necessary to conduct continuous evaluation of community engagement and consideration of stakeholder's concerns, as well as using approaches such as social cartography to define local groups of stakeholders;
- Consideration of the fact that public perception of radiation risks has shown that scientific arguments are not in themselves enough to address social and political concerns;
- Consideration of a social licensing dimension to the entire mining life cycle, from exploration to exploitation and on to decommissioning;
- Development of strategies to avoid poor communication of activities and events in the operation unit by the operator and to improve transparency;
- Application of effective communication in terms of providing timely and complete information, as well as presenting information from by the stakeholder's point of view and interest.

Although the nuclear regulatory body has advanced in the communication and transparency culture, in searching for social legitimacy, it still presents a reactive behaviour, often in response to judicial demands. Therefore, it is necessary for development and/or improvement of:

- Implementation of a proactive policy, improving communication in terms of availability of information;
- Coordination of programmes among the different regulatory authorities, including the development of a forum for critical situations. Coordination among regulators is important to avoid duplication of effort and address omissions and gaps or overlaps of competences;
- Implementation of effective communication pathways among regulatory agencies and the community;
- Development of a legal basis as well programmes ensuring stakeholder engagement, transparency and communication, including:
 - Planning (objective and strategy);
 - Implementing;
 - Evaluation and adjustment.

Even though the development of actions in terms of information provision, it is essential that the continuous evaluation and promotion of further efforts to address discussions about the development of transparency culture, enhancement of credibility and public confidence, timely and effective engagement and communication, among others, will allow establishment of social participation practices as a part of the decision making process and effective stakeholder engagement and social communication approaches.

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DASA: AFRICA'S NEWEST WORLD CLASS URANIUM DEPOSIT IN NIGER, WEST AFRICA — A GLOBAL ATOMIC CORPORATION PROJECT

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The DASA deposit is situated in the northern central part of Niger, West Africa. It is 100 km north of the city of Agadez, 80 km south of the uranium mining area of Arlit and 1000 km east of the capital Niamey. The project area is located within the sedimentary Tim Mersoi Basin, one of the world's foremost uranium producing districts. It is accessible using an all-weather road connecting Agadez, Niger's second largest city, with the town of Arlit. Global Atomic Corporation (GAC), a Canadian junior exploration company, has six exploration permits in Niger. The DASA deposit is positioned within the Adrar Emoles 3 permit.

The initial discovery of uranium mineralization was made on the surface in 1956 near Azelik, just west of the GAC property. An intensive geological exploration programme was implemented between 1957 and 1967 by the Commissariat à l'énergie atomique (CEA) and this resulted in the discovery of the uranium deposits at Azelik (1960), Madaouela (1964) and, finally, Arlit–Akouta (1966–1967). The CEA eventually became COGEMA in 1975 and is now known as ORANO (formerly AREVA).

In 2007, GAC signed exploration agreements with the Government of Niger on six permits totalling approximately 3500 km². The DASA deposit was discovered in 2010 through surface prospection which led to the discovery of a high grade (>30% U_3O_8) outcrop.

Since 2010, GAC has conducted significant drilling programmes (>120 000 m to date) in conjunction with other exploration surveys leading to the definition of the DASA deposit. The GAC Adrar Emoles 3 permit, on which DASA is located, has a surface area of 121.3 km². Exploration and drilling programmes are ongoing.

1. GEOLOGY AND STRATIGRAPHY

The GAC permits are located predominantly over continental sediments of the Tim Mersoi Basin, which is bordered to the east by the metamorphic Precambrian terrain of the Air Massif. Most of the rocks of the Air Massif are intrusive and their erosion has provided much of the sediments in the basin. Uplift of the Air Massif has tilted the sediments in the forelands, with a shallow dip to the west.

The sediments are predominantly clastic and contain minor carbonates. They have been deposited in fluvial and deltaic settings. The general direction of transport is assumed to have been from east to west and in the area of interest a more NE–SW direction of transport would have prevailed.

Within the GAC permits, sediments range in age from Cambrian to Lower Cretaceous. Units present on the properties recognized in drill holes and surface mapping are presented below from bottom to top.

The Precambrian basement is exposed in the Air Massif some 15 km to the east. The oldest rocks drilled on the GAC permits are coarse-grained granites inside the DASA Graben at depths of over 700 m.

Cambrian–Devonian sediments exist in this part of the Tim Mersoi Basin. Some have been identified in the DASA drill holes and they predominantly correspond to sandstones and conglomerates, possibly including Devonian glacial deposits.

The Carboniferous fluvio-deltaic Tagora Formation of Upper Visean age is observed in many of the deeper GAC drill holes. The Lower Tagora, up to 180 m thick, contains sandstones representing the Guezouman Formation. This is a major uranium carrier in the Akouta area (Cominak–ORANO underground mine).

The Upper Tagora, up to 140 m thick, often starts with a thin layer of conglomerate overlain by the sandstones of the Tarat Formation. The uranium deposits in the Somair–ORANO open pit mines at Arlit are hosted in the Tarat. The top of the Carboniferous is completed by sandstones and siltstones of the Madaouela Formation. They are host to the GOVIEX Madaouela uranium deposits.

The Carboniferous in the entire basin is characterized by reducing conditions displayed in predominantly greyish colours; abundant pyrite and organic matter provide ideal conditions for the precipitation of uranium.

Permian sediments are characterized by the predominance of arkosic sandstones containing significant volcanic debris and abundant calcite. Reddish colours are dominant. This indicates an oxidizing milieu. Around the project area, the thickness of the Permian strata varies considerably and reaches a maximum thickness of some 300 m.

Initially, the Triassic shows a continuation of the Permian conditions with conglomerates overlain by sandstones. The Triassic sediments, over 200 m thick, contain abundant volcanic debris and tuffs. Massive analcimolite intercalated with sandstone layers is found on top, reflecting a very active eruptive volcanic phase.

The Jurassic commences with the Tchirezrine 1 Formation (Tch1) corresponding to channel sedimentation of a large river flowing from north to south. Graben syn-sedimentary tectonism has caused variations in thickness. In general, the Tch 1 is quite similar to the overlying Tchirezrine 2 Formation (Tch2) except that it does not contain uranium mineralization.

The Tch2 attains thicknesses of 40–200 m. It was deposited in a fluvio-deltaic and lacustrine environment. The sediments are predominantly coarse-grained, poorly cemented sandstones and micro-conglomerates with cross-bedding at the base. The formation was affected by syn-sedimentary tectonism and later by shearing. This has contributed to the considerable thickness reported in some GAC drill holes. The rocks are rich in analcimolite and organic matter and contain coal beds, a very favourable environment for uranium precipitation. This formation contains most of the uranium discovered on the GAC property and in the large ORANO Immouraren uranium deposit nearby.

The Cretaceous begins with the Assaouas Formation, up to 30 m thick, consisting of reworked older quartzrich sediments and overlain by fine-grained sandstones and argillites. The overlying Irazher Formation consists of reddish mudstones and silts which cover much of the basin, but is confined within the GAC property to the Asouza Graben. The thickness, up to locally 300 m, is marked by syn-sedimentary tectonism within the graben and with important lateral variations in thickness. The stratigraphic column of the project area culminates with the barren sandstones of the Tegama Formation which unconformably overlies the Irazher sediments. Tegama sandstones are present in two pronounced hills within the Asouza Graben.

2. STRUCTURAL GEOLOGY

The Tim Mersoi Basin developed as a result of N–S and E–W compression with NNW–WNW sinistral shears originating from counterclockwise rotation in the NE of the basin. The intersection between these structures caused rotational deformation and generated dome and basin structures. This mechanism has created horst and graben structures.

Major movements are related to N–S zones which strike parallel to the eastern and the western edges of the Air Massif. The compressional sinistral strike-slip movements have caused three main structural directions which are N–S, N40–80° and N90–140°. Where these directions meet, their continual movement has opened up ideal pathways for circulating uranium-bearing fluids, prerequisites for the formation of deposits.

The N–S fault system is a major crustal structure of regional scale and is displayed in the fold–fault of In Azaoua–Arlit. A N30° family of structures is most evident on surface in the basin. They appear in the Air Massif in the east and truncate at the In Azaoua–Arlit lineament in the west. In the sedimentary cover, the deformation is characterized by flexures creating, in some instances, a substantial vertical displacement of the order of 100–200 m.

The N70–80° and N130–N140°E series of faults are brittle structures. The N70–N80°E faults are conjugate to the N130–N140°E directions and are present mainly in the southern half of the Tim Mersoi Basin. During the Carboniferous both families of structures controlled the sedimentation in the basin. These faults played a major structural role in the regional context of the basin by localizing large scale dextrous strike-slip faults. Fold-like structures are revealed along sectional variations in the dip of the strata. According to geological drilling data the thickness and dip variations in some strata from west to east are linked with synsedimentary tectonic activity.

The DASA site corresponds to a major structural intersection of the Adrar–Emoles flexure and the Asouza Fault which has resulted in the doming and creation of the Asouza (DASA) Graben. Much of the uranium is found here, especially along its southern flanks. The intersection formed a dome and at its opening, the Asouza Graben was created, moving the Cretaceous formations to the same topographic elevation as the surrounding Jurassic sandstones.

Major NE–SW vertical faults are associated with the Asouza Graben and characterized by significant vertical displacement of several hundred metres between the centre of the graben and its shoulders. The creation of the graben prevented the erosion of the Tegama and Irhazer Formations that are normally found much further to the west, in the deeper areas of the Tim Mersoi Basin. The Tch2 Formation is also preserved here and is significantly eroded on the sides of the graben. This vertical displacement has had a major impact in the continuation of potential host rock geology and has also provided feeder faults and mineralization traps for ore forming fluids, as evidenced by veining within the sandstones.

The NNW–SSE striking faults observed NW of the graben are particularly interesting. These faults cut the sandstone formations of the Tch2, inducing significant vertical displacement with evidence of fluid circulation causing localized alteration and copper mineralization in analcimolite formation of the Tch2.

3. PALAEOGRAPHY

The development of the palaeography has had a major influence on the sedimentation and the lithology of the host rocks where uranium mineralization is currently found. During the deposition of the Lower Carboniferous, this part of the Tim Mersoi Basin was quite stable and experienced very little subsidence. Volcanism commenced towards the end of the Lower Carboniferous in the Air Massif. Increasing precipitation in the Upper Carboniferous manifested itself in the Tagora Series with its fluvio-deltaic cycles.

Palaeovalleys and channels existed with marshy zones that were filled with fine-grained sediments and large accumulations of organic matter.

In the Permian, desert conditions usually prevailed, while in the Triassic, less desertic environments appeared. Structural activity caused lineaments to evolve which in turn created variations in the thickness and facies of the sediments.

During the Jurassic, tectonic adjustments occurred and a wide N–S trending trough developed. It was limited in the west by the N–S trending Arlit Fault, the Madaouela Fault in the north and the Magagi Fault in the south. Volcanic activity was widespread and the depositional environment changed to fluviatile–lacustrine. The flow directions maintained their main SW–NE vector. During the Tch2 deposition, large amounts of organic matter were incorporated into the sediments. The sandstones often show whitish–greyish or greenish colours, indicating a much higher reduction potential for uranium. This is most obvious in the massive mineralization seen at DASA.

4. URANIUM MINERALIZATION AND ECONOMICS

All known uranium mineralization in Niger is located exclusively in sediments of the Tim Mersoi Basin and occurs in almost every important sandstone formation, although not always in viable concentrations.

The uranium in many of the deposits of the basin is generally oxidized. Thin section petrographic studies on DASA samples have revealed that the uranium host rocks vary in their oxidization. The original cement between the grains of quartz and feldspar consisted of sericite and carbonate, which were replaced during later stages by goethite and amorphous Fe-hydroxides. The quartz and the feldspar grains contain microfractures filled, in part, with U-rich oxide. The latter also rims some of the silicates. Uranophane in the form of radiating aggregates forms cement between the silicates and partly replaces them.

Five main uranium-bearing minerals have been identified in DASA samples: carnotite $(K_2(UO_2)_2(VO_4)_2.3H_2O)$, uranophane $(Ca(UO_2)_2SiO_2O_7.6H_2O; U$ -rich titanite $(U,Ca,Ce)(Ti,Fe)_2O_6$, torbernite $(Cu(UO_2)_2(PO_4)_2.8H_2O)$ and autunite $(Ca(UO_2)_2(PO_4)_2.12H_2O)$.

All known uranium occurrences and deposits in Niger are classified as sedimentary tabular and roll-front sandstone type. Sandstone hosted uranium deposits are marked by epigenetic concentrations of uranium in fluvio-lacustrine or deltaic sandstones deposited in continental environments. These are located frequently in the transition areas of higher to lower flow regimes such as along palaeoridges or domes. Impermeable shale or mudstones often cap, underlie or separate the mineralized sandstones and ensure that fluids move along within the sandstone bodies.

DASA is unique amongst the uranium deposits in Niger. It shows higher grades and accumulations than virtually any other known deposits. It contains economic reserves in both of Niger's main uranium-bearing formations (Carboniferous and Jurassic) and displays a very strong structural component (DASA Graben) which has enhanced both the grade and thickness of the mineralization.

The origin of the uranium at DASA is very likely from two main sources: leaching of uranium during the erosion of the Air Massif for the Carboniferous ores and leaching of the volcanic tuff and ash intercalations for the Jurassic ores. This began as pre-concentrations during the early sedimentation period. Favourable reducing environments such as organic-rich lower flow regimes containing sulfides, Fe minerals and amorphous humate as well as favourable lithological settings played their parts. The first stratiform orebodies emerged from this setting. Subsequent structural deformation and fluid movements within coarser grained organic and sulphide-rich sediments initiated roll-front type redistribution and concentration over several stages. The uranium followed favourable lithological and structural surroundings and traps, reflected in the present shape of the orebodies.

The grade and thickness of the mineralized intersections differentiates DASA from most other sandstone deposits worldwide. Some of the better intersections assayed (XRF) are hole 476 with 4462 ppm U_3O_8 over 94.5 m, hole 478 with 7033 ppm U_3O_8 over 42 m, hole 256 with 3307 ppm U_3O_8 over 110 m and hole 312 with 2811 ppm U_3O_8 over 76 m. A NI 143-101 compliant report by CSA Global Pty Ltd in 2017 listed indicated reserves of 21.4 million pounds (9700 tU) with an average grade of 2608 ppm U_3O_8 using a cut-off of 1200 ppm U_3O_8 . The inferred reserves were calculated as 49.8 million pounds (22 600 tU) at 2954 ppm U_3O_8 again using the 1200 ppm U_3O_8 cut-off. This makes DASA potentially a 70 million pound plus (32 000 tU) deposit. The deposit is open along strike (NW–SE) and down dip. Ongoing exploration work is expected to increase the resources further.

It is possible to develop DASA within a short time frame producing ore from both open pit and underground operations. CAPEX to production would be low, with an estimated investment of US \$50 million to development as the ore would be processed at the nearby ORANO mine sites in Arlit where all necessary facilities, such as a mill, already exist. To this extent, GAC signed a Memorandum of Understanding with ORANO in 2017.

The infrastructure, both within and surrounding the GAC property is excellent. Easy access to a major road system linking to the port of Cotonou in Benin, West Africa, is already being used for the shipment of production from the ORANO mines in Arlit. Electricity is available from an existing high-tension power line crossing the property and a large pool of experienced mine workers provides a source of labour.

The discovery of the DASA deposit has given rise to new incentives for exploration in the Tim Mersoi Basin. There is considerable potential to find additional DASA type deposits, not only on the GAC property, but also in other parts of the basin.

NATURAL RADIATION EXPOSURE TO THE PUBLIC IN THE URANIUM AND THORIUM BEARING REGIONS OF CAMEROON: FROM MEASUREMENTS, DOSE ASSESSMENT TO A NATIONAL RADON PLAN

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Abstract

The present paper summarizes the findings of studies carried out since 2014 in the uranium- and thoriumbearing regions of Poli and Lolodorf, respectively, located in northern and southern Cameroon. It also underlines future prospects for strengthening the radiological protection of members of the public exposed to environmental natural radiation in Cameroon. In situ gamma spectrometry and car-borne surveys were performed in the above regions to determine activity concentrations of natural radionuclides in soil and air kerma rates to assess the effective external dose received by members of the public. High natural radiation areas were located and selected for indoor radon, thoron and thoron progeny measurements. Raduet detectors and thoron progeny monitors were deployed in 300 dwellings to measure radon, thoron and thoron progeny indoors in order to assess the inhalation dose received by members of the public. External effective dose ranges of 0.15–0.63 mSv/year with the average value of 0.4 mSv/year in the uraniumbearing region of Poli and 0.1–2.2 mSv/year with the average value of 0.33 mSv/year in the uraniumbearing region of Lolodorf. The inhalation dose due to radon and thoron ranges, respectively, between 0.87–2.7 mSv/year and 0.08–1.0 mSv/year with average values of 1.55 mSv/year and 0.4 mSv/year for Poli, and between 0.6– 3.7 mSv/year and 0.03–3.0 mSv/year with the average values of 1.84 mSv/year and 0.67 mSv/year for Lolodorf.

Contribution of thoron to the total inhalation dose ranges around 3-34%, with an average value of 20.3% in the uranium region of Poli and 1-79% with the average value of 27% in the uranium- and thorium-bearing region of Lolodorf. Thus, thoron cannot be neglected in dose assessment in order to avoid biased results in radio-epidemiological studies.

1 INTRODUCTION

Numerous environmental radiation surveys have been carried out in Cameroon over the past decade [1–10]. Most of these studies deal with natural radioactivity measurements and corresponding dose assessment in mining and ore-bearing regions of Cameroon. These started by collecting soil, foodstuff and water samples and by deploying Electret ionization chambers (commercially E-PERM) and passive integrated radon–thoron discriminative detectors (commercially RADUET) in dwellings before determining activity concentrations of naturally occurring radionuclides. This determination is followed by assessing inhalation, ingestion and external radiation dose helpful in performing radiation risk assessment. The present work uses a car-borne survey method to measure air absorbed dose rates and in situ gamma spectrometry to determine activity concentrations of natural radionuclides in soil in all the uranium- and thorium-bearing regions of Poli and Lolodorf. The radiological mapping of these regions was established to locate the high natural radiation areas. This information was used to deploy RADUET and thoron progeny monitors in 400 houses for radon (²²²Rn), thoron (²²⁰Rn) and thoron progeny measurements indoors. Measurements of absorbed dose rates in air, ²³⁸U, ²³²Th, and ⁴⁰K activity concentrations in soil, radon, thoron and its progeny indoors were followed by external and inhalation dose assessment helpful in assessing radiation risk to members of the public in the above regions.

The above results highlight the importance of putting in place a national radon plan in Cameroon in agreement with IAEA Safety Standards Series No. GSR Part 3: Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [11]. An IAEA Technical Cooperation project (CMR9009) on Establishing a National Radon Plan for Controlling Public Exposure Due to Radon Indoors was initiated and is ongoing for the IAEA Technical Cooperation cycle 2018–2019.

2 MATERIAL AND METHODS

1.1. Car-borne survey

The detailed method of undertaking a car-borne survey has been described in many publications [12–14], but only an outline is described here. A car-borne survey which used a 76 mm \times 76 mm (3 in \times 3 in) NaI(Tl) scintillation spectrometer (EMF-211, EMF Japan Co., Japan) was carried out in the uranium- and thoriumbearing regions of Poli and Lolodorf from November 2015 to August 2016. This spectrometer was positioned inside the car and the car speed was kept at around 30-40 km/h. Measurements of the counts inside the car were carried out every 30 s along the route. In order to generate a dose rate distribution map, the latitude and longitude coordinates were recorded using a global positioning system at each measurement point at the same time as the gamma ray count rates. Since count rate is measured inside the car, it is necessary to estimate the shielding factor of the car body with respect to terrestrial gamma rays in order to represent the unshielded external dose rate. The shielding factor was estimated by making measurements inside and outside the car at 150 points. Those measurements were recorded consecutively at 30 s intervals during a total recording period of 2 min. Measurements of gamma ray pulse height distributions were also carried out 1 m above the ground surface outside the car for 15 min at 24 points along the survey route. The gamma ray pulse height distributions were unfolded using a 22×22 response matrix for the estimation of absorbed dose rate in air. These dose rates were used to evaluate the dose rate conversion factor (nGy·h⁻ $^{1} \cdot cpm^{-1}$).

1.2. Radon-thoron discriminative measurements indoors

To determine the concentrations of radon and thoron, RADUET detectors developed at the National Institute of Radiological Sciences (NIRS) in Japan were used in this study [15]. CR-39 was used to detect alpha particles emitted from radon and thoron as well as their progenies. To determine conversion factors of radon and thoron concentrations, these detectors were placed into the radon and thoron chambers at NIRS, respectively [16, 17]. After exposure tests, CR-39 plates were taken out of the chamber and chemically etched with a 6.25M NaOH solution at 90°C for over 6 h, and alpha tracks were counted with a track reading system. The evaluation of a track in image J and microscopic methods has been well described by Bator et al. [18]. Using two alpha track densities of low and high air exchange rate chambers (N_L and N_H), radon and thoron concentrations were determined by solving the following equations [15]:

$$N_{H} = X_{Rn} \cdot CF_{Rn2} \cdot T + X_{Tn} \cdot CF_{Tn2} \cdot T + B$$

$$N_{H} = X_{H} \cdot CF_{H} \cdot T + X_{H} \cdot CF_{H} \cdot T + B$$

$$(1)$$

$$N_L - A_{Rn} \cdot C \Gamma_{Rn1} \cdot I + A_{Tn} \cdot C \Gamma_{Tn1} \cdot I + D$$
(2)

where X_{Rn} and X_{Tn} are the mean concentrations of radon and thoron during the exposure period in Bq/m³, CF_{Rn1} and CF_{Tn1} are respectively the radon and thoron conversion factors for the low air exchange rate chamber in tracks of 2.3 cm⁻²·kBq⁻¹·m³·h⁻¹ and 0.04 cm⁻²·kBq⁻¹·m³·h⁻¹, CF_{Rn2} and CF_{Tn2} are respectively the radon and thoron conversion factors for the high air exchange rate chamber in tracks of 2.1 cm⁻²·kBq⁻¹·m³·h⁻¹ and 1.9 cm⁻²·kBq⁻¹·m³·h⁻¹, T is the exposure time in hours, and B is the background alpha track density on the CR-39 detector per cm². The lower detection limit of the detector was practically estimated on the basis that one concentration depends on the other. The lower detection limits were 3 Bq/m³ for radon and 4 Bq/m³ for thoron.

RADUET detectors were placed at a height of 1–2 m and 20 cm from the wall in 100 and 150 dwellings of the uranium- and thorium-bearing regions of Poli and Lolodorf, respectively, for 2–3 months.

Spot outdoor and indoor gamma dose rate measurements were performed using a RadEye dose rate survey meter calibrated using a Gamma-RAD5 NaI(Tl) scintillation spectrometer. Measurements were conducted at a height of 1 m above the ground surface.

1.3. Inhalation dose due to radon and thoron

The inhalation dose is given by the following equation [19]:

$$E_{inh} = \left[\left(X_{Rn} \times e_{inh,Rn} \times F_{Rn} \right) + \left(X_{Tn} \times e_{inh,Tn} \times F_{Tn} \right) \right] \times F_{occ} \times t$$
(3)

 X_{Rn} and X_{Tn} are the median radon and thoron concentrations, respectively, and $e_{inh,Rn}$ is the inhalation dose conversion factor of 9 nSv/(Bq·h⁻¹·m⁻³) for radon and $e_{inh,Tn}$ is the dose conversion factor of 40 nSv·Bq·h⁻¹·m⁻³) for thoron, F_{occ} is the occupancy factor of 0.6 for the studied areas, $F_{Rn,Tn}$ is the equilibrium factor considered to be 0.4 for radon and 0.02 for thoron, *t* corresponds to a year expressed in hours. The occupancy factor was derived from an in situ enquiry performed in the studied areas during field work. The equilibrium factor used is the default value given by United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) [19].

3 RESULTS AND DISCUSSION

In the uranium-bearing region of Poli, activity concentrations of ²³⁸U, ²³²Th, and ⁴⁰K range, respectively, between 13–52 Bq/kg, 10–67 Bq/kg and 242–777 Bq/kg with respective average values of 32 Bq/kg, 31 Bq/kg and 510 Bq/kg. In the uranium- and thorium-bearing region of Lolodorf, activity concentrations range between 6–158 Bq/kg, 6–450 Bq/kg and 98–841 Bq/kg with 34 Bq/kg, 58 Bq/kg and 200 Bq/kg as respective mean values. The world average values for these radionuclides given by UNSCEAR [19] are, respectively, 33 Bq/kg, 45 Bq/kg and 420 Bq/kg. Air kerma rates range, respectively, between 25–102 nGy/h and 11–357 nGy/h for the uranium- and thorium-bearing regions of Poli and Lolodorf, with mean values of 57 and 54 nGy/h. At the worldwide level, they range around 24–160 nGy/h with an average value of 57 nGy/h. The annual effective dose ranges respectively between 0.20–0.83 mSv/year and 0.1–2.2 mSv/year with a mean value of 0.35 mSv/year and 0.33 mSv/year less than the world average value of 0.5 mSv/year given by UNSCEAR [19].

In the uranium-bearing region of Poli, radon and thoron concentrations indoors range respectively between 46–143 Bq/m³ and 18–238 Bq/m³ with average values of 82 Bq/m³ and 94 Bq/m³. The inhalation dose due to radon and thoron ranges, respectively, between 0.87–2.7 mSv/year and 0.08–1.0 mSv/year with the average values of 1.55 mSv/year and 0.4 mSv/year. The total inhalation dose due to radon and thoron ranges around 0.95–3.7 mSv/year with the average value of 1.95 mSv/year.

In the uranium- and thorium-bearing region of Lolodorf, radon and thoron concentrations indoors range respectively between 31-197 Bq/m³ and 6-700 Bq/m³ with the average values of 97 Bq/m³ and 159 Bq/m³. The inhalation dose due to radon and thoron ranges respectively between 0.6-3.7 mSv/year and 0.03-3.0 mSv/year with the average values of 1.84 mSv/year and 0.67 mSv/year. The total inhalation dose ranges around 0.6-6.7 mSv/year. At the worldwide level, inhalation dose due to radon ranges around 0.2-10 mSv/year with the mean value of 1.26 mSv/year.

The contribution of thoron to the total inhalation dose in the uranium- and thorium-bearing regions of Poli and Lolodorf ranges, respectively, between 3-34% and 1-79%, with average values of 20.3% and 27%.

Thus, thoron cannot be neglected in dose assessment to avoid biased results in radio-epidemiological studies.

4 CONCLUSION

Natural radioactivity in most of the surveyed areas is normal. However, there are high natural radiation areas found in most of the areas studied. Radon and thoron exposure is a reality in Cameroon. The thoron contribution to inhalation dose is higher than 20% and therefore thoron cannot be neglected in dose assessment. Thoron is abundant in the uranium- and thorium-bearing regions of Poli and Lolodorf. However, extensive measurements of radon and thoron at nationwide scale are needed. In case high inhalation doses are confirmed, epidemiological studies could be planned. An IAEA TC project (CMR9009) dealing with Establishing a National Radon Plan for Controlling Public Exposure Due to Radon Indoors is ongoing since the beginning of 2018. This two-year project is funded within the framework of the TC programme between the IAEA and Cameroon.

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THE TEST OF A NEW UAV GAMMA-RAY SPECTROMETER AT A REAL URANIUM ANOMALY

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1. INTRODUCTION

Localization of size-limited gamma-ray objects plays a fundamental role in uranium prospecting and environmental studies. Unmanned Aerial Vehicle (UAV) mini-airborne measurements have been applied for many environmental issues, including radiation protection and nuclear accident monitoring [1-6]. The instrument reported by Sanada and Tori [5] was based on LaBr₃:Ce scintillator, which is not appropriate for measurement of natural radiation due to the contamination of the detector material itself by natural radionuclides ¹³⁸La and ²²⁷Ac [5]. Instruments employed by MacFarlane et al. [1], Martin et al. [2-4] and Falciglia et al. [6] have very good energy resolution, but they are not suitable for radioactive ore prospecting due to their small volume and insufficient sensitivity for weak natural radiometric anomalies.

The instrument suitable for prospecting radioactive geological objects and used in this project was the Georadis D-230A, a newly developed gamma-ray spectrometer specially designed for UAV and equipped with two BGO (Bismuth germanium oxide) scintillation detectors. The objective was to evaluate this equipment for localization of a size-limited U mineralization. The chance to detect an anomaly depends on size, shape and gamma-ray intensity of the anomaly and on the instrument sensitivity, flight speed and flight altitude [7].

The mini-airborne gamma-ray spectrometer Georadis D-230A, having two 51 mm \times 51 mm BGO scintillation crystals, provides a sensitivity of 0.55 cps (counts per second) per 1 ppm eU on the ground. The sensitivity of a standard 76 mm \times 76 mm NaI(Tl) scintillation detector is approximately 0.33 cps per 1 ppm eU [8]. The sensitivity of Georadis D-230A is about 300 times greater than the sensitivity of the 1 cm³ CZT (Cadmiun zinc telluride) detector, which was used for many previous UAV surveys in environmental applications [1-4].

2. METHODS

A uranium mineralization near the village of Třebsko, five km to the south from the town of Příbram, Central Bohemia, Czech Republic, served as a test site for the performance of the Georadis D-230A gamma-ray spectrometer. The spectrometer was attached to a powerful hexacopter. The radiation anomaly at the test site is related to an outcropping U mineralized vein.

Concentrations of radionuclides at the anomaly were assessed by a detail ground measurement with a portable gamma-ray spectrometer GS-256 equipped with a 76×76 mm NaI(Tl) scintillation detector. Calibration of the GS-256 spectrometer was performed at the calibration facility in the Czech Republic, in conformity with the standard procedures as recommended by the IAEA [8]. Registered field data were interpolated by the kriging method and the U contour map of the anomaly was compiled.

The hexacopter by Robodrone Industries (Czech Republic), type Kingfisher, was used as an airborne platform. The hexacopter has up to 5 kg payload capacity, dimensions $120 \times 140 \times 22$ cm, maximal endurance

45 min. Endurance with an attached 4 kg instrument was 16 min, maximal speed was 70 km/h and wind resistance 10 m/s [9]. The navigation could be manual or autonomous. The autonomous mission was specified by waypoints given by GPS coordinates and the flight altitude as the third coordinate. The system measures the altitude by a barometric pressure sensor MS5611-01BA03 [10]. The atmospheric pressure altimeter is calibrated to zero height on the ground before each flight.

The mini-airborne 1024 channel gamma-ray spectrometer Georadis D-230A (Czech Republic) has two BGO scintillation detectors with a volume of 103 cm³ each and an automatic spectrum stabilization using energy lines of natural radionuclides. The instrument energy resolution of 13.6 % at 662 keV was determined experimentally. The instrument weight was approximately 4 kg including a rechargeable battery and a dural holder fixing the instrument under the aircraft.

Mini-airborne measurement was carried out on three 100-m-long NW – SE parallel lines perpendicular to the longer axis of the anomaly (NE – SW). The distance between profiles was 10 m. The data recording time interval was 1 second. Each of the three profiles was flown at eight altitudes from 5 m to 40 m above the ground with vertical steps of 5 m. Flight velocity was 1 m/s. The navigation was performed in the autonomous GPS flight mode. The result of flight operation was 1s interval 1024 channel gamma-ray spectra, which was processed to U concentration and total count (TC) count rate.

3. RESULTS AND DISCUSSION

The resulting U contour map obtained from the ground assay shows an anomaly approximately 80 m by 40 m large with an average U concentration of 25 ppm eU, which locally attains 700 ppm eU in the 0.25 m^2 region.

The results show the significant dependence of the recorded anomalous gamma-ray field converted to TC data and apparent U concentrations on the flight altitude.

The anomaly was recognized in all profiles and flight altitudes. Recorded maxima of count rates exceed the N + 3S level [8] at all cases.

A comparison between sensitivities and data quality of a standard airborne survey and the mini-airborne survey is illustrative. Grasty and Minty [11] reported U sensitivity of an airborne spectrometer at 80 m flight altitude approximately as 8 cps per 1 ppm eU. The flight speed of the aircraft is about 50-60 m/s for fixed-wing surveys [8]. The Georadis D-230A has U sensitivity on the ground 0.55 cps per 1 ppm eU. Uranium sensitivity at the altitude of 40 m is approximately 50% of the sensitivity on the ground [11, 13], which means about 0.25 cps per 1 ppm eU. Flight speed of the UAV multicopter can be slowed down to 1 m/s. Theoretically, a standard airborne survey at a flight altitude of 80 m over 100 m long profile with a uranium concentration of 1 ppm U will generate in the U energy window 16 counts while for the Georadis D-230A at a flight altitude of 40 m and with a speed of 1 m/s, 25 counts will be recorded at 100 m long profile. It is obvious that UAV mini-airborne survey, because of its low speed and lower flight altitude capacity, can collect data with comparable quality, on a detailed scale, as standard airborne survey.

4. CONCLUSION

The presented issue deals with the methodology and potential of mini-airborne gamma-ray spectrometric survey for radioactive ore prospecting using unmanned aerial vehicles. The research has shown real operational possibilities of the tested mini-airborne system with a progressive BGO gamma-ray spectrometer with a relatively large volume detector.

Experimental measurement profiles over a size-limited U anomaly at flight altitudes from 5 m to 40 m showed the rapid decrease of the gamma-ray field with increasing flight altitude. Flight altitude is important

option for mini-airborne survey as well as for standard airborne survey. Based on our results, the flight altitude for mini-airborne surveys can be up to 40 m and take into account all important conditions like size and intensity of an assumed anomaly, detector sensitivity, flight speed and vegetation character.

A detailed ground gamma-ray spectrometry investigation of the U anomaly enabled analysis and comparison with airborne data. A small UAV can fly at low altitudes and enables detection of size-limited radiation objects which are undetectable by conventional airborne gamma-ray spectrometry at standard flight altitude of about 80 m. In this sense UAV systems fill a gap in technical possibilities between ground and conventional airborne measurement.

The UAV mini-airborne instrument can collect the same number of counts per unit distance on a profile as a standard airborne survey, due to low speed and lower flight altitude. The main limitations of mini-airborne gamma-ray spectrometry are short operational time and slow survey speed causing the method to be not applicable for regional surveys.

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URANIUM MINING TOWARDS SUSTAINABLE CLEAN ENERGY: INDIAN SCENARIO

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1. INTRODUCTION

Energy plays a key role in the development and functioning of the world's economy. However, increased energy use and mechanization to support ever growing industrialization brings with it the burdens of environmental pollution that adversely affects health, safety, lifestyle, etc. Ideally, a mature society should find ways to keep a balance between socially desirable, economically workable and ecologically sustainable measures through an adaptive process of integration. Achieving a sustainable clean energy supply for humankind is an essential factor for sustainable development. The global energy sector is characterized by specific sources of energy such as coal, oil and gas, nuclear power, hydropower, solar, etc. However, the challenge lies in finding ways to reconcile the necessity and demand for energy resources with an acceptable impact on the environment and within the available natural resource base.

India, with a population of more than one billion people, has been facing formidable challenges in addressing its energy needs. Though fossil fuels and hydropower dominate the country's energy production scenario, recognition of nuclear power as a clean, reliable and abundant source of energy with no greenhouse gas emissions is a significant step towards a sustainable development process. It has great potential to protect the Earth from irreversible environmental damage.

2. URANIUM MINING IN INDIA AND SUSTAINABILITY

India's nuclear programme adopts a unique three-stage strategy based on a closed fuel cycle, where the spent fuel of one stage is reprocessed to produce fuel for the next stage. The objective is to utilize both fertile and fissile components of uranium as well as thorium. This scheme also takes into account the country's unique atomic mineral resource base (modest uranium and abundant thorium) with a goal for clean energy security. India's PHWR programme (first stage of a three-stage strategy) has reached a state of commercial maturity over the years, with indigenous capability and the county is now entering into the second stage of U–Pu based fuel reactors. The third stage of reactors using thorium as fuel has been developed at pilot scale and development of commercial technology is under way.

Indian uranium deposits are of low grade and moderate size. Most of the country's uranium resources are hosted in carbonate rock that calls for adoption of alkaline leaching, which is acknowledged as a complex and costly process. These resources do not lend themselves for development on plain commercial considerations. However, the integrated economic model of the nuclear power production programme (exploration, uranium mining, fuel fabrication, power production, waste management) of the country compensates for the commercial disadvantage of indigenous uranium production, but also provides fiscal latitude for adoption of new technology with a higher level of safety standards and environmental measures. With successful commissioning of the first alkali leaching plant at Tummalapalle, additional projects are planned to be developed in the near future to extract uranium from carbonate host rock.

Uranium mining technology in India is appropriately chosen with the aim generating a minimum of waste rock and to use waste rock as fill in underground mines, as well as creating minimum disturbance to surface topography through continuous filling of voids created by underground mining and reuse and recycle of the liquid waste, etc. Adoption of decline entry, ramps as entry into stopes, use of electro-hydraulic underground equipment instead of diesel powered units, etc., in underground mining will help in maintaining the

operations within the absorptive capacity of local sinks for wastes. Uranium mining in India is gradually absorbing the globally acceptable technology of trackless mining with improved efficiency and safety features. The recently commissioned Tummalapalle underground uranium mine with three declines as entry points and conveyor transport of ore from mine through a central decline to the plant is a landmark development in the Indian mining industry.

Uranium ore processing through acid leaching is dominant in the uranium production scenario of the country and continuous efforts are made for upgrading with utmost consideration on maximising recovery, reducing discharge of effluents and maximizing the recovery of by-products. Recovery of by-products ensures optimum utilization of all useful materials from the ore in an integrated sequence (single flowsheet). This helps in minimizing waste streams and mine site problems, demonstrating comprehensive extraction of resources. Extraction of magnetite from ores of Singhbhum and proposed extraction of sulphides from ore from the Rohil uranium deposit illustrate the challenges in recovering values from the waste. Adopting a shorter processing route, implementing measures to maximize the reuse of water, producing environmentally benign product such as uranium peroxide, etc., are some of the distinctive features which exemplify the values of sustainability.

Management and eco-restoration of uranium tailings impoundment (solid and liquid wastes) facilities are the crucial part of uranium mining all over the world. In India, the technology for management of tailings has been continuously upgraded, in keeping with international practices. Tailings ponds have been designed with improved floor lining to prevent downward movement of effluent and a robust monitoring mechanism has been devised to maintain the permissible discharge quality of water. Eco-restoration of the filled tailings pond with an appropriate thick layer of soil for arresting radon emanation, planting specific varieties of nonedible grass to control soil erosion and preventing radioactive incursion into the food chain through grazing animals, etc., are well acknowledged in the society. Currently, a new innovative method of tailings management known as near surface trench disposal is being developed which aims at effective utilization of land within a mining area, which is located away from the public domain to ensure ease of handling and the monitoring of tailings.

Avoiding the transfer of a large financial burden to future generations to shoulder is a part of the 'futureproofed' sustainable development goals. Future financial liabilities and costs associated with the closure of uranium mines, decommissioning of process plants and reclamation of tailings impoundment facilities are adequately set aside to ensure funds are available when needed in the future.

Displacement and disruption of settlements around mining sites is generally seen as a major cause of resentment among communities. A well-defined human resource development strategy for skill development and education to students in the area around uranium projects in India at an early stage of project development helps create a skilled society in the area, thus avoiding large scale influx of trained personnel from other parts of the country. It also helps in promoting the growth of secondary industries in the neighbourhood. Local industries are encouraged to progressively develop the competency to support the need for critical components by enhancing the skill base of the community. The uranium production facilities in the country have helped in creating a self-sustainable skilled society for mining and processing industries, thereby supporting other similar industries.

3. CONCLUSION

With a limited uranium resource base, India advances in its goal of achieving a multiple increase in uranium production and nuclear power generation by delicately balancing the sustainability of the community around the production facilities through an appropriate mix of technology, environmental measures, social harmony, finance and governance. Apart from strengthening the operations in its eight mines and three process plants, efforts are under way for setting up new units in different parts of the country.

Sharing of knowledge on past practices and collective wisdom of good systems is essential for establishing a sustainable uranium industry, particularly to engage those countries with little or no experience in such fields. India's experience, assimilated over time from working with low grade small to medium sized deposits, and the organizational structure of its nuclear power sector may become a model for new practitioners in the field of uranium production and nuclear power in the world.

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URANIUM, THE ENVIRONMENT AND SUSTAINABLE DEVELOPMENT: LESSONS FROM NAMIBIA

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1. INTRODUCTION

Namibia has a well-established uranium exploration and mining sector, and proudly looks back on four decades of uranium mining at the Rössing uranium mine. The Langer Heinrich mine has produced uranium for a decade, and another milestone was reached in 2016 with the opening up of the Husab mine, which is set to become one of the largest uranium mines in the world. Namibia also has a number of known deposits at an advanced exploration or early development stage, just awaiting an improvement in the uranium market to become active contributors to the Namibian economy. Furthermore, active exploration is ongoing and received a boost when a moratorium on nuclear fuel licences was lifted by the Ministry of Mines and Energy last year.

The Namibian uranium sector has an excellent record of cooperation with Government, including active collaboration on environmental issues. The Ministry of Mines and Energy's Strategic Environmental Management Plan, which is assessing the environmental performance of uranium exploration and mining activities, is implemented with active participation of the industry. This is an important aspect, as the industry is operating in a sensitive arid environment.

2. BACKGROUND

Uranium mining in Namibia is carried out in the Erongo region in the central western part of the country. This region is characterized by its aridity, vast desert landscapes, scenic beauty, high biodiversity and endemism and heritage resources. It has the second largest economy of all the Namibian regions, and mining plays a very important part in this economy. Walvis Bay and Swakopmund are amongst Namibia's five largest towns, at the same time, large parts of the Erongo region, especially along the coast, are under active conservation in the form of national parks [1].

The Namibian uranium deposits belong to two main types, namely, primary uranium mineralization in light coloured granite (alaskite) (Rössing, Husab), and secondary uranium mineralization in calcrete (Langer Heinrich). Secondary mineralization is the result of weathering of rocks with primary mineralization. The predominant uranium mineral in alaskite is uraninite (UO₂], but betafite [U(Nb,Ti)₂O₆(OH)] can also be a major mineral phase in some places. Secondary uranium deposits are found in calcrete which formed in palaeovalleys of ancient rivers flowing westwards from the Great Escarpment around 88–25 Ma. The main uranium mineral in calcrete is carnotite $[K_2(UO_2)_2(VO_4)_2 \times 3H_2O]$. It occurs in cracks and as coatings on sediment grains in the calcretized fluvial channels. Both mineralization types are amenable to open cast mining methods [2].

Namibian uranium exploration and mining activities occur in the ecologically sensitive central Namib Desert, and in an area partly belonging to the Namib-Naukluft and Dorob National Parks. Mining is vital for the growth of the Namibian economy and the country must therefore reconcile development objectives and mineral exploitation with environmental protection for its long term socioeconomic growth and stability. An integrated approach is required so that development of one resource will not jeopardize the potential of another. In order to support and facilitate such an integrated approach, the Namibian Uranium Association was formed by the industry in 2013.

3. THE NAMIBIAN URANIUM ASSOCIATION (NUA)

Members of the NUA include all Namibian uranium mining operations, Namibia's leading uranium exploration companies and associated contractors. The NUA is the leading point of contact for government, media, stakeholders, the general public and anybody interested in the position and policies of the Namibian uranium industry. Members of the NUA accept product stewardship as a pillar that supports the overarching concept of sustainable development. In this way, the Association makes a lasting contribution to the socioeconomic development of Namibia while at the same time minimizing the environmental footprint and promoting the Namibian uranium brand [2].

Product stewardship ensures that the industry focus on economic development, environmental impact management and social responsibilities through partnership building over the uranium life cycle to ensure that production, use and disposal are consistent with global sustainable development goals and global best practice. Cumulative socioeconomic and biophysical impacts of mining cannot be successfully addressed by one company only, and unsustainable practices by one company can impact negatively on the entire industry. Proactive cooperation in health, environment, radiation safety and security and community issues between companies is therefore a necessity.

4. THE NAMIBIAN URANIUM INSTITUTE (NUI)

As part of its stewardship mission, the NUA has established the NUI. The NUI is guided by respected independent scientists who serve on the NUA's Scientific Committee. The main purpose of the NUI is to act as a hub for the uranium industry in Namibia, and to promote knowledge and capacity building in specialized skills in environmental management, radiation safety and health. The NUI therefore provides an opportunity for NUA members to work together to improve safety and health performance through the implementation of world class best practice. As such, the NUI is working closely with the Namibian Government and with the Namibian University of Science and Technology.

The NUI's activities are guided by a Sustainable Development Committee, which was formed to assist the uranium industry in safeguarding its reputation as a safe and responsible industry. The committee was also established to assist the NUI in promoting best practice with regard to health, environment, and radiation safety and security; and in its oversight responsibilities by reviewing, monitoring and advising both the NUI and the NUA from a uranium industry wide perspective. At the policy level, the Sustainable Development Committee reviews and guides NUA policy formulation to ensure that it incorporates principles of sustainable development early in the process. These principles include public participation, intergenerational equity, sustainable use of natural resources and public access to information. The Sustainable Development Committee's duties include the assessment and monitoring of all risks associated with health, environment and radiation safety and security matters of the uranium industry; assistance with the development and implementation of internal compliance and control systems and procedures to manage risks; coordination of assessment and monitoring of the effectiveness of controls instituted; and the review and formulation of recommendations to the NUI and the NUA in relation to risk management. In order to achieve this, the Sustainable Development Committee has also appointed four working groups, namely, the Services Working Group, the Radiation Safety Working Group, the Water and Air Quality Working Group and the Swakop River Farmer's Working Group.

The NUI's Communication Technical Advisory Committee (C-TAC) was established in order to recommend to the NUI the overall strategic direction of the institute's communications. It is an advisory committee tasked to advise and assist the NUA, through the NUI, in carrying out its mission and strategic plan by developing and monitoring communication protocols, initiatives and policies, and formulating and implementing a stakeholder engagement and communication strategy for the uranium mining industry in Namibia.

5. TRAINING

An integral part of the NUI's activities is teaching, in order to improve knowledge, safety and the implementation of best practice in the field of occupational health, environmental management and radiation safety. As part of its stewardship mission, the NUI has developed partnerships with various scientists to develop standards, guidelines and training courses to cater for the needs of the uranium industry. The NUI is officially registered with the Ministry of Labour and Social Welfare as an Approved Inspection Authority in terms of the Regulations made under Schedule 1(2) of the Labour Act, 2007 (Act 11 of 2007), with competencies in the fields of health, environment and radiation safety and security [2].

6. THE STRATEGIC ENVIRONMENTAL MANAGEMENT PLAN

Some 10 years ago, when prices for fuel for civil nuclear reactors were rising fast, resulting in a worldwide boom in uranium exploration and mining, the Namibian uranium industry recommended that the Government of Namibia undertake a strategic environmental assessment of the Namibian uranium province, where exploration for uranium was also expanding rapidly. Subsequently, such an assessment was carried out by the Geological Survey of Namibia (Ministry of Mines and Energy) and provided vision and fostered a culture of cooperation between the uranium mining industry, government and the public. A strategic environmental management plan (SEMP) was developed as a result of the strategic environmental assessment, and has been implemented by the Geological Survey of Namibia in cooperation with the Namibian uranium industry since 2011. It is an overarching framework and roadmap addressing the cumulative impacts of existing and potential developments and the extent to which uranium mining is impacting the central Namib. The SEMP has 12 themes, the so-called environmental quality objectives, each articulating a specific goal, providing context, setting standards and having a number of key indicators which are monitored. These themes include socioeconomic development, employment, infrastructure, water, air quality, health, impact on tourism, ecological integrity, education, governance, heritage and future, and mine closure and future land use [3].

Implementation of the SEMP is guided by a steering committee that is chaired by the Geological Survey of Namibia (Ministry of Mines and Energy). Members include the Department of Water Affairs in the Ministry of Agriculture, Water and Forestry; the Ministry of Health and Social Services, which includes the National Radiation Protection Authority; the Ministry of Environment and Tourism; the Gobabeb Research and Training Centre's Namibia Ecological Restoration and Monitoring Unit; the Namibian Coast Conservation and Management Project and the NUA.

The NUI is actively contributing to the compilation of the annual SEMP reports. A great achievement of the SEMP to date is the fact that these annual SEMP reports have established a long term monitoring and decision making tool through which potential impacts are highlighted in order that measures can be developed to avoid unnecessary impacts or to mitigate unavoidable impacts. The aim of the SEMP process is to increase the commitment of key government institutions, the uranium industry and NGOs to undertake whatever actions are needed to take the region towards its desired future state of the SEMP.

7. SUSTAINABLE DEVELOPMENT

In Namibia, sustainable development is a constitutional imperative. In Article 95, the Namibian Constitution obliges the State to actively promote and maintain the welfare of the people by adopting policies that are aimed at the maintenance of ecosystems, essential ecological processes and the biological diversity of Namibia as well as the utilization of living natural resources on a sustainable basis for the benefit of all Namibians both present and future. Hence, there is a duty to ensure that Namibia's environment remains healthy and productive and that Namibians use their natural resources in sustainable and productive ways to combat poverty and improve people's quality of life. Through the implementation of its stewardship

principles, which ensure a focus on economic development, environmental best practice and social responsibility, the NUA is actively involved in the sustainable development of Namibia.

In September 2015, 17 Global Sustainable Development Goals (SDGs) were adopted in New York by world leaders under the United Nations 2030 Agenda for Sustainable Development. Even before this event, the African Union has formulated a Consolidated African Position in support of the United Nations 2030 Agenda for Sustainable Development. In addition, the African Union Agenda 2063 is a global strategy formulated to optimize the use of Africa's resources for the benefit of all Africans. The domestication of the African Union Agenda 2063 and the SDGs was launched in Windhoek in June 2016 by the Deputy Prime Minister and the Director General of the National Planning Commission. The Namibian National Development Plan 5 has sustainable development as its overarching theme, and alignment of the African Union Agenda 2063 and the SDGs with NDP 5 is under way. The NUA's contributions towards sustainable development and the work of the NUI's Sustainable Development Committee are therefore fully in line with Government policies. The NUI was actively involved in the drafting of NDP 5 at national planning commission level and is also represented on the Government's Sustainable Development Advisory Council.

The mining industry has the potential to contribute positively to all 17 SDGs. The SDGs have 90 indicators and an analysis showed that 53 of these are already met by the uranium industry in Namibia. These fall under SDG 1 (No Poverty), SDG 2 (No Hunger), SDG 3 (Good Health), SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 6 (Clean Water and Sanitation), SDG 7 (Good Jobs and Economic Growth), SDG 8 (Renewable, Affordable, Clean Energy), SDG 9 (Innovation and Infrastructure), SDG 10 (Reduced Inequalities), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption), SDG 13 (Climate Action), SDG 15 (Life on Land), SDG 16 (Peace and Justice) and SDG 17 (Partnerships for the Goals).

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FEATURES OF GEOLOGICAL MODELLING, MINERAL RESOURCES AND RESERVE ESTIMATION OF URANIUM ROLL-FRONT DEPOSITS

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1. INTRODUCTION

Roll-front deposits in Kazakhstan are the source of 40% of global uranium production [1]. These deposits are characterized by having low production costs due to the use of in situ recovery (ISR) methods of uranium extraction. Consulting companies prepared reports based on international standards (NI 43-101, JORC) and local standards (GKZ system) before 2012. This approach often led to an underestimation of mineral resources [2]. CSA Global developed a robust methodology for geological modelling mineral resource and ore (mineral) reserve estimation of roll-front deposits in Kazakhstan from 2012 through 2017. This methodology was applied to Budenovskoye and South Inkai deposits in Chu-Sarysu province, and to Zarechnoye and Kharasan-1 deposits in Syrdarya province [3–7].

2. CHARACTERISTICS OF ROLL-FRONT DEPOSITS

The first characteristic of roll-front deposits is the very complicated morphology of mineralization. Uranium mineralization occurs in unconsolidated lacustrine-alluvial sediments of Late Cretaceous-Palaeogene horizons in two regional basins in south Kazakhstan: Chu-Sarysu and Syradarya. Mineralized bodies comprising these deposits are represented as weaving ribbons of various width and length per unit area which are controlled by the oxidation zone boundary. The mineralized bodies consist of several morphological elements, including noses, knees, upper and lower wings (limbs), and residual bodies (satellites) located at the rear of the roll-front. An important feature is the variation in the proportion of uranium and radium throughout these bodies. Uranium dominates in the nose and decreases in the wings, whereas radium dominates in the residual bodies. The uranium: radium ratio is described by the radioactive equilibrium factor (REF), which is part of a more general definition of radiological factors. The width of the deposits may vary from tens to hundreds of metres and is often dependent on the thickness and frequency of impermeable lenses/interbeds, which complicate the boundary of the zone of formation oxidation (ZFO). The extended upper limb of a roll, complicated by step-wise 'sliding' of the geochemical boundary, is, as a rule, observed when the thickness of the horizons is considerable, and several confining lenses are available in the area of ZFO boundary thinning. Multistage bodies consisting of a number of mineralized lenses are typical of the deposit stratigraphy and confirm the extreme complexity of the enclosing rock sequence.

The second characteristic of roll-front deposits is their amenability to ISR methods. ISR transfers a significant proportion of hydrometallurgical processing to the subsurface to directly obtain solutions of uranium. For ISR to be successful, deposits need to be permeable and the uranium readily amenable to dissolution by leaching solutions in a reasonable period of time, with an acceptable consumption of leaching reagents [8].

3. MODELLING AND MINERAL RESOURCE ESTIMATION

Modelling and mineral resource estimation of roll-front uranium deposits consist of the following stages which takes account of the characteristics of these deposits:

• Selection of mineralized intervals by correct application of radiological factors. The first radiological factor is radon removal/concentration, which is evaluated based on a comparison

between gamma logging results and the results of core sampling and analysis for radium [9]. The second step is determination of a radium cut-off grade of 0.01% U equivalent in different geochemical zones (oxidized, reduced), which allows radium halos around uranium mineralized bodies to be excluded. Radium halos at the boundaries have a significant influence on mineralized intersections. These halos are diffuse and manifest themselves as mineralized intersection margins in which equilibrium is shifted towards an abundance of radium. Finally, a correction for REF = C (radium)/C (uranium) is introduced to calculate the uranium grade after having established the mineralized interval boundaries and calculated the average radium grade. REF studies are carried out for various geological and geochemical environments such as the nose, wing and residual parts of rolls, as well as in permeable and impermeable sediments and different mineralized horizons. The uranium:radium ratio is calculated using assay data for uranium and radium and extrapolation of defined patterns to intervals defined by gamma logging.

- **Estimation of permeable–impermeable intervals**. Electrical logging (resistivity logging and spontaneous polarization) is the most common method of lithological interpretation. Comparison of core lithological logging, granulometry and electrical logging allows identification of impermeable zones.
- Modelling of sedimentary cycles (horizons) which are controlled by continuous clay-silt horizons which control the distribution and location of ZFOs. Analysis of the distribution of mineralized intervals and oxidized sediments shows that mineralization in different horizons (cycles) occurs in separate roll-fronts. However, sometimes mineralization 'overflows' between horizons due to breaks in the clay horizons between cycles. Digital terrain models are used for modelling borders between sedimentary cycles. Continuous impermeable layers should be modelled at this stage, together with sedimentary cycles.
- Mineralized intervals are divided into morphological elements, nose, knee, upper wing, lower wing and residual parts, separately for each ZFO. This is completed by using geochemical data as follows:
 - The intervals where mostly reduced rocks are developed both in the mineralized interval and above and below are attributed to the nose or knee.
 - The intervals where reduced rocks are developed in the mineralized interval and mainly above are attributed to the upper wing.
 - The intervals where reduced rocks are developed in the mineralized interval and mainly on the lower side are attributed to the lower wing.
 - The intervals where there are mainly oxidized rocks developed above or below the mineralized interval are attributed to the residual part. The mineralized interval itself can be represented by both reduced and oxidized rocks.

The distribution of nose/knee parts is controlled by the ZFO. Three dimensional modelling of rollfront deposits allows the morphology to be clarified and the positioning of ZFOs and oxidized sediments, which control the distribution of mineralization. For example, at the Zarechnoye deposit, the location of the ZFOs were changed and as result the understanding of the direction of flow of uranium-bearing solutions. The orientation was changed from north-west to south-west. New uranium mineralization was discovered due to the new interpretation.

- **Modelling of interbeds of impermeable sediments inside mineralized horizons**. This allows construction of a lithological wireframe model with mineralized bodies and permeable–impermeable sediments and can be used for design of operation blocks and for defining intervals for screens (filters).
- Interpolation of grades into mineralized bodies by ordinary kriging or multiple indicator kriging.
- A gridded model is generated for each wireframe in order to estimate uranium grade thickness (GT) based on block models. GT or productivity cut-off is more appropriate for ISR deposits than cut-off grades used in other styles of mining [8]. The vertical extent of the cells of the gridded model depends on the thickness of the mineralization. Uranium GT is calculated by
multiplying the vertical size of the cells by the uranium grade. Gridded models are two dimensional. In order to estimate the GT in three dimensional space, it is necessary to compare each cell of the gridded model with a column of cells in the original block model. This is completed by indexing the block model cells by comparison with the cells of the gridded model. Using the indices, the GT values of the mineralized bodies from the gridded model is coded into the block model.

• **Depletion of mineral resources**. For ISR deposits, the depletion of mineral resources is measured not by how much rock is removed, as is the case with most traditionally mined resources, but, rather, by lowering of uranium grade (and GT).

4. ORE (MINERAL) RESERVE ESTIMATION

'Modifying factors' are considerations used to convert mineral resources to ore (mineral in NI 43-101) reserves. These include, but are not restricted to, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors [10]. The main technical modifying factors for ore reserve estimation are mining and metallurgy.

The ratio of liquid:solid required to achieve the desired extraction of uranium. This ratio is calculated based on the volume of solutions that pass through the operational block over the entire period of operation and on the tonnage of the operational block [8]. Graphic extraction versus liquid:solid is the most relevant consideration for exploration target evaluation. Usually, target extraction is calculated by decreasing uranium concentrations in pregnant solutions to breakeven cut-off grade, which is reflected graphically by a flattening curve.

Dilution is included in the operational block calculation as the volume is based on the effective thickness of the production zone. The mineral resource estimate includes measured and indicated resources within the operation blocks. Dilution estimates are prepared based on the difference in tonnage between the mineral resource estimate and the operation block tonnage estimate.

5. DISCUSSION AND CONCLUSION

Application of 3-D modelling techniques for roll-front deposits allows the creation of lithological and resource models and reliable mineral resource/ore (mineral) reserve estimation. According to the experience of the author, the difference between mineral resources and ore (mineral) reserves, based on operational wells and the geological/resource model, does not exceed 5–7%. These models are used for more accurate screen set-ups in operational wells, hydrodynamic and physicochemical modelling of uranium leaching in operational blocks and, finally, more accurate estimation of mineral resource depletion after the constraining of operational blocks.

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Sr-Nd-Pb ISOTOPE SYSTEMATICS OF U-BEARING ALBITITES OF THE CENTRAL UKRAINIAN URANIUM PROVINCE: IMPLICATION FOR THE SOURCE OF METASOMATIZING FLUIDS

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1. INTRODUCTION

Sodium metasomatites are relatively widely distributed throughout the world and often contain uranium mineralization that occasionally may reach an exploitable scale [1]. Uranium concentrations in deposits of this type are rather low but resources can be quite large, especially in the areas where sodium metasomatites attain wide distribution. As was pointed out in Ref. [1], deposits of this type are significantly underexplored and may represent a promising target for further exploration. This is especially true as sodium metasomatites often contain complex mineralization that, besides U, includes Sc, V, Nb, HREE and Ag.

The Central Ukrainian Uranium Province (CUUP) hosts several large deposits and numerous subeconomic deposits and occurrences. Production started in 1951 and since that time two deposits have been completely exhausted. The remaining U resources of the CUUP exceed 300 000 tU with grades varying between 0.05 and 0.20 wt% U [1].

In spite of the long history of exploration and exploitation of Na-metasomatite type U deposits in Ukraine, many questions regarding their origin still remain unanswered. The main questions that were debated over decades related to the source of the metasomatic fluids and the source of the ore components. Numerous studies focused on the geological structure of U deposits in the CUUP, on their mineralogical and chemical compositions, and on stable isotope systematics. Results of these studies are summarized in Refs [0–3]. However, high quality geochemical data regarding these deposits were absent until recently [1, 4], whereas radiogenic isotope data are still absent, which hampers a reasonable discussion about the origin and evolution of the Na-metasomatites and about the source of ore components.

Current ideas regarding the origin of metasomatic fluids and their ore load are controversial. The main problems are:

- 1) The source of the very large volumes of high temperature hydrothermal solutions (with meteoritic waters, basin waters and magmatic fluids being the main alternatives) and complex sources evolving over time have also been invoked [1]);
- 2) A source of U and Na, as large volumes of these elements cannot be derived from low crustal and mantle lithologies, and middle to upper crustal sources have been considered. However, simple calculations indicate that hydrothermal leaching of the host upper crustal rocks cannot produce such enrichment as these rocks are relatively poor in both U and Na, and huge volumes of leached rocks are unknown in the area;
- 3) The association of elements typical for this type of deposit includes elements that are more typical for mafic alkaline igneous complexes rather than for felsic crustal rocks.

This contribution presents new Sr-Nd-Pb isotope data obtained for Na-metasomatites in the CUUP and for a large variety of host rocks and discusses the possible contribution of different sources to the origin of this type of U deposit.

2. GEOLOGICAL SETTING

The CUUP is located in the central part of the Ukrainian Shield, within the predominantly Palaeoproterozoic Inhul mobile belt, and partly within the Mesoarchaean Middle Dnieper domain. Most of the deposits and occurrences are located near the southern contact of the Korsun-Novomyrhorod anorthosite–mangerite–charnockite–granite (AMCG) complex (dated at 1757–1744 Ma [5]) where they are hosted by the Novoukrainka gabbro–monzonite–granite massif (dated at 2038–2028 Ma [6, 7]) and granites and migmatites of the Inhul Complex (dated at 2022–2062 Ma [Error! Reference source not found.–10]). Several deposits are located within the Kryvyi Rih synform structure, which is filled mainly with siliciclastic sediments and banded iron formation. The age of this structure remains poorly understood and is commonly regarded as Palaeoproterozoic–Neoarchaean.

Na-metasomatites are confined to the major fault zones closely associated with the numerous mafic dykes which are widely distributed in the same area. Some of the mafic dykes are older than metasomatites and can be affected by sodium metasomatism whereas other dykes clearly cut metasomatic bodies. Available geochronological data [11] indicate the formation of the mafic dykes at ~1800 Ma.

Depending on the lithology of the host rocks, Na-metasomatites are represented by two main mineralogical types. The first type develops after felsic igneous rocks and is represented by albitite. The second type includes aegirine–riebeckite metasomatites that develop after iron rich rocks of the banded iron formation. In all cases, metasomatic bodies are confined to the major fault zones and occur as irregular elongated zoned bodies that have been traced along strike for several kilometres whereas the widths of metasomatic bodies may exceed several hundred metres. The largest bodies have been traced by drilling to depths of 1200 m and deeper.

This paper will focus on the first type of the Na-metasomatites, i.e. on U-bearing albitites. In a generalized form, zoning in these rocks can be described as a gradual transition from unaltered host rock (granite, migmatites, gneiss, etc.) to quartz free (desilicified) microcline–albite metasomatite ('syenite') and then to albitite. This rock succession formed during the progressive (albititic) stage of the alkaline (sodic) metasomatic process. The late stage mineral assemblage that includes phlogopite (or late chlorite), carbonate, andradite, diopside, Mg-Ca amphibole and haematite are often superimposed on the internal parts of albitites. Besides this, secondary quartz, epidote and microcline are often superimposed on the intermediate and external parts of the metasomatic bodies. These minerals are regarded as having developed during removal of silica, calcium and potassium from central (albititic) parts of metasomatic bodies [1–3].

3. MINERAL COMPOSITION

Albite occurs as the main (up to 90%) rock forming mineral, whereas the amount of mafic minerals usually does not exceed 10%. The typical mafic minerals are alkaline amphibole, alkaline pyroxene, epidote, chlorite, diopside, actinolite and garnet. The proportion of albite and mafic minerals is generally defined by the composition of the initial rock. The amount of pyroxene varies from almost 0 to 10%. Pyroxenes belong to aegirine (the amount of the Ca component varies from 0 to 45 mol.%) and diopside–sahlite (the amount of the Na component varies from 0 to 20 mol.%). Pyroxenes that contain over 10% Sc₂O₃ occur as well-defined inclusions within the aegirine–pyroxene matrix. Amphibole usually associates with pyroxene and varies in composition from riebeckite to slightly alkaline actinolite. Garnet belongs to the andradite–grossular series and occurs mainly in deposits located in the Novoukrainka granite massif where the amount of garnet may reach 50%. Garnet occurs in association with diopside, actinolite and epidote; sometimes it may be found in association with aegirine. Epidote is a rock forming mineral in so-called 'syenites' and certain types of albitite. It often replaces garnet in the garnet–diopside metasomatites. Epidote in albitites of the Partizanske orefield contains a large amount of Sr.

Accessory minerals in albitites comprise apatite, zircon, titanite, monazite, uranothorite and allanite, which are present in all types of U-bearing sodic metasomatite. Phenakite, thortveitite and schorlomite are rare minerals. The origin of accessory minerals is not clear as they may represent relict phases left from the initial (pre-metasomatic) rocks.

Albitites also contain various opaque minerals, including haematite, magnetite, titanomagnetite, rutile, ilmenite, galena, pyrite, chalcopyrite, sphalerite, etc. Native silver in concentrations reaching up to 1% in Na-metasomatites of the Kryvyi Rih–Kremenchuk zone has been known for a long time. In the northern part of the Vatutinske deposit concentration of silver reaches 300 ppm. The accompanying minerals are galena, pyrite, marcasite, chalcopyrite, sphalerite, minerals of U, Ti and Ba.

The principal U minerals are uraninite (U⁴⁺, U⁶⁺, Pb, Ca, REE, Zr)O_{2-x}, brannerite (U⁴⁺, Ca, Th, Y)[(Ti, Fe)₂O₆] \cdot nH₂O and U-ferropseudobrookite (Fe²⁺[Ti,U⁴⁺]₂O₅). Uraninite is unevenly distributed and absent in some deposits. Electron microprobe analyses have revealed the presence of up to 20.51% PbO, 6.20% CaO, 0.78% Y₂O₃, 3.90% Ce₂O₃ and 1.72% ZrO₂. Brannerite occurs as the main ore mineral in many of the deposits in the CUUP. It often develops after Ti and Ti-bearing minerals; there is a persistent association of brannerite with rutile, anatase, carbonate minerals, quartz and sericite. According to Ref. [1], U-ferropseudobrookite forms anhedral crystals which replace magnetite and generally precedes brannerite and/or uraninite deposition.

4. GEOCHEMISTRY

The data obtained demonstrate regular variations of the chemical composition in the vertical profile across the albitite bodies. When compared with the host granite, albitites demonstrate a sharp decrease in the abundances of SiO_2 and K_2O . The Al_2O_3 content increases slightly near contacts with host granites and then decreases in the central part of the metasomatic body. Most other major oxides show significant enrichment in albitites. Oxides such as Fe_2O_3 , CaO, TiO₂ and MgO demonstrate pronounced enrichment in the U-rich central (axial) parts of the albitite body. In addition, Na₂O is sharply increased in metasomatices, but demonstrates a moderate decrease in the axial part of the body.

According to Ref. [1], the distribution of REE in barren albitites is very close to that in the host granite. In general, barren albitites are slightly enriched with respect to LREE, and depleted in HREE, when compared with the host granite, but these differences are not significant. The new data indicate that albitite samples rich in U are highly enriched in HREE. It is thought that metasomatic fluids responsible for U enrichment were also rich in HREE. This feature is not typical for felsic rocks that may be considered as the main source of U (and Na).

5. Sr-Nd-Pb ISOTOPE SYSTEMATICS

A set of whole rock samples was collected at the Novokostyantynivka and Novooleksiivka deposits. These rocks were analysed for Sr, Nd and Pb isotopes. As can be seen from Sr isotope data, metasomatic rocks have an isotopic signature typical for crustal rocks. Specifically, rocks of the Novokostyantynivka deposit have ⁸⁷Sr/⁸⁶Sr₍₁₈₀₀₎ in the range 0.7087–0.7105, whereas in the rocks of the Novooleksiivka deposit ⁸⁷Sr/⁸⁶Sr₍₁₈₀₀₎ varies from 0.7172 to 0.7207. There is no strict correlation between ⁸⁷Rb/⁸⁶Sr and ⁸⁷Sr/⁸⁶Sr ratios that prevents the construction of isochrons and production of reasonable Rb–Sr isotope ages. This indicates inhomogeneity of the Sr isotope composition that could result from the variable host rock/metasomatic rock ratio in the samples.

In the Novooleksiivka deposit, samples were collected systematically across the vertical section of the metasomatic body. As follows from the results, there is a tendency for albitite samples in the axial part of the body to have less evolved initial Sr isotope composition. This tendency may indicate that the

metasomatic fluids were derived from a source that had a lower Rb/Sr ratio than the upper crustal granites. However, this question requires further confirmation on other deposits.

Neodymium isotope composition, in contrast to Sr, is much more consistent in both studied deposits and allows construction of a relatively good isochron. The age yielded by the isochron (1728 \pm 110 Ma) corresponds within error to the U–Pb age previously obtained for the U deposits in the CUUP. The ϵ Nd value according to the isochron is -4.8, which indicates the crustal source of albitites, in accordance with Sr isotope data.

There is a small systematic difference between the Novokostyantynivka and the Novooleksiivka deposits; the average $\epsilon Nd_{(1800)}$ value for the Novokostyantynivka albitites is -3.7, and that for the Novooleksiivka albitites is -4.5. These results are consistent with Sr isotope data, according to which the Novooleksiivka deposit reveals a more 'evolved' crustal source.

Lead isotope compositions indicate the great prevalence of radiogenic Pb, whereas 'common' Pb is virtually absent. This allows calculation of the Pb–Pb age of deposit formation. There is no significant difference in the age of the Novokostyantynivka and Novooleksiivka deposits; both deposits were formed at 1810 ± 17 Ma. This age is in good agreement with the previously obtained U–Pb ages and with the Sm–Nd isochron age (sees above).

The obtained isotope results can be compared with data available for the main lithologies present in the area. Albitites of the Novokostyantynivka deposit plot between fields of the Novoukrainka massif and Korsun-Novomyrhorod AMCG complex, and closer to the Novoukrainka field. In contrast, albitites of the Novooleksiivka deposit plot entirely within the field defined by the Inhul granitoid complex. It has Nd isotope characteristics similar to the Novoukrainka massif but differs by their much higher Sr isotope values.

6. DISCUSSION AND CONCLUSIONS

Many features of the U-bearing Na-metasomatites of the CUUP have received significant attention from researchers. These features include the geological structure of the deposits, their mineral composition and some aspects of the isotope geochemistry (O, C and H isotopes, see Ref. [1] for an overview). However, some features are very important for understanding the origin of Na-metasomatites and related mineralization, and these remain underexplored. For instance, high quality geochemical data regarding metasomatic rocks are still very limited in number. This is especially true with respect to U ore geochemistry, which is still poorly studied. The same also applies to the isotope geochemistry of Sr, Nd and Pb.

In the author's opinion, the following features are very important for the understanding of the origin of Nametasomatites and related mineralization:

- Close spatial relationship of the Na-metasomatites with the Korsun-Novomyrhorod AMCG complex. Most of the deposits and occurrences are located within 30 km of the contact of the complex. In addition, Na-metasomatites are closely associated with numerous mafic and ultramafic dykes of tholeiitic affinity;
- 2) Close temporal relationships with mafic dykes which according to the available geochronological and geological data intruded simultaneously with the formation of Na-metasomatites at around 1815–1800 Ma. The Korsun-Novomyrhorod AMCG complex is 50–60 Ma younger, but its formation may have started around 1800 Ma, as evidenced from the occurrence of older xenoliths of anorthositic rocks;
- 'Mixed' geochemical characteristics of the Na-metasomatites; these rocks are rich in Na, U, Th, Sc, V, Nb, HREE and Ag. This combination of elements is not typical for felsic rocks and can possibly be related to mafic alkaline sources;

4) Newly obtained Sr and Nd isotope data indicate crustal sources for the bulk of Na-metasomatites.

Formation of the mafic dykes and the Korsun-Novomyrhorod AMCG complex has been linked to a long lived mantle plume [5, 11], although the relationship of mafic magmatism to the rotation caused by crustal extension and mantle melting has also been proposed [12, 13]. In any case, emplacement of numerous mafic dykes and formation of the extensive Korsun-Novomyrhorod AMCG complex implies the presence of the large-scale thermal anomaly in the mantle and low crust. Metasomatizing fluids were probably generated in the upper mantle and on the way through the crust they have achieved a crustal isotope signature. However, their useful load was probably derived from the mantle as crustal felsic rocks can hardly be considered as a source of such elements as Sc, V, Nb and HREE. It is assumed that metasomatizing fluids may be related to mafic alkaline melts which were responsible for the formation of various alkaline (syenites, aegirine–riebeckite syenites) and subalkaline (monzonites) rocks that are present in the Korsun-Novomyrhorod plutonic complex.

Interestingly, available isotopic and geochemical data indicate the significant dependence of the isotope composition of the Na-metasomatites on low crustal(?) rocks. Both studied deposits occur within the Novoukrainka gabbro-monzonite-granite massif and there is no reason to assume that host rocks for these two deposits are very different in terms of their isotopic composition. However, one of the deposits (Novokostyantynivka) has an Sr–Nd isotopic composition more typical of the Novoukrainka rocks, whereas another deposit (Novoleksiivka) reveals an Sr–Nd isotopic composition more typical of the Inhul granites. Some differences in their mineralogy and geochemistry may also occur, but this question requires further detailed investigation. According to model proposed, metasomatizing fluids were derived from the hot upper mantle melts from which inherited their elemental composition. On the way through the low crust they achieved their crustal isotopic signature which apparently was not significantly modified during the interaction with the upper crustal rocks.

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URANIUM POTENTIAL OF THE SINGHBHUM SHEAR ZONE, INDIA: FUTURE PROSPECTS

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1. INTRODUCTION

The Singhbhum Shear Zone (SSZ), Jharkhand, India, hosts several uranium deposits and is one of the major uranium producing provinces of India. The SSZ uranium province has the potential to host significant uranium resources in addition to metals such as Cu, Ni, Mo, REE, Fe and Mg. Proven uranium resources in the province as of July 2017 were 64 392 tU₃O₈ (54 604 tU). The producing centres, namely, Jaduguda (from 1968), Bhatin (from 1986), Narwapahar (from 1995), Turamdih (from 2003), Bagjata (from 2008) and Mohuldih (from 2012) have been developed as underground mines and Banduhurang (from 2009) as an open pit. Recent conceptual work carried out by the Atomic Minerals Directorate for Exploration and Research based on new exploration strategies, has paved the way for additional resources to be located in the adjoining blocks of the existing mining centres, thereby extending the lifespan of the mines. The conceptual exploration strategy has also given encouraging results and has helped to identify new potential zones. Some significant recent discoveries are reorienting the exploration programme to enhance the resource base of the SSZ significantly. The present paper describes some of the results and the plan for future exploration by Atomic Minerals Directorate, India.

2. GEOLOGICAL SETTING

The SSZ is a 200 km long arcuate belt of high strain characterized by multi-phase deformation, intense ductile shearing and multiple metasomatic features, including imprints of sodic metasomatism and polymetallic mineralization [1]. It was subjected to subsequent ductile deformations which obliterated a majority of the earlier features [2]. The arcuate shaped SSZ involves various Archaean-Neoproterozoic lithological units. The oldest rocks (\geq 3.4–2.6 Ga) are represented by the older metamorphic group, the older metamorphic and tonalite gneiss, unclassified mafic-ultramafic rocks occurring as enclaves within Singhbhum granitoids, banded iron formation of the Badampahar-Gorumahisani Belt, acid volcanics and ultramafic dykes of 2.6 Ga [3] which have also suffered the SSZ related deformation, especially along the arcuate belt. Uranium proto-ore was probably supplied from these Archaean lithologies and was concentrated in the overlying quartz pebble conglomerate (QPC), occurring at the base of the iron ore group (IOG) and also the Dhanjori Group. The IOG comprises conglomerate, phyllite-shale-wacke, quartzite, banded magnetite quartzite, ultramafics, acid volcanics, tuffaceous units, grits, etc. The Dhanjori Group comprises a volcano-sedimentary sequence containing quartzite-conglomerate, mafic ultramafic flows and intrusives with tholeiitic (pillow) basalts interlayered with tuffs (2.1 Ga) overlying the IOG. Rocks of the Dhanjori Group are overlain by the Singhbhum Group which comprises quartzite-conglomerate (oligomictic and polymictic), feldspathic schist, granite mylonite, sericite-quartz-schist, chlorite-quartzschist (and their mineralogical variants), metabasic sills, mica schists and quartzites. The lower part of Singhbhum Group comprising the Chaibasa Formation represents a metasedimetary package in which sedimentary structures are preserved despite many deformational episodes. Deep to shallow marine turbidite and shallow peri-tidal to fluvial depositional environments have been proposed. Perhaps more than one environment coexisted in the region. The upper part of the Singhbhum Group is the Dhalbhum Formation, comprising phyllites and ortho-quartzites which have been interpreted as a meandering channel system [1]. Apart from the extensive Singhbhum granite which comprises different phases, several younger isolated granitic bodies are also exposed along the SSZ, such as Chakradharpur granite, Arkasani Granophyre and Soda Granite (now interpreted as originally feldspathic schists). Several younger mafic and ultramafic

bodies have been emplaced along the shear zone. These bodies vary in age and therefore show repeated opening of the mantle during the process of shearing or even in the post-shearing period.

The rocks of the SSZ are characterized by compositional banding running subparallel to the major foliation. Large scale fold structures with subhorizontal to low plunging axes are seen on the northern side of the SSZ. The shear zone is characterized by the presence of small scale reclined folds, a strong foliation as well as a well-marked set of down-dip lineations of tectonic origin. Mylonites are commonly present in almost all rock types involved in shearing. They can be classified as L–S type tectonites [4]. Gentle warps along N–S axial planes mark a late deformation event post-dating the shearing event. Rocks of the shear zone have been affected by progressive and retrogressive metamorphism. The grade is greenschist in the central part, which hosts major uranium deposits. The chlorite–quartz schist and quartz–chlorite schists are the major host rocks for uranium and copper mineralization.

3. NATURE OF URANIUM MINERALIZATION

The uranium mineralization is confined to the arcuate SSZ from Duarpuram in the west to Baharagora in the south-east. The arcuate shape is possibly due to the fact that the Singhbhum Craton acted as a barrier against stresses from the NNE. The resultant structure is an anticlinorium of isoclinally folded rocks dipping consistently north and marked by a prominent shear zone with crushed and mylonitized rocks [5]. This has provided an ideal situation for mineralizing fluids to form shear controlled, hydrothermally generated metamorphite type deposits in addition to proto-ore and QPC environments. The metamorphite deposits occur as disseminations, impregnations and veins along shear planes within or affecting metamorphic rocks of various age. These deposits are highly variable in size, resource and grade [6]. Deposits of the central sector of the SSZ (Narwapahar, Turamdih and Mohuldih) are peneconcordant, , stratabound and hosted in relatively lower metamorphic grade rocks, whereas the deposits of the eastern sector (Jaduguda, Bhatin, Bagjata and Kanyaluka) are discordant and vein-like and associated with host rocks of a relatively higher grade of metamorphism. Uranium mineralization is confined at the Chaibasa-Dhanjori contact and is dependent on the intensity of the shear. In most cases, mineralization is present at the base of the lowest unit of the Chaibasa Group or in the upper level of the Dhanjori metasediments. Sericite-quartz schist has been considered as a marker at the base of uranium mineralization [7]. The mineralization in the SSZ is present in sheared low grade metamorphic rocks, i.e. guartz-chlorite schist or guartz-biotite schist. However, it is absent in hornblende (or actinolite) schist. This feature indicates that favourable host rocks for U mineralization are of greenschist facies rather than epidote-amphibolite facies or rocks of ultrabasic composition (actinolite schist) [8]. Uranium mineralization is represented by uraninite, minor pitchblende, brannerite, U-Ti complexes, which occur in many instances in association with sulphide mineralization comprising chalcopyrite, minor bornite, chalcocite, covellite, molybdenite and oxides such as magnetite, ilmenite, titano-magnetite, etc. The mineralogy is complex and the chemistry of the ores, particularly U and Cu ores, is greatly influenced by the host rock involved in shearing. The shear zone, when affecting the Dhanjori Group (Jublatola), is richer in U, Cu, Ni, Mo (± Bi, Au, Ag, Te, Se), whereas when in schists and quartzite of the Chaibasa Formation it is poorer in these metals. The peneconcordance of the orebodies with the host lithologies is seen in the Chaibasa Formation [9].

4. CONCEPTS ON ORE GENESIS

Various modes of occurrence for uranium mineralization have been reported in the SSZ. Titanium oxide– uranium oxide grain aggregates found in the Jaduguda–Bhatin deposits are related to a QPC type environment where primary and secondary brannerite have been reported [10]. Three generations of uraninite have been observed in the SSZ in which the last phase is post-sulphide mineralization. The refractory uranium-bearing minerals (allanite, xenotime, monazite, etc.) and uranium associated with apatite–magnetite veins are the product of pneumatolytic–hydrothermal metasomatism probably related to younger granitic phases referred to earlier (Arkasani Granophyre and Soda Granite). The uraninite associated with feldspathic schist (~Soda Granite) in the Narwapahar–Turamdih sector has been correlated

with a metasomatic feldspathization process and subsequent remobilization to form orebodies [11]. On the basis of various observations, it was proposed that the geochemical source of U was the Singhbhum granitoid, whereas the basic rocks of the Dhanjori Group provided Cu, Ni and Mo for the formation of U-Cu deposits in the SSZ [12]. Mahadevan [9] has concluded that U was enriched in the Singhbhum granite by partial melting of the upper mantle/lower crust around 2900–3000 Ma. This continued until 1900 Ma (Mayurbhanj and Nilgiri granitoids) and 1420 Ma (Soda Granite). The QPCs at the base of the IOG and the Dhanjori Group show evidence of detrital accumulation of uranium-bearing minerals. These U concentrations, along with host rocks, were folded into a major synclinal sequence prior to their involvement in shearing episodes. Shearing episodes have further remobilized and reconstituted uranium mineralization concomitant with the early folding events, F_1 and F_2 . The localization of U–Cu lodes with predominantly platy minerals, particularly chlorite, is controlled by deformation and metamorphism of the Chaibasa and Dhanjori rocks simultaneously. The younger granites, namely the Chakradharpur granite, Arkasani Granophyre and Soda Granite, along with younger basic units, formed by partial melting of the upper mantle-lower crust interface which generated the geothermal gradient [9]. Mantle metasomatism or crustal contamination of ascending melts cannot be ruled out in such cases, which would have generated a diverse type of uranium mineralization unknown in the present-day. The chemical and structural characteristics of various uraninites differ from E–W and from N–S, i.e. along and across the strike of the SSZ. The uraninite composition varies from UO_{2.31} to UO_{2.44} and the cell dimension from 5.42 Å to 5.45 Å [11]. Larger cell dimensions have been found in the eastern and western parts of the SSZ while it is comparatively smaller in the central sector (Jaduguda).

5. URANIUM MINERALIZATION-NEW CONCEPT/ ENVIRONMENT

5.1. QPC-related U mineralization

The potentiality of the QPC as a economic horizon for $U \pm Au$ is yet to be established in Singhbhum Province. The QPC at the base of IOG and Dhanjori are present in the SSZ area. They have been involved in shearing episodes as well but their primary features have been preserved in some shadow zones. Recent non-core drilling up to a depth of 300 m has provided insight into QPC-related horizons and indicated their spatial continuity in lenses. Exploration in the western half of the SSZ (Jamshedpur as centre) has resulted in the identification of subsurface conglomerate bands with U–Th mixed anomalies (placer type) at shallow levels while uraniferous bands are found at deeper levels (250–300 m). The repeated nature of Th, U+Th and U-enriched layers at Gura and the occurrence of intermittent yet significant QPC horizons over a considerable length (35 km) of the Udalkham–Manikbazar–Simulbera sector has strengthened the concept of exploration for QPC type mineralization. Magnetite is predominant in these conglomerates and haematite is absent. Similarly, deformed uraniferous conglomerates of Jaduguda occurring above the Dhanjori metabasic/basalt and its probable western continuity at Nimdih and further west towards Chirugora, and its eastern extension to Rakha mines, has generated interest in exploring the whole belt where QPC has no surface expression. The concept is being tested by Atomic Minerals Directorate through comprehensive non-core and core drilling programmes.

5.2. Arkasani Granophyre-related U mineralization

The SSZ bifurcates into two arms at Narwapahar and continues further westwards where the Bangurdih–Gurulpada sector forms the southern segment of the shear while Sankadih–Galudih forms the northern shear plane of the SSZ. The surface uranium occurrences, defining an E–W trend along Banaykela, Gurulpada, Mahalimurup, Dhadkidih, Dugridih, Nilmohanpur, Ukri and Bijay areas, are confined to the southern shear while Sankadih, Saharbera, Sarmali and Tirildih are situated along the northern segment. The Arkasani Granophyre and the Soda Granite are associated within the northern shear as evidenced by outcrops. Recent efforts to explore the soil covered area between Sankadih and Galudih by non-core drilling has discovered uranium mineralization over a strike length of 360 m and up to a depth of 120 m in two drilling profiles with grades in the range 0.021-0.043% U₃O₈. Ground geophysics has helped to define planned borehole

location and depth of the targets. A potential area with an 800-m strike length is located west of the main Sankadih ore block. The uraniferous mineralization that can be correlated is confined to the Arkasani Granophyre/feldspathic schist. The subsurface continuity in this unit has generated a new concept, namely, to explore the Arkasani Granophyre magmatic–hydrothermal mineralization adjacent to the SSZ.

The shear controlled chlorite–biotite–quartz schist hosted uranium mineralization at Sankadih occurs near the Arkasani Granophyre contact. Even schistose rocks occurring within the Arkasani Granophyre show the presence of uranium [13]. This phase of uranium mineralization has been correlated with a major episode of deposit formation in the SSZ. The emplacement of the Arkasani Granophyre and Soda Granite is syn- to post-major shearing phase. The chalcopyrite developed in the schist shows magmatic (+0.9 to +1.4 δ^{34} S°/_{oo}, n = 2) and metamorphic (+2.6 to 3.4 δ^{34} S°/_{oo}, n = 3) parentage, indicating later remobilization under metamorphic conditions [13]. In other words, it is interpreted that the Arkasani Granophyre has caused magmatic and metamorphic effects on shear zone rocks and probably supported the recycling of U mineralization in subsequent episodes. The concept developed has been tested. The investigations have resulted in encouraging values of uranium mineralization related to the Arkasani Granophyre.

5.3. Serpentinized peridotite hosted U-Fe-Mg-Cr-Ni-Mo-REE-C mineralization

In order to develop new concepts and to get more information, a few boreholes were planned to extend below the quartz–chlorite and quartz–sericite schist (marker for the base of uranium mineralization in the SSZ) of the Chaibasa Formation in the Kudada–Turamdih area. The investigation discovered a new type of environment where polymetallic (U–Fe–Mg–Cr–Ni–Mo–REE–C) mineralization hosted by serpentinized peridotite was established in four boreholes of the Kudada area, south of the Turamdih Group of deposits. The corresponding surface mineralization has been located in the Kudada Protected Forest Area. The peridotite is emplaced at the interface of the IOG and the Chaibasa Formation, as the Dhanjori Group of volcano-sedimentary rocks appear to be absent in this sector. The possibility that the peridotite belonging to IOG or Dhanjori need further study, however present knowledge place it in IOG as it intrudes quartzites of IOG.

The host peridotite comprises relict olivine (after serpentinization) and pyroxenes (after chloritization) of 200–300 µm in size. Also, the presence of chromite and magnetite has been established. Uraninites (subhedral to anhedral) varying from a few µm to 600 µm are disseminated within the serpentinized peridotitic groundmass. Uraninite clusters (~3 grains) is a common feature. The unit cell dimension of uraninite ranges from 5.4498 to 5.4650 Å (n = 2) and corresponds well with that of other uraninites in the SSZ, indicating a high temperature of crystallization. XRD studies have confirmed the presence of uraninite and of beta-uranophane and monazite traces. Other metalliferous minerals are magnetite, molybdenite, cobaltite (CoAsS), nickeline (NiAs), vaesite (NiS₂), cerussite (PbCO₃), pyrite, chalcopyrite and chamosite. Talc and fluorapatite occur as gangue [14]. Chemical analysis (n = 10) of peridotites gives the following values: MgO (18–28%), FeO (3–17%), Fe₂O₃ (t) (2–23%), Cr (1623–3165 ppm), Ni (221–1347 ppm), Mo (<10–485 ppm), Co (43–633 ppm) and V (36–230 ppm). REE (t) is enriched up to 1457 ppm (n = 5) when compared with non-mineralized host rock (558 ppm, n = 4).

The geological environment for the uranium mineralization intercepted in the Kudada–Turamdih area is an unusual one and has not been reported in the SSZ, and hence requires detailed study. Recent investigations have enhanced the potential of the SSZ with respect to the hosting of a large deposit.

5.4. Tirukocha Fault-related exploration

The eastern part of the SSZ records a few prominent faults related to brittle deformation as a post-shearing phenomenon. The Tirukocha Fault between Bhatin and Jaduguda, and the Gohala Fault between Bagjata and Kanyaluka have affected the uranium mineralization. Both faults have been identified by total magnetic intensity imaging in the central part of the SSZ. The integrated studies carried out are based on geological

mapping and the collection of subsurface data from boreholes and from the underground Jaduguda mines suggests its oblique slip nature. The surface manifestation of the Tirukocha Fault is identified by the clear displacement of the quartzite unit of the Chaibasa Formation in Jaduguda by about 1 km dextrally on plan. The level plan made on marker quartzite depicts a lateral displacement of about 1.07 km with a vertical separation of 570 m [15]. These measurements are significant and aid both geological understanding and also exploration in the Jaduguda–Tirukocha region where substantial areas remain unexplored. The concept is tested and a few boreholes have identified mineralization based on the above understanding. Exploration so far indicates that richer grades are extending further east. This will necessitate meticulous planning in the east where the orebody and the fault plane make an intersection line plunging steeply towards the northeast. Calculation of the intersection of the two planes indicates that intercepts of better grade and thickness values can be expected further eastwards with each deeper series.

6. CONCLUSION

Comprehensive studies on the SSZ have generated additional geophysical, mineralogical and geochemical data. They have been integrated to provide new concepts and develop an exploration strategy to be applied to the SSZ over the next five years. The exploration strategy will focus on four types of mineralization:

- 1) QPC-related uranium mineralization;
- 2) Arkasani Granophyre-related uranium mineralization;
- 3) Altered peridotite hosted polymetallic mineralization;
- 4) Mineralization related to brittle tectonics along the Tirukocha Fault.

Atomic Minerals Directorate for Exploration and Research has planned substantial coring and non-coring drilling to prove the existence of at least 15 000 tU_3O_8 as an additional resource from these new concepts.

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COMPREHENSIVE EXTRACTION SCHEME FOR MULTIMETAL RECOVERY FROM METASOMATITE-ALBITITE HOSTED LOW GRADE INDIAN URANIUM ORE

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1. INTRODUCTION

India is making focused efforts to reach, by 2040, a human development index (HDI) of 0.9+, a number considered to indicate a decent state of living, from its present index value of 0.6 [1]. Meeting the projected HDI necessitates, among others, the strategies for utilization of various energy resources in a sustainable way. The contribution of nuclear energy in the overall mix is very critical to achieving the target HDI, primarily due to its low carbon footprint and local availability of fertile thorium resources [1]. The installed capacity of commercial uranium fuel based nuclear power plants in India at the end of 2017 was 6780 MW(e)[2]. It is planned to increase the capacity to about 35000 MW(e) by the year 2022, comprising mainly of PHWRs and LWRs together with minor contributions from FBR (500 MW(e)) and an AHWR (300 MW(e)) [3]. It is reported that the identified conventional uranium resources in India so far are sufficient to support 10–15 GW(e)of installed capacity of PHWRs operating at a lifetime capacity factor of 80% for 40 years[3]. Continuous efforts are being made by different agencies in India to increase indigenous uranium production for realizing domestic fuel demand, which includes exploration for new deposits, establishment of new mills and augmentation of existing ones.

The majority of the Indian uranium occurrences discovered so far fall into the low-grade category [4,5]. Maximum utilization of mined ore or comprehensive extraction is an ideal approach for the exploitation of lean tenor ores as it addresses the sustainability principles as well as commercial viability terms. Successful cases in this respect which are familiar for the uranium ore processing industry are the Palabora copper mine (South Africa) [6], and-Olympic Dam polymetallic copper mine (South Australia) [7] and the Jaduguda uranium mines (India) where a byproduct recovery plant was in operation for recovering useful metals such as Cu, Ni, Mo and Fe (magnetite) [8]. With growing interest in rare earth elements, which are needed for green energy applications, many phosphate mine operators are looking into their recovery in addition to the already established schemes for phosphate and uranium [9-11].

Among the most promising new uranium findings explored for by the Atomic Minerals Directorate for Exploration and Research, the uranium exploration agency in India, counts the Rohil–Ghateswar uranium ore deposit in the Sikar district of Rajasthan [12]. The Rohil–Ghateswar uranium ore is a metasomatite type deposit hosted by albitized metasediments of the Delhi Supergroup in north-west India. The metasomatite uranium occurrences in India reportedly represent about 3.3% of the total domestic uranium resources and the most important among them is the Rohil–Ghateswar multimetal uranium ore, which contains Cu, Mo, Ni and Co. This paper gives details of the process development studies carried out for multimetal recovery from the Rohil–Ghateswar low-grade uranium ore.

2. ORE SAMPLE AND CHARACTERIZATION

A composite feed for the experimental studies is prepared by judicious mixing of split core borehole ore samples from different locations in the Rohil–Ghateswar ore deposit. The XRD and optical microscope study of the feed indicated uraninite as the chief uranium-bearing phase, along with traces of brannerite and davidite. The other minerals identified are: chalcopyrite, molybdenite, pyrite, pyrrhotite, riebeckite, quartz,

traces of albite, biotite, boulangerite, chlorite, covellite and goethite. Chemically, the ore sample showed U_3O_8 :~0.04%, Cu: 0.14%, Mo: 0.024%, total S: 4.3%, FeO: 13%, SiO₂: 58.9%, CaO + MgO: 6.7%, Na₂O: 4.3%, K₂O: 1.04% and LOI: 4.3%. Among the sulphides, the pyrrhotite content is about10% and pyrite 1.1%. Uraninite is mostly liberated, although it occurs occasionally as very fine-grained and associated with non-pyrrhotite sulphides. The Bond's Work Index of the sample is 21.4 kW·h/t.

3. PROCESS DEVELOPMENT

The predominance of siliceous minerals in the Rohil–Ghateswar ore led to the choice of a sulphuric acid based hydrometallurgical processing scheme for the recovery of uranium. However, the presence of an excessive content of sulphide minerals, particularly pyrrhotite and pyrite, in the ore necessitated physical beneficiation being integrated with the chemical extraction process. Similarly, a scheme suitable for recovering copper and molybdenum values in the ore, inspite of their low concentration, needs to be evaluated. The occurrence of the Rohil–Ghateswar ore body in an arid region makes design of the process scheme for multimetal recovery a challenging task. Different options have been formulated for achieving the objective of maximizing recovery of multimetals with minimum freshwater requirement. The options include:

- Option I: Comminution physical separation of all the sulphide minerals (magnetic + froth flotation) — hydrometallurgical recovery of uranium — tailings disposal;
- Option II: Comminution separation of Ferro-magnetic pyrrhotite by physical separation (magnetic) hydrometallurgical recovery of uranium tailings disposal;

Option III: Comminution — hydrometallurgical recovery of uranium — separation of sulphide minerals from leach residue by physical separation (magnetic + flotation) — tailings disposal;

Option IV: Comminution — separation of Ferro-magnetic pyrrhotite by physical separation (magnetic) — hydrometallurgical recovery of uranium — gravity separation of leach residue for non-magnetic heavy sulphide minerals recovery — tailings disposal.

Option I helps in prior removal of sulphides which are detrimental during leaching of uranium and simultaneously offer exclusive Cu–Mo sulphide pre-concentrates in addition to yellowcake. Further, the negative effects of acid mine drainage are also minimized. However, two disadvantages arise: (i) loss of some uranium values in the sulphide float due to their composite nature, and (ii) need for larger volumes of water during froth flotation and the difficulty in effective recycling of flotation reagent water, which consists of residual collector reagent and frother. Although treatment of the reagent water post-flotation on a biologically activated carbon column is reportedly removes organics, the process is nevertheless expensive. Option II yields higher uranium recovery, requires relatively less water due to the absence of froth flotation, but the problem of acid mine drainage persists due to sulphides (Cu–Mo and pyrite) in leach residue or solid tailings. Option III too needs higher volumes of water but gives sulphide-free tailings and slightly higher or similar uranium recovery to Option II. Although the surface of sulphide minerals may undergo partial chemical modification due to previous chemical leaching (Option II), the availability of specific collector reagents for mixed oxide–sulphide minerals (unlike alkyl xanthates) would minimize Cu–Mo losses. The major advantage of Option IV is maximum uranium and by-product recovery with minimum water inventory due to easy recyclability of water used in both magnetic and gravity separation stages.

The experimental studies were carried out by optimizing the various parameters of each unit operation both in physical separation and hydrometallurgical processes. Pyrrhotite values were separated using a wet low intensity magnetic separator (applied magnetic field 4 kGauss), while pyrite, chalcopyrite and molybdenite were pre-concentrated using froth flotation with an alkly xanthate–pine oil' reagent combination. Gravity separation was conducted on a wet shaking table using a slimes deck. Uranium was recovered in the form of uranium peroxide by adopting the following unit operations in sequence, namely, conventional agitation leaching with sulphuric acid–pyrolusite reagents, filtration, ion exchange purification, multi-stage precipitation, i.e. initially the iron–gypsum cake at pH 3 followed by precipitation of uranium peroxide.

Separation and purification of uranium from the leach liquor was carried out on a strong base anion exchange resin in sulphate form but eluted with chloride reagent. The overall recovery of uranium for the different options was 80-83%. The U₃O₈ assay of uranium peroxide product was 73.8%. The mass and water balance computations showed fresh water requirements of about four times more when flotation of sulphides is incorporated in the process flowsheet over the scheme which relies on specific gravity difference for preconcentration of Cu–Mo values.

A recovery of about 75% was obtained with respect to Cu and Mo by-products at the pre-concentration stage of the Rohil–Ghateswar ore. The sulphide mineral concentrate consists of Cu, Mo and Fe with traces of Ni and Co. Anand Rao et al. have demonstrated a sulphide roasting–leaching process for quantitative separation of Cu, Mo, Ni and Co values while keeping the Fe oxide phases as an insoluble fraction [13].Roasting converts sulphides of Cu, Ni and Co to their respective sulphates and transforms the sulphides of Mo and Fe to their respective oxides by careful control of the roasting temperature. The sulphates of Cu, Ni and Co are soluble in mild acidic aqueous medium and MoO in alkaline medium, whereas FeO is insoluble. A forward integration approach helped in treating low grade concentrates in order to maximize overall recovery of Cu and Mo.

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AN OVERVIEW OF GEOLOGY AND OCCURRENCE OF UNCONVENTIONAL URANIUM RESOURCE: POTENTIAL RECOVERIES FROM PRECAMBRIAN BASEMENT AND CRETACEOUS SEDIMENTARY ROCKS OF NIGERIA

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1. INTRODUCTION

Uranium occurs in Nigeria as conventional and unconventional resource in both Precambrian basement and Cretaceous sedimentary rocks. The history of exploration for uranium resources Nigeria started in North-Eastern Nigeria, by three major government Organizations. The Geological Survey of Nigeria (Now Nigerian Geological Survey Agency) in 1973, Nigerian Mining Corporation and Nigerian Uranium Mining Company, (NUMCO) from 1979, 1980, 1981, which was stopped in 2001. The areas discovered for Conventional Uranium deposits in Precambrian basement rocks in Northeastern Nigeria are Mika, (132 tU) at 0.63% U at 130m, Gumchi with (100 tU) at 0.9 % at 200m, Gubrunde (60 tU) at 0.7% U and Cretaceous Bima Sandstone hosted Sedimentary rocks of Mayo lope and Zona areas, (130 tU) [9].

This paper is aim at evaluating the uranium potential in the Basement Complex of Central Nigeria as well as in the sedimentary phosphate rock, of illumeden (Sokoto) basin North West Nigeria. This paper will also discuss an overview of geology, and occurrence of prospective unconventional uranium resource from intrusive pegmatites of the north-central basement complex and Cretaceous (Maastrichtian-Paleocene), sedimentary phosphate rock, of North-West Nigeria, involving the integration of Geology, Geochemistry, recently acquired High resolution Airborne Radiometric, Magnetic and processing of remotely sensed Landsat 8 data set to delineate areas of high potential.

The prospect of sedimentary phosphate rocks is located about 500km, Northwest of Abuja the capital of Nigeria. This deposit has been reported and studied by several authors [4, 8, 10, and 11].

The phosphate rocks occur in Paleocene Dange formation, Mastrichian Dukamanje, Taloka and Wurno Formation in Sokoto Illumeden basin. The Federal Government of Nigeria in 2016 through the Nigerian Geological Survey Agency as part of policy thrust to diversify its economy through solid mineral sector and to bridge the power supply need of the country by commencing the assessment of uranium and Rare Earth elements (REE). The project is also ongoing for unconventional source of uranium from Phosphate rock. Exploration has delineated about thirteen prospective areas [8,]. The phosphate rocks occur as irregular, cylindrical, sub rounded, elongate, hard, cream reddish concretion nodules interbedded with shales, clays, siltstone and gypsiferrous shale. The phosphate rocks resulted from ocean upwelling and high organic productivity during Cretaceous to Eocene. The Sokoto phosphate is linked to Tethys sea incursion during the Paleocene, that extend from Libya, Chad, Niger Republic and Sudan, [15].

2. METHODS AND RESULTS

In the Sedimentary Basin, Gamma ray spectrometric measurements of radio-elements and lithologic logging was carried out with a portable hand-held RS-320 spectrometer along exposed sections on two out of the thirteen (13) prospective areas. Chemical analysis of Phosphate samples from Paleocene Dange formation at CETEM Laboratory indicated average uranium concentration of 73.5 ppm U and 34.5percent P2O5. Uranium gamma ray spectrometric analysis gave 16.25ppm U on lateritic ironstone (Tertiary Gwandu

formation), and 20.2 to 30 ppm Th in the Grey Shales (Paleocene Dange formation). The lithologicspectrometric log has shown a downward increase uranium content in the phosphatic shale which signifies higher potential with depth. The presence of pyrite nodules in the basal unit marked reducing conditions favorable for uranium concentration towards the basal Maastrichtian Wurno formation. The phosphate rocks in the basin contains uranium and further exploration for un-conventional uranium resources is ongoing.

Also within the Basement Complex of Nigeria, the identified pegmatite zone has an enormous potential for Unconventional Uranium and Thorium resources. The Pegmatite zone is Apaku is located about 150km south east of Abuja, the capital of Nigeria. The Ministry of Solid Minerals Development, in 1998, evaluated pegmatites veins for their technology metal potential resources, including, tantalite (Ta), columbite (Nb), and lithium (Li). Beryllium (Be) and tin (Sn). This exploration work has led to the discovery of fourteen pegmatite blocks as prospective sources of unconventional uranium [6]. The pegmatite area is quite extensive, covering an area of approximately 225 km2. The pegmatites range in size from 100m to 2km in length and 100 to 500m width. They are being massively worked by more than 500 different artisanal small-scale miners, exploiting tantalite, niobium, tin, lithium, columbite, beryl and REE.

Several workers have shown that the pegmatites are associated with the Pan-African orogeny and reactivation tectonic activity. The pegmatite zone is part of a well-defined ENE-WSW trending zone of 400km extending from Jos-Wamba-Jemma Central Nigeria to Ijero- Ibadan South-western Nigeria [16, 10]. The Apaku zone that has uranium potential resources is 1.4 long and 0.7 km wide is one of viable mineralized pegmatite prospect. The work done in these areas by [6], involved interpretation of panchromatic aerial photographs as base map to delineate structures and lithologies, random regional geological, geochemical sampling of whole rock, weathered, fresh pegmatites and alluvial deposits at a scale of 1:50,000. Chemical analysis for tantalum oxide (Ta2O5), niobium Oxide (Nb2O5), uranium oxide (U₃O₈), thorium oxide (ThO2), and other major, minor elements concentrations using Inductively Couple Plasma Mass Spectrometry (ICP-MS) and X-ray fluorescence (XRF).

The results of chemical analysis indicate elevated values of niobium oxide(Nb2O5) concentration of14%, tantalum oxide (Ta2O5) of 40%, thorium oxide (ThO2) of 900 ppm, uranium of 1900 ppm, tin (Sn) of 1500 ppm.

3. REMOTE SENSING AND GEOPHYSICAL DATA INTEGRATION

The prospecting for uranium has been challenging in Nigeria, therefore remote sensing technology can bridge the gap possibly to discover new potential deposits and enhance wider coverage of previous areas surveyed by [6,9]. Remote sensing technology has been used to directly or indirectly discriminate uranium bearing rocks and mapping of hydrothermal alteration zones [13, 16].

The present study involved the integration of geochemical result, processing and interpretation of high resolution recently (2010) acquired airborne- geophysical data set. Landsat 8 Operational Land Imager (OLI), an enhanced resolution Multispectral image (band), against the panchromatic aerial photographs used earlier in the study areas. Digital Image processing, (principal component analysis, (PCA, band ratio, (band 5/4 for clay mineral, 5/7 for hydroxyls and 3/1 for iron oxide and Color composite were also used.

The ternary image and composite as RGB based gives the distribution of the three radioelements, uranium, thorium and potassium (U-Th-K) which reflect the composition of the lithologies in the area. U/Th Ratios was used to track the possible host rocks of identified uranium anomalies, since uranium is highly and thorium least mobile. The total magnetic intensity (TMI (1VD) grey scale was used to extract suspected shallow and deep-seated lineaments as possible subsurface structural traps for uranium accumulation. Ground follow- up or field checking was done to confirm the alteration zones. The minerals identified in the area are kaolinite and iron minerals are limonite and hematite, with disseminated pyrite in brecciated quartz.

4. DISCUSSION

Geologically, the Apaku area is underlain by Proterozoic migmatites, occurring with weathered low-lying muscovite schist/ phyllites, and metapelites, quartz veins, granite-gneiss, and medium to coarse grained granite within the north-eastern segment. Pegmatite veins occur as flat-lying out crops intruding the Proterozoic migmatite, granite gneiss, schist, Pan-African and Younger granites.

The Uranium mineralization is associated with granitic rocks occurring in the area, which result from the Pan-African orogeny, and are associated to contact metamorphism and thermal effects. Uranium anomaly and uranium-thorium ratios maps have confirmed that the source of the uranium are the granites and gneiss surrounding the study area. A NNE-SSW, NE-SW structural trend extracted from Magnetic TMI (1Vd) data indicate shallow and deep-seated lineaments as possible subsurface structural traps for uranium accumulation. Hydrothermal fluids have been mobilized, and uranium has been concentrated from the reduction of the oxidizing fluids by reducing minerals such as pyrite [10, 12]. The plagioclase feldspars of the fresh granitic rocks have been hydrothermally altered, to kaolinite. The ferromagnesian minerals biotite, hornblende, amphibole, were altered into to limonite and hematite, as observed on Pegmatite vein in contact with the granite outcrop in the area. This was enhanced by chemical weathering typical of tropical climatic condition with little to moderate rainfall, surface- and ground-waters rich in oxygen.

The potential for uranium recovery in Nigeria is very high, with 73.5 U (ppm) average concentration of uranium in Cretaceous phosphate sedimentary rock, and 1900 U (ppm) pegmatites veins. The occurrence of uranium within the phosphate rock is supported by recent radiometric Airborne Survey in Cretaceous sandstone (Continental Terminal) in the southern part of the Illumeden basin in Niger Republic [5]. The Sokoto Basin is part of Southward continuation of Illumeden Basin, where uranium in hosted in the Agadez Sandstone of the Niger Republic. The sediments in the basins are surrounded by Proterozoic crystalline and volcanic rocks, that are potential hosts of uranium mineralization [10]. This uranium is probably derived from the Carbonaceous to Jurassic peralkaline Younger Granitic rocks from the Paleozoic ring complex of the Niger Republic, which are petrologically and geochemically similar to the Mesozoic (Jurassic) ring complex of Nigeria [2]. The areas with high anomalies and geochemical results from the Cretaceous sedimentary phosphate rocks and pegmatites of the present study have shown a NNE-SSW, NE-SW structural trend similar to the one observed in the Niger Republic with two major Regional tectonic structure: the Arlit-in-Azawa fault trending N-S and the Madeoula fault trending NNE-SSW and controlling most of the discovered uranium deposits [5].

5. CONCLUSION

In conclusion, the discovery of high concentration of uranium in Apaku, one of the Proterozoic pegmatites out of fourteen identified pegmatite blocks and two out of thirteen prospect of Cretaceous phosphate rocks in the Sokoto Basin is prospective for Uranium investors and prospectors in Nigeria. When these areas adequately explored and when new remote sensing prospecting techniques will be adopted in Nigeria, the estimation of unconventional resource potential will be high. Ground follow- up or field check has confirmed, that altered granitic rocks in the Proterozoic Basement area and the Cretaceous phosphate rocks correlate with areas of high uranium as shown by U/Th ratios, conductivity, subsurface lineament, ternary, and geochemical results. The well-established deposits of uranium in the Niger Republic in the Illumeden Basin which is contiguous to the sedimentary phosphate rock of Nigeria makes the potential of similar occurrences very high. Further work including feasibility studies is recommended in these areas that have good potentials for un-conventional uranium resource.

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CONVENTIONAL AND UNCONVENTIONAL URANIUM RESOURCES IN THE CARAJÁS MINERAL PROVINCE, BRAZIL: PROSPECTIVITY CRITERIA FOR IOCG AND GRANITE-RELATED DEPOSITS

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1. INTRODUCTION

The Amazonian Craton (South America) hosts several favourable areas for uranium exploration that are underexplored. The most significant recognized resources are located in Carajás Mineral Province, the oldest known Archaean crustal fragment of the craton. Identified uranium resources are unconventional, hosted by the world class iron oxide–copper–gold (IOCG) deposits of the Carajás copper–gold belt [1, 2]. Nevertheless, the potential for granite-related resources is also notable, as Palaeoproterozoic A type granitic plutons cover several thousand square kilometres of the province's surface and present very high uranium background values [3, 4].

This paper aims to present an overview of the uranium potential in the Carajás Mineral Province and assess regional prospectivity criteria for uranium-rich IOCG and granite-related uranium deposits, based on airborne geophysics and regional to deposit scale structural and geological data.

2. TECTONOSTRATIGRAPHIC FRAMEWORK

There are three main rock generation ages in Carajás Province tectonostratigraphic evolution, namely in the Mesoarchaean (3.02–2.83 Ga), the Neoarchaean (2.76–2.55 Ga) and the Palaeoproterozoic (1.88 Ga). The oldest rocks are gneisses, greenstone belts and granitoids developed under an accretionary–collisional system reported as the Itacaiunas Belt [5, 6]. Collisional peak metamorphism has been dated at 2.85 Ga and metamorphic fabrics are of medium to high amphibolite facies [6, 7]. This rock association represents the basement of the Carajás Basin (2.76–2.70 Ga), a Neoarchaean rift-related meta-volcano–sedimentary sequence [8, 9] that hosts supergiant banded iron formation deposits and other exhalative resources, such as Cu–Zn volcanogenic massive sulphides [9]. Coeval bimodal magmatism is represented by several A-type granites and mafic–ultramafic intrusions. Late stage granitic dykes persist until 2.55 Ga and are spatially and chronologically related to several magnetite-rich IOCG deposits [2, 10]. At about 1.88 Ga, the region experienced an anorogenic magmatic event, which also affected all the central–eastern side of the Amazonian Craton and is known as the Uatumã magmatism. This event produced a second generation of A-type granites in the province [3], emplaced at shallower depths and related to widespread hydrothermal activity in a brittle, fluid dominated extensional environment.

Neoarchaean rocks were only deformed and metamorphosed in the Palaeoproterozoic. There are two events of ductile to ductile-brittle deformation and metamorphism that can be recognized. The oldest one is the Transamazonian Orogenic Cycle (2.20–2.05 Ga), a collisional system that agglutinated several Archaean nuclei and Rhyacian magmatic arcs and greenstone belts [6, 11], related in the province to low greenschist (south) to high amphibolite (north) metamorphic fabrics and structures. To the north, the Archaean units are limited by a collisional suture from Rhyacian plutonic assemblages that are imbricated over the province [6]. The youngest one is the Sereno Event, an intracontinental orogeny correlated to Orosirian accretionary– collisional belts that surrounded the Amazonian protocraton at 2.00–1.98 Ga [6]. Sereno fabrics are of very low grade, from sub-greenschist to greenschist facies.

The Mesoarchaean main structural trend is ductile in character and of an E–W direction, while the Transamazonian trend varies between ENE–WSW and NE–SW. The Sereno structures are widespread, although less penetrative and of a ductile–brittle style, in an X-shaped pair of oblique structures in WNW–ESE and ENE–WSW directions [6].

3. URANIUM RESOURCES IN THE CARAJÁS MINERAL PROVINCE

The Carajás Mineral Province hosts some of the largest and oldest IOCG deposits in the world, renowned for their relatively high uranium contents in comparison with the majority of other deposits from the same class. The main orebodies are Archaean (2.70–2.55 Ga), but several of them present a Palaeoproterozoic (1.88 Ga) granite-related hydrothermal overprint, responsible for local remobilization, endowment in copper sulphides and, as a result, the formation of high grade oreshoots and/or spatially-related secondary orebodies, considered by some authors as a second IOCG-like event [2, 10, 12].

The deposits show a wide range of host rocks but share several characteristics, such an intense Fe metasomatism associated with the occurrence of low sulphidation sulphides, LREE enrichment, high yet variable amounts of Co, Ni, Pb, Zn, As, Bi, W and U, spatial and chronological correlation to A-type granitic plutons/dykes and breccia-like textures [1, 2, 10]. However, Archaean and Palaeoproterozoic orebodies differ from each other in their hydrothermal assemblage and ore minerals, reflecting variations in the fluid oxidation stage, pH, fO_2 and fS_2 [10, 12]. Older deposits are magnetite-rich and thought to be formed at deeper crustal levels, while the secondary younger orebodies are haematite-rich, silica saturated and developed in shallower environments [2]. In addition, Archaean deposits were deformed and metamorphosed by the Transamazonian and Sereno events, while Palaeoproterozoic deposits are posttectonic, preserving their original textures and mineralogy [13].

The most significant uranium-bearing minerals are uraninite, thorianite and thorite [10]. Allanite and monazite concentrations may also be relevant, although uranium grades are much smaller. All phases occur as inclusions or within massive sulphides and Fe oxide masses in the ore mineral assemblage. Additionally, uraninite and allanite are common accessory minerals in the potassic alteration assemblage, usually occurring as inclusions in biotite and garnet.

Known uranium resources are of 150 000 tU [14], but that value is a massive underestimate as it considers only four out of a dozen known IOCG deposits (Salobo, Sossego–Sequeirinho, Cristalino and Igarapé Bahia–Alemão). Grades are low, ranging from 60 to 130 ppm U [14].

Palaeoproterozoic granite-related (and metasomatic?) uranium deposits remain undiscovered in the province, but the exploration potential for this uranium host is remarkable, especially where plutons and dykes are affected by late to post-magmatic structures and alteration. Uranium background values are very high in comparison to other A-type granites, varying from 10 to 43 ppm U, while Th/U ratios are between 1.11 and 4.71. The A-type granites are subalkaline to alkaline and developed through fractional crystallization of variable material derived from Archaean crust [3, 4]. Hydrothermalism and brittle deformation also affect the granites, along NE–SW and NW–SE structures. Greisen zones are common within the granitic bodies, sometimes related to tin mineralization [4].

4. DISCUSSION: PROSPECTIVITY CRITERIA FOR URANIUM RESOURCES

Some authors suggest that high uranium grades in IOCG systems are dependent on higher background values of host rocks, as observed in Australian IOCG-U provinces [15, 16]. In the Carajás Mineral Province, however, uranium (and gold) grades are usually higher in Palaeoproterozoic oreshoots and orebodies, especially those that are close to or are cross-cut by coeval granites. This indicates that the uranium (and gold?) endowment is at least in part linked to granite-related hydrothermal input. The uranium source, in this case, would be mostly magmatic rather than leached from host rocks.

The energy drive for Palaeoproterozoic fluid circulation is thought to be related to the granitic magmatism, but the critical control for both magmatic and hydrothermal activities seems to be structural. Granitic plutons and dykes were emplaced in sites where structures are denser and their geometry roughly follows previous structural patterns. Besides this, the structural framework of the host rocks, reactivated under brittle conditions during granitic intrusion, coincides with the main granite-related and IOCG-like alteration zones.

Structures that acted as primary fluid pathways usually exhibit breccia textures and silicification, showing a singular prominent topography that is recognizable even in shuttle radar topography mission images. A regional alteration assemblage that indicates proximity to mineralized sites includes quartz, chlorite, epidote, albite, carbonate, actinolite, scapolite, greenish biotite, sericite, tourmaline and stilpnomelane. The main oxide is haematite, but occasionally magnetite is also found, while sulphides include chalcopyrite, bornite and chalcocite. This mineral assemblage can pervasively replace the host rocks or can occur in zoned sintaxial veins, usually forming stockworks.

Airborne radiometric data are a powerful tool to regional targeting of IOCG and granite-related deposits. The uranium concentrations normalized using thorium (Ud) strongly correlate with the extensional structures. Field relations also confirm that Ud anomalies are coincident with regional undeformed Palaeoproterozoic alteration zones. The Ud maps also highlight several potential sites worthy of uranium research inside the granitic plutons, especially along cross-cutting structures trending NE–SW and NW–SE.

5. CONCLUSIONS

The development of prospectivity models for the Carajás Mineral Province is challenging, as three different mineralization ages are recognized. Isolating objective prospectivity criteria for each metallogenic epoch and mineral system is critical to the development of more precise exploration guidelines in the region.

The main regional prospectivity criteria to target uraniferous IOCG deposits in the Carajás Mineral Province are:

- Coincidence between high Ud values and fault zones;
- Proximity to deep structures;
- Proximity to 1.88 Ga granitic plutons and dykes;
- Occurrence of silicified fault zones;
- Occurrence of cross-cutting structures and higher structural density;
- Occurrence of undeformed, post-tectonic, haematite-bearing hydrothermal assemblages.

Prospectivity criteria for granite-related deposits are still being investigated, but the most favourable sites seem to be those indicated by Ud anomalies and which are coincident with post-magmatic alteration sites.

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DETERMINATION OF URANIUM-BEARING SAMPLES IN TERMS OF POSSIBLE CONTAMINATION, ARIKLI URANIUM REGION, ÇANAKKALE, TURKEY

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1. INTRODUCTION

Radioactive mineralization sites and related exploration activities threaten the ecosystems of surrounding areas. Nowadays, this is an issue of concern to many countries [1, 2]. Natural and artificial factors cause the dispersion of radioactive isotopes from the sites and increase the likelihood of contamination in the surrounding area [3, 4]. It is observed that the isotopes may be liberated, transported and precipitated under certain oxidation conditions and can accumulate in different regions and this process may even lead to secondary mineralization under appropriate conditions. Over time, these accumulations and transport environments may act as secondary sources and damage human and environmental health [5–7].

The radioisotope distribution varies continuously among landscape components (e.g. rock, soil, groundwater and surface water) [3, 8, 9]. As an example, groundwater interacts with rocks, leaches radioisotopes and then influences the chemical composition of the surface water and soils [10].

Sampling strategy is one of the most important issues in contamination research. Methods which are suitable for one environment may be quite inappropriate for another. For example, the mechanisms of formation of uranium deposits vary widely and hence the geochemical signature of the deposits also vary [3]. Therefore, careful measurements and analyses are needed to understand the geological and physical structure of the area before cost-effective analyses.

Generally, for the determination of the radioactive element distribution originating from an exploration site, the easiest and cheapest step is to carry out outdoor absorbed gamma dose rate measurements (OAGDR). The distance between the measurement points should be adjusted according to the detector range and the integration time. As a result of the gamma measurement values, the target area can be reduced. For example, if erosion is dominant in the area, drawing the borders along the hilltops, gives the advantage of understanding the flow of elements. The catchments of the exploration sites should be investigated first, but measurements should also be taken in neighbouring catchments to effect comparison of the results and assess the risk of contamination.

Then, the next step is geochemical analysis of the samples. Geochemical parameters such as pH, electrical conductivity, organic matter, carbonate and clay contents, and oxidation state help to evaluate the migration patterns.

Proper GIS operations and the use of maps such as lithology, topography, soil type, land cover, erosion, hydrology, flow accumulation, run-off, etc., can significantly reduce the number of samples required. Statistical analyses such as homogeneity test of univariate distributions, bivariate scatter plots, multivariate cluster analysis and principal component analysis are used to separate populations in the dataset which may indicate various geochemical processes.

For the case study reported in the present work, which was conducted in the Arikli uranium region, a methodology was developed which included geochemical, radiometric and GIS based landscape analysis for the determination of uranium-bearing samples to assess the possible uranium-related contamination.

2. DESCRIPTION

The restricted study area, after the OAGDR orientation measurements, covers the Arıklı site (Ayvacık– Çanakkale) where uranium mineralization is present in the surrounding area. In 1959, the Turkey General Directorate of Mineral Research and Exploration Office discovered radioactive anomalies in the area during an airborne survey. In 1967, the field was surveyed by exploration ditches and from 1968 to 1982 a total 56 uranium exploration drill holes were completed [11]. Although it had been reported that the area contained favourable resources of uranium, the last drilling programme (1982) was terminated as the Government considered the resources were uneconomic [12].

According to the geochemical analyses performed on samples taken from rock dumps and exploration ditches, the phosphate–uranium association, and in some samples thorium enrichment, were detected. Although, based on these analyses, the area was considered to be favourable as regards phosphate, it was abandoned due to insufficient economic reserves. Later, as stated in the report of Gök [13], magnesite lenses and radioactive minerals were also found in some parts of volcanic tuff layers in samples taken from the vicinity of Arıklı and in 1980 the Mineral Research and Exploration Office took two samples from the region for analysis and values of 1050 mg/kg and 1300 mg/kg uranium were detected by the Turkish Atomic Energy Authority laboratories [13, 14].

Using results from the phosphate related studies on Arıklı tuffs (ignimbrites) performed by Günaydın [11], Çelik et al. [15], and Günaydın and Çolak [16], it was concluded that uranium and phosphate enrichments were the result of hydrothermal fluids and that they accumulated in brecciated fault zones [11, 15, 16]. Bayleyite $[Mg_2(UO_2)(CO_3)_{3.}18H_2O]$ and ningyoite $[(U,Ca,Ce)_2(PO_4)_{2.}1-2H_2O]$ were defined as uranium minerals in the area. During the studies, 1:5000 scale geological maps were prepared [11]. It was noted that significant faults were developed in NE–SW and NW–SE directions.

Using results from the outdoor gamma measurements, the final study area was reduced to approximately 12 km² at the south-east of Ayvacık (in the Ayvalık İ17-d4 pedestal). In 2000, about 256 people were living in Arıklı village, where cattle and chicken farming, beekeeping and a very important olive production are the main activities in the village. The region also has its own private drinking water source originating in the Kaz Mountains, but groundwater is also used as drinking water. Additionally, groundwater is also used for agriculture and animal farming in the region. Streams flow into the Edremit Gulf, but the water flows are intermittent during the year. The area contains deep valleys with narrow plains. Kocakaya Hill, the highest peak in the region, is 742 m high. Olive trees grow on the southern coastline, pine forests to the northern side and some small trees and bushes can also be found there.

The study area consists of four main geological formations, Upper Cretaceous ophiolitic rocks at the base, volcanic units, lacustrine sediments and alluvial sediments. The Çetmi ophiolitic melange is a complex unit with volcanic lavas, pyroclastic rocks, limestone blocks, shale and greywacke and these form the basement of the study area. They are covered by volcanic and Neogene lacustrine sediments known as the Küçükkuyu Formation, which contains volcanic intercalations with conglomerate, sandstone, siltstone, claystone and marl [17–20]. In the study area, the main unit is represented by the Arıklı tuff which consists of andesite/andesitic tuffs and andesitic agglomerates. The SiO₂ content indicates that the unit has a moderate acidic character and the chemical composition corresponds to rhyolites and rhyodacites [11]. Siliceous and altered nodules of 2–7 cm radius, some exhibiting iron oxide banding, are present within the tuffs. Uranium enrichment developed via Ca⁺²–U⁺⁴ ion exchange in the phosphate nodules found in the Arıklı volcanics [20].

3. MATERIALS AND METHODS

Taking into consideration the studies made by the Mineral Research and Exploration Office, OAGDR orientation measurements were first undertaken in the current survey and included the villages of Arıklı, Nusratlı, Ahmetçe, Hüseyinfakı, Demirciköy and Kayalar, representing an area of approximately 50 km². For the measurements, a portable ESP-2 Na(I) probed Eberline gamma detector was used at 1 m above the ground level using a 100-s interval for each measurement [21]. The measurements were planned according to the lithological units. The map of the OAGDR data was prepared by the kriging geostatistical interpolation method using Arc-GIS software. As a result, the study area was restricted to a 2.63 km × 4.25 km rectangle (~11 km²) which included the catchment area of the Arıklı mineralization site and Arıklı village.

The restricted area was first split into a 500 m \times 500 m grid inside the catchment and the grid was then reduced to 250 m \times 250 m. OAGDR measurements were taken at the corners of each square. Open exploration ditches were identified and their OAGDR measurements were also taken.

Soil samples were collected from the measurement points. Before collecting soil samples, the sampling points were cleared of vegetation, roots and rocks, and then 250 g of material from the first 10 cm of the topsoil was packaged. The samples were dried under sunlight to remove the moisture, transported to the laboratory and then they were sieved in 1 mm mesh, packaged and labelled.

For pH measurements, a 6-g sample was mixed with 15 mL of distilled water and after 12 h, measurements were taken. For calibration of the pH meter (Multi 340i and pH/Cond 340i Handheld Multimeter), pH4.00, 7.00 and 9.00 buffer solutions were used. The same solution was also used at the same time and with the same device, but with a different probe, for electrical conductivity measurements [22].

For carbonate analysis, 3-10 g of soil was mixed with 0.1M HCL solution. The probe of the Scheibler calcimeter was filled with the HCL solution and once fixed into the polyethylene wide-mouth 250 mL tube, the solution was mixed into the samples which were agitated by magnetic stirrer. The CO₂ pressure was measured by the Scheibler calcimeter chamber filled with 0.1M sodium hydroxide solution. The results of the gas volume were converted to per cent CaCO₃ by calculation [23].

The barium chloride method was used for cation exchange capacity analysis. A 4-g sample was mixed in 0.1M BaCl₂ solution and buffered up to pH8.0 with tetraethyl ammonium. After 2 hours of agitation by shaker at 480 rpm, the solution was filtered and centrifuged. Finally, the Ba²⁺ content was measured by ICP-OES [24].

To take account of the topography, run-off, slope break and watershed, models were derived from the digital elevation model for 5 m \times 5 m grid cells [25]. A drainage map and a land cover map were derived from the topographic map using Arc-GIS software. All the multisource prediction maps were superimposed by GIS operations using Surfer Software Homogeneity tests of univariate distributions, bivariate scatter plots, multivariate cluster analysis and principal component analysis being used for statistical analysis.

4. RESULTS

The highest outdoor gamma levels were detected in the Karakisla region. In the study area, other anomalous measurement levels were found in the exploration ditches of Feyzullah Hill. At both sites, the ditches were still open and the maximum depth reached 5 m. It was advised that the ditches be filled in and the radon emission at the sites checked.

Since the area was under the effect of slope driven soil erosion, the OAGDR measurements, there was more correlation with topographical units than with the lithological units. The gamma levels at the alluvial

accumulating flat bottoms of valleys were also higher than the background level owing to the erosion effect and the hills acting as physical barriers to prevent the dispersal of the radioactive contaminants from the catchment.

According to the results of the soil chemical analyses, it is concluded that the higher values of electrical conductivity and cation exchange capacity measurements were driven by topographical and hydrological barriers. For example, in the alluvial accumulations at the bottoms of valleys and along the meanders of stream branches, where water flow is slower, deposition took place which resulted in higher values for electrical conductivity and cation exchange capacity. As regards pH and carbonate measurements, their results correlated with each other and recorded the highest values in the sediment samples.

5. CONCLUSION

This interdisciplinary developed methodology helps to analyse the characteristics of the uranium distribution originating from the Arıklı mineralized site. The methodology characterizes the geochemical and topographic units and provides an insight into the mechanisms controlling the distribution of elements.

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THORIUM AS NUCLEAR FUEL: WHAT, HOW AND WHEN?

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1. INTRODUCTION

Even though thorium is considered a sustainable fuel cycle option, owing to the abundance of uranium and its relative ease of handling, serious attention has not been paid to developing a commercial thorium fuel cycle. Recently, the focus has again shifted towards thorium utilization because of the favourable aspects of thorium fuel [1]. Advantages of thorium include its relative abundance compared with uranium and its occurrence as a co-product or by-product of deposits mined for other minerals [2]. Other benefits of thorium include the better waste profile of the fuel cycle and non-proliferation advantages. For these reasons, research and development activities are currently being carried out on several types of advanced reactor that can use thorium.

2. THORIUM AS A FUEL

The thorium fuel cycle differs from the uranium fuel cycle in several respects. Natural thorium (Th) contains only trace amounts of fissile material, although these are insufficient to initiate a nuclear chain reaction. In a Th-fuelled reactor, ²³²Th absorbs neutrons to eventually produce ²³³U. The ²³³U either fissions in situ or is chemically separated from the used nuclear fuel and formed into new nuclear fuel. The sustained fission chain reaction could be started with existing ²³³U or some other fissile material such as ²³⁵U or ²³⁹Pu. Subsequently, a breeding cycle similar to that with ²³⁸U-²³⁹Pu, but more efficient, can be constructed [3, 4].

Thorium based fuels exhibit several attractive nuclear properties relative to uranium based fuels, such as efficient fertile conversion and better neutron economy and breeding possibilities in thermal spectrum reactors. In addition, thorium dioxide (ThO₂) has a higher melting point, higher thermal conductivity, lower coefficient of thermal expansion and higher chemical stability than U–Pu fuel. In addition, thorium offers an advantage from the waste perspective. The production of Pu and minor actinides (neptunium, americium, curium), which are the major contributors to the radiotoxicity of the wastes in the U–Pu cycle, is drastically reduced if actinides are recycled [5]. The ²³³U produced in thorium fuels is inevitably contaminated with ²³²U, a hard gamma emitter; therefore, heavily shielded facilities are required for handling it. As a result, thorium based used nuclear fuels possess inherent proliferation resistance.

Some of the unique features of the thorium fuel cycle often prove to be the significant challenges in its application. Initial fissile requirements for ²³⁵U, ²³³U, or Pu make thorium unsuitable for rapid expansion of nuclear energy. Thorium introduction could be preferred after a sufficient stock of fissile material (in the form of either Pu or ²³³U) has been built up [6]. If thorium is used in an open fuel cycle (i.e. utilizing ²³³U in situ), higher burnup is necessary to achieve a favourable neutron economy. If thorium is used in a closed fuel cycle in which ²³³U is recycled, remote handling is needed because of the high radiation dose resulting from the decay products of ²³²U.

3. PREVIOUS WORK ON THORIUM FUEL

Research towards utilizing thorium as a nuclear fuel has been ongoing for over 50 years. Basic research and development, as well as the operation of test reactors utilizing thorium fuel, has been conducted in Canada, Germany, India, Japan, the Netherlands, Norway, the Russian Federation, Sweden, Switzerland, the United Kingdom and the United States of America.

Light water reactors can be operated with thorium fuel. In the USA, thorium fuel was tested in pressurized water reactors (PWR) at the Indian Point plant in New York initially (start up in 1962), but this reactor was later converted to a uranium fuel cycle. The Shippingport reactor in Pennsylvania, a 'seed blanket' PWR, operated with thorium fuel from 1977 to 1982. Boiling water reactors (BWRs) offer design flexibility that can be optimized for thorium fuels. Thorium was used in a BWR at the Elk River reactor in Minnesota, USA, from 1963 to 1968. Thorium fuel was also tested in the 60 MW(e) BWR in Lingen, Germany, until 1973.

Heavy water reactors could offer excellent neutron economy and faster neutron energy, and therefore are considered better for breeding ²³³U. Conceptual design studies have indicated that thorium and uranium fuel concepts have many common design characteristics and that the thorium cycle could be used in a plant designed for the uranium cycle without substantial performance penalties. In Canada, Atomic Energy Canada Limited has gained more than 50 years of experience with thorium based fuels. India is continuing the use of ThO₂ pellets in pressurized heavy water reactors, used for neutron flux flattening of the initial core after startup.

There is no advantage in using thorium instead of depleted uranium as a fertile fuel matrix in fast breeder reactor (FBR) systems owing to a higher fast fission rate for ²³⁸U and the fission contribution from residual ²³⁵U in this material. Thorium-232 in the blanket can be advantageous in a mixed reactor scenario. India has a three-stage nuclear energy scenario in which FBRs play an important role. Thorium has been used in the blanket to breed ²³³U in a 40 MW(t) FBR test reactor near Kalpakkam, India. As a pilot study, the Kamini 30 kW(t) experimental neutron source research reactor, adjacent to the FBR test reactor, uses ²³³U as fuel.

High temperature gas cooled reactors (HTGRs) are thermal spectrum reactors moderated with graphite and cooled by helium. In Germany, reactors testing Th based nuclear fuels have included the 15 MW(e) AVR (Arbeitsgemeinschaft Versuchsreaktor) and a 300 MW(e) Th high temperature reactor. Other examples of experimental HTGRs using Th as fuel have included: (i) the Peach Bottom high temperature, graphite moderated, helium cooled reactor in Pennsylvania and the Fort St Vrain test reactor in Colorado (USA), and (ii) the experimental 20 MW(t) Dragon reactor (UK).

In April 2013, Thor Energy of Norway commenced a test of two thorium based fuels in the Halden research reactor in Norway. Fuel irradiation is being tested to determine if a mixed Th–Pu (mixed oxide) fuel can be used in commercial nuclear power plants.

Molten salt reactors (MSRs) offer attractive concepts for thorium utilization. In 1954, scientists at the Oak Ridge National Laboratory in Tennessee, USA, designed a 2.5 MW(t) MSR with the intent of attaining a high-power density for use as an engine in a nuclear powered aircraft [7]. The Pratt and Whitney Aircraft Reactor No. 1 (PWAR-1) was a zero power MSR that was tested at Oak Ridge in 1957. The reactor used NaF–ZrF₄–UF₄ as the primary fuel and coolant [8].

4. THORIUM RESOURCES

Thorium is part of the group of elements referred to as the high field strength elements (HFSE), which have a valence state greater than two (high charge) and small- to medium-sized ionic radii, thus producing a high electric field (high field strength). These attributes inhibit the ability of the HFSE, which include the rare

earth elements (REEs), to achieve charge balance and fit into the structure of most common igneous minerals. As a result, thorium and other HFSE co-occur in anomalous concentrations in unusual rocks, such as carbonatites, alkaline igneous intrusive complexes and associated veins and/or dykes and massive magnetite–apatite bodies. Additionally, some moderate to high grade metamorphic rocks (amphibolite facies and higher) contain monazite, a REE–Th–phosphate, as an accessory mineral. Monazite is the principal thorium mineral. Thorium-bearing xenotime (YPO₄) and thorite (Th,U)SiO₄ are other Th minerals in some REE–Th deposits, but these are less common.

Carbonatites host large tonnage REE deposits and commonly have associated enrichment in thorium [9]. Thorium and the REEs have a strong genetic association with alkaline igneous processes, particularly peralkaline magmatism [9]. Alkaline rocks typically have higher enrichment in REEs and Th than most other igneous rocks. Thorium-rich veins of uncertain origin also exist. Most of these types of vein deposit are interpreted as being related to concealed alkaline magmatism. Massive iron oxide deposits of magmatic–hydrothermal origin can contain elevated concentrations of Th and REEs, usually in relatively small amounts.

Heavy mineral sands are sedimentary deposits of dense (heavy) minerals that accumulate with sand, silt, and clay in coastal and alluvial environments, locally forming economic concentrations of heavy minerals [10]. Expansive coastal deposits of heavy mineral sands are the main source of titanium feedstock for the titanium dioxide (TiO₂) pigments industry, through the recovery of the minerals ilmenite (Fe₂TiO₃), rutile (TiO₂), and leucoxene (an alteration product of ilmenite). Heavy mineral sands are also the principal source of zircon (ZrSiO₄); it is often recovered as a co-product. Other detrital heavy minerals produced as co-products from some deposits are sillimanite/kyanite, staurolite, garnet and monazite, which are a source of REEs and thorium.

Globally, the important thorium resources occur as minor minerals within a variety of REE deposits and some heavy mineral sands. Significant REE deposits of all deposit types also represent the largest thorium deposits. Actively mined REE ore deposits are economic by virtue of their REE production, not for their Th content. Heavy mineral sands operations are economic on the basis of their production of titanium minerals (ilmenite and rutile) and zircon, but they can also often produce detrital monazite as a by-product, and sometimes xenotime. Thus, if a market develops for thorium in the future, mineral deposits that are economic as sources of REEs, including specific types of crystalline rocks and many heavy mineral sands, can be evaluated as sources of by-product or co-product thorium [1, 2].

5. FUTURE THORIUM UTILIZATION

China, in collaboration with the USA, has gained extensive experience from ongoing research on thorium utilization in MSR designs. This is a dual programme involving an early solid fuel stream and advanced liquid fuel stream. In 2011, the China Academy of Sciences launched a research and development programme on a liquid fluoride thorium reactor known as the thorium breeding MSR.

Since 2008, CANDU Energy of Canada and the China National Nuclear Corporation have been cooperating in the development of thorium and recycled uranium as alternative fuels for new CANDU reactors. CANDU Energy (now part of SNC Lavalin) works on Advanced Fuel CANDU Reactor (AFCR) technology, which aims at thorium utilization. The AFCR will be designed to use recycled uranium or thorium as fuel, thus reducing spent fuel inventories and significantly reducing fresh uranium requirements. Spent fuel from four conventional PWR reactors can fully supply one AFCR unit (as well as providing recycled plutonium for mixed oxide fuel).

In India, research on thorium utilization has been carried out since the 1950s. A three-stage nuclear energy programme with uranium fueled pressurized heavy water reactors, plutonium fueled FBRs, and thorium–²³³U based advanced heavy water reactors has been proposed as the long term plan. A 500 MW(e) prototype

FBR is in the final stages of completion. Additional 500 MW(e) FBRs are planned for immediate deployment and beyond 2025 and a series of 1000 MW(e) FBRs with metallic fuel, capable of high breeding potential is also proposed. The large-scale deployment of thorium is expected to occur in three to four decades after the commercial operation of the FBR, with short doubling time when thorium can be introduced to generate ²³³U.

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POTENTIAL FOR UNCONFORMITY-RELATED URANIUM DEPOSITS IN THE NORTHERN PART OF THE CUDDAPAH BASIN, TELANGANA AND ANDHRA PRADESH, INDIA

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1. INTRODUCTION

The intra-cratonic, Mesoproterozoic Cuddapah Basin in the Dharwar Craton hosts several types of uranium deposit in various stratigraphic levels. Uranium mineralization is recorded in the lower part of the Gulcheru and Vempalle Formations and along the unconformity between the granitic basement and the overlying sediments of the Srisailam/Banganapalle Formation in the upper part of the Cuddapah sequence. The Srisailam and Palnad sub-basins, located in the northern part of the Cuddapah Basin, host Proterozoic unconformity-related uranium mineralization. Mineralization in these sub-basins occurs close to the unconformity between the basement complex containing granitoids, basic dykes of Palaeoproterozoic age, greenstone belts of Archaean age and arenaceous, argillaceous and calcareous sediments of Mesoproterozoic-Neoproterozoic age. Sub-surface exploration over two decades has established the presence of three small to medium tonnage uranium deposits at Lambapur (~1200 tU), Peddagattu (~6400 tU) and Chitrial (~8000 tU) which are located along the unconformity between the basement Mahabubnagar granite and the overlying Srisailam Formation in the Srisailam sub-basin; and one small deposit at Koppunuru (~2300 tU) close to the unconformity contact between basement granite and the Banganapalle Formation of the Kurnool Group in the Palnad sub-basin. In all these deposits, uranium mineralization is concealed and lies below the cover rocks at a depth of <5–150 m. Uranium mineralization located in these sub-basins show dissimilarities with those unconformity-type uranium deposits known in Australia and Canada, especially in respect of their geometry, basement composition and the absence of palaeosol (regolith).

2. GEOLOGICAL SETTING AND URANIUM MINERALIZATION

The Cuddapah Basin, covering about 44 000 km², is the second largest Proterozoic basin in India. It contains a thick sequence of sediments and subordinate volcanics and hosts Proterozoic unconformity-related uranium deposits in its northern part in Telangana and Andhra Pradesh states [1]. The Cuddapah Basin comprises four sub-basins, Papaghni, Srisailam, Palnad and Nallamalai. The Srisailam and Palnad sub-basins lie in the northern parts of the Cuddapah Basin and contain, respectively, the sediments of the Srisailam Formation and of the Kurnool Group [2]. The Srisailam, Palnad and part of the Nallamalai sub-basins cover an area of about 10 000 km² and are developed over the basement Palaeoproterozoic granitoids.

The basement complex for the Srisailam and Palnad sub-basins comprises Archaean schists (Peddavoora Schist Belt), Palaeoproterozoic granites, basic dykes, pegmatites and quartz veins of Palaeoproterozoic age $(2268 \pm 32 \text{ Ma to } 2482 \pm 70 \text{ Ma})$ [3]. Well-developed fracture systems (trending N–S, NE–SW, NW–SE) along with basic dykes intruding both cover rocks and basement cross-cut the unconformity surface. The N–S to NE–SW trending dykes in the basement have played a major role by increasing the thermal gradient, permitting the release of uranyl ions into the solutions and effecting their remobilization along fractures and the unconformity plane. A grit to pebbly horizon immediately above the unconformity surface acts as a conduit system for uranium mineralization.

The Srisailam sub-basin, covering an area of around 3000 km² forms a prominent plateau, exposing Neoproterozoic sediments of the Srisailam Formation, the youngest unit of the Cuddapah Supergroup. The

sediments have sub-horizontal dips to the south-east and attain a maximum thickness of 300 m. The Srisailam Formation comprises a sequence of feldspathic quartzite with intercalated shale, siltstone and grit. The sediments directly overlie the basement rocks in the northern margins of the sub-basin, whereas in the south-eastern margin the sediments are underlain by the Nallamalai Group metasediments with an angular unconformity. The northern fringes of the Srisailam sub-basin have a highly dissected topography with several isolated flat-topped outliers above the basement and rising 100–150 m above ground level. The Lambapur, Peddagattu and Chitrial uranium deposits are located in such individual outliers [4]. The outliers of the Srisailam Formation are characterized by a sequence of pebbly–gritty arenite horizons successively overlain by shale, shale/quartzite intercalations and massive quartzite with a thickness of 5–70 m and a gentle 3–5° dip towards the south-east.

The basement granitoids are sodic in nature, with a moderate to high Na₂O/K₂O ratio (0.09–1.62). Their composition varies from granite to granodiorite and they are strongly peraluminous, with the A/CNK ratio >1.1 [4]. The granitoids mineralogically correspond to biotite-granites and consist of an assemblage of albite–oligoclase, quartz, K-feldspar, with accessory hornblende, biotite, apatite, sphene, zircon, allanite and epidote. They are equivalents of the Closepet granite from the Eastern Dharwad Craton. Alteration such as chloritization, sericitization, calcitization and epdotization are pronounced in the basement, especially when close to the unconformity. Pyrite, chalcopyrite, galena, ilmenite, anatase and hydrated iron oxides are the opaque minerals. The study of granitoid core samples shows the presence of two to three sets of foliations, cross-cut by dolerite dykes and quartz veins. Granites are U-enriched (average 20 ppm U) with a U/Th ratio of 6.68 [5].

In the three deposits of the Srisailam sub-basin (Lambapur, Peddagattu and Chitrial), uranium mineralization occurs close to the unconformity, both in the granites, basic dykes and quartz veins of the basement and in the overlying pebbly arenites, with most of the mineralization (>85%) located in the basement [6]. Although the orebody appears to be blanket-shaped along the unconformity, scout drilling in various areas covering the entire outliers has indicated that the U-rich pods and ore shoots are confined to definite trends, i.e. NNE-SSW and NW-SE (Lambapur), WNW-ESE and N-S (Chitrial) and N-S (Peddagattu). The intensity of fracturing within the granite and their intersections with the unconformity, apparently controls the grade of mineralization [7]. The orebodies show gentle dips towards the south-east and follow the basement slopes. Mineralization comprises pitchblende, uraninite and coffinite as primary minerals and uranophane and autunite as secondary minerals. It is well exposed on the outcrops of granitoids at Lambapur and along road cuttings in the Peddagattu and Chitrial plateaux. Botryoidal and massive pitchblende occurs as thin veins lying sub-parallel to the unconformity surface, as massive pods, in the fracture planes of feldspars, as irregular segregations and also adsorbed onto globular organic matter. In places, the massive pitchblende is replaced by coffinite. Extensive hydrothermal activity, both in the basement and in the overlying sediments, is evidenced by high amounts of sulphides such as pyrite, chalcopyrite and galena. The pitchblende veins are found to cut across the basement granitoid and enter into the cover rocks.

EPMA studies of radioactive granitoids core samples from the Chitrial area have indicated that the UO_2 content in pitchblende and coffinite lie in the range 71.37–88.14% and 59.97–73.91%, respectively, and have also confirmed the presence of complexes such as U–Si, U–Si–Ti and U–Si–Al. X ray diffraction studies indicate that the unit cell dimension of uraninite in the Lambapur area is in the range of 5.3973A–5.4285 Å in contrast with the uraninite of the Chitrial area which is 5.3959 Å. The oxygen content in the formula unit (UO₂) is in the range of UO_{2.30} to UO_{2.69} in uraninite of the Srisailam sub-basin deposits. Evidence of remobilzation has been observed in the samples. At Lambapur, radiogenic lead gives ages of 480–500 Ma while the Sm–Nd data of uraninite yield an isochron age of 1327 ± 170 Ma, indicating two mineralizing events.

The Palnad sub-basin has a surface area of around 4500 km² and hosts the Koppunuru uranium deposit in its western part [8]. The sub-basin exposes the Neoproterozoic Kurnool Group, which comprises a thick
sequence of clastic and calcareous sediments. In the northern part of the basin, basement granite and gneisses are unconformably overlain by sub-horizontal sediments. The Banganapalle Formation, the lowermost sequence of the Kurnool Group, comprises gritty arenite successively overlain by shale/siltstone intercalations and quartzites of high mineralogical maturity [9]. The fertile nature of the basement granite is indicated by high uranium values (average 32 ppm U, n = 16) and a high U/Th ratio (average 4.41, n = 16), compared with the average U/Th ratio of normal granite of 0.25. A granite inlier is exposed to the east of Koppunuru, along the upthrown block of the Kandlagunta fault, which trends WNW–ESE. Both the basement and the sediments are fractured and cross-cut by quartz veins trending N–S, NNE–SSW and WNW–ESE.

Uranium mineralization at the Koppunuru deposit occurs both in the cover sediments and in the basement. It is composed of three sub-horizontal ore lodes, two hosted in the arenites and one in the basal polymictic grit/conglomerate of the Banganapalle Formation, locally transgressing the basement granite [10]. Pitchblende and coffinite are identified as primary uranium minerals. Traces of carbonaceous matter are associated with uranium mineralization along with sulphide minerals. EPMA analysis has indicated that pitchblende and coffinite contain 73.47–78.58% UO₂ and 63.45–71.53% UO₂ respectively, while mixed phases contain lesser uranium oxide (42.14–47.90% UO₂). In addition, uranophane, phosphuranylite, metazeunerite and U–Ti complexes occur as secondary uranium minerals. The radioactive minerals are epigenetic in nature and occur as thin veins, fracture/cavity fillings and grain boundary coatings. Other metalliferous minerals are galena, pyrite, chalcopyrite, pyrrohotite, marcasite and traces of pentlandite. X ray diffraction studies of uraninite indicate that the cell unit dimension for the Koppunuru deposit is in the range 5.4382–5.4534 Å. The oxygen content in the formula unit (UO₂) is in the range UO_{2.15} to UO_{2.29} for uraninite in the Palnad sub-basin.

The radiometric age of mineralized granite samples is 1545 ± 140 Ma. In addition, dating of uraniferous quartzite samples by the Pb–Pb step leaching method has indicated mineralization ages of 576 ± 180 Ma, 891 ± 160 Ma and 936 ± 60 Ma. This confirms the episodic nature of mineralization, where uranium concentration/enrichment took place during several phases.

3. DISCUSSION AND CONCLUSION

The northern margins of the Cuddapah Basin represent favourable areas for hosting Proterozoic unconformity-related uranium mineralization. Litho-structural and metallogenic characteristics are well established for the Lambapur, Peddagattu, Chitrial and Koppunuru uranium deposits. In the Srisailam and Palnad sub-basins, two major mineralization events are suggested. The primary mineralization event took place at 1500–1300 Ma with a major mobilization/rejuvenation event around 950–450 Ma.

Comprehensive exploration efforts in the northern margin of Srisailam sub-basin has established a resource of about 20 000 t of uranium oxide at relatively shallow depths (75–120 m). Large areas of the Srisailam sub-basin, which have a considerable thickness of cover rocks, are still unexplored and are likely to increase resources at depths of 200–250 m. Extensive surficial exploration in other outliers and also in other areas of the main Srisailam sub-basin, i.e. Amrabad, Akkavaram, Udimilla, has resulted in the discovery of several surface uranium showings, indicating the persistence of metallogenic features observed in the Lambapur, Peddagattu and Chitrial deposits, in the entire Srisailam sub-basin.

Similarly, in the Palnad sub-basin, the Koppunuru uranium deposit is unique in respect to its mineralization pattern in the sediments, proximal to the unconformity contact with the basement granitoids. Structures have played a major role in controlling the mineralization. A 150 km long area along the northern margin of the Palnad sub-basin with litho-structural characteristics similar to those at Koppunuru may warrant exploration. Ground radiometrics and 'heli-borne' geophysical surveys along the northern margin of the sub-basin have delineated several surface uranium showings at R.V. Tanda, Mathamapalle, etc., and

geophysical anomalies at Durgi, Daida, Gurajala, etc. Intensive sub-surface exploration is envisaged in several sectors of the Srisailam and Palnad sub-basins.

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ENVIRONMENT ASPECTS OF Th-230 ACCUMULATED IN RESIDUES COMPONENTS AT THE URANIUM PRODUCTION LEGACY SITE PRIDNEPROVSKY CHEMICAL PLANT

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1. INTRODUCTION

This paper presents an overview of the results of recent studies carried out at the former uranium production facility Pridneprovsky Chemical Plant (PChP) in Ukraine. It describes specific activity concentrations of radionuclides of the U–Th decay series with specific focus on identified high activity concentrations of ²³⁰Th associated with different environment compartments. These include soils, aerosols, bottom sediments and U production residues accumulated in the tailings and uranium extraction facilities remaining at the PChP site.

The PChP was one of the largest facilities of the military complex of the former Soviet Union, where production of uranium for the Soviet atomic programme was carried out from 1949 until 1992. The plant is situated in a densely populated area in the industrial zone of Kamyanske (formerly Dniprodzerzhynsk) and located close to the Dnieper River.

The processing procedures for uranium ores at the PChP were typical for technologies used in the former Soviet Union, including grinding, hydrometallurgical extraction, sorption, radiochemical separation and purification of U concentrate from radium and thorium impurities. Sulphuric and nitric acids were used for leaching the uranium-bearing ores of different origin from deposits located in Ukraine, and the former German Democratic Republic and the former Czechoslovakia. From 1984, phosphorus ore containing uranium from Kazakhstan (Melovoe deposit) was also processed at the PChP. The phosphorus ore processed is considered a major source of ²³⁰Th, which is currently dispersed at the PChP site.

Since 1992, when the PChP uranium industrial production complex ceased, no measures have been taken to decommission and remediate the former uranium production facilities. Some ambitious remediation planning activities were initiated in recent years with financial assistance provided by the EC and funded also by several national remediation projects. In order to provide safety assessment and collect data for remediation planning, extended site characterization and monitoring programmes were carried out at the PChP legacy site over recent decades, including detailed a spatial gamma dose survey and assessment of contamination status of the environment by radionuclides of the U–Th decay series and safety conditions at the uranium tailings facilities [1].

Interest in the specific activities and chemical speciation of 230 Th at this site was prompted by the presence of large amounts of thorium-containing materials at the site (up to 6 t of thorium concentrate produced annually as a result of the uranium ore purifying process) and relatively high activity concentrations have been observed at many locations at the PChP site, exceeding the levels for exclusion from regulatory control, such as 1 Bq/g, as well as its high radiotoxicity in the environment.

2. METHODS AND RESULTS

The methods used in this study consist of several components, such as:

- (a) Historical analysis of the technologies which determined the existing state of ²³⁰Th in a complex of other radionuclides of the U–Th series and its physical and chemical speciation in the affected environment.
- (b) Application of analytical methods used for determination of thorium isotopes and other radionuclides of the U–Th decay series in soil, aerosols and tailings material samples using modern gamma and alpha spectrometry methods with radiochemical support procedures [2] and dose assessment methodology.
- (c) Provision of site specific safety assessment and estimation of the contribution of thorium present in the current conditions forming at the legacy site and provision of remediation strategy planning. Methods for remediation of the highly contaminated environment, as well as a strategy for management of remediation wastes containing thorium and other radionuclides of the ²³⁸U decay series, are also discussed.
- (d) Determination of the radioactivity of thorium isotopes in different environmental entities collected at the PChP legacy site, such as soil spill and sludge materials, dust, bottom sediment and water samples, have been carried out in the framework of State remediation and site-specific monitoring projects.

In general, the activity concentrations of thorium isotopes (²³⁰Th, ²³⁴Th, ²³²Th, ²²⁸Th) were quantified by gamma spectrometry analysis, using a coaxial n-type high purity germanium detector Gamma-X (Ortec) with 40% relative efficiency and resolution of 1.8 keV for 1332.5 keV ⁶⁰Co energy. The detector efficiency was determined using a mixed standard solution of known activity containing ¹⁵²Eu, ²⁴¹Am and ²²⁶Ra in fixed sample geometry. The emission gamma spectrum was analysed using GammaVision32 software in accordance with the UNI 10797:1999 standard, and with sealing of the beaker.

The concentrations of 230Th were measured directly from its gamma peak at 67.67 keV with an emission probability of 0.38%. The activity of the 234Th daughter radionuclide of the 238U series was determined by its gamma peak at 63.29 keV with an emission probability of 3.7%. For the determination of 232Th, assuming secular equilibrium in the sample, the gamma lines of 911.2 keV and 338.4 keV, with emission probabilities of 26% and 11%, respectively, were used.

Calibration quality control was carried out by means of a soil standard sample SRM (IAEA-434), IAEARGU-1 and IAEA-RGTh-1 whose concentrations of the main natural radionuclides have been certified by the IAEA in the same geometry as the measurement. The quality of the determination of Th isotopes in the Ukrainian Hydrometeorological Institute (UHMI) laboratory has been regularly checked by participation in the IAEA's proficiency tests (e.g. Ref. [3]).

To verify the accuracy of the determination of ²³⁰Th and other thorium isotopes by gamma spectrometry, the alpha spectrometry method with radiochemical pretreatment was used. Radioanalytical procedures consist of chemical dissolution of samples, chemical separation of thorium by ion exchange, preparation of the counting source by the electro-deposition method and measurement of thorium by alpha spectrometry. Thorium in water samples was separated by co-precipitation. For determining the chemical yield, ²²⁹Th tracers were used. The relative errors were less than 20% for both analytical techniques used.

The basic set of monitoring data collection and site characterization analyses carried out at UHMI during the past decade, contains long term time series specific activity concentrations of radionuclides of the U–Th decay series (e.g. ²³⁸U, ²³⁴U, ²³⁰Th, ²²⁶Ra, ²¹⁰Pb and ²¹⁰Po) contained in the U ore, production residues

and the contaminated environment at the site, which may vary in activity over a wide range between <1.0 Bq/g to 3–4 thousand Bq/g.

Special attention in this study is given to the analysis of spillage and sludge materials containing high activity concentrations of thorium, which still remain in large amounts in some buildings used for thorium removal and at the sludge pond accumulating complex for holding the thorium fractions before their transportation to the storage facility. Since different technologies used for purifying uranium concentrates by removing thorium impurities have been applied, different concentrations of thorium are contained in various objects of the uranium production legacy site, which vary from several becquerels per gram to hundreds of becquerels per gram in the environment.

The background activity concentrations of ²³⁰Th outside the PChP site vary in the range 0.04–0.07 Bq/g. High activity concentrations of ²³⁰Th were found at many locations within the PChP legacy site and in particular in soils and spillage materials accumulated in the former uranium extraction facilities and buildings used for removal and purification of uranium concentrates from thorium-bearing impurities. At many locations, high ²³⁰Th activities were observed in the residue production which range from several tens to several hundred becquerels per gram. At some locations, the horizons of soils with the highest ²³⁰Th activities are covered at the soil's surface, while at other places the layers with maximum activities are covered with clean soils with relatively low contamination and radionuclides of the U–Th series identified at a depth of up to 1.5 m. Results of vertical profile studies of radionuclides of the U–Th series of different origin are discussed in this paper.

The ratios between ²³⁸U, ²³⁰Th and ²²⁶Ra in soils at the different locations may reflect the impacts of the uranium production residue according to the differing origins and technologies applied for purifying uranium ores are these are also discussed in this paper. Sufficient amounts of residue materials from uranium production, containing high activity concentrations of ²³⁰Th, were identified in several sludge pond cells. In the lower layers of sludge material accumulated in the settling pond, specific activities of ²³⁰Th were found to lie in the range 10–170 Bq/g. Other naturally occurring radionuclides in most of the samples taken from the sludge columns were characterized by specific activities of 1 Bq/g or less. Some by-products of uranium production, notably those containing thorium, will define the regime of regulatory control, because thorium in sufficiently high activities identified in some NORM products produced at the site is a significant limiting factor in the further use of these materials. The surface layer of sludge in the settling pond also has high levels of ²²⁶Ra and other radionuclide and chemical pollutants.

Specific activity concentrations in the spillage materials remained on the floor and in some filled tanks, where ²²⁶Ra activity concentrations may reach several hundred becquerels per gram in dry samples. In the spillage materials resulting from 'yellowcake' production found at several locations in Building 103, high concentrations of uranium predominated, reaching several thousand becquerels per gram of dry samples and relatively low ²³⁰Th activity concentrations.

Specifically, high activity concentrations of ²³⁰Th in spillage materials were found at several locations in Building 104m which was used for thorium removal from phosphorus ores. Specific activities of ²²⁶Ra and ²¹⁰Pb in such spillage materials varied around relatively low values ranging from 2–3 Bq/g up to 20–30 Bq/g. The same samples gave ²³²Th activity concentrations in the range 2.3–4.4 Bq/g. In spite of relatively low activity, concentrations of uranium and radium isotopes were found, and ²³⁰Th activity concentrations in such spillage materials reached in some locations values of 200–600 Bq/g. Such dispersed materials presented in the dust fractions and having very high thorium activity concentrations compared with exemption levels such as 1 Bq/g, may pose a significant risk of inhalation exposure for remediation workers. Therefore, detailed radiation protection plans and possible decontamination of these

buildings prior to the dismantling of the most contaminated equipment and demolishing are strictly required.

The levels of ²³⁰Th activity concentration in aerosols were measured in just a limited number of samples collected in the contaminated buildings and in the surrounding areas. The results of the measurements showed that in the buildings where the uranium concentrate derived from phosphorus ore was purified, the content of thorium in dust and aerosols exceeded the activity of uranium and radium by 10–100 times. In other buildings involved with uranium extraction after leaching and purifying, the ²³⁰Th in the production residues and tailings materials were found in much more lower activity concentration, with ²²⁶Ra the dominant isotope.

The variety of conditions and the forms of radionuclides in the U–Th series at various former sites of uranium production also determines the variety of radiological risks to personnel in the vicinity of the former uranium production complex. At most sites, the main contribution to the radiation dose is determined by direct gamma irradiation, which is mainly derived from 226 Ra.

The averaged doses for 1 h residency in the most contaminated facilities were estimated to be in the range $3-10 \mu$ Sv/h (at those locations with low concentrations of radioactive residues) and up to 1 mSv/h in some buildings near tanks, where high activity concentrates of ²²⁶Ra in the residues are still stored. The main dose factor in such buildings is the high gamma dose rate. In those facilities characterized by high ²³⁰Th contamination, the highest doses are due to gamma dose exposure as well, together with relatively high ²²²Rn ambient activity air concentration. In general, the contribution from inhalation exposure due to aerosol particles containing radionuclides of the U–Th series is estimated at no more than 10% of the total exposure dose. However, in some specific cases, maintenance activities dealing with spillage materials containing thorium with high activity concentrations in the spillage and dust materials may result in significant inhalation dose exposure for remediation workers.

In previous studies at the stage of the safety assessment, it was assumed that the uranium, radium and thorium contents in dust and aerosols are approximately in equilibrium. In fact, as has been shown by the authors' investigations that the content of ²³⁰Th in dust and materials that can form aerosol contamination in some buildings, and in storage facilities for the residues of thorium concentrates, radiation dose can be of the order of tens and hundreds of times higher than it would be under secular equilibrium conditions. Therefore, the dose estimates of inhalation exposure, which were obtained at the stage of rehabilitation planning, taking into account the high radiotoxicity and dominance of thorium in some former uranium production facilities, can be significantly underestimated.

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WNU SUP – EFFICIENT CAPACITY BUILDING TOOL IN U-PRODUCTION CYCLE

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1. INTRODUCTION

The World Nuclear University - School of Uranium Production (WNU SUP) international training centre was founded in 2006 and is operated by the DIAMO State Enterprise under the auspices of the World Nuclear University in London and in collaboration with OECD/NEA and IAEA. Making use of knowledge and equipment of the DIAMO State Enterprise and the connections it has with universities, research institutions, supervisory authorities and other experts from the Czech Republic and abroad, the International Training Centre develops and presents schemes focused on professional training throughout the range of aspects of uranium production, be it deposit surveys and extraction using various means, treatment of uranium ores, environmental protection and protection of the health of workers, and even removal of the consequences of mining operations. DIAMO State Enterprise was chosen to be the location of the training centre. The decision-making process took into account the extensive experience of the staff of this state-owned company in the underground acid uranium leaching method, one that can be used with success even at new sites abroad. Furthermore, the DIAMO State Enterprise offers extensive experience in remediating sites after conventional exploitation and treatment of uranium ores, remediating the bedrock environment after chemical extraction of uranium, treatment of mine water, radiation protection of staff and populations, environmental protection, etc.

2. MOTIVATION AND MISSION

During increases in the global demand for uranium, particularly in countries where uranium exploration and mining has been on the rise such as China and India, Pakistan, Brazil, Argentina and others, has – in the past - led to an increase in global market prices and a re-evaluation of the stock of the material. Contrasting to the above is the significant shortage of skilled professionals in uranium mining and processing observed in the last twenty years.

In more recent years, termination of uranium mining projects has been under way around the world. Many countries need to deal with the disposal and remediation of the consequences of uranium mining, which includes removal of old uranium burdens such as deep mines, ISL mines, treatment plants and tailings ponds. This sector is also experiencing a shortage of qualified experts globally.

In accordance with the fact that the proper management of uranium production requires skilled personnel and a broad dissemination of scientific, engineering and social knowledge, WNU School of Uranium Production aims to:

- Educate students in all stages of the uranium production cycle, including surveys, planning, development, operations, as well as remediation, rehabilitation, treatment of mine water and other environmental aspects of closure of uranium mining and production plants;
- Contribute to the improvement in the areas of surveys, mining and remediation after extraction of uranium through research and development;
- Provide a forum for exchanging information and lessons learned related to best practices in the field of uranium mining and processing.
- 3. COURSES

Each of the courses consists of a theoretical, lecture-based part and accompanying programmes that take the form of technical field trips to the DIAMO State Enterprise sites and premises, whose structure conveniently covers all aspects of the mining process. The high professional level and practical experience of specialized staff members of the enterprise is also leveraged with success. In addition to the DIAMO State Enterprise staff, teaching activities also involve lecturers from abroad, originating from mining institutions or freelance consultants active in diverse fields such as geology, hydrogeology, geomechanics, chemical technology, radiation protection, environmental protection, etc., with regard to the focus of the individual courses.

The courses are designed for groups of 5 to 18 participants. Examples of the courses:

- "Extraction using underground in situ leaching (ISL), both alkalic and acidic leaching" is a 2- or 4-weeks course for operators or 2-5 days course for managers;
- "Remediation of the consequences of in situ leaching" offers 1- or 2-weeks course focused on the remediation of the underground rock environment after acidic ISL, pump and treat method, processing of the acid solutions in the surface technologies and liquidation and reclamation of the surface;
- "Survey" 2- or 4-weeks of a combined course focused on surveying uranium deposits and extraction in sandstone type deposits (ISL preferred);
- "Remediation of consequences of uranium mining and processing." 1-week course focused on remediating heaps and tailings ponds, environmental monitoring, and radiation protection;
- "Alkaline-based uranium processing" is 1- or 2-weeks course focusing on the uranium ore mineralogy, technological requirements and processing, handling waste water and sludge, radiation protection and environmental monitoring, and field hands-on sessions in GEAM (uranium treatment plant);
- "Legal aspects of uranium mining" 1-week course for senior management and supervisory staff focused on discussions with representatives of national authorities in charge of extraction and radiation protection; hands-on sessions in the field, in the DIAMO State Enterprise premises;
- "Radiation protection in mining practice" 1-week course for senior management and supervisory staff;
- "Treatment of underground and mine water" offers 1- or 2-weeks course focusing on treatment of waste water, hydrochemistry, sampling, analysis, and technology;
- "Application of mathematical modelling in the U-production cycle and remedial process" 1week course targets on the use of different mathematical models during the geological survey, mining process and remedial activities, modelling of groundwater flow and transport of contaminants, environmental models for the risk analysis;
- "On-demand custom courses" can be designed to meet your individual needs. The course date, scope and contents can be specified upon agreement based on what is required by the applicant.

4. PARTNERS

The School of Uranium Production cooperates with a number of world-renowned institutions and uses their expert capacities and experience. Cooperating institutes include the International Atomic Energy Agency, Headquartered in Vienna, Nuclear Energy Agency in Paris, World Nuclear Association in London, World Nuclear University in London, University of Nottingham, Czech Technical University in Prague – Faculty of Nuclear Sciences and Physical Engineering, Technical University of Ostrava, Charles University in Prague and State Office for Nuclear Safety in Prague.

5. CONCLUSION

From beginning, the International Training Centre became a globally renowned facility of professional training. The number of participants – from a total of more than 20 countries – passing almost 50 distinct programmes has already reached 500. This number includes both projects of technical cooperation with IAEA and commercial contracts.

URANIUM MINING REMEDIATION IN AUSTRALIA'S NORTHERN TERRITORY

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1. INTRODUCTION AND HISTORY

Uranium was first identified in the Northern Territory in the late part of the nineteenth century [1]. However, it was only in the years immediately after World War Two that the mineral took on strategic importance and exploration efforts really took off. The discovery of the Rum Jungle deposit by Jack White in 1949 is generally accepted as the start of the modern era of uranium mining in the Northern Territory [2]. Located about 75 km south of Darwin, the Rum Jungle mine operated from 1954 to 1971 and produced 3530 t of uranium oxide and 22 000 t of copper. A number of smaller mines in the vicinity also contributed to the development of the industry. However, when contracts were fulfilled or deposits worked out, little effort was put into remediation of the sites and many were simply abandoned. In some cases, these legacy sites were relatively benign but others became sources of contamination; usually due to the development of acid and metalliferous drainage arising from the sulphides in the remaining waste rock piles. Only in later years did legislation and public concern lead to action being taken. Some of those actions are described later in this paper.

2. THE SECOND MINING ROUND

After the uranium 'rush' of the 1950s, the taste for uranium seemed to quieten down until the prospect of uranium as a fuel for nuclear power became firmly set in people's minds. In the late 1960s, exploration returned to locations which had been successful previously. The Northern Territory was one of those areas, especially around the Pine Creek geosyncline. The results of the exploration effort in the Alligator Rivers region were the deposits at Ranger, Jabiluka, Nabarlek and Koongarra. However, by the time the development proposals were being formulated, a new paradigm had been established with respect to mining, environmental management and remediation. Society was no longer prepared to accept that mining, especially uranium mining, would be a one-time user of land in the Northern Territory.

The result was Australia's first environmental inquiry, the Ranger Uranium Environmental Inquiry, which is perhaps better known as the Fox Inquiry after the Chairperson, Mr Justice Fox. The Inquiry produced two reports [3, 4] which decided that: (i) Australia could become involved in nuclear fuel cycle activity by mining uranium, but that would be the limit of the involvement, and (ii) that the four identified deposits in the Alligator Rivers region would be able to proceed to development, subject to the process of an environmental impact assessment required under recently promulgated laws.

Only two of the four identified uranium resources have been developed to date: Nabarlek and Ranger [5]. Both sites are subject to strict environmental regulation set down in the environmental requirements of the Commonwealth Government. Koongarra has been returned, unworked, at the request of the Aboriginal Traditional Owners of the land to become a part of the surrounding World Heritage listed Kakadu National Park. Jabiluka was investigated and an environmental impact statement submitted, but the site has been put back into long term care and maintenance with the disturbed areas now in an advanced state of remediation following the removal of all infrastructure and the backfilling of the underground development trial workings [6].

3. MODERN REMEDIATION

Small scale operations from the 1960s in the South Alligator Valley had been simply abandoned when production quotas were filled. About 13 mines and three processing sites produced approximately 850 t of uranium oxide in this programme [7]. The sites were not remediated until the area was designated to be included in Stage 3 of the Kakadu National Park, at which time a series of hazard reduction works were undertaken to improve public safety, both physically and radiologically [8]. As part of a longer term lease agreement with the Aboriginal Traditional Owners in 1999, a programme was begun to undertake the planning and implementation of the various mining and processing sites in the valley [9]. This programme was begun eventually in 2007 and completed in 2008 with the various small containments built under the earlier hazard reduction works programme being opened up and the contents relocated to a central customized central containment built to modern standards. The containment was equipped with instrumentation and monitoring is ongoing. Various reports have been made regarding the success of this project and presented at international meetings [10, 11].

The Nabarlek mine operated between 1979 and 1988; mining of the relatively high-grade ore was undertaken in one dry season and the stockpile was processed over the following ten years at an annual production rate of about 1000 t of U₃O₈ [12]. From the outset, the mine had a remediation plan and a fund to cover the cost of the works was guaranteed. After about a year or so, the mine employed a decommissioning engineer whose main task was to ensure that the plan was kept up to date and that every opportunity for progressive remediation was taken up. One of the environmental requirements for uranium mines in the Alligator Rivers region was that all mill tailings had to be returned to the mined-out pits at the end of the mine life. In the case of Nabarlek, the orebody was excavated entirely in 1979 and then processed over the following ten years with tailings being returned directly to the pit. In 1989, the mine was mothballed in the expectation that another orebody would be found. However, this was not the case and the mine was decommissioned and remediated in 1995, with the final work of seeding the site being completed before the onset of the wet season in December 1995. Since then, the site has continued to revegetate with varying degrees of intervention from successive lease holders. Some exploration activity has been based at the site and in the surrounding areas since that time, although the mine site has been allowed to continue remediation. Revegetation has been moderately successful, despite severe damage from a tropical cyclone in 2006 [12].

The Rum Jungle uranium and copper mine operated from 1954 to 1971 [2] and produced 3530 t of U₃O₈ and 20 222 t of copper. The site was abandoned with little remediation having been undertaken, apart from a token effort made in 1976. Ongoing acid and metalliferous drainage production resulted in significant impacts to the Finniss River. As a result, A\$18.6 million was spent on remediation between 1983 and 1986 and the programme was hailed as best practice at the time. Unfortunately, the works did not completely resolve all the issues and by 2000 the situation was deteriorating. A series of investigations began in 2004 which eventually resulted in the Northern Territory and Commonwealth Governments entering into a National Partnership Agreement in 2009, which was the beginning of a long term comprehensive programme intended to characterize the site and develop new designs for its remediation.

Under the National Partnership Agreement and successive project agreements, a wide variety of studies have been undertaken to obtain data which has facilitated a comprehensive characterization of the site, assisted in improving the day-to-day management of the site and enabled development of an improved remediation plan for the site.

A major feature of the programme has been the extensive consultation with the Aboriginal Traditional Owners of the land and their inclusion in the process of determining final land form and land use objectives. The project has also provided business development opportunities for the land owners which has resulted in small business ventures being created and developed at the project, which have then gone on to compete successfully in the local market.

The final design data are currently being collected and contracts made to develop the final remediation plan, which includes preparation of an environmental impact statement for assessment under Northern Territory and Commonwealth legislation. This work is due to be completed in 2019, with the production of costed designs for the final remediation programme.

4. CURRENT ACTIVITY

The Ranger Uranium mine, operated by Energy Resources of Australia Ltd (ERA), is, after 36 years, the longest producing uranium mine in Australia. Located about 250 km east of Darwin, the mine is surrounded by, but not part of, Kakadu National Park. Operating since 1980, the mine has produced more than 125 000 t of uranium oxide to date. ERA finished open pit mining in 2013 with the end of work in Pit 3. The previous pit, Pit 1, was backfilled with tailings between 1996 and 2004, in accordance with the environmental requirements. In 2017, work started on completing the backfilling of Pit 1 using waste rock to commence construction of the final land form. Details of the final land form design are yet to be finally agreed with Aboriginal Traditional Owners but the requirement is that the area could be incorporated into Kakadu National Park if desired, without the need for any special management [11]. ERA is continuing to process ore from existing stockpiles on-site. The present administrative arrangements require ERA to cease production and processing in January 2021 and to have completed remediation of the site by January 2026.

Since 2013, ERA has continued to implement progressive remediation works as and where it has been possible to do so, compatible with the last of the processing operations. When mining ended in Pit 3, work began immediately on preparing the void to be used as a disposal site for mill tailings. The main part of this programme was the placing of 33 million t of waste rock in the base of the pit to provide a level floor for deposition of tailings. Since 2015, mill tailings have been deposited directly into this pit. As well as the tailings in Pit 1, ERA also has a tailings dam of approximately one-kilometre square containing nearly 23 million t of tailings. Since 2016, work has been under way transferring these tailings into Pit 3 using a custom-built dredge. This operation is scheduled to last until 2021. At that time the excess process water will be disposed of through treatment and the tailings allowed to dry out and stabilized using prefabricated vertical drains. The final land form construction will then begin using waste rock with the final surfaces being made of material containing less than 0.02% uranium oxide, i.e. non-mineralized material. All this work is due to be completed in 2025 to allow planting to be completed by 2026, as required by the current administrative arrangements.

The Ranger site currently has a considerable inventory of process water which cannot be released from the site. A brine concentrator, built in 2013, treats process water to produce 1.8 GL of clean distillate annually, which is suitable for controlled release. The residual brines are to be injected into the void space in the back fill at the base of Pit 3. Other, less contaminated, waters on-site are passed through conventional water treatment plants (reverse osmosis) and the permeate is released in accordance with the appropriate approvals. As the climate has marked wet and dry seasons, discharge of clean water is only permitted when creeks and rivers are running. During the dry season, when ephemeral rivers have ceased to flow, water may only be released through evaporation. ERA is introducing 'turbomisters' during the dry season as a way of enhancing natural evaporation losses for treated water.

The progress of the remediation work is overseen by a Mine-site Technical Committee, comprising ERA, the Northern Territory Department of Primary Industry and Resources, the Supervising Scientist and, to represent the Aboriginal Traditional Owners, The Northern Land Council and the Gunhdjeimi Aboriginal Corporation. The Commonwealth Government Department of Industry, Innovation and Science attends meetings as an observer. ERA is producing a mine closure plan as a document for publication to the community; standards and criteria for the remediation programme are developed in consultation with the Mine-site Technical Committee members and other interested parties, as appropriate.

5. CONCLUSION

Uranium mine remediation in Australia's Northern Territory has come a long way from the days of simple abandonment that were the normal procedure only 50 years ago. Recent and current sites are being remediated in accordance with current leading practice and considerable attention is paid to consultation with stakeholders to ensure all concerns are understood and have the opportunity to be addressed. The efforts have not stopped there with a number of legacy uranium sites being cleaned up as well. There have been valuable lessons learned at every stage of this story and they are in turn being applied to the future work programmes for remediation of these and other mines in the region.

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RARE-EARTH ELEMENTS IN URANINITE: BRECCIA PIPE URANIUM DISTRICT NORTHERN ARIZONA, USA

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1. INTRODUCTION

Interest in rare earth minerals (REEs) originated in 1883 with the development of incandescent gas mantles containing rare earth and zirconium oxides. The knowledge that the supply of REE will not be able to keep up with new and ever-growing demands has been no secret in the geological community for years. However, it was not until it was presented to the US Congress as a "potential shortage that could impact US renewable energy sources, communications and defense industries" that politicians and the public tumbled to how critical these metals are and just how vulnerable the United States of America currently is to supply disruption. In 2008, China produced 97% of the world's REEs (primarily from Bayan Obo), India 2.2%, Brazil 0.5% and Malaysia 0.3%. Up until 2002, the Mountain Pass REE Mine in California produced about 5% of the world's REE supply. China's lock on the world's supply will be difficult to break. Starting in 2005, China put export taxes on REEs of 15–20% and put on export restrictions. Forecasts predicted a critical shortage for the rest of the world outside of China by as early as 2012. Consequently, REE prices went up. Just as the Mountain Pass Mine was getting ready to go into production in 2012, China eased their export restrictions and the price of most of the REE plummeted downwards. Three years later, in 2015, Mountain Pass mine went into bankruptcy.

REEs were extracted as a by-product of uranium mining in Canada during 1966–1970 and 1973–1977 at the Blind River and Elliott Lake deposits. The ore mineral uraninite contained sufficient REEs to make extraction of REE profitable from the raffinate fluids. From 1966 to 1970, uranium mines in the Elliot Lake district were the world's major source of yttrium concentrate. All REEs have been detected in these ores. The Elliot Lake ores also contain about 0.11% uranium oxide (U_3O_8) and 0.028% REE oxides [1]. The economic appeal of this occurrence is that the REEs are concentrated in the uraninite, which was already being concentrated from the ore, so the REEs are a bonus. "For a short period of time, HREEs were extracted from the raffinate fluids that emanated from the chemical processing of uraninite at Blind River, Ontario" [2]. Since REEs are significantly concentrated within the uraninite from breccia pipes in northern Arizona, they likewise could be extracted from northern Arizona uraninite.

2. POLYMETALLIC NORTHERN ARIZONA BRECCIA PIPE DISTRICT

A unique polymetallic-rich uranium, solution–collapse breccias-pipe district lies beneath the plateaus and in the canyons of northwestern Arizona. It is known for its large reserves of high-grade uranium (average grade of $0.65\% U_3O_8$ [3]) that were estimated by the US Geological Survey (USGS) to host over 40% of the USA's domestic uranium resources [4]. The breccias-pipe uraninite contains REE enrichment similar to that of the Athabasca Basin's uranium deposits in Canada, and their genesis is also associated with highly saline basinal brines.

From the late1980's until about 2004, the price of most metals had been sufficiently depressed, such that little was done to explore or study these polymetallic ores, particularly the REEs that are rich in the district's

uranium deposits. Starting in 2008, the price of most REEs had increased over tenfold by 2011. This is true of all energy critical elements, including Co and Cu, also heavily enriched in the breccias-pipe ore. However, since 2011, REE prices have fallen. These important elements commonly comprise over 1% of the breccia-pipe ore.

The northern Arizona metallic district can be thought of as a palaeokarst terrain, pock-marked with sink holes, where in this case most 'holes' represent a collapse feature that has bottomed out over 850 m (3000 ft) below the surface in the underlying Mississippian Redwall Limestone. These breccia pipes are vertical pipes that formed when the Palaeozoic layers of sandstone, shale and limestone collapsed downwards into underlying caverns. A typical pipe is only approximately 90 m (300 ft) in diameter and extends upwards as high in the stratigraphic column as the Triassic Chinle Formation. Although each breccia pipe in itself is not a huge ore deposit — up to 4500 tU (10 million lbs) of uranium per pipe — in total the resources in the district are enormous. Many of the various small, mineralized pipes are clustered together providing somewhat contiguous mineralization, which reduces the mining costs. The water table is deep below the orebodies, which lie at depths of 150–450 m (500–1600 ft) below the surface, sufficiently above the water table to minimize the potential contamination of the aquifer.

Mining activity in the Grand Canyon breccia pipes began during the nineteenth century, although at that time mining was primarily for copper, with minor production of silver, lead and zinc. It was not until 1951 that uranium was first recognized in the breccia pipes. The intrinsic geology of these pipes, together with a growing understanding of the nature of tele thermal ores, (a classification category to which the base-metal deposits of the pipes belong), are important components in modelling their genesis. The mineralized pipes are base-metal bearing and, regionally, bear a slightly later metal overprint of uraninite. A model was proposed for genesis of these ores as members of the class of Mississippi Valley Type (MVT) deposits, but with late-stage uranium mineralization [3]. Uranium–lead age determinations on uraninite gave ages of 200 and 260 Ma [5] and link the mineralization with Pangean time, events, and mid-continent MVT ores. Chemistry and fluid-inclusion temperatures on sphalerite and dolomite of 80–173°C also link them with MVT deposits [3]. Mixing of oxidizing groundwaters from overlying sandstones with reducing brines that had entered the pipes owing to dewatering of the Mississippian limestone created the uranium deposits. Proximity to the west of the Cordilleran miogeocline and various uplifts to the east allow consideration of a basin-dewatering mechanism as the genetic mechanism [3].

3. REEs IN BRECCIA PIPE URANINITE

REEs are significantly enriched in much of the breccia pipe ore. Whole-rock analyses of uranium orebearing rock from across the district show REE enrichment that is not uncommonly 20 times average crustal abundance. A study of REE occurrence within uraninite was undertaken at the facilities of CREGU-GeoRessources-Lorraine University, Nancy, France, using laser ablation ICP-MS in conjunction with electron microprobe analyses of the uraninite [6]. This research has confirmed that a significant percentage of the bulk rock REE content is tied up in the uraninite crystal structure. Although the breccia-pipe, bulkrock REE content is not as enriched as in the carbonatites at Mountain Pass, California, the breccia-pipe uraninite contains concentrations of Nd that are, for example, around 15–20% of the Nd concentrations in the bastnaesite at Mountain Pass. Considering that at Mountain Pass the bastnaesite (REE ore mineral) has to be mined strictly for REE, the uraninite in the breccia pipes is already processed for the uranium. Hence, the Nd and other REE collected from the raffinate fluids are an added value to the profit. Additionally, the more valuable heavy REEs (HREEs) are enriched in the uraninite, whereas the Mountain Pass, CA and Bayan Obo, China ore deposits contain essentially little significant HREEs.

4. REE PRIMARY AND REMOBILIZED ORE-DEPOSIT SIGNATURES

Distinctive REE signature in uranium oxides is directly related to the variability of the mineralizing processes and geological setting between uranium deposit types [7]. All the uranium oxides from unconformity related deposits, such as the Eastern Alligator district in Australia and Athabasca Basin district in Canada, are characterized by a bell-shaped REE pattern centered on dysprosium. This type of pattern seems to be characteristic of uranium oxide primary ore deposited from high-salinity basinal brines. The Sage and Pinenut breccia pipes of northern Arizona have bell-shaped chondrite-normalized distributions that are remarkably similar to the Athabasca Basin's McArthur River (which currently produces 25% of the world's uranium) and Shea Creek uraninites [8], with a normalized maximum centered on Sm–Eu–Gd. Interestingly, the Pinenut breccia pipe, with its bell-shaped REE pattern, is the oldest, at 260 Ma [5] of those that were part of the current study, suggesting it is primary ore (no age determination was completed on the Sage orebody by Ludwig and Simmons [5]).

The REE element patterns of uraninite samples from three of the breccia-pipe uranium mines (Pigeon, Kanab N and Hack 2) have chondrite-normalized distributions that show some fractionation and a negative Eu anomaly. They distinctly resemble chondrite-normalized plots of uraninite samples [9] from the Athabasca Basin's Eagle Point deposit, but with overall lower REE content. The rocks from the three breccia pipe orebodies and from Eagle Point show striking oxidation–reduction fronts within some of the ore. Such samples correspond to uranium oxides that are remobilized by oxidized meteoric fluids. These fluids mobilized the LREEs preferentially over the HREEs. Therefore, the uranium oxides from the redox front are characterized by LREE enrichment, which differs from the primary ores, and clearly demonstrate their distinct conditions of formation from those of the primary ore [9]. The HREE part of the chondrite-normalized distribution is preserved. The negative Eu anomaly of these samples could possibly be a result of oxidizing meteoric fluids albitizing the detrital feldspars in the clastic host rocks, permitting preferential incorporation of Eu over the other REEs into the albite structure (similar to magmatic plagioclase creating a negative Eu anomaly).

The three uraninite orebodies (Pigeon, Kanab N and Hack 2) that are more highly fractionated are younger, with ages of 200 Ma [5], than the Pinenut 260 Ma ore that has a bell-shaped REE pattern. All of the brecciapipe orebodies are believed to have formed as a result of mixing of high-salinity basinal brines (based on fluid inclusion results) and oxidizing groundwaters [3]. Hence, the primary ore, breccia pipe uraninite samples fit the same REE chondrite-normalized pattern as do uraninites from the primary uranium deposits of McArthur River and Shea Creek. Interestingly, the Pigeon, Kanab N and Hack 2 mines all lie along a N45° E trend that is parallel to one of the two major fracture directions in northern Arizona. Consequently, they may have been more open to oxidizing groundwaters than the Pinenut and Sage orebodies. More samples from each mine and from other uraninite deposits within the district will provide insight into the fluids containing the REEs. However, the pipe-in-pipe structure in many breccia pipes proves secondary dissolution. It is quite possible that all of the breccia-pipe orebodies have an older primary ore preserved and a later secondary oxidation/reduction front ore. The primary ore would have higher U and REE grades.

5. BRECCIA PIPE URANIUM AND REE RESOURCE ESTIMATES

The northern Arizona breccia-pipe district contains the highest-grade uranium in the USA, with the potential for reserves that greatly exceed any other province in the USA. With an average grade of 0.65% U₃O₈, and an environment conducive to relatively low cost conventional mining, these deposits are still economic in the US \$45/lb cost category [10]. Unfortunately, in 2011, President Obama chose to issue an executive order withdrawing the million acres of northern Arizona land that encompassed most of the mineralized breccia pipes in the district. With the current emphasis by President Trump enabling exploration for strategic metals, these lands may soon be reopened to mineral exploration. Multiple approaches to uranium-resource

calculations on these lands by separate researchers have shown remarkably similar results. These can be summarized as follows:

- (i) A uranium-resource estimate (referred to as resource endowment [11]) based on industry drilling over the 2719 km²(1050 mi²) 'mineralized corridor' of the breccia-pipe district have been made by Spiering and Hillard [11], who defined a 'mineralized corridor' within the breccias-pipe uranium district where they believe most of the mineralized pipes lie. It provides a smaller focused area to work with where more data are available. However, these authors still believe that considerable mineralized rock abounds beyond this corridor on private and public lands (the NE quadrant of the Hualapai Reservation is an example). Spiering and Hillard calculated the uranium resources by (a) using VTEM airborne geophysics results and concluded that the mineralized corridor had 122,500 tU (270 million lbs) of U₃O₈ and (b) using known pipe density they concluded the corridor has 122,000 tU (269 million lbs) of U₃O₈ [11];
- (ii) In 1987, the USGS [4] calculated the uranium endowment of the entire breccia-pipe district. Spiering and Hillard [11] show that these calculations, when applied to the mineralized corridor, give resources of 170,000 tU (375 million lbs) of U₃O₈;
- (iii) Using a control area of detailed surface mapping of solution-collapse features and mineralized rock [12] on the NE portion of the Hualapai Reservation, the current authors calculated that the mineralized corridor contains 118,000 tU (260 million lbs) of U₃O₈ and the entire withdrawal area contains 175,000 tU (385 million lbs) of U₃O₈.

These three independent resource estimates average 137,000 tU (302 million lbs) of U_3O_8 . The estimate by Spiering and Hillard and that by Wenrich et al., using completely different types of data within different geographic parts of the district (industry drilling versus detailed surface mapping) have come to remarkably similar resource endowment estimates, i.e. 118,000 tU versus 122,500 tU (260 million lbs versus 270 million lbs) of U_3O_8 .

Yet, the USGS in 2011, within the final environmental impact statement for the breccia-pipe land withdrawal, arrived at a paltry 36 000 tU (79 million lbs) for its resource estimate. However, it appears no use was made of industry drilling [11] nor previous USGS maps [12] nor extensive resource calculations [4], but, rather, a 1987 non-peer reviewed elementary article, written for the general public by Wenrich, where it was stated that about 8% of collapse features and breccia pipes appeared to be mineralized. However, there were no data provided to support this statement. The USGS estimate contrasts sharply with the other three resource calculations, which are in striking agreement. It appears that the USGS data of 2011 ignored industry drilling and other resource calculations, including their own, which suggests an incomplete and potentially politically biased analysis.

A fourth approach is also applicable, which results in an estimate closer to the IAEA's reasonably assured resources (RAR)¹³ rather than a resource endowment. Prior to 1989, over 110 breccia pipes were drilled; 71 of which were identified as having ore-grade mineralization [13]. At an average of 1300 tU (2.9 million lbs) of uranium per pipe, the IAEA's RAR or 'indicated reserves' (USGS definition) total 93 400 tU (206 million lbs) of resources in the part of the district covered by Sutphin and Wenrich's map [13]. Of these 71 mineralized pipes, 9 became uranium mines, 27 are known to contain an orebody, and 46 were mineralized but had undergone insufficient drilling to identify an orebody. As the district is known to have very little low grade mineralization, if a pipe is mineralized with ore-grade mineralization, the odds are high that it contains an orebody. Since 1989, there has been significant exploration for uranium in the northern Arizona breccia-pipe district and more pipes have been located that are known to be mineralized. Hence, this RAR estimate of 93 400 tU (206 million lbs) is probably not an unreasonable one based on the historic drilling

¹³ Reasonably assured resources (RAR) are defined by the IAEA as "uranium that occurs in known mineral deposits of delineated size, grade, and configuration, such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology can be specified."

undertaken in the district, but low because it only includes drilling prior to 1989, whereas the estimate of Spierling and Hillard [11] include drilling data up to 2012.

The US Energy Information Administration (EIA) (US Uranium Reserves Estimates (2008)) estimates that in the cost category of US \$50/lb uranium, US reserves amount to 244,000 tU (539 million lbs) of U_3O_8 [14]. The EIA states that the definition of 'reserves' for these estimates "...corresponds, in general, to the category of 'Reasonably Assured Resources' often used in international summaries of uranium reserves and resources..." Comparing the US RAR of 244,000 tU (539 million lbs) of U_3O_8 with the RAR calculated above as being 93,400 tU (206 million lbs), the breccia-pipe district contains 38% of the USA's uranium reserves (a low estimate because this breccias pipe RAR calculation does not include drilling information after 1989).

Using the minimum reserve calculation of 93,400 tU (206 million lbs) of U₃O₈ and the maximum endowment of 170,000 tU (375 million lbs), the mineralized corridor contains US \$10-18 billion dollars in the US \$50/lb uranium cost category and US \$21–38 billion dollars in the US \$100/lb uranium cost category. REE analyses of breccias-pipe uraninite ore (this study) in France showed the total REE content of the uraninite to be around 0.43%. Hence, between 214 t (471,000 lbs) and 390 t (860,000 lbs) of LREE and between 184 t (405,000 lbs) and 334 t (737,000 lbs) of HREE could be produced from the breccia-pipe district. The more valuable HREE have a higher concentration in uraninite ores than in bastnaesite ores from the Bayan Obo and Mountain Pass districts. The value added by REE (\$3.10/lb of U₃O₈) to the uranium ore would be between US \$639 million dollars and US \$1.2 billion dollars (based on 2011 REE prices). The REEs, a strategic component needed for energy and industrial technology, coupled with the US \$10-38 billion dollars of uranium, is a significant amount of money and energy reserves to lose from the US economy due to a land withdrawal scheme that has essentially no significant scientific or environmental basis, as shown in the final Environmental Impact Statement analysis. These monetary estimates do not include any value added components attributable to other metals that are significantly enriched (many reaching and exceeding 1%) in the breccia-pipe polymetallic ore. These metals include Ag, Co, Cu, Mo, Ni, Pb, V and Zn [3].

6. CONCLUSIONS

REEs are significantly enriched in much of the breccia-pipe ores. A study of REEs within uraninite has confirmed that a significant percentage of the whole rock REE content is tied up in the uraninite crystal structure.

All the uranium oxides from unconformity related primary ore deposits from the Eastern Alligator district in Australia and the Athabasca Basin district in Canada are characterized by a bell-shaped pattern centered on dysprosium. The Sage and Pinenut breccia pipes have bell-shaped chondrite-normalized plots that are remarkably similar to the Athabasca Basin, McArthur River and Shea Creek uraninites. The Pinenut breccia pipe, with its bell-shaped REE pattern, is the oldest, at 260 Ma [5], in the district, suggesting it is primary ore. The REE patterns of uraninite from Pigeon, Kanab N and Hack 2 breccia pipes (age of 200 Ma) have chondrite-normalized distributions that show some fractionation and a negative Eu anomaly, similar to the Athabasca Basin's Eagle Point uranium deposit. The rocks from these three breccia pipe orebodies and the Eagle Point deposit show oxidation–reduction fronts within some of the ore, suggesting remobilization by oxidized meteoric fluids.

Multiple approaches to uranium resource calculations have been made by separate scientists. Uranium resource estimates based on industry drilling within the 2720 km² (1050 mi²) mineralized corridor have been made by Spiering and Hillard [11] and calculated to be 122,000 tU (270 million lbs) of U₃O₈. In 1987, the USGS [4] calculated the uranium endowment of the entire breccia pipe district. Spiering and Hillard [11], show that these calculations, when applied to the mineralized corridor, give resources of 170 000 tU (375 million lbs) of U₃O₈. A resource estimate (part of this study) using detailed surface mapping of breccia pipes

and mineralized rock [12] in the NE portion of the Hualapai Indian Reservation, showed that the mineralized corridor contains 118, 000 tU (260 million lbs) of U_3O_8 and the entire withdrawal area contains 175 000 tU (385 million lbs). Uraninite analyses (this study) show that the total REE content of the uraninite to be 0.43%. Hence, using the average uranium resource of 137, 000 tU (302 million lbs) of the above three estimates, an estimated 590 t (1.3 million lbs) of REE could be produced from the breccia pipe district's mineralized corridor, adding a REE value to the uraninite of US \$936 million. Between 28 and 48% of the REE production would be the more valuable HREEs.

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DEVELOPMENT OF MINE WATER QUALITY, SUBSEQUENT SEDIMENTS CONTAMINATION AND PASSIVE 226Ra TREATMENT IN ZADNÍ CHODOV, CZECH REPUBLIC: A CASE STUDY

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1. INTRODUCTION

The uranium deposit Zadní Chodov was discovered using a car-borne gamma survey in the year 1952. In 1958, the uranium mining area Zadní Chodov was established, covering 7.16 km². During operation, five mining shafts were constructed on the deposit [1]. Shaft No. 1, with a total depth of 401.6 m, was closed in 1963, and Shaft No. 2, reaching a depth of 761.8 m, was closed in 1989. Shaft No. 3 was excavated to 28th floor level in depth of 1263.2 m. Furthermore, there were Shafts No. 12 (780.4 m depth) and No. 13 (1083.8 m depth). As with many other ore deposits in the Czech Massif, local uranium ores were exploited by using method of cut-and-fill stopping and gradual top-slicing stopping under a man-made ceiling.

2. MINING HISTORY

Uranium ore was mined at the site for 40 years and the total production exceeded 4,000 t U (the 6th largest deposit in the Czech Republic). The exploration activities were completed in 1988, and mining operation ceased in 1992, concurrently with many other mines during the first wave of ordered mining activities reduction. The mine was closed and the surface area remediated, while waste dumps material was processed into crushed aggregates. In February 1993, underground water pumping was discontinued and spontaneous flooding of mine was allowed.

3. MINE WATER TREATMENT

Due to mine flooding, in March 1995 the water streamed to the surface, yielding 15 L/s. To resolve these circumstances, a hydrogeological study of the region was performed aimed to asses a final management system for the water outflow and subsequent treatment [2]. A drainage system was built in the area of concern, connected to an accumulation pond followed by a decontamination station (water treatment plant). The captured mining waters were continuously sampled prior to entry, while the dissolved contaminants, especially uranium and radium, were monitored.

The initial high uranium and radium concentrations associated with the first flush effect, after the first five years (1995 - 2000), went to a declining trend.

In November 2001 a borehole HVM-1 was drilled from the surface to the second mine level, from the area with the lowest surface elevation (from the "melioration ditch") and thus was created a new pathway, allowing efficient, spontaneous flow of the mine water to the surface, while reducing the water level inside the mine. This was done to eliminate any previous outflows and enable the deposit to be gravitationally drained.

In 2010, the mine water reached quality which allowed its release into the watershed, without pumping and cleaning. Since then, the mine water has been experimentally discharged without cleaning into the

melioration ditch that leads to Hamer Creek; however, the mine water treatment plant (decontamination station) is still on standby and ready to be reactivated if necessary.

4. MINE WATER, SEDIMENTS AND LEGISLATION FRAME

As mentioned above, initially high uranium and radium concentrations associated with the first flush effect formed declining trend after five years. Nowadays mining water has a low content of dissolved solids (about 300-350 mg/L) and hydrochemistry has greatly stabilized. Concentrations of $U_{nat.}$ (less than 0.1 mg/L on average) and 226 Ra (1,600 mBq/L on average) do not show significant anomalous variations since 2010.

In accordance with valid Czech legislation in the field of radiation protection, the quality of the discharged mine water is continuously monitored and the concentration of ²²⁶Ra is also monitored in the sediments along the melioration ditch up to the Hamer Creek estuary. Currently along approximately 900 m of the stream there are 11 monitoring locations. Measured concentration values are compared with reference levels. Particular attention is paid to the accumulation of ²²⁶Ra in the sediments along the upper segment of the melioration ditch. If the values of the radium concentrations in the sediments were to consistently exceed the reference levels, and contamination spread towards Hamer Creek, the situation would have to be addressed. One possible solution would be reactivation of the decontamination station. Therefore, a preliminary exploration of the area was launched in 2017 to test other potentially useful methods of 'cleaning' mine water on the site.

5. ENVIRONMENTAL IMPACT ASSESSMENT

Through the year 2017, an in-situ gamma spectrometric survey of the area, surrounding the mine water outflow, was conducted to determine the background values of natural radionuclides and localized possible anomalies of ²²⁶Ra or U_{nat} mass activities. This was carried out mainly in locations of the previous water outlets and in the area of the melioration ditch. The monitored locality is minimally populated and presently used as a grazing pasture for cattle. The gamma spectrometry method did not show exceedances of exemption levels of radionuclides in the soil; the only possible source of cattle contamination could be the pasture watering system. Based on known concentrations of radionuclides in water, a commitment effective dose was estimated for a representative person, resulting from the consumption of meat from cattle grazing on the site under observation, in the usual pasture regime. At the recommended consumption of 20 kg of beef from Zadní Chodov area, the estimated commitment effective dose was calculated at less than 1 μ Sv.

6. WATER VOLUME-LIMITED TREATMENT EXPERIMENTS

Experimental treatment of the outflowing mine water using adsorbents was started in May 2017, based on studies documented in [3 - 7]. Two different adsorbents – peat and zeolites (grain size 1-1.25 mm, 2.5-5 mm and 4-8 mm), was placed at the bottom of the 200 L barrels. A part of borehole water flow entered the barrels at the base and passed through the adsorbent layers and finally overflowed the barrels. The water flow rate was measured continuously. The peat had low effectiveness from beginning of the experiment and washed out due to its low specific weight. The treatment using zeolites grain size 4 - 8 mm resulted in very low efficiency and thus both experiments were terminated.

Next step was the use of smaller adsorbent pellets (grain size 1-2.5 mm and 2.5-5 mm) starting in June 2017. The testing continued for 4 months and the water samples for radionuclides concentration measurement (before and after treatment) were taken 5 times per week and later 3 times per week. The relative effectiveness of ²²⁶Ra treatment was calculated.

7. DISCUSSION

The water flow rate in barrels was approximately 0.25 L/s, effective height of barrels was 80 cm and the thickness of the zeolite layer was 20 cm. Taking into account that the zeolite layer decreased effective flow volume by about 50 percent, the contact time between water and zeolite is estimated to be 1 minute 40 seconds. In case of zeolite with grain size 1.0-2.5 mm the average initial adsorption removal reached 70%, which after 3 month of experiment duration decreased to level of 40%. In comparison the zeolite of grain size 2.5-5 mm had average initial adsorption removal of approximately 80%. The linear trend describing radionuclides concentration removal indicates adsorption removal ability of about 50% after 4.5 months of operation.

The average water flow rate from the drilling well HVM-1 from October 2016 to September 2017 was 14.92 L/s. It could be expected that with increasing of the adsorbed radioactive contaminants (and minerals) the adsorption ability of the zeolites will decrease. In case of desired higher water flow rate the amount of required adsorbent would have to increase proportionally, to maintain the same treatment effectiveness. Introductory experiments performed to date do not enable accurate estimation of the dependencies between amounts of zeolite used, water throughput and treatment efficiency. Given the above-mentioned parameters interdependence, for cleaning mine water using throughput of 15 L/s would require 60 times higher volume of adsorbent to achieve 50% capture effectiveness for 226 Ra. That corresponds to 3 tonnes of zeolite utilization during each 4-month period.

8. COST BENEFIT ANALYSIS

In the years 2008 - 2010, the average annual cost of running the mine water treatment plant (using the conventional barium chloride active treatment process) was on the order of millions of Czech crowns. Searching for less expensive alternative, a zeolite-based cleaning technology could be passive, greatly reducing the operating costs. If we consider the use of common "pool mixes" and the adequate amount of approximately 10 tonnes, the cost of adsorbents consumption can be at the level of hundred thousand Czech crowns per year. In that case it is necessary to add the cost of maintenance, control, monitoring, removal of contaminated materials and landfill. All these operations are expected to be one order less expensive than operating the existing water treatment plant.

9. CONCLUSIONS

On the basis of the available data, the passive method of mine water treatment at the site of Zadní Chodov, using zeolite adsorbents, appears to be potentially applicable. Mining water at the site has low mineralization with a low proportion of suspended matter, which has a positive effect on the life of the sorbent [4]. For the first experiments, commonly available "pool mixes" of adsorbent based on clinoptilolite were utilized. However, it would be desirable to utilize adsorbents based on synthetic zeolites which could have much higher efficiency for adsorption of ²²⁶Ra. Higher efficiency and capacity of the adsorbent would, of course, mean overall cost saving, lower consumption, simplification of the loading, unloading and transport process, while reducing the amount of "waste" to be deposited at the tailings pond. Assembling a technological unit utilizing the zeolite technology will be the subject of further deliberation. The main issues will be:

- Choice between settling tank and closed piping system;
- Ensuring a uniform flow through the adsorbent avoiding preferential path formation;
- Testing the effectiveness of different types of adsorbents;
- Adsorbent recycling options;
- Potential use of a wetland system a natural way of the mine water cleaning.

These and other tasks are planned for the next stages of testing the mine water treatment process in Zadní Chodov. It is assumed that the findings will also be used at other localities, where the deposition of mine water can cause an ecological load of contaminants.

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A MILESTONES APPROACH TO URANIUM MINING AND DEVELOPMENT: AN IAEA INITIATIVE

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1. OVERVIEW

Many IAEA Member States without any current uranium production activities have expressed interest in uranium mining, in order to meet their or other countries' energy needs.

To introduce or reintroduce uranium mining and processing, a wide range of issues needs to be considered. With the assistance of experts from around the world, the IAEA is preparing a guide setting out a milestones approach to the uranium production cycle. This will assist Member States to take a systematic and measured approach to responsible uranium mining and milling.

The information in the guide will be provided within the context of other IAEA guidance and materials relevant to development of the uranium production cycle, including the IAEA Safety Standards Series. Although not the emphasis of the guide, the vital importance of appropriate radiation protection, security and non-proliferation safeguards is acknowledged.

In the development of the guide, four generalized stages with associated milestones of preparedness are being considered (subject to amendment):

- 1) Those considering exploration or mining of uranium for the first time, or after a hiatus of many years, but without an identified project;
- 2) Those seeking to initiate/reinvigorate uranium mining with one or more identified projects;
- 3) Established producers of uranium wishing to enhance existing capacity/capability;
- 4) Historic producers with closed sites in the stage of closure and rehabilitation/remediation or aftercare.

The situation of each Member State will be unique, at least in detail. It is also acknowledged that, despite there being a reasonable sequence in which to address the stages, any given Member State may, simultaneously, be in more than one of these generalized stages. Nevertheless, the report will comment on common threads and good practice, and assist a Member State to identify areas within a stage where they are less prepared, and give advice to enable progression towards a later stage. However, an important consideration with uranium mining and milling is whether uranium ore may or may not actually be present in a particular Member State. Hence, even with excellent work in uranium exploration, with good policies, legislation, regulation and well-trained experts, a Member State may remain in the earliest stage. This is in contrast to the milestones approach for some other purposes, where the opportunity to progress through the various milestones to their successful implementation is more generally applicable, should a Member State choose.

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The uranium production milestones guide will be designed for use around the world, but the specific involvement of African Member States and the IAEA's Technical Cooperation Regional Africa Projects in launching the work is acknowledged.

To date, the following experts from around the world have been directly assisting the IAEA in the preparation of the milestones guide:

Abbes, N.	Groupe Chimique Tunisien, Algeria
Blaise, J.R.	Consultant, France
Brown, G.	Boswell Capital Corporation, Canada
Dunn, G.	Hydromet Pty Ltd, South Africa
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Hilton, J.	Aleff Group, United Kingdom
Itambo, H.	Ministry of Mines and Energy, Namibia
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Consultancy Meetings were held in Vienna, Austria, on 12–14 December 2016 and 4–7 September 2017. It is intended that a full draft document will be made available for comment to Member States during 2018.

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GEOLOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE HUAYANGCHUAN U–Nb–Pb DEPOSIT, SHAN'XI, CHINA

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1. INTRODUCTION

The Huayangchuan U–Nb–Pb deposit is located in the western part of the Xiao Qinling area on the southern margin of the North China Block. This deposit has proved to be the largest U–Nb–Pb polymetallic deposit to have been discovered in China in recent years [1–9]. The Huayangchuan deposit is located at a junction between Huashan granites (142–92 Ma) [10] to the north and the Laoniushan granites (228–146 Ma) [11] to the south. An Archaean gneissic suite is the host rock in the area and includes biotite–plagioclase gneiss, hornblende–biotite–plagioclase gneiss, pyroxene–hornblende–plagioclase gneiss, hornblende gneiss, granite gneiss, etc. The NW trending (290–310°) Huayangchuan Fault controls the distribution of the orebodies and dykes in the area. The fractures are well developed in the deposit and trend mainly NNW and NW. Calcite veins are the main ore-bearing host.

On the basis of the collection and analysis of regional geological data and on the exploration and investigation work performed in recent years, the authors have clarified the ore genesis, the characteristics of ore-bearing pegmatite and carbonate rock, and the characteristics of U–Nb–Pb mineralization. The ore controlling mechanism and the genesis of the ore deposit are principally discussed in this paper.

2. DESCRIPTION

2.1. Characteristics of dykes and vein fillings

Various dykes and vein fillings crop out in the Huayangchuan deposit area, including biotite amphibole, biotite granite porphyry, pegmatite, calcite veins, lamprophyre, fine-grained granite, etc. These dykes and vein fillings have been divided into three groups (pre-mineralization, mineralization and post-mineralization groups) on the basis of their nature, relationship with the mineralization and their cross-cutting relationships.

Biotite granite porphyry dykes, located to the south of a fault zone, are NNW trending, 4 km long and 10–200 m wide. They are cut by the ore-bearing quartz–calcite veins. Guo et al. [10] suggests two episodes of intrusion of biotite granite porphyry veins (225.5 ± 4.2 Ma and 207 ± 2.3 Ma) using U–Pb dating on zircon. Qi et al. [11] dated the feldspar within the ore-bearing carbonate veins using the K–Ar dating to 204–206 Ma. Yu [12] dated the phlogopite in carbonate using the K–Ar to 181 Ma and He et al. [6] obtained the age (39 Ar– 40 Ar) of 133.01 ± 0.74 Ma from biotite in the carbonate, and a 39 Ar– 40 Ar age of 91.49 ± 1.97 Ma from biotite in pegmatite. The age of ore-bearing carbonate veins is younger than the age of biotite granite porphyry, which confirms its emplacement prior to the mineralization. Lamprophyre, amazonite pegmatite and fine-grained granite dykes cross-cut the mineralized quartz and calcite vein rock, but are not cut by other veins indicating that they were emplaced after the mineralization episode.

The mineralization event is divided into two stages: pegmatite and carbonate. Veins in the pegmatitic stage includes granite pegmatite veins and anatectic pegmatite veins. The granite pegmatite has a porphyritic and graphic texture and a 'lumpy' structure. Anatectic pegmatite veins mainly consist of K-metasomatic pegmatite, biotite–actinolite pegmatite and biotite–feldspar–quartz veins [13]. Irregular U–Nb mineralization is developed during this stage in both types of pegmatite.

The carbonate stage includes quartz–calcite veins, feldspar–aegirine-augite veins, baryte–quartz–calcite veins with aegirine-augite and sodium amphibolite, baryte–quartz–calcite veins with biotite and a small number of aegirine-augite and baryte–quartz–calcite veins with zeolite. The mineralization suites are characterized as follows:

- Quartz-calcite veins are the most widely distributed ore-bearing veins in the region, consisting of quartz (>50 %), calcite (30-40%,), baryte and small amounts of plagioclase. The quartz is mostly 'brecciated'. Calcite also occurs as xenomorphic brecciated grains. Galena was found in this type of vein. There is no obvious uranium mineralization;
- 2) Feldspar-aegirine-augite veins exhibit strong U-Pb mineralization. The dark minerals in this type of vein are dominated by aegirines and the light coloured minerals are mainly microcline, followed by quartz, calcite and baryte. Galena is often disseminated in the aegirine-augite and forms irregular clumps and thin veins between the feldspar and calcite grains;
- 3) Baryte–quartz–calcite veins with aegirine and sodium amphibolite present clear banding. The main mineral is calcite followed by aegirine, microcline, quartz and baryte;
- 4) Baryte-quartz-calcite veins with biotite and a small number of aegirine-augite veins are not large, generally 0.5–1 m wide, and characterized by the presence of biotite. Calcite is mainly grey and white. The galena and blomstrandite are finely disseminated. The niobium minerals (blomstrandite, fergusonite and niobium rutile) are poorly represented. The mineral distribution in the veins is irregular;
- 5) Baryte-quartz calcite veins with zeolite veins are generally 1–2 mm wide and they are reticular and form fine vein fillings in earlier formed fractures. The galena occurs as grains included within baryte, calcite and quartz. There is no U mineralization. These veins represent the last ore-bearing episode and they cut all earlier mineralized veins. The second and third type of veins are the most important U–Nb–Pb mineralized veins.

The single ore-bearing vein is not large (several tens of centimeters wide), although it is dense. Veins of different types and scales penetrated in different directions and occur different types of fracture. The veins of different stages are interlaced and interwoven with branches and meshes on the wall-rock. The overall trend is NW, especially that of the mineralized veins.

2.2. Characteristics of the mineralization

The Huayanchuan deposit is mainly a U–Nb–Pb deposit, associated with precious metals and rare earth elements. The uraniferous minerals are mainly blomstrandite and uraninite, followed by the uraniumbearing changbaiite and fergusonite. The Nb mineralization minerals are mainly blomstrandite followed by minor amounts of fergusonite and niobium rutile. The Pb mineralization minerals are mainly galena and a small amount of oxidized cerussite. Other elements, notably Ag, Bi, Cd, Se and Te, are dispersed in the galena. Rare earth elements are mainly La, Ce and Y, mainly hosted in xenotime, allanite, monazite, bastnasite and fergusonite.

Biotitization, actinolitization and potassification are typical alterations associated with the uranium mineralization during the pegmatite stage. In pegmatite exhibiting biotitization, the uranium grade usually exceeds 0.1%. Blomstrandite has been found in the area where biotitization and actinolitization are developed.

The mineral assemblages of biotite–(aegirine-augite)–sphene–zoisite–amphibole–apatite are closely related to U mineralization and the greater their development, the more uranium mineralization is found. Among these assemblages, the biotite–(aegirine-augite)–titanite assemblage is especially closely correlated with the U mineralization. The galena mainly occurs at the boundary and in general where pyritization is developed, where strong Pb mineralization occurs. The assemblage of aegirine-augite and pyrite is the main metallogenic association with galena.

3. DISCUSSION AND CONCLUSION

The wall-rock of Huayangchuan deposit is Archaean gneiss. The boundary between ore-bearing veins and wall-rock is clear but wall-rock alteration is not obvious. There is no specific wall-rock that is specifically related to the mineralization. However, there are differences in the degree of fracturing among the different types of wall-rock. For example, a denser fracture and fissure system is developed in the biotite–plagioclase gneiss than in the hornblende gneiss and granite gneiss. The degree of development of fractures and fissures in the region directly affected the density of ore-bearing veins and the grade of the mineralization.

The metallogenic processes can be divided into two stages: the pegmatite stage and the carbonate stage. The ages, 204–206 Ma and 181 Ma obtained on the carbonate veins can be compared with those for the intrusion of Laoniushan granites (228 and 146 Ma) [11] and the ages, 91.49Ma and 133.01 Ma obtained on the pegmatite and carbonatite [6] are nearly coeval with the intrusion of the Huashan granites (142–92 Ma) [10]. There is a high degree of temporal and spatial consistency and affinity between the formation of pegmatite and carbonate veins and the emplacement of the Huashan and Laoniushan granites. During the different stages, evidence of hydrothermal metasomatism was found. The authors propose that the Huayangchuan U–Nb–Pb deposit is the result of the simultaneous action of the carbonate veins and the emplacement of the Huashan and Laoniushan granite veins and the proposed for the deposit.

In summary, the authors conclude that:

- 1) The Huayangchuan U–Nb–Pb deposit occurs in the Archaean gneiss. The main ore-bearing rocks are pegmatite and various carbonate veins;
- The U–Nb mineralization occurred during the pegmatite stage within granitic pegmatites and migmatite-pegmatite veins. The U–Nb–Pb mineralization mainly developed during the carbonate rock stage within quartz-carbonatite veins;
- 3) Orebodies trend NW and are mainly controlled by the NW trending Huayangchuan Fault, followed by NNW trending secondary fractures;
- 4) The characteristics for the uranium mineralization within the pegmatite stage are presence of biotite-actinolite assemblages and in the carbonate rock stage are the biotite-aegirine-kaoliniteamphibole-apatite assemblages. In contrast, the characteristics of Pb mineralization are marked by brecciated aegirine-augite and metal sulphide combinations;
- 5) The authors propose that the Huayangchuan deposit is the magmatic-hydrothermal superposition type.

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THE RESULTS OF LABORATORY AND FIELD IN SITU LEACHING TESTS AT THE NYOTA URANIUM DEPOSIT (UNITED REPUBLIC OF TANZANIA)

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1. INTRODUCTION

The Nyota uranium deposit is located in the southern part of the United Republic of Tanzania (Tanzania). The geological setting of the deposit and its hydrogeological properties suggest that part of the resource could, potentially, be amenable to in situ leaching (ISL). In 2015–2016, the Uranium One Group conducted a range of studies to evaluate the possibility of ISL mining of the deposit. The studies consisted of laboratory core leaching, hydrogeological pumping tests and a field ISL test, carried out without processing of pregnant solutions. The ISL test aimed at determining the main ISL process parameters which are used for calculation of ISL mining parameters. The main ISL parameters are: uranium recovery, average uranium content in pregnant solutions, specific lixiviant consumption and the liquid:solid ratio.

2. DESCRIPTION

The Nyota uranium deposit, which forms a part of the Mkuju River Project, is located in southern Tanzania, some 470-km south-west of Dar es Salaam. The deposit is associated with a series of Lower Triassic continental sediments of the Karoo Supergroup, which are represented by poorly lithified gravels, sandstones and siltstones. There are three basic mineral forms that represent uranium mineralization: metaautunite, meta-uranocircite and phosphuranylite. The minerals form a dense interspersed yellowish-green colour in the mica–hydrogoethite cement and on the surface of detrital grains. Ore hosting rocks are of low CO_2 content are therefore considered as being non-calcareous.

Orebodies are defined using a 0.01% uranium cut-off grade. Within the orebodies, ore grade varies from >0.01% to 1.8% U. Within the central part of the deposit, orebodies are detected at shallow depths ranging from the surface down to depths of 60–70 m. Within the northern part of the deposit, uranium mineralization has been detected at a depth of 150–170 m. Groundwater depths range from 1–2 m within river valleys to 40–50 m at watersheds. Consequently, uranium mineralization is located partly above groundwater level and partly below. The ore hosting aquifer is unconfined and has neither overlying nor underlying regional aquitards.

On the 31.12.2016, proven and probable reserves of the Nyota deposit were estimated at 25 900 tU and measured and indicated resources were estimated at about 48 000 tU [1]. The existing development plan of the deposit provides for conventional open pit mining with hydrometallurgical processing of ore. Owing to the recent decline in the uranium market, Uranium One Group is considering other mining possibilities in addition to the open pit mining method. The geological and hydrogeological setting of the deposit suggested the potential for uranium mining by the in-situ leach method. In 2015–2016, Uranium One Group conducted research to evaluate the amenability of the uranium mineralization for ISL mining. The studies consisted of laboratory core leaching tests, hydrogeological tests and an ISL field test.

Laboratory tests were conducted on core samples obtained during the drilling campaign of 2015. The borehole location provided core sampling in the central, the north-eastern and the southern parts of the deposit. Core samples were crushed to the size of sand grains (0.5-1.5 mm) and averaged.

Laboratory leach tests were conducted in two modes: static and dynamic. The main objectives of static leaching were to determine the amenability of uranium to dissolve in the leaching solutions; to select an appropriate composition for the leaching solution and to determine a degree of homogeneity of the samples in terms of leaching. In static tests, 10 g samples were leached in flasks at a constant liquid:solid ratio of 10. On the basis of the results of preliminary leaching tests, a sufficient test duration was defined as 24 h. A series of preliminary tests also revealed sulphuric acid to be the most efficient lixiviant. Therefore, further static tests numbered 222 (71, 73 and 78 respectively). The test results showed that: (a) uranium mineralization is easy to leach, (b) all the samples are of the same type in terms of leachability and (c) uranium recovery for the entire sample batch is independent of uranium head grade and equals 100%.

In dynamic tests, filtration of leaching solutions through the core material was modelled. For this purpose, leach solutions were pushed upwards through the column loaded with 200 g core samples. Pregnant solutions were collected as samples of equal volume (25 mL) from the overflow and then analysed for uranium content, acid concentration and pH. Tests duration varied from 3 to 26 h. The results of the dynamic leaching tests were: uranium recovery 85–99%, average uranium content in pregnant solutions 69–1270 mg/L, sulphuric acid specific consumption 4–60 kg/kgU and a liquid:solid ratio of 1–4. These results are considered positive.

Hydrogeological studies consisted of single and cluster pumping tests which were conducted in hydrogeological wells drilled in 2015. The pumping tests were conducted in line with the ordinary technique, i.e. pumping at a constant discharge rate and monitoring at groundwater levels at the draw-down stage and recovery stage after pumping had stopped. Considering the possibility of deposit development by both open pit and in situ leaching, studies were conducted to evaluate hydrogeological properties of the upper part of uranium hosting aquifer. For that purpose, well screens were installed in hydrogeological wells at a depth interval of 6–83 m. Estimation of hydrogeological properties showed that uranium mineralization is distributed within the aquifer represented by sandstones of non-uniform permeability. Hydraulic conductivity of the sandstones determined in cluster pumping tests is 25–63 m²/d, suggesting that the aquifer is permeable in general.

The results of hydrogeological and laboratory leaching tests show that uranium mineralization is located in permeable sediments and can be dissolved by sulphuric acid solutions. These results made it possible to pass on to the implementation of an ISL field test.

ISL field testing was executed using the two-spot scheme, which was invented in the Russian Federation [2]. There are only two operating wells: the injection and the recovery ones. The flowrate of the recovery well should be greater than that of the injection well, and the ratio of these flowrates should be maintained constant throughout the test as this maintains the hydrodynamic isolation of the geological medium involved

in the ISL test. This ensures movement of the solutions from the injection to the recovery well and only within the sampling volume. The planar area of the sampling volume can be calculated using a formula, with the distance between the injection and the recovery wells and the ratio of their flowrates indicated. There is no time variable in the formula which means that the volume is stable over time. These features of the testing scheme allow reliable estimation of uranium reserves within the sampling volume, and uranium recovery in field tests as well. Maintaining a stable sampling volume of the geological medium is the main advantage of the two-spot testing scheme.

Pregnant solutions which are moving towards the recovery well are diluted by fresh groundwater when they are pumped off. The degree of dilution of pregnant solutions is controlled by the flowrate ratio of the recovery and the injection wells. The pregnant solutions from the recovery well are sampled and then pumped into a discharge well. There is no processing of the pregnant solutions. The discharge well is usually located far enough from the test site so as to avoid influencing the discharge on the test. The main objective of the ISL test is a determination of ISL parameters as follows: uranium recovery, average uranium content in pregnant solutions, specific consumption of lixiviant and the liquid:solid ratio. Taken together, these parameters are usually used for evaluation of amenability of deposits or orebodies to ISL mining in terms of geology and hydrogeology.

Two-spot tests were widely implemented on the deposits of the former USSR and Mongolia and they are currently applied in the Russian Federation and China [3]. The duration of ISL tests vary from 2 to 6 months, with an average of 3 months. Thus, two-spot testing is a comparatively cheap and quick exploration method which allows evaluation of the suitability of deposits for ISL mining.

Site selection for the ISL field test was based on the results of exploration drilling. Eventually it was decided to conduct the test in the southern part of the deposit, where uranium mineralization occurs below the groundwater table. There are two orebodies detected within the selected test site. The upper orebody is at a depth of 25–35 m, the lower one is at a depth of 43–50 m. The orebodies are divided by a layer, 8–10 m thick, in which the uranium grade is significantly below 0.01% U. The upper orebody is more regular in thickness within the test site and has a higher grade than the lower orebody. For these reasons it was decided to conduct the ISL test only on the upper orebody.

The test site has the following geological and hydrogeological characteristics (for the upper orebody): 9.6 m average thickness of the orebody; 0.078% average uranium grade; 13.2 kg/m² average productivity; the aquifer is unconfined; groundwater depth is 18 m; the upper boundary of the orebody lies at a depth of 27 m; discharge flowrates of the injection and the recovery wells are about 2 m³/h; the orebody has neither overlying nor underlying aquitards which is typical of the entire deposit.

The following parameters were set out for the test: the distance between the injection and the recovery wells was 6 m, screening interval was 25-35 m for the whole thickness of the orebody, the recovery and the injection flowrates ratio was 5. Concentration of sulphuric acid was initially planned to be 15 g/L, but almost at the beginning of the test it was increased to 30 g/L and maintained at this level throughout the test. The test duration was 10 months.

During the test, groundwater level monitoring was conducted in 5 monitoring wells and in 2 operating wells, the injection and discharge flowrates were monitored, leaching and pregnant solutions were sampled. In leaching solutions, sulphuric acid concentration and pH were analysed, in pregnant solutions uranium content, sulphuric acid concentration and pH were analysed.

3. RESULTS AND DISCUSSION

On test completion, the actual flowrate ratio of the recovery and the injection wells was 5.1, which is very close to the design value.

The uranium content in pregnant solutions throughout the test was typical for leaching with rapid increase in values at the beginning, rising to maximum of 170 mg/L and followed by slowly decreasing values. By test completion, the uranium content in pregnant solutions was 125 mg/L.

The average uranium content in pregnant solutions was increasing throughout the test. By the test completion it was 109 mg/L.

Sulphuric acid specific consumption always decreased during the test, as normally happens. By test completion, the specific consumption was 70 kg/kgU.

The liquid:solid ratio varied linearly during the test and was equal to 2.2 when the test was stopped.

According to the requirements of the actual guidance documents, ISL two-spot testing should be conducted until the leaching process is complete. ISL process completion is considered to occur when the uranium content in pregnant solutions decreases to minimum industrial values (10–15 mg/L). Only completed ISL tests give reliable uranium recovery and other process parameters which can be used for further feasibility analysis. Taking into account that the uranium content at the end of the test was still 125 mg/L, the test should be regarded as not completed to the normal end. Its results cannot, therefore, be used directly for any estimations, as they are not supposed to characterize the ISL process in full. In this case, ISL parameters can be estimated by their extrapolation beyond the test time frame. Extrapolation is available if the ISL parameters' trends clearly appeared during the test. The results available show that these trends appeared, so they were used for extrapolation of the relevant parameters.

A liquid:solid ratio value typical for ISL mining or which is often used in ISL development plans is 4. Therefore, the other test parameters were extrapolated to this liquid:solid ratio. According to uranium leaching dynamics, a liquid:solid ratio of 4 could have been achieved by the 458th day of the test. By that time, uranium recovery could be about 85%. By the end of the test, actual sulphuric acid specific consumption achieved the level values which were not expected to change significantly even if the test had been completed. Therefore, the final sulphuric acid specific consumption is on the same level as it was at the end of the test, i.e. 70 kg/kgU. The average uranium content of the pregnant solutions will be definitely higher than minimum industrial level of 10–15 mg/L and it is expected to be about 60–90 mg/L.

ISL tests results are usually assessed by comparison with their criterion quantities. The results are considered positive if all the parameter values meet their criterion quantities, which are as follows: uranium recovery >50%, average uranium content \geq 20 mg/L, sulphuric acid specific consumption <150–200 kg/kgU and a liquid:solid ratio <10. The extrapolated results tally with their criterion quantities. Consequently, the studies conducted by Uranium One Group confirmed the distinct possibility of applying ISL mining to the Nyota deposit.

The described ISL test at the Nyota deposit is the first one ever carried out in Africa and it yielded encouraging results. On this basis, it can be concluded that ISL mining is definitely possible, thereby making the mining business more economically efficient and environmentally friendly.

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ADVANCES IN HYPERSPECTRAL REMOTE SENSING TECHNOLOGY FOR THE EXPLORATION OF HYDROTHERMAL TYPE URANIUM DEPOSITS IN CHINA: A CASE STUDY IN THE XUEMISITAN AND LONGSHOUSHAN AREAS

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1. INTRODUCTION

Hyperspectral remote sensing technology has unique technical advantages in mineral identification [1], and is successfully used worldwide in mineral exploration [2, 3]. Since 2008, with the introduction of the internationally advanced compact airborne spectrometer imager (CASI), shortwave airborne spectrometer imager (SASI) and thermal airborne spectrometer imager (TASI) hyperspectral measurement systems in the Beijing Research Institute of Uranium Geology (CNNC), research into applications relevant to uranium exploration using hyperspectral remote sensing technology has entered a new stage of rapid development [3]. The Xuemisitan area in northern Xinjiang, is an important Cu–Fe–Au–W–Mo–U–Be metallogenic belt. Mineralization is mainly related to volcanic and magmatic hydrothermal activities. In the belt, a volcanic type U-Be-Mo polymetallic deposit (Baiyanghe) and a series of uranium anomalies have already been discovered. Therefore, favourable uranium polymetallic ore forming conditions and high prospecting potential are present in the Xuemisitan area. At the Baiyanghe uranium deposit and its surrounding area, the main formations are Devonian and Carboniferous volcanics, granite, granite porphyry, diabase veins, etc. The uranium orebodies are mainly located within the 50 m of the zone of contact between microcrystalline granite porphyry (the Yangzhuang pluton) and the underlying intermediate and acid volcanic rocks of the Upper Devonian Talbahaitai Formation (D_3t). The main hydrothermal alteration minerals are haematite, hydro-muscovite, carbonate and fluorite, and processes include silicification [4]. The Longshoushan polymetallic metallogenic belt is located in the Gansu province, where U, Th, Cu, Ni, Fe, Au, Ag and other mineralization have previously been discovered. There exist good metallogenic conditions and exceptional prospecting potential. The main strata are Proterozoic metamorphic rocks and Upper Palaeozoic Devonian, Carboniferous and Permian sequences. The magmatic activity during the Caledonian period included development of numerous intrusions, comprising ultrabasic, intermediate, acid and alkaline rocks. Hydrothermal activity was strong in the area and the main hydrothermal alteration related to uranium mineralization include albitization, carbonation, chloritization, haematitization, silicification and sericitization. The alkaline metasomatic type uranium deposits, such as at Jiling and the siliceous belt type uranium deposit at Gemigou, as well as the uranium deposits related to the alkaline body at Luchaogou were previously discovered in this zone. These areas are well exposed and suitable for the testing the application of hyperspectral remote sensing technology to uranium exploration, which could open up a new chapter in uranium exploration.

2. HYPERSPECRAL DATA AND PROCESSING METHODS

The hyperspectral remote sensing data used in this study include CASI/SASI/TASI airborne hyperspectral data acquired in 2011 and 2017, in addition to ground based spectrometric data and spectrometric data derived from borehole core. The spatial resolution of the CASI data was 1.0 m, its spectral resolution was 20 nm and the spectral coverage was 404–1047 nm. For the SASI data, the spatial resolution, spectral resolution and spectral coverage was 2.0 m, 15 nm and 950–2450 nm, respectively. For the TASI data, they were 2.0 m, 125 nm and 8000–11500 nm, respectively. The ground and borehole core hyperspectral data were obtained by using Field Spec Pro FR portable spectrometer supplied by the ASD company in the
United States of America. The spectrum of ASD data ranged from 350 to 2500 nm, with spectral resolution of 3 nm in 350–1050 nm and 8 nm in 1050–2500 nm. In order to extract the altered minerals, information from the airborne hyperspectral data, including the application of radiation, geometric and atmospheric corrections, spectral reconstruction, separation of temperature and emissivity, and mineral mapping were performed. For ground and borehole core spectrometric data, the main processes used were spectral curve analysis, mineral identification and statistical analysis. After extraction of mineral information, field verification and chemical analysis of samples were needed to ensure the accuracy of hyperspectral mineral mapping.

3. PRINCIPAL ADVANCES

In recent years, research on, and application of, hyperspectral techniques in uranium exploration has resulted in new advances. The applications to uranium exploration in China are presented below.

3.1. Hyperspectral remote sensing technology suitable for the exploration of hydrothermal type uranium deposits

Through systematically introducing the CASI/SASI/TASI airborne hyperspectral remote sensing technology to uranium exploration, a set of airborne hyperspectral detection technologies, combining data acquisition, mineral mapping, information analysis, model construction and exploration prospecting were established. The detection technologies specifically include CASI/SASI/TASI hyperspectral data acquisition technology, CASI/SASI airborne hyperspectral data processing and mineral mapping technology, TASI airborne thermal infrared hyperspectral data processing and identification technology of quartz-silica zones, information analysis technology for airborne hyperspectral mineral mapping, model construction technology for uranium deposits using hyperspectral information and prediction technology for uranium exploration using hyperspectral information. Among them, the information analysis technology for airborne hyperspectral mineral mapping, model construction technology for uranium deposits using hyperspectral information, and prediction technology for uranium exploration using hyperspectral information are the most important new advances. The information analysis technology mainly includes the genesis analysis technology of high-Al sericite, medium-Al sericite and low-Al sericite identified by airborne hyperspectral, mineral association analysis technology based on the concept of favourable metallogenic geochemical barrier and metallogenic environment analysis technology. Through research, a new concept about the genesis of high-Al sericite, medium-Al sericite and low-Al sericite was proposed. In this, high-Al sericite is considered to be formed in a relatively high temperature and acid hydrothermal fluid environment, whereas low-Al sericite was formed in a relatively low temperature and alkaline hydrothermal fluid environment. At the same time, three new types of mineral associations within the hyperspectral altered mineral suite were proposed to predict the favourable volcanic uranium hosting environment. The prediction technology for uranium exploration using hyperspectral information includes the method based on the above three types of mineral association, the method based on the uranium deposit location model and the method that integrates mineral mapping information with airborne radioactive information.

3.2. Analysis of hyperspectral characteristics of the Baiyanghe volcanic type uranium deposit

Using different scales of hyperspectral remote sensing data from airborne and ground surveys and drill holes, the hydrothermal alteration types on the surface and at depth in the Baiyanghe uranium deposit and its surrounding area were identified. Subsequently, the hyperspectral characteristics of the uranium deposit and the hydrothermal fluid expression on the surface and at depth were studied and analysed.

3.2.1. Alteration minerals

Alteration minerals such as pyrophyllite, dickite, alunite, kaolinite, high-Al sericite, medium-Al sericite, low-Al sericite, haematite, silicification, etc., have been identified in the deposit and its surrounding area.

According to the spatial distribution of these minerals, three alteration areas can be separated: northern, deposit and southern alteration areas. In the northern alteration area, a set of acidic hydrothermal alteration minerals comprising pyrophyllite, dickite, alunite and high-Al sericite were developed. High-Al sericite, medium-Al sericite, haematite and silicification are mainly developed in the deposit alteration halo, whereas low-Al sericite and medium-Al sericite are developed in the southern alteration area. The mineral assemblage of the northern alteration area is considered as an assemblage typical of an advanced argillic belt formed by volcanic gas and liquid boiling [5], developing from hydrothermal fluids sourced from an ascending magma [6] and indicating that the metallogenic fluids may have risen from shallow depths. Therefore, the northern alteration area is possibly a volcanic structure and regional hydrothermal fluid activities are centred on the Baiyanghe deposit and its surrounding area. The Baiyanghe deposit alteration area is characterized by strong development of high-Al sericite and medium-Al sericite and is an area of obvious fluid activity located on the side of the regional hydrothermal system. The southern alteration zone was an area of obvious hydrothermal fluid activity with temperatures decreasing with distance from the fluid activity centre.

3.2.2. Alteration temperature

In uranium deposit area, the hydrothermal alteration temperature is considered to be higher in the middle and west than in the east, and higher in the northern margin than in the southern margin. The northern margin is the contact zone between the Yangzhuang sub-volcanic body and Devonian intermediate and basic volcanic rocks; the alteration temperature was higher in the middle and western parts than in the east. This idea is based on the hyperspectral mineral information and the genesis analysis of high-Al sericite, medium-Al sericite and low-Al sericite already discussed. The SiO₂ content extracted from airborne thermal hyperspectral data is comparatively lower in the central and western parts than that in the eastern part. In the northern margin contact zone, high-Al sericite and medium-Al sericite developed, whereas in the southern edge low-Al sericite and medium-Al sericite developed. Moreover, in the northern margin contact zone, the alteration minerals varied from high-Al sericite to a mixture of high-Al sericite and medium-Al sericite; the Al–OH absorption wavelength of sericite altered mineral changed from being relatively short in the central and western regions to being comparatively long in the east. In vertical profiles in the contact zone, the Al–OH absorption wavelength of sericite showed the same variation according to proximity to or distance from the contact zone.

3.2.3. Hydrothermal episodes

At least two episodes of hydrothermal fluid activity are recorded at depth in the Baiyanghe uranium deposit. On the basis of mineral characteristics and sericite Al-OH absorption wavelength changes identified from drill hole core hyperspectral data, two phases of hydrothermal fluid activity at depth in the Baiyanghe uranium deposit have been discovered: direct flow and separate flow types. The direct flow type had the characteristics of continuous and directional Al-OH absorption wavelength change from 2195 nm to 2208 nm and to 2215 nm. This reflected the temperature of the hydrothermal fluid changing gradually from the relatively high temperature at depth to the more moderate temperatures in the vicinity of the contact zone and the relatively low temperatures in granite porphyry. Two drill holes (ZK5432 and ZK5630-1) located in the main mineralized area in the central and western regions were characterized as this type. It may be related to diabase veins, which are more developed at this location. The separate flow type had the characteristic variation in Al-OH wavelength from 2200 nm in the contact zone to 2210 nm at depth and to 2215 nm in the shallow zones, respectively. It reflected the relatively high temperature of the hydrothermal fluid in the vicinity of the contact zone. Drill holes ZK 3310 and ZK2710, which were drilled in the eastern part of the deposit, belong to this type. The temperature change of the hydrothermal alteration is also consistent with that in the northern margin of the deposit. The same fluid activity patterns appeared in different horizontal and vertical profiles.

3.2.4. Relationship between mineralization and hydrothermal activity

The relationship between uranium mineralization and hydrothermal fluid activity. From the spatial distribution of uranium mineralization and anomalies in the Baiyanghe deposit and its surrounding area, it is concluded that uranium mineralization had a positive correlation with hydrothermal fluid activity. Firstly, the uranium mineralization has specific relationship with the centre of regional hydrothermal activity. Identification of the hydrothermal activity centre is very important in predicting the regional uranium exploration area with respect to ore forming environments. Secondly, uranium mineralization is closely related to the relatively high temperature of the hydrothermal fluids. Drill holes ZK5432 and ZK5630-1 record good mineralization attributed to the direct flow type of fluid activity, which may be related to the invasion of basic rock veins and diabase veins. Therefore, this provides new evidence to support the close relationship between uranium mineralization and basic veins in the Baiyanghe uranium deposit area. Thirdly, the uranium mineralization and enrichment in the core occur mainly in the transitional zone between high-Al sericite and low-Al sericite alteration, where the hydrothermal activity was characterized by relatively high to moderate temperatures a chemistry varying from acid to neutral/weakly alkaline. Therefore, uranium mineralization may be closely related to the change zone of hydrothermal fluid temperature and acidity–alkalinity.

3.3. Analysis of the hyperspectral characteristics of uranium deposits in alkalic metasomatic and siliceous belts

By analysing the characteristics of different types of uranium deposit in the Longshoushan area using airborne hyperspectral information, preliminary ore forming features have been defined.

3.3.1. Hydrothermal alteration

The hydrothermal alteration characteristics in the Longqiangshan area are strong in the east and weak in the west, strong to the south-east and weak to the north-west. Hydrothermal alteration is closely related to NW, NNW and E–W trending faults. The hydrothermal alteration strength is relatively weak in the main uranium prospecting area. Hydrothermal alteration is mainly distributed in the outer part of the contact zone, between granite, alkalic bodies and basement metamorphic rocks. Alteration is relatively weak in the interior of granite bodies.

3.3.2. The Jiling deposit

The Jiling alkalic metasomatic type uranium deposit is located at the contact zone between granite and diorite, and the orebody is located in the red alkalic metasomatic alteration bodies that have been albitized. The main alteration minerals in and around the Jiling uranium deposit are haematite, medium-Al sericite, low-Al sericite, chlorite, carbonate and serpentine, and evidence of silicification present. Among this mineral suite, chlorite, carbonate and serpentine are mainly distributed along the ore controlled regional Malugou Fault. Secondary faults have mainly developed some medium-Al sericite and low-Al sericite alteration. The hydrothermal alteration surrounding the deposit is weak in the upper levels and on the surface but stronger in the outer parts along the NW trending Malugou Fault. The SiO₂ content is reduced in the north-west part.

3.3.3. The Gemigou and Lucaogou deposits

The Gemigou and Lucaogou deposits are considered to be part of the same hydrothermal activity system. The former is located at the contact zone between the granite body and the metamorphic rocks, and the Gemigou ore controlling fault. The latter is located on the interior side of contact zone between alkaline rocks body and metamorphic rocks. Whereas the former is characterized by silicification, kaolinization, high-Al sericite and carbonate, the latter is characterized by alkaline rock with alkali feldspar identified by

thermal infrared hyperspectral analysis. From the margin of the alkaline body to the south to the granite and metamorphic rocks to the north, there exist different alteration zones of Fe-rich chlorite, carbonate and low-Al sericite, high-Al sericite, kaolinite and silicification.

3.4. Uranium exploration prediction

Prospective areas for uranium were determined on the basis of the hyperspectral characteristics of volcanic type uranium deposits in the Xuemisitan area and of different types of uranium deposit in the Longshoushan area. In the Xuemisitan area, the hydrothermal activity centre was selected on a regional scale in the first instance. Then, these areas developed high-Al sericite and medium-Al sericite, especially haematization, acidic and basic rock veins were outlined as the target areas. Applying this new concept, several new uranium anomalies were discovered. In one of the selected areas, trenching has demonstrated that there is good uranium mineralization and ore controlling faults at depth. In the Longshoushan area, favourable areas were also predicted, although these still need to be verified. In addition, using hyperspectral remote sensing techniques has significantly improved the prediction results for Cu–Au prospecting in the Xuemisitan area.

4. CONCLUSIONS

Hyperspectral remote sensing technology has made a major contribution in identifying hydrothermal alteration minerals, analysing hydrothermal alteration and fluid activity and determining ore controlling structures in the Xuemisitan and Longshoushan areas. This is an important new technology for uranium exploration and has made new breakthroughs in uranium and polymetallic mineral exploration. In the future, it is necessary to strengthen the comprehensive analysis of alteration minerals, structure and lithology identified by hyperspectral remote sensing. It is very important to combine hyperspectral information with fluid metallogensis and uranium ore forming models, so as to exploit the prospecting information provided by hyperspectral remote sensing data to the full. If this can be achieved, then hyperspectral remote sensing technology will flourish and exploration for uranium will be more effective.

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THE FUNDAMENTAL RESEARCH AND INDUSTRIAL APPLICATION OF THE CO2 AND O2 IN SITU LEACHING PROCESS IN CHINA

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1. INTRODUCTION

Owing to the advantages of reduced chemical reagent consumption and groundwater pollution, the CO_2 and O_2 in situ leaching (ISL) process became to be one of the important research fields in uranium mining. China was the second country in world to apply the CO_2 and O_2 ISL process in uranium production. This extended abstract describes the development and characteristics of the CO_2 and O_2 ISL process in China, including the main principles, technological processes, well-field design, production well construction and uranium processing. Finally, the industrial application status and development potential of the CO_2 and O_2 ISL process in China is summarized.

2. DISCOVERED URANIUM RESOURCES STATUS AND DISTRIBUTION

There are 21 known uranium ore deposits in China, distributed in throughout 13 provinces, including Inner Mongolia, Xinjiang, Jiangxi and Guangdong. Since 1994, the exploration targets changed from those deposits suited to conventional mining in southern China to deposits in northern China which are amenable to in situ leaching. A number of medium–large scale sandstone uranium deposits have been discovered. As a result, the U resources/reserves have increased rapidly since 2000.

China's identified resources (reasonably assured and inferred) amount to 370 900 tU, although the potential for more than 2 million tU is predicted. Uranium deposit types and their share of uranium resources in 2016 were listed as follows: sandstone (56.9%: 210 000 tU), granite (23.6%: 87 000 tU), volcanics (11.1%: 41 000 tU), carbonaceous–siliceous–pelitic (7.5%: 28 000 tU) and others (0.9%: 3500 tU). The sandstone hosted uranium resources mainly come from six basins located in northern China: Yili, Turpan-Hami, Ordos, Erlian, Songliao and Bayin Gobi. The Yili and Songliao Basins are the key and potential areas for future development.

Most sandstone uranium deposits in China are complex and about 70% of these are have adverse factors such as high carbonate content (>2.0% CO₂), low permeability (<0.17 m/d), low uranium grades (~0.03%) and high salinity groundwater (total dissolved solids 5–10 g/L).

3. BRIEF DEVELOPMENT HISTORY OF CO₂ AND O₂ ISL

The CO_2 and O_2 in situ leaching process for uranium has been under development in China since 2000. Some CO_2 and O_2 leaching experiments have been carried out to simulate CO_2 and O_2 leaching characteristics and some technical parameters have been obtained.

Since 2006, a field test and industrial tests have been implemented at the Qianjiadian uranium deposit in the Songliao Basin, Inner Mongolia. The depth of orebody is 251.8–298.31 m and it has a thickness of 6.46–15.75 m, a mean grade of 0.025% U and a mean uranium content of 3.95 kg/m². The modes of occurrence of uranium in the Qianjiadian deposit include absorbed uranium, uranium minerals and uranium-bearing minerals. The ratio of U(VI):U(IV) is 0.266:1.116 with an average value of 0.761.

The permeability coefficient of the ore-bearing aquifer is 0.025-0.223 m/d and the depth of confined water is 5.29-7.06 m. The type of water (chemistry) is a combination of HCO₃-Na and HCO₃-Cl-Na with a salinity range of 3.10-5.7g/L, a pH of 7.2-8.4, and an Eh of 100-200 mV.

An industrial scale well field had been established, including 10 production wells and 32 injection wells. Depending on orebody geometry and surface topography, 7 spot well patterns and a 35 m well spacing were used. For injection wells, the average flow rate is 2.8 m³/h, the equivalent average flow rate for recovery wells is $8.1 \text{ m}^3/\text{h}$.

4. CO₂ AND O₂ LEACHING PROCESS

Both gaseous oxygen and carbon dioxide are added to groundwater to produce lixiviant. Oxygen is typically added to maintain the strongly oxidizing conditions required to oxidize tetravalent uranium in ore minerals to the hexavalent stage. The oxygen concentrations vary from 150 mg/L to 500 mg/L for different leaching stages, depending on uranium concentration and the dissolved oxygen of the lixiviant. Carbon dioxide is added for pH control and increasing bicarbonate concentration. Carbon dioxide concentrations vary from 100 mg/L to 300 mg/L.

After 2 years of operation, uranium recovery has been up to 53.1% with a liquid:solid ratio of 2.64, while average uranium concentration was about 32 mg/L. Specific consumption of CO_2 was 10.8 t/tU and specific consumption of O_2 was 12.0 t/tU. The flow rate of the recovery well and injection well remained stable, which indicated that calcium carbonate scaling was not generated, which may otherwise adversely impact the field test.

Uranium mobilization and processing excess water must be properly managed. The production wells extract slightly more water than is re-injected into host aquifer. The production bleed is more than 0.3–1.0% of the circulation rate. The main purpose is to maintain the negative balance and help to minimize the potential movement of lixiviant.

Some technical parameters include the following:

Well pattern: 5 spot and 7 spot; Well-spacing: 30-35 m; Drilling hole structure: gravel filling type; Depth: 240-320 m; Lixiviant: 100-300 mg/L CO₂ + 150-500 mg/L O₂; Recovery rate: >75%; Uranium extraction: ion exchange process with fixed bed column; Water waste treatment: reverse osmosis and evaporation ponds.

5. URANIUM PROCESSING

The ion exchange resin D261 is widely used in ISL projects in China and the ion exchange circuit is accomplished in two fixed bed columns in series. On the basis of average uranium concentrations (about 32 mg/L), more than 97% of the uranium is extracted during the ion exchange process. The stream exiting the lixiviant columns normally contains less than 0.1 mg/L. Before entering the ion exchange columns, CO_2 was added into the pregnant solution with the concentration varying from 100 to 300 mg/L. The purpose is to maintain the pH in the range 6.8–7.2 and increase the saturated resin load.

The elution process is accomplished in columns arranged in series by contact of the resin with a mixed solution of sodium chloride and sodium bicarbonate, thus obtaining a pregnant eluant solution with about 35–50 g/L. Typical operational parameters are 80–120 g/L of sodium chloride and 10–20 g/L sodium

bicarbonate. The recovery rate of the elution process is normally around 99.9%. After enough pregnant eluant solution is obtained, it is moved to the precipitation circuit.

In the precipitation circuit, the pregnant eluant is typically acidified using hydrochloric acid to destroy the uranyl peroxide. The pH of the pregnant eluant decreased to about 3.0–4.0 and was maintained for 4 h, accompanied by stirring. Caustic soda is then added to precipitate the uranium as sodium diuranate at a pH of 6.0–7.0. Finally, the resulting slurry is sent to a plate-and-frame filter press where it is filtered and washed. According to the natural uranium product quality standard, the uranium content is required to be equal to or exceed 60% in solid material and the water content is required to be equal to or less than 30%.

During the process, some liquid waste is generated which may contain elevated concentrations of radioactive and chemical constituents. Reverse osmosis is commonly used to segregate contaminants. Through the reverse osmosis process, two fluids were yielded: clean water (about 70% $Cl^- <350 \text{ mg/L}$) that can be reinjected into the aquifer and brine (about 30%) which is sent to the evaporation pond.

6. ISL MINES PRODUCTION STATUS AND POTENTIAL APPLICATION

Owing to the advantages of low operating cost, shortened loading period and reduced environment pollution, the proportion of uranium produced by in situ leaching mines has increased rapidly. In China, in situ leaching production dominates uranium production, accounting for 65.6% of production in 2016, exceeding both heap leaching and conventional mining, the second and third principal modes of extraction.

In the period 2006–2009, the first CO_2 and O_2 ISL project came into commercial operation at the Qianjiadian uranium deposit in Inner Mongolia. As regards the ongoing discovery of ISL amenable sandstone hosted uranium resources, two CO_2 and O_2 ISL mines have now been put into operation respectively, in the Songliao and Yili Basins. Other two mines are undergoing pilot scale tests in the Erdos and Erlian Basins. These will be put into production soon.

China National Nuclear Corporation has shut down some high cost underground and open pit uranium mines in southern China, and instead is focusing on the development of ISL amenable sandstone uranium resources in northern China and on plans to build three 1000 tU/year ISL mines by 2020.

7. CONCLUSION

Owing to successful application results and strict environmental requirements, CO_2+O_2 ISL has become a priority option and indeed the only option for sandstone type uranium deposits with high carbonate contents and high salinity groundwater. According to the development plan, about 90% of natural uranium production will be provided by ISL, especially by the CO_2 and O_2 method. Some large scale and 'green' mines are undergoing planning and implementation.

URANIUM FROM DOMESTIC RESOURCES IN POLAND

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1. INTRODUCTION

Uranium mining activities in Poland were undertaken in the Sudetes from the end of the 1940s until 1968. The R-1 industrial plant in Kowary processed uranium ores until 1973. Outside the Sudetes region, uranium was also discovered and mined from the Staszic pyrite deposit in Rudkiin, in the Holy Cross Mountains. Total production of uranium in Poland during this period is estimated at about 650 tU [1]. The mining activities resulted in the legacy of some 100 dumps, mostly abandoned, of waste rock and ore totalling approximately 1.4×10^6 m³ as well as one tailings pond, which has been the object of a remediation project partly funded by European Commission aid since 2001 [2].

In the Polish lowland, in the area of the Podlasie Depression (north-eastern Poland), concentrations of uranium were discovered in the Lower Ordovician Dictyonema shale. In the 1970s, about 1400 tU were discovered at an average content of 250 ppm and 3800 tU at a content of 75 ppm (the 'Rajsk' deposit). Even then, this occurrence was considered to be uneconomic. The most interesting uranium mineralization in the Poland occurs in the Lower and Middle Triassic rocks of the central parts of Peribaltic Syneclise (northern Poland). The highest concentrations were found in the sandstone–conglomerate continental series of the Upper Bundsandstein, with a layer thickness of about 3.4 m. The average uranium content is 0.34%, with a maximum content greater than 1.5% U. Uranium is accompanied by other metals, such as V, Mo, Pb and Se.

In January 2014, the Government of Poland adopted the Programme of Polish Nuclear Energy [3]. One of the objectives of this Program is to assess the recovery of uranium from domestic uranium deposits as a potential source of nuclear fuel for domestic nuclear reactors. Studies on the prospects of recovery of uranium from domestic resources are ongoing and reflect the inevitable growth in uranium demand and the perspectives of the global uranium market.

2. CONVENTIONAL RESOURCES OF URANIUM IN POLAND

Poland, in common with many countries, only has only low-grade uranium ores. In the period of 1948–1972, there were five mines actively extracting uranium ores in Poland. Four of them were located in the Sudetes, and one outside of this region, at Rudki near Nowa Slupia, in the Holy Cross Mountains [1]. The uranium content in these deposits was typically about 2000 ppm U. Currently, there is no active uranium mining in the country. In the second half of the 20th century, the Polish Geological Institute (PGI) made numerous assessments of the prospects for discovering uranium ore deposits in Poland [4]. According to the PGI estimates, the Ordovician Dictyonema shales of the Podlasie Depression seem to be the most prospective, with uranium concentrations in the 75–250 ppm range and the sandstones of the Peribaltic Syneclise (Paslek–Krynica Morska), where uranium concentrations even attain 1.5%. These deposits, as a potential source of uranium for domestic nuclear power plants, were investigated by the PGI and the Institute of Nuclear Chemistry and Technology (INCT) as part of the Operational Programme–Innovative Economy (POIG) project implemented in 2010–2013. Within the framework of the POIG project, Polish uranium deposits and their exploitation options were reassessed. On the basis of archival ore samples recovered from

previously tested boreholes, various technological schemes and methods of extracting uranium from domestic ores were examined with an initial economic assessment of the studied processes. Optimal leaching conditions for uranium from both the Dictyonema shales and the sandstones as well as uranium separation from other metals, such as rare earth elements that have undergone leaching into the aqueous phase, have been found [5–8]. It has been shown that it is possible to sequentially separate these metals from the solution by means of ion exchange [9]. Uranium can also be separated using solvent extraction [10]. An alternative to solvent extraction carried out in traditional reactors or columns is extraction using membrane contactors, which constitute modern separation systems, allowing for two processes to be carried out: extraction and re-extraction at one installation [11, 12]. An effective and selective extractant plays an important role in the extraction process. In recent years, great interest has been shown in new uranium leaching agents such as calixarene derivatives [13]. The project has developed a synthesis path for these compounds. These compounds may also find other applications in the nuclear fuel cycle, e.g. for the separation of fission products and minor actinides from spent nuclear fuel. By using a membrane module with a helical flow in the uranium ore leaching process, high U leaching rates were obtained. In this system, it is possible to simultaneously separate the leachate from the remaining solid phase (parent rock) [14]. Such a method of conducting the leaching process, with the simultaneous filtration of the sludge in the membrane contactor with the helical flow, became the basis for the patent application submitted to both the Patent Office of the Republic of Poland and the European Patent Office [15].

In 2014, Poland completed a geological and technological analysis and modelling of the process of uranium extraction from low grade Ordovician Dictyonema shale (black shale type). Analysis has shown that the cost for obtaining raw material for production of 1 kg of uranium would be several times higher than the current market price [16].

3. URANIUM FROM UNCONVENTIONAL SOURCES

Although uranium concentrations in unconventional sources are low, when combined they comprise an inexhaustible resource of uranium for future use. One of these sources is phosphate, which constitutes the raw material for the production of chemical fertilizers. Phosphate-bearing rocks contain the highest quantity of uranium of all unconventional uranium deposits worldwide. In Poland, phosphorites are found in vicinity of Annopol, in the Holy Cross Mountains. The exploitation of phosphate rock in the country began in the interwar period and was discontinued in the 1970s. The mine at Chalupki was closed in 1961 and that at Annopol in 1971. At present, domestic demand for phosphate rock is entirely covered by imports from countries such as Algeria, Egypt, Morocco, Senegal, the Syrian Arab Republic and Tunisia.

The first stage in the production of phosphate fertilizers from phosphate-bearing rock is the production of phosphoric acid. In this process, ground phosphorite is treated with sulphuric acid, which forms phosphoric acid and an insoluble calcium sulphate (gypsum) precipitate that contains the remaining raw material. Phosphogypsum, after washing with water, is stored as waste. Most of the uranium contained in phosphorite reports to the phosphoric acid. In the 1980s, both INCT and the Wroclaw University of Technology worked on a technology for recovering uranium from phosphoric acid that was developed for expected use at the chemical works at Police. According to this technology, uranium can be extracted from phosphoric acid in a coupled extraction–re-extraction process. The mixtures of mono- and dinonyl-phenylphosphoric acids (NPPA) and D2EHPA and TOPO were used as extraction agents in this process.

In 2015, INCT, together with PwC Sp. zo.o, as part of the Bridge Mentor project, prepared a preliminary analysis of the possibilities of obtaining uranium from industrial phosphoric acid by the hybrid method, which was a combination of solvent extraction coupled with membrane processes. The project was undertaken at the chemical works in Police (at present the AZOTY Group).

Phosphogypsum typically contains many different components such as heavy metals, among them some quantities of uranium. During the production of phosphate fertilizers, part of the uranium contained in

phosphate rock passes to solid waste and is collected in waste heaps. In Poland, phosphogypsum dumps are located in Police, Wizow and Wislinka, near Gdansk. These landfills are heterogeneous in chemical terms, because over the years, various raw materials have been used for the production of phosphate fertilizers. In phosphogypsum samples collected from the landfill in Wislinka in 1997, the uranium concentration was 4.03 ± 0.08 mg/kg, while in the samples dating from 2007, the uranium concentration was significantly lower (0.65 ± 0.05 mg/kg) [17, 18]. The waste heap in Wizow, which is a residue from the production of fertilizers from apatite originating from the Kola Peninsula (magmatic rocks), does not contain uranium, but has a significant concentrations of rare earth elements. Uranium from phosphogypsum can be recovered by washing with sulphuric acid [19, 20].

In some parts of the world, there exist carbon deposits with elevated uranium content. The average uranium concentration in Polish coal from mines located in the Upper Silesia, Lower Silesia and Lublin regions is approximately 2 ppm. Research conducted at the Polish Geological Institute did not show differences in content according to the origin of the coal [21]. Uranium can also be obtained from coal ash; its content in coal ash from domestic coal-fired power plants amounts to several parts per million [22].

Another source of uranium could be the copper industry. As in the case of the Olympic Dam mine in Australia, uranium can be obtained as a by-product of the production of copper by KGHM. Studies of copper industry waste as an alternative source of uranium were conducted by INCT as part of the POIG project. The uranium content in the tested waste samples was not high, while the occurrence of other valuable metals was observed [23]. The recovery of uranium and other metals from industrial waste, by-products and phosphates is currently being investigated by INCT as part of a project coordinated by the IAEA.

Determination of uranium content in the fluids recovered from the hydraulic fracturing of shales in the process of searching for domestic natural gas deposits has also been carried out at INCT. The highest uranium concentration found in the fluid samples was 3.5 ppm U. The possibility of recovering uranium from these wastewaters has been demonstrated [24].

The other possible secondary source of uranium could be uranium tailings and old dumps, which were abandoned after mining of uranium at Sudetes ceased. Reserves of uranium in waste heaps derived from prospecting and extractive operations in this region during the period 1948–1967 are estimated at 10–30 tU.

4. CONCLUSION

Research projects conducted in Poland in recent years have confirmed the presence of low grade uranium deposits. Methods for its extraction from black shale and sandstones within the framework of the POIG project were developed. The results collected as part of the project confirmed that currently there is no economic justification for the exploitation of Polish host rock with low uranium content, but the situation may change with the continuing development trend of nuclear energy in the world and gradual depletion of high grade uranium resources.

The secondary sources of uranium in the country were also assessed. The most promising ones are waste from the copper industry and phosphoric acid obtained in the production of phosphate fertilizers.

In May 2012, September 2013 and October 2013, three concessions for prospecting for polymetallic uranium deposits for a private company were granted ('Radoniow', 'Wambierzyce' and 'Dziecmorowice' areas in the southern part of Lower Silesia). At present, geological exploration for uranium mineralization is not conducted in Poland.

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THORIUM RESOURCES IN CHINA: SPATIAL DISTRIBUTION, GENETIC TYPE AND GEOLOGICAL CHARACTERISTICS

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1. INTRODUCTION

Thorium is a radioactive element and widely distributed in nature, with average content of 10.5 ppm in the upper crust of the Earth [1]. Nowadays, the thorium resource has been regarded as a potential energy source, as more nations are seeking clean energies to reduce carbon dioxide emissions caused by the traditional oil, gas and coal fired power plants. Several test reactors designed in Europe, Japan, India, the Russian Federation and the United States of America have successfully generated electricity using thorium fuel sources [2], although it still remains in the experimental stage.

The specialized and systematic exploration and evaluation of thorium resource have not been carried out in China to date. However, at least 90 Th-bearing deposits or occurrences have already been reported as having been discovered during exploration for other resources (e.g. U, REE, Nb). In recent years, some reconnaissance work for thorium resources has been carried out in China, using a combination of literature research and comprehensive analysis, as well as geological investigation of some representative deposits. This has resulted in a preliminary summary of the spatial distribution, genetic type and geological characteristics of the thorium deposits in China.

2. SPATIAL DISTRIBUTION

The thorium deposits have been recognized in all the first-level tectonic units in China, from north to south, including the Central Asian Orogenic Belt, North China Craton and Tarim Block, Central China Orogen (Kunlun–Qilian–Qinling–Dabie Orogenic Belt), Yangtze Craton and South China Block, as well as the Tibet–Sanjiang Orogenic Belt. Most of these Th deposits or occurrences are concentrated in the following tectonic subunits:

(i) The northern margin of the North China Craton, represented by the well-known Bayan Obo Th–Fe–REE deposit [3] and the Saima U–Th–Nb–REE deposit [4];

(2) The Central Asian Orogenic Belt, represented by the Ba'erzhe (or Balingyao) U–Th–REE–Nb deposit [5];

(3) Central China Orogenic Belt, represented by the Huayangchuan U–Th–Nb deposit [6];

(4) South China (including Yangtze Craton and South China Block), including a series of placer Th deposits and several hydrothermal type Th deposits (e.g. Xiangshan U–Th orefield);

(5) Mian'ning-Dechang metallogenic belt in south-western China, represented by the Maoniuping, Muluozhai and other similar Th–REE deposits [7].

3. GENETIC TYPE

Most of the Th deposits in China have other commodities, including U, REEs and high field strength elements (Nb, Ta, Zr). According to the geological and geochemical features, the major genetic types of Th deposit identified in China so far mainly include: (i) magmatic, (ii) hydrothermal and (iii) placer. These deposits have different ore element assemblages.

The magmatic type deposits can be further divided into:

- (a) The alkaline silica undersaturated nepheline syenite-related Th–U–Nb–REE mineralization system, as exemplified by the Saima deposit in north-eastern China at the northern margin of the North China Craton [4].
- (b) The alkaline silica oversaturated granite-related Th–U–Nb–REE deposit, Ba'erzhe deposit in the eastern Central Asian Orogenic Belt [5] and Boziguo'er [8] in Xinjiang Province at the south-western margin of the Central Asian Orogenic Belt are both examples of this type.
- (c) The carbonatite-related Th–U–REE deposit, represented by the renowned Bayan Obo Th–Fe–REE deposit (the largest REE and Th deposit in the world [4]) and a series of Th–REE deposits (including Maoniuping, the third largest REE deposit in the world) in the Mian'ning–Dechang metallogenic belt in south-western China [7].

The hydrothermal type Th deposits are those typically related to hydrothermal fluid activities and are relatively uncommon compared with magmatic type Th mineralization systems. This is consistent with the relatively stable geochemical behaviour of thorium, although some hydrothermal type Th deposits have been recognized, including the Zoujiashan U–Th deposit in the Xiangshan orefield, south China [9] and the Xinshuijing U–Th deposit in the Longshoushan metallogenic belt in north-western China [10].

The placer type monazite deposit is the most common Th deposit type, not only in the world but also in China. The placer monazite deposits are widespread in south China (in both the Yangtze Craton and South China Block) where the river systems are well developed, which is favourable for the formation of this type of Th mineralization. Examples of placer type Th deposits include the Juanshui monazite placer in the Mufushan area in the Central Yangtze Craton and several similar ones along the south-eastern coastal areas.

4. SUMMARY OF GEOLOGICAL FEATURES OF EACH Th DEPOSIT TYPE

For magmatic type Th deposits, the main geological features include:

- (i) All exhibit intimate spatial-temporal and genetical relationships with the host magmatic rocks, no matter whether they are peralkaline nepheline syenite (Saima), peralkaline granite (Ba'erzhe) or carbonatites (Bayan Obo).
- (ii) The mineralization is commonly controlled by the morphology of the causative plutons or the contact zone between the magmatic rocks and host rocks, although local fracture zones and faults are also favourable locations for ore mineral precipitation. For instance, Th–U–REE orebodies are mostly concentrated along the contacts between the nepheline syenite and host marbles in the Saima deposit [4].
- (iii) The major ore minerals are commonly refractory accessory minerals, including zircon, thorite, pyrochlore, monazite, xenotime, F⁻, CO₃²⁻-bearing REE minerals (bastnaesite, synchysite, parisite).
- (iv) Although the mineralization is mostly related to the magmatic fractionation crystallization process, the enrichment and overprinting of volatile-rich fluids sometimes also play important roles in the formation of the polymetallic mineralization. For example, the mineralization stage of the Saima deposit includes the magmatic crystallization stage, skarn mineralization stage and later hydrothermal type pitchblende vein stage [4].
 - (v) Magmatic type Th deposits were mostly formed in post-collisional or 'within plate' extensional tectonic settings, although the age of formation can vary from Neoproterozoic (Bayan Obo), to Late Palaeozoic (Boziguo'er), to Mesozoic (Saima and Ba'erzhe) or to Cenozoic (Maoniuping).

The representative geological characteristics of the hydrothermal type Th deposits are mainly:

- (i) Strictly controlled by linear structures, including faults or fracture zones.
- (ii) Most of these systems are intimately related to the alkali metasomatism, with the typical alteration assemblage of albite + haematite + chlorite + carbonate, such as in the Xiangshan and Xinshuijing deposits.
- (iii) The major Th minerals are thorite and uranothorite, but some fine-grained Th-phosphate aggregates have also been recognized in certain deposits, suggesting low temperature conditions [10].

Placer type Th deposits in China have the following features:

- (i) Can be further divided into the river/stream placer, beach placer or off-shore placer subtypes according to different sedimentary environments.
- (ii) The major ore minerals are dominated by monazite, together with other heavy minerals including ilmenite, rutile, magnetite, xenotime, zircon, etc., resulting from weathering of the solid source rocks, which are mostly granites.

5. CONCLUSIONS

(1) Thorium deposits have been recognized in all the first level tectonic units in China but are mostly concentrated in the northern margin of the North China Craton, the Central Asian Orogenic Belt, South China and the Mian'ning-Dechang metallogenic belt.

(2) The major genetical types of the Th mineralization systems recognized in China are magmatic, hydrothermal and placer types.

(3) The magmatic type Th deposits are mostly located at the craton margins or in the collision belts and are genetically related to alkaline syenite, alkaline granite or carbonatite magmatic activities during different geological times, and sometimes overprinted by the post-magmatic hydrothermal fluid processes. The hydrothermal type ones are commonly controlled by faults, fractures or breccias, while the placer Th deposits are mostly located in south China in both the coastal areas and inland river systems.

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ABSTRACTS

CENTRAL JORDAN URANIUM PROJECT: MONITORING THE PROJECT MATURITY VIA THE APPLICATION OF THE UNFC-2009

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Abstract

The uranium deposits in the Central Jordan Uranium Project (CJUP) are primarily hosted by the Muaqar Chalky Marl Formation of upper Maastrichtian age, part of the Upper Cretaceous to lower Tertiary Belqa Group. Uranium exploration and resource estimation were performed over two phases in this project, Phase I (2009-2014) and Phase II (2016). Metallurgical testwork indicated the amenability of the ore to static leaching using alkaline lixiviants. Higher level process development and engineering endeavors are currently culminating into the construction of a processing pilot plant. This case study demonstrates the advantages of using the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to monitor the project maturity of CJUP over different phases of exploration and technical viability. The project progressed from a "Potentially Commercial Projects/Development on Hold" project in Phase I to a more mature "Potentially Commercial Projects/Development Pending" in Phase II. The application of UNFC-2009 to the CJUP study in Jordan clearly demonstrates the advantage of tracking the project from a lower maturity level of assessment to a higher level. Therefore, classification and reporting of uranium project results using UNFC-2009 have clear advantages for policy makers in Jordan, as well as for internal company requirements for monitoring the progress of a project over time.

SUPPORTING SUSTAINABLE DEVELOPMENT OF URANIUM RESOURCES IN AFRICA

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H. TULSIDAS United Nations Economic Commission for Europe, Geneva, Switzerland

Abstract

The IAEA contributes to the balanced development of uranium resources in Africa by facilitating the application of good practices in uranium production cycle, from exploration to closure and remediation, which in turn contribute to the socioeconomic development of the region. From 2014 it enacted a major, four-year regional Africa project through its Technical Cooperation (TC) programme on supporting the sustainable development of uranium resources. This project, RAF2011, was in continuation of a regional Africa uranium-themed project that was commenced in 2009, and the work will be continued with a follow-on regional project from 2018. The main activities were general and specialized workshops and training courses held in African Member States, supporting the sustainable development of uranium resources there. A Uranium Production Site Appraisal Team review mission was undertaken for the first time in Africa (in Tanzania) under the framework of this project. This paper summarizes the activities of the project and looks forward to planned activities for the follow-on project, which have been refined based on feedback from the participants and the specialized experts who have assisted the IAEA with this project.

COST EFFECTIVE HEAP LEACHING, THE CASE STUDY OF MUTANGA, ZAMBIA

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Abstract

GoviEx Uranium Inc ("GoviEx") holds several contiguous mining and prospecting licences in Southern Zambia that are grouped as the Mutanga Project. The deposit comprises of shallow sandstone hosted uranium ore. The Mutanga Project contains a mineral resource of 96.2 million tonnes ("Mt") of ore at an average grade of 283 ppm U_3O_8 (~240 ppm U) containing 60.0 million pounds ("Mlb") of U₃O₈ (~23,000 tU) in six deposits (Mutanga, Dibwe East, Dibwe. Gwabe, Njame, and Njame South). located over 65 km strike. Processing of the ore has been demonstrated to be effective using sulfuric acid leaching with ion exchange recovery of uranium. Test work has confirmed heap leaching is viable and permeability of the ore is good with low acid consumption at 3-18 kg/t. The process is robust, simple and has a low environmental profile. Overall uranium recovery varies with recoveries from each of the deposits averaging 74 to 94%.

An important aspect of improving project economics is to rely on a central process recovery close to the main deposits of Mutanga and Dibwe East and using satellite heaps and adsorption circuits to obtain uranium and transport it absorbed on ion exchange resin to the main recovery plant. This allows a large cost saving in transport of ore and allows for optimization of heap conditions in each of the heaps focused on the locally mined ore. For Mutanga-Dibwe East leach pad, pregnant leach solution will be pumped to the adjacent central process plant for stripping and concentrating uranium. For the other deposits pregnant leach solution will be pumped to an adsorption plant where uranium will be stripped of uranium and loaded onto resin. Approximately 24,000 L/d of resin will be transported by truck to the central process plant for concentrating, barren resin will be trucked back to satellite operations. Uranium production recovery is expected to be on average of 2.4 Mlbs U₃O₈ (~900 tU) per annum of uranium contained in uranium oxide. Life of mine capital cost for the project is low at USD167M and operating costs of approximately USD20/t of ore processed (equivalent to USD31/lb). The return on the project has reasonable post tax Net Present Value of USD114M (at 8% discount) and internal rate of return of 25% based on a uranium price of USD58/lb U₃O₈. To achieve this with a low grade deposit required lateral thinking about exploiting efficiencies of the different ores and removing redundant processes in order to deliver a realistic project. Such an approach can improve project economics (even at low uranium prices) and provide sustainable mining operations.

IAEA SAFEGUARDS ASPECTS OF, AND ISSUES IN, URANIUM MINING AND ORE PROCESSING

B. BOYER, J. DISSER International Atomic Energy Agency, Vienna, Austria

Abstract

As part of the efforts to strengthen international safeguards, including enhancing its ability to provide credible assurance of the absence of undeclared nuclear material and activities, the IAEA is making use of increased amounts and types of information on Member States' nuclear and nuclear related activities. This information includes declarations provided by States (e.g. in accordance with safeguards agreements and/or the Additional Protocol), information collected by the IAEA (e.g. inspectors' findings, environmental sampling data) and other information available to the IAEA (e.g. open sources, satellite photographs and data). In seeking technical tools to aid enhanced information analysis, the IAEA's Department of Safeguards developed the Physical Model under Task 5 of Programme 93+2. This includes all the main activities that may be involved in the nuclear fuel cycle. Volume 1 of the Physical Model addresses the key aspects and indicators associated with uranium mining and processing. The revised Volume 1, entitled Mining and Ore Processing, is the product of a group effort of experts from within the Department of Safeguards, other Departments within the IAEA and Member States. This presentation will provide an overview of the role of Volume 1 of the Physical Model.

OVERVIEW AND UPDATE ON THE SEAWATER URANIUM RECOVERY FROM TECHNOLOGY DEVELOPMENT SPONSORED BY THE U.S. DEPARTMENT OF ENERGY

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S. KUNG U.S. Department of Energy, Washington, D.C.

United States of America

Abstract

The ocean contains a large quantity of dissolved uranium (over 4 billion tonnes U) and has long been regarded as an inexhaustible uranium resource. However, due to its low concentration in seawater (3.3 parts per billion), developing a cost-effective recovery method remains a challenge. In October 2010, the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) held a workshop on "Technology and Applied R&D Needs for Nuclear Fuel Resources" to evaluate the emerging research areas that have the potential to significantly impact the future technology development needed to ensure the availability of natural uranium resources for global nuclear expansion. Based on the workshop report, DOE-NE assembled a multidisciplinary team from national laboratories, universities, and research institutes to start a technology driven, science-based research program focused on extraction of uranium from the most challenging but highest-payoff unconventional resource: seawater. The program objective is to develop advanced adsorbent materials that can simultaneously enhance uranium sorption capacity, selectivity, kinetics, and durability to reduce the technology cost and uncertainties. Through these efforts, the seawater uranium recovery technology costs have been significantly reduced. This presentation will provide an overview and update on the technology developments of the DOE-NE sponsored uranium extraction from seawater program.

URANIUM MINING WASTE, RISK PERCEPTION BY POPULATIONS AND ENVIRONMENTAL REMEDIATION IN PORTUGAL

F.P. CARVALHO Instituto Superior Técnico/ Laboratório de Protecção e Segurança Radiológica, Lisbon, Portugal

Abstract

Mining of radioactive ores for radium and uranium production took place in Portugal from 1908 up to 2001. Over the years, several companies produced salts of radioactive elements according to mining laws in force at the time. Following closure of the last uranium mine and milling facilities at Urgeiriça, local populations and municipalities claimed for surveillance and responsibility on the legacy of uranium waste. An environmental radioactivity assessment and a public health assessment were carried out in the years 2003–2005 and on the basis of these results and recommendations, the Government approved an environmental remediation plan. Local communities have been listened to and they have intervened constructively in the process and contributed to solving radiation protection and environmental contamination issues. Up to the present day, more than half of the former uranium sites have been remediated, milling waste confined and mine water treatment stations either installed or upgraded. At the same time, a radiation monitoring programme of uranium areas is being carried out by the LPSR/IST and the results are delivered on an annual basis to the Government and also rendered public. The results have demonstrated an effective reduction in ambient radiation dose, treatment of acid and radioactive mine drainage before discharge, and abatement of radiation exposure in several areas.

RADIOACTIVITY MONITORING AND ENVIRONMENTAL RESTORATION OF A LEGACY MINE AND MILLING SITE

F.P. CARVALHO, J.M. OLIVEIRA, M. MALTA University of Lisbon, Lisbon, Portugal

Abstract

A former radium and uranium producing mine at Forte Velho, Guarda, Portugal, operated between the1940s and the 1960s. After mine closure, waste piles remained uncovered for decades, until a radiological assessment of the site attracted attention to elevated ambient radiation doses. An aerial radiation dose rate survey was carried out using a detector mounted on a drone and a ground level survey was also undertaken. Ambient radiation dose rates attained 9.5 μ Sv/h on the waste piles. As the waste piles lay on a mountain slope, the site was a source of contaminated materials and leach products being gradually transported downslope with surface run-off. Natural vegetation covered the waste piles and radionuclides were analysed in herbaceous plants and pine trees. Results showed that uranium progeny were easily transferred to plants. Remediation action was taken in 2015. After the remediation of the Forte Velho mine site, a clean soil layer and plants were introduced. A post-remediation radiation survey of the Forte Velho site was conducted which confirmed a suitable degree of abatement of ambient radiation doses and conformity with basic safety standards and remediation goals.

FLUID INCLUSION EVIDENCE FOR URANIUM EXTRACTED FROM THE ATHABASCA BASIN AS A SOURCE FOR UNCONFORMITY-RELATED URANIUM MINERALIZATION

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Abstract

It is generally accepted that the ore forming fluids in unconformity-related uranium deposits of the Athabasca Basin in northern Saskatchewan were derived from evaporitic seawater in the basin. However, it remains controversial whether uranium was extracted from the basin sediments or from basement rocks. It has been argued that oxidizing conditions and the availability of fluid in the basin were favourable for uranium leaching from the sediments and that the present-day low concentrations of uranium in the sedimentary rocks reflects such leaching. However, no direct evidence for this mechanism has been documented. Microthermometric and Laser Ablation – Inductively Coupled Plasma – Mass Spectrometry (LA–ICP–MS) analyses of fluid inclusions in quartz overgrowths from sandstones distal to ore deposits in the Athabasca Basin, as documented in this study, reveal the presence of Ca-rich and U-rich brines within the basin. Such fluids have been previously found within the unconformity-related uranium deposits and interpreted as indicating a local basement derivation of the metals. The development of such fluids throughout the basin during diagenesis suggests that at least part of the uranium in the unconformity-related uranium deposits was derived from the basin. This finding is important for the refining of the exploration model for unconformity-related uranium deposits.

RECOVERY OF URANIUM FROM SEAWATER BY POLYMERIC ADSORBENT SYSTEMS

S. DAI, P. BRITT Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States of America

Abstract

In order to maintain a sustainable reserve of nuclear fuels for the nuclear power industry, tremendous research efforts have been devoted to the development of advanced adsorbent materials for extracting uranium from seawater. Uranium exists uniformly in the world's oceans in the form of a tricarbonate complex at a concentration of $3.3 \ \mu g \ L^{-1}$. Adsorbents which have been developed include inorganic adsorbents, which showed poor selectivity and low capacity, to the most recent polyethylene-fiber-based sorbents containing amidoxime–carboxylic acid copolymers. This presentation will focus on the development and performance of three classes of advanced adsorbents developed as a part of the integrated research effort overseen by the U.S. Department of Energy Office of Nuclear Energy to reduce the technology cost of extracting uranium from seawater: (1) high-surface area polymer fiber adsorbents based on radiation-induced grafting, (2) polymer fiber adsorbents derived from atom-transfer radical polymerization (ATRP), and (3) surface-functionalized polyacrylonitrile fiber adsorbents. The pros, cons, and cost of each technology will be discussed along the recent developments on improving the capacity and the uranium to vanadium selectivity. The potential for these adsorbents to be used in other applications, such as cleanup of heavy metals in mine tailings, will be discussed.

GEOCHEMICAL AND MINERALOGICAL STUDIES OF URANIUM POTENTIAL OF THE LATE DEVONIAN TO EARLY CARBONIFEROUS TAKORADI BLACK SHALE, SEKONDIAN GROUP, GHANA

S.B. DAMPARE, S.S. BLAY, D.K. ASIEDU, J.E. AGBETSOAMEDO University of Ghana,

F. AIDOO, J. HANSON Ghana Atomic Energy Commission,

Acrra, Ghana

Abstract

Geochemical and mineralogical studies were carried out on the Late Devonian to early Carboniferous Takoradi Shale Formation (TSF) of the Sekondian Group, Ghana to investigate its potential to host uranium, thorium and other trace elements. The TSF is typically composed of hard, compact, black/dark grey fissile shale/sandy shale, rich in organic matter, and its upper part is characterised by inclusions of large discoidal siderite nodules. Mineralogical studies of the shales were performed by powder X-ray diffraction. The main mineral phases identified include quartz, vermiculite, zeolite and other clay minerals as well as uranium oxide and uranyl-oxide minerals. Whole-rock geochemical analysis of 19 representative black shale samples by ICP-MS has revealed Th and U concentrations of 18.05–22.06 ppm and 6.89–8.99 ppm, respectively. Thorium, Zr, Nb, Ta, V, La, total Rare Earth Elementss and Ti which are typically enriched in uraniferous black shales are also enriched in the Takoradi Shales relative to Post-Archean Average Australian Shale. Uranium shows strong positive correlation with compatible trace elements such as Cr, V, Zr and Ni. Further studies will be conducted to confirm these elemental associations and the low uranium potential of the TSF.

YELLOWCAKE PRODUCTION AND ENVIRONMENTAL REMEDIATION AT THE SIERRA PINTADA MINE, ARGENTINA: LACK OF SOCIAL LICENCE

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Abstract

The Sierra Pintada uranium mine was in production between 1975 and 1997 when the operations were stopped for economic reasons. In 2004, a project was presented to the provincial authorities proposing the recommencement of production and the concomitant fulfilment of environmental liabilities. The response of the authorities was that before the recommencement of productive activities, the operator (Comisión Nacional de Energía Atómica) had to manage the existing environmental liabilities and establish a scale of priority for their management based on their characteristics. In 2006, a project was presented for the management of environmental liabilities as a first priority, which was technically approved although the required public hearing did not materialize. As a result, authorization was not granted to commence environmental management tasks. In 2014, a new project for remediation was presented and is being evaluated by the provincial authorities. During the entire period of operation and until the cessation of activities, Sierra Pintada had had general approvals for its normal operation. During the time of trying to resume production in synchrony with the remediation, the Government and the social licence were revoked. The mine site became a deposit with apparent resources, with all the facilities needed to resume production, but without authorization to operate. In this context, the future of the project is uncertain.

MAPPING THE WORLD DISTRIBUTION OF URANIUM DEPOSITS

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W. SLIMMON Saskatchewan Geological Survey, Regina, Canada

Abstract

Since the publication of the first edition of the IAEA map, entitled World Distribution of Uranium Deposits, more than two decades ago, knowledge of the distribution of different types of uranium deposit has advanced significantly. This has allowed the creation of a more sophisticated and comprehensive database of world uranium deposits (UDEPO). Increased insights, such as a new deposit type classification scheme, additional new discoveries as well as disaggregation of previously known discoveries, and enhanced GIS techniques have also allowed the generation of a new, second edition map. This provides a valuable decision making tool for a wide variety of stakeholders interested in existing deposits and in assessing the potential for new uranium discoveries.

SPATIAL AND QUANTITATIVE MODELLING OF URANIUM RESOURCES

M. FAIRCLOUGH International Atomic Energy Agency, Vienna, Austria

M.J. MIHALASKY US Geological Survey, Spokane, United States of America

Abstract

Considerable effort has recently been directed towards enhancing and expanding the IAEA database for world uranium deposits: UDEPO. The database is now sufficiently comprehensive to allow use of the data for a wide range of applications, both spatial (such as global map production and mineral potential modelling) and quantitative. The latter application has commonly been undertaken for a wide variety of mineral resource commodities, but rarely for uranium, using a variety of techniques, including the Three Part Method pioneered by the United States Geological Survey. This, and other methods of using known deposit data to provide insights into undiscovered resources, rely heavily on robust statistical inputs. These include grade and tonnage models coupled with appropriate descriptive deposit models. In combination, these provide an opportunity for more defensible and systematic assessments of potential future uranium resources that assist in answering the questions of 'where', 'how many' and 'how much'.

3D MODELING OF ROLL-FRONT TYPE URANIUM DEPOSITS IN KAZAKHSTAN

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Abstract

Nowadays Inkai is one of the unique deposits of uranium resources in the world. Resources of uranium are estimated more than 700 000 tonnes. The owners of sites 1, 2 and 3 at Inkai are National Company "Kazatomprom" and Cameco Corporation. Inkai is roll front sandstone deposit where mineralization of U is related to redox zone. The main uranium minerals are sooty pitchblende (85%) and coffinite (15%). Average grades of U are 0.06-0.07%.

Resource estimation was performed by using the grade-thickness estimation method on two-dimensional blocks in plan view. Nowadays due to implementation of various types of software into mining process an approach to mineral resource estimation and geology interpretation was essentially revised. Joint Venture Inkai, with Cameco corporation assistance, made a decision to adopt 3D modeling into the workflow. At the current time project of 3D implementation has achieved its median but we already value all potential and advantages of using 3D tools. Taking into account that Kazakhstan is in Committee for Mineral Reserves International Reporting Standards family since 2016, the practice of applying block modeling for resource estimation and public reporting will be encouraged.

EXPERIENCE OF PLASMA-PULSE ACTION FOR ISL URANIUM WELLS

O. GORBATENKO Inkai Joint Venture, Kazakhstan

A. MOLCHANOV Scientific Production Center GeoMIR, Russian Federation

Abstract

While processing deep production horizons of the Inkai uranium deposit, being developed using the technology of drill hole in situ leaching, (ISL), it is essential to maintain high pumping rates of wells. To increase the working cycles of production wells, the plasma-pulse action method has provided the opportunity for a reduction of the number and duration of repair and renewal operations.

NUCLEAR ENERGY AND URANIUM: LOOKING TO THE FUTURE

L. GRANCEA Organisation for Economic Co-operation and Development, Nuclear Energy Agency, Paris, France

Abstract

In recent years, nuclear power has continued to supply significant amounts of low carbon baseload electricity, despite strong competition from low cost fossil fuels and subsidized renewable energy sources. However, there is ongoing debate on the role that nuclear energy will play in meeting future energy requirements. Key factors that will influence future nuclear energy capacity include projected electricity demand, public acceptance of nuclear energy and proposed waste management strategies, as well as the economic competitiveness of nuclear power plants. Concerns about the extent to which nuclear energy is viewed as being beneficial in meeting greenhouse gas reduction targets could contribute to even greater projected growth in uranium demand. Key issues in terms of nuclear market developments will be discussed in this presentation and how they could impact the broader nuclear and uranium industry.

INDOOR RADON LEVELS IN GACHIN (ISLAMIC REPUBLIC OF IRAN)

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A. JAMJUR Shiraz University of Medical Sciences, Bandar Abbas

M. HADDADI Shiraz University of Medical Sciences, Shiraz

Islamic Republic of Iran

Abstract

Indoor radon gas (²²²Rn) has been recognized as one of the causes of lung cancer. Considering the risk, the measurement of its indoor concentration is therefore considered necessary. The Gachin region is located in the vicinity of the city of Bandar Abbas, Islamic Republic of Iran, and is an interesting area owing to traces of naturally occurring uranium. This study was conducted to determine radon concentrations in Gachin houses. In this study, 100 radon passive dosimeters (CR-39) were left on different floors of houses constructed with different materials, such as cement, fired brick and clay as raw brick, at every floor, for 6 months. The electrochemical etching method was applied to determined. This study showed that the average radon concentration was 39 Bq/m³ in the houses. On different floors and according to the construction material used, the average effective dose equivalent of lung tissue was 0.97 mSv/year. On the basis of these results, it can he concluded that the indoor radon levels in Gachin houses are within an acceptable range.

INTEGRATION AND COST SAVING UTILIZATION OF THE SEISMIC REFLECTION TECHNIQUE IN THE ATHABASCA BASIN, CANADA

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University of Saskatchewan, Saskatoon, Canada

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Abstract

The Seismic Laboratory of the University of Saskatchewan, through industrial partnerships, has conducted many seismic reflection experiments within the western and eastern Athabasca Basin. Results to date illustrate that the seismic investigations deliver high quality primary structural images of the subsurface, with a resolution unmatched by other geophysical techniques. Correlation of similar seismic signatures from section to section has defined the mineralization fault systems and allowed spatial extension of previously unrecognized exploration target zones. Extended analysis of seismic signal attributes and full-wave data offer detailed lithological characterization, including data on anomalous alteration zones and petrophysical attributes. Although seismically detected anomalies are primary indicators of mineralization, the seismic method is still not a 'standard basin' exploration tool because of its negative attributes. Unquestionably, locally, drilling of boreholes provides the most explicitly reliable information to a certain depth. Comparing the costs of all geophysical techniques to the cost of a single logged drill hole illustrates that the results of a properly designed seismic data acquisition programme not only leads to more effective drilling campaigns, but also to much quicker recognition of the major mineralized zones and their 'fingerprints'. This integrated approach to exploration would translate into a significant reduction in the required number of exploratory boreholes and a commensurate saving in total exploration expenditure.

GENETIC DEPOSIT MODEL FOR CALCRETE URANIUM IN THE SOUTHERN HIGH PLAINS REGION, UNITED STATES OF AMERICA

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Abstract

The semi-arid Southern High Plains physiographic region hosts calcrete uranium deposits in Pliocene and Pleistocene sediments. This region was identified by the United States Geological Survey as prospective for calcrete uranium deposits, although no deposits of this type had been identified in the USA. The existence of deposits in the area was confirmed through historic exploration reports that identified two drilled deposits and additional prospects in the region. Outcropping mineralization adjacent to a known deposit was sampled and analysed and combined with analysis of regional geology to develop a genetic deposit model. Dating by the United States Geological Survey of uranyl vanadates and volcanic ash found in the host rock indicates periodic mineralization occurred between about 631 000 and 4000 years before present. The entire Southern High Plains is characterized by elevated levels of uranium in solution in groundwater, likely derived from the Triassic Dockum Group or from volcanic ash in the host sediments. Elevated levels of vanadium in solution in groundwater, coupled with areas of higher hydraulic conductivity, define the areas most highly prospective for the formation of carnotite, the major ore mineral for this deposit type. Mineral-solution equilibrium modelling indicates that evaporative concentration of local groundwater could produce saturation with carnotite, which suggests that the mineralizing systems may remain active.
BLACK SAND IN SUDAN FOR ECONOMIC THORIUM FUEL CYCLES

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Abstract

The Sudan Mining Department is conducting project research into the potential use of the thorium fuel cycle by tracing alpha radiation emitted from isotopes of uranium and thorium found in the surface marine sediment on the Sudanese coast of the Red Sea at Port Sudan localities. Using radiochemical procedures and alpha particle spectrometry the activity concentrations of ²³²U, ²³⁴U, ²³²Th, ²³⁰Th, ²²⁸Th were measured. Based on those findings the National Council for Radiological and Nuclear Control in Sudan is conducting a research project investigating the potential of the thorium fuel cycle in a possible future nuclear industry in Sudan.

The investigations were conducted to both study and investigate aspects of the development of nuclear power and the methods of involving thorium as an additional fuel resource (long-term outlook). It also studied the utility of introducing thorium to operating reactors (short-term outlook and medium-term aspect).

This paper considers and evaluates the potential benefits that the thorium fuel cycle may offer as an alternative to the existing uranium fuel cycle.

IAEA COORDINATED RESEARCH PROJECT: GEOCHEMICAL AND MINERALOGICAL CHARACTERIZATION OF URANIUM AND THORIUM DEPOSITS

A. HANLY International Atomic Energy Agency, Vienna, Austria

Abstract

In the last decade there have been a multitude of new methodologies and techniques which have been developed in the mineral sector but these have, for the most part, not been applied to uranium and thorium resources. The main objective of this coordinated research project is to undertake geochemical and mineralogical studies of mineralised samples and apply this to understanding the genesis of uranium and thorium deposits and geochemical and mineralogical constraints on mineralization processes. This new knowledge and experience will assist in exploration for uranium and thorium and defining resources. The project involves thirteen Member States: Argentina, Canada, China, Egypt, Ghana, the Islamic Republic of Iran, France, Kenya, Madagascar, Mongolia, Philippines, Ukraine, and Venezuela.

UNCONFORMITY-TYPE URANIUM DEPOSITS: A NEW IAEA TECHNICAL DOCUMENT

A. HANLY International Atomic Energy Agency, Vienna, Austria

Abstract

The IAEA has produced several volumes focussed on uranium deposit types that were the result of several expert-led working groups. In the last 25+ years, since these volumes have been published, there has been considerable research and advances in the understanding of uranium deposits, particularly for unconformity type deposits. Up until 2009, the world's largest share of production came from unconformity-type deposits and identified resources account for 10% of the world total. They are one of the most economically viable deposit types mainly due to their relatively high-grades in comparison to other deposit types, and warrant a technical document that can be used as a reference to properly assess the potential to discover and exploit these deposits. Currently, unconformity-type deposits are only being worked in Canada and Australia but there are known occurrences and potential worldwide, which should be evaluated.

This new technical document will provide a summary on unconformity-type uranium deposits including geology, mineralogy, metallurgy, mining methods, resources, genesis, exploration techniques and other topics that would be useful for evaluation. Users should be able to utilize this document to assess the potential to evaluate the potential to discover and exploit unconformity-type deposits.

WORLD URANIUM RESOURCES AND PRODUCTION

A. HANLY International Atomic Energy Agency, Vienna, Austria

L. GRANCEA Organisation for Economic Co-operation and Development, Nuclear Energy Agency, Paris, France

Abstract

The need for a long-term view on uranium resources and supply was recognized early in the development of the civilian nuclear power sector. In 1965, a working group was formed to compile worldwide uranium resource estimates by the precursor to the Nuclear Energy Agency, and in co-operation with the International Atomic Energy Agency since the mid-1980s this group has been producing reports on global uranium supply and demand, currently every two years ('Red Book').

Over the course of its history, the Red Book has become recognized as an authoritative source of governmentsponsored information on the uranium industry. More than 100 countries have contributed data to the 26 editions published to date. The Red Book summarizes information from various countries, analyzing the evolution of the market and developing conclusions about the evolution of the global uranium resource base, mine production and uranium demand.

EFFECT OF CAUSTIC SODA FUSION TEMPERATURE ON MALAYSIAN XENOTIME

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Abstract

Xenotime is mineral rich in rare earth elements, a mainly phosphatic mineral which is particularly enriched in yttrium. An alkaline fusion method was used in this study of the preparation of waste arising from thorium and rare earth element extraction. This method could minimize radioactive waste volume, using dilute acid for dissolution and recovering phosphate as a by-product. The method studied included caustic soda fusion, solid–liquid separation and leaching. The raw material used was a concentrate containing about 60–75% total rare earth oxides, 1–2% thorium oxide and 23–26% phosphorus pentoxide. Different ratios of xenotime and NaOH (1:0, 1:1, 1:2 and 2:1) were studied and underwent fusion at different temperatures (400, 500, 600 and 700°C). The resulting powder was analysed by X ray diffraction, X ray fluorescence, particle size analysis, field emission scanning electron microscope, Raman spectrometry and simultaneous thermal analysis. It was possible to extract almost 90% of the thorium, rare earths and phosphate by these processes.

THE EMERGING URANIUM INDUSTRY LANDSCAPE: PUSH OR PULL RESOURCE RECOVERY?

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H. TULSIDAS United Nations Economic Commission for Europe, Geneva, Switzerland

L. LOPEZ Comisión Nacional de Energía Atómica, Buenos Aires, Argentina

Abstract

The simultaneous idling of the world's richest and one of the largest uranium deposits and cutbacks in production against a background of low prices has brought to a head the strategic question of what future path the troubled global uranium industry should tread? If there is a positive way forward, the practical consequence is to define in detail how uranium recovery and production pathways should be 'redesigned' for a more predictable and sustainable future. This paper will discuss the inevitable impact of these change drivers as causing the uranium sector to pivot from a 'push' to a 'pull' business model, one based on uranium as a critical material for climate action, not as a traded commodity. This paper will detail the necessary interactions of policy and technology innovation from which this new 'push' model can be developed, taking into account the demand that mineral resource recovery of any kind is a low or zero waste generating activity. This means rethinking uranium as a new economic resource and placing innovative uranium extraction technologies and flowsheets at the centre of process design and operation, with particular emphasis on uranium as a co- or by-product.

URANIUM AND ITS ENVIRONMENTAL BEHAVIOUR: A NEW IAEA TECHNICAL REPORTS SERIES PUBLICATION

A.R. IURIAN International Atomic Energy Agency Vienna, Austria

Abstract

Although uranium is a naturally occurring element that is present at low concentrations in all environmental media, elevated concentrations can be found in some minerals, e.g. uranium ores. Assessment of the impact of uranium on humans and other biota poses a specific challenge because of the combination of different types of hazard and potential exposure. The IAEA is preparing an overview publication intended to provide IAEA Member States with information on the environmental behaviour of uranium for use in environmental impact assessment of routine discharges and accidental releases, for uranium impact assessment in different contamination scenarios and for remediation planning of sites contaminated with uranium. This report covers the behaviour of uranium in the atmosphere and in terrestrial, freshwater and marine environments. The primary focus of the report is the environmental behaviour of uranium, as the environmental behaviour of uranium progenies (such as radioisotopes of radium, radon, polonium and thorium) are considered in other IAEA publications. The information presented is relevant to the environmental transfer of uranium to both humans and to non-human biota.

RECOVERY OF URANIUM AND ACCOMPANYING METALS FROM THE SECONDARY RAW MATERIALS

K. KIEGIEL, G. ZAKRZEWSKA-KOLTUNIEWICZ, D. GAJDA Institute of Nuclear Chemistry and Technology, Warsaw, Poland

Abstract

In the last years interest in uranium recovery from secondary sources is growing. In Poland, the advanced studies are undertaken concerning the possibility of obtaining uranium from domestic resources and also secondary resources such as phosphate rocks and industrial wastes, including flotation tailings from the copper industry and phosphogypsum.

There are two main reasons for these kind of studies:

- recovery of heavy metals form the industrial wastes is important to the society, industry and environment;
- the selective separation of uranium is a very important in the context of energy production and treatment of nuclear wastes.

In the studies described the solid materials were leached with using either acid or alkaline solutions in stationary reactors or with percolative leaching. The obtained liquors were separated from solid residue and then were purified by liquid-liquid extraction or ion exchange chromatography.

The studies were supported by the financial resources for science in the years 2017-2018 granted for the implementation of the international project co-financed 3643/IAEA/16/2017/0, IAEA Research Contract No: 18542.

URANIUM ONE DEVELOPMENT OUTLOOK

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Abstract

The Russian State Corporation Rosatom acquired Uranium One in 2010 to secure long- term uranium supply for its nuclear fuel cycle chain and consolidated on this basis high quality uranium assets in Kazakhstan and in other countries. Uranium One has increased annual production almost 5 times during the last 7 years and became the fourth largest global producer of uranium. It has a diversified production base in Kazakhstan and the USA and a development project in Tanzania. Known resources and mining capacities secure further sustainable uranium production growth at favorable market conditions.

Through its shares in five joint ventures and six mines, Uranium One owns 20% of attributable uranium production and 17% of attributable resources in Kazakhstan, being the second after Kazatomprom and the first among foreign companies there. The designed production capacity of the six uranium mines is 12 kt U, half of which is attributable as Uranium One's share. The successful, innovative technical policy, in conjunction with the geologically and technically unique characteristics deposits, provide significant competitive advantage for Uranium One as the global company with the lowest cost uranium production.

STRUCTURAL CHARACTERISTICS AND ITS CONTROL ON URANIUM MINERALIZATION IN XIANGSHAN URANIUM ORE-FIELD

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Abstract

The Xiangshan uranium ore-field is the largest volcanic-related hydrothermal uranium deposit in China. Based on high precision deep geophysical survey, 3D geologic modeling and scientific drilling projects, EW-trending faults in basement were rejuvenated by strong shearing of the Suichuan-Dexing fault during later Jurassic to Early Cretaceous, the tectonic-stress field changed from compression to extension at the beginning of Early-Cretaceous. This is advantageous to the ascension of deep-derived materials, with ore-bearing hydrothermal fluid transiting, precipitating and enriching. Favorable positions for uranium mineralization include the junctions of faults with different directions, the junctions between main faults and subsidiary fractures, the junctions between branch fractures of main faults and derived fractures of subsidiary faults. EW-trending faults in basement is the main means in which substance can transmit to surface, whilst the linear, ring-like and radial pattern structures which are connect with faults in basement control the shape, occurrence, scale and spatial locations of uranium ore bodies; these faults are main orehosting structures. Therefore, we consider that fault structures should still be the emphasis of ore-finding, especially the belts where deep E-W faults and surface faults intersected are favorable areas to explore uranium resources.

GUIDANCE AND TRAINING FOR NUCLEAR SECURITY IN THE URANIUM EXTRACTION INDUSTRY

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Abstract

Regardless of its chemical form, uranium ore concentrate (UOC) is a valuable commodity in the commercial nuclear market and a potential target for unauthorized removal. With the global expansion of uranium production capacity, the protection and control of UOC is emerging as a potential cause for concern in the nuclear supply chain. In response to requests for assistance from States producing UOC and those planning such activities or which are involved in the protection of UOC during transport, the IAEA Division of Nuclear Security has developed a guidance document, TDL-003, entitled Nuclear Security in the Uranium Extraction Industry [1] and a subsequent training course led by members of the consultancy team that drafted TDL-003. The publication was prepared in a series of seven consultancy meetings with input from more than thirty experts from ten Member States, including experts from three operating organizations of uranium extraction industry facilities. The publication describes a suggested interpretation of 'prudent management practice' in the context of the uranium industry and the information provided does not represent international consensus guidance, but, rather, an attempt to show States and organizations that wish to follow the suggested approach how it can be achieved.

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UNDERSTANDING OF URANIUM EXTRACTION MECHANISMS FROM PHOSPHORIC AND SULPHURIC MEDIA USING DEHCNPB

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Abstract

Phosphate rocks are widely exploited for the manufacture of phosphoric acid and fertilizers but they also contain uranium (30-300 ppm). Therefore, recovering this uranium would enable the decontamination of phosphoric acid while valorizing uranium for the nuclear industry. New extractant molecules were investigated in the past few years to develop a new solvent extraction process. An amidophosphonate, the butyl-1-(N,N-bis-2-ethylhexylcarbamoyl)nonyl phosphonic acid (DEHCNPB), showed good uranium extraction efficiency while meeting U/Fe decontamination requirements (as demonstrated during pilot scale trials). Afterwards, DEHCNPB was also used for the extraction of uranium from conventional resources (from sulfuric lixiviation media). However, pilot scale trials showed poorer performances, as uranium losses in raffinates were higher than expected.

The objective here is to study uranium and iron extraction mechanisms from those twodifferent media (phosphoric and sulfuric). Thermodynamic data were acquired such as: extraction isotherms, slope analysis, phosphates/ sulfates and water extraction. These data showed different behaviors depending on the initial medium. Spectroscopic techniques such as FTIR, NMR, ESI-MS and EXAFS were also investigated to study uranium-DEHCNPB complexes formed in the organic phase, enabling the determination of stoichiometries and coordination modes.

EFFECTIVE AND ENVIRONMENTALLY COMPLIANT IN SITU RECOVERY OF SEDIMENTARY HOSTED URANIUM

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Abstract

This poster is the companion to the oral paper (Contribution 219) that reviews recent advancements in Development of in-situ recovery (ISR) projects for uranium including – dedicated exploration/delineation methods and field tests for gathering deter-mining data, – efficient lab tests and assays of core samples, including up-scaling methodology applied to (1D) column leach tests for a reliable feasibility study of (3D) field ISR, Planning and optimization of ISR processing comprising:

- wellfield hydrology
- leaching chemistry
- monitoring and process control
- economics
- environmental compliance
- post-mining measures for ISR aquifer restauration in accordance to regulatory requirements including
- conceptual methodology (combining test procedures and model predictions) for ISR project development and permit procedure
- monitoring and optimization.

The effective and environmentally compliant ISR of uranium will be demonstrated for recent ISR projects operated by Heathgate Resources in the Frome Basin, South Australia.

NEW U–Pb AGES AND GEOCHEMISTRY FROM THE WHEELER RIVER URANIUM DEPOSITS, ATHABASCA BASIN, CANADA

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University of Saskatchewan, Saskatoon, Canada

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Abstract

The Wheeler River Project hosts the high grade Phoenix (sandstone hosted) and Gryphon (basement hosted) uranium deposits within the eastern part of the Athabasca Basin. The conditions and timing of the mineralization event(s) at each deposit were established from the isotopic ages and geochemistry of uranium oxides determined from 13 samples. The oldest zones of analysed UO₂ (i.e. 1433 ± 15 Ma, 1340 ± 17 Ma, 1275 ± 17 Ma) for most of the samples are tentatively considered to be primary mineralization ages. These ages and their chemical contents are different for each sample, indicating different P-T-X conditions and timing for the formation of the UO₂ at Wheeler River. This difference is visible between the deposits, but also on the scale of one deposit (Phoenix). Younger age determinations obtained within all of the samples are interpreted as reflecting secondary fluid events. These new results provide excellent evidence for multiple uranium events related to changes over time on the Wheeler River property. Such results demonstrate that the evolution of the Wheeler River property, and on the larger scale of the Athabasca Basin, has been complex since the deposition of the basin and could thus explain the exceptional characteristics of the unconformity-related uranium deposits.

URANIUM LEGACY SITES OF THE FORMER SOVIET UNION IN TAJIKISTAN: PROBLEMS AND THE WAY FORWARD

U. MIRSAIDOV, S. BAHRONOV Nuclear and Radiation Safety Agency, Dushanbe, Tajikistan

Abstract

During the second half of 20th century, Tajikistan was one of the uranium raw material suppliers in the former Union of Soviet Socialist Republics (former USSR). More than 20% of produced uranium in the former USSR was delivered from Tajikistan. Altogether, 10 uranium mining tailing dumps covering 170 hectares and containing more than 55 million t of waste were accumulated, with an activity of more than 6.5 kCi, from the beginning of the uranium industry in Tajikistan on the territory of six districts in the Soghd region. An essential limitation on carrying out the required remediation measures is a lack of relevant infrastructure. In this regard, the regulatory authority of Tajikistan faces many challenges, such as:

- (a) Development of legislative basis;
- (b) Assessment of radiological consequences on uranium industry sites;
- (c) Assessment of the condition of remediation measures;
- (d) Analysis of compliance with international standards and recommendations;

(e) Development of an action plan on minimizing the impact of uranium industry sites on public and environment;

(f) Having sufficient and suitable analytical equipment for monitoring.

It is necessary to mention that implementation of international projects with the active participation of the IAEA has facilitated expanding cooperation and mutual understanding among Central Asian countries in issues concerning environmental protection. Re-establishment of radiation control systems on former uranium industry sites in Tajikistan is the first step to their full remediation.

POSSIBILITY OF URANIUM INDUSTRY WASTES REPROCESSING IN TAJIKISTAN

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Abstract

Total amount of wastes in tailings of former uranium industry in Republic of Tajikistan is approximately 55 million tonnes. The total activity of wastes, according to different assessments, is from 6.5 to 7.7 kCurie. Mining dump fields are not well arranged, and their volumes and area are not exactly determined. Practically all tailings and waste rock dump fields are subject to erosion processes and drained by underground waters to adjoining creek and river networks.

The surface of tailings, especially those which do not have protective coverage, are subject to destructive effect of natural factors or digging animals and present a threat of considerable dispersion of contaminated substances and residues of tailings beyond of their initial locations.

Uranium ore reprocessing methods are known which would allow extraction of uranium oxide from low grade ores. However, these methods require preliminary preparation of the ore, such as grinding, and in addition may contaminate the environment.

We propose a method of uranium ore reprocessing with the purpose to extend the base of raw material and allow the production of uranium oxide from uranium industry wastes with uranium content from 0.03 up to 0.3 mass per cent. Final product is uranium ore concentrate containing 75% U_3O_8 . Product recovery is from 90 to 99%.

ORGANIC SOLVENT EXTRACTION OF URANIUM FROM ALKALINE NUCLEAR WASTE

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Abstract

During the dissolution process of irradiated uranium target plates, uranium and some fission products are precipitated as mixed hydrated oxides to form a residue. This residue is commercially valuable, as a feed stock for recovering and purifying uranium from the other fission products and trans-uranium elements. PUREX (Plutonium Uranium Redox Extraction) is a worldwide known technique for the extraction of uranium using the conventional acid route. However, during the PUREX extraction of uranium, plutonium and thorium are also extracted in this process. In addition, there are proliferation issues, which make the PUREX process not favorable. The aim of this research was to evaluate organic extraction ligands that can operate in alkaline media to remove uranium from the nuclear waste and the objective was to characterize the most effective organic solvent for extracting uranium only, from alkaline media. Uranium oxide was dissolved in sodium carbonate solution to form the uranium tri-carbonate aqueous feed solution. 5% (v/v) Aliquat 336 in either xylene or toluene was used as the organic extractant. The samples were analyzed using the VARIAN CARY 100 UV-VIS Spectrometer set at 450 nm, at an optimum solution pH of 12. The results from this work indicate that Aliquat 336 in Xylene has a less effective extraction percentage of 72% for uranium within the time of 60 minutes, if extraction is performed immediately after the preparation of the uranium feed solution. Toluene extracted 82% of the uranium from the feed solution after 30 minutes. However, toluene showed a decrease in extraction capability to 76% after 60 minutes. Plutonium and thorium were not detected in the final uranium product, indicating that the organic solvent alkaline extraction method could be a valuable technique in uranium processing.

PRACTICAL APPROACH TO IMPROVING CONVENTIONAL SAFETY PERFORMANCE AND CULTURE IN URANIUM MINES AND MILLS

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Abstract

Conventional safety management in uranium mines and mills is equally as important as radiation protection, and unfortunately, conventional mining accidents are known even at modern, well managed uranium operations. Management of conventional safety performance in daily operations must be a core value of all employees and contractor personnel, from the most senior managers and executives, through middle management and the professional and technical ranks, to all workers. This presentation will provide a global overview on leadership, management oversight, operational attitudes and behaviour, and the impact that the business climate has on safety performance, competence and training, hazard identification, risk tolerance, communication and safety based reporting. Finally, this presentation will highlight some effective and proven practical steps to improve safety performance and ultimately improve safety culture in the workplace. The IAEA will be promoting the importance of conventional industrial safety, as well as radiation protection, in several uranium-related technical and training meetings to be convened over the coming years.

FIVE YEARS AFTER THE UPSAT MISSION: PROGRESS AND CHALLENGES

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Abstract

Regulating the uranium extraction industry is a complex process which involves multi-regulators with different requirements. The United Republic of Tanzania has had several regulators with little experience in the uranium mining domain. Different items of governmental legislation and regulations lacked clarity and consistency. Overlapping mandates between different government departments complicated the issue, with the operator unsure which laws should be followed. The IAEA Uranium Production Site Appraisal Team (UPSAT) was the answer to a request for assistance in addressing this challenge. UPSAT was first assistance mission of its kind sent to Africa. The mission assessed the following five primary parameters: (i) the regulatory system, (ii) the sustainable uranium production life cycle, (iii) health, safety and environment, (iv) social licensing and (v) capacity building. This paper presents the progress and development made since the UPSAT mission in 2013.

IAEA-TDL-003: A CORNERSTONE FOR NUCLEAR SECURITY FOR URANIUM ORE CONCENTRATES FOR NEWCOMERS

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Abstract

United Republic of Tanzania is a potential future uranium producer with an estimated annual production of 2300 tU from Mkuju River uranium project. Nuclear security with respect to uranium ore concentrates (UOC) did not formerly exist in the country and up until recently, there was literally no guidance directly related to UOC which explicitly explained how to implement prudent management practice as recommended by the Convention on the Physical Protection of Nuclear Material and by INFCIRC/225 (Physical Protection of Nuclear Material and Nuclear Facilities) [1].

To ensure the applicable nuclear security recommendations on prudent management practice are incorporated into national legislation and regulations, the Tanzania Atomic Energy Commission requested technical assistance from the IAEA in the form of a national training course on nuclear security for uranium ore concentrates in 2014. The IAEA TDL-003 publication on Nuclear Security in the Uranium Extraction Industry [2] was the main reference during the national training course. The training methodology was classroom lecturing, interactive tabletop practical exercises and real life simulation of an event and how to deal with worse case scenarios in protecting UOC.

This paper presents the experience acquired from IAEA TDL-003 technical assistance and experience in drafting nuclear security regulations for UOC in the United Republic of Tanzania.

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REMOVAL OF URANIUM AND THORIUM FROM URANIUM AND RARE EARTH ORES PROCESSING CASE STUDY OF QA/QC ON ENVIRONMENTAL ANALYSIS

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Abstract

The removal of uranium and thorium from unconventional mining ores such as graphite, phosphate, or beachsands has been carried out for decades. During processing the ore for the main products, the mining tailing contains considerable amounts of radioactive elements such as uranium and thorium, which would be accumulated at some storage (in beach sand exploitation) or just released at the site (as Naturally Occurring Radioactive Material /Technologically Enhanced Naturally Occurring Radioactive Material waste from phosphate or graphite production). The study of these deposits became more intensive to ensure a safe environment. Several research projects have then been set up for the recovery of by-products including uranium and/or thorium.

Furthermore, a small amount of these accompanied elements as impurities in the mineral products or rare earth raw compounds should be controlled for export or for further processing. The quality assurance/quality control on analysis of these element would thus be posed. X-Ray Fluorescence and other analytical techniques have been studied for supplying the demands from research projects. The use of certified reference materials and secondary standards for quality control contribute to reliable and unbiased results and narrow uncertainties. Analytical results of samples and of various reference materials are presented and discussed with focusing on concentration range, matrix compositions, and determination limits.

ACTUAL PROBLEMS OF DEVELOPMENT AND CARRYING OUT OF REPAIR AND RESTORATION WORKS OF UNDERGROUND URANIUM LEACHING WELLS

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Abstract

The article discusses the issues of complex problems of well development at the stage of their construction, ERW, and the ways of their solution, methods and technology. It also gives an analysis of the causes of problems in well development. New advanced technologies and methodologies have been introduced to improve well productivity, both at the construction stage and at the stage of the ERW.

INVESTIGATION OF U-238 AND Th-232 IN FINGERNAILS, TOTAL BLOOD AND DRINKING WATER AMONG WELL USERS IN KADUGLI TOWN, A HIGH NATURAL BACKGROUND RADIATION AREA IN SUDAN

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Abstract

The Sudan Atomic Energy Commission has an ongoing national programme for monitoring radioactivity in Sudan to establish baseline data that form a useful reference for radiation protection in the country. The Nuba Mountains, in south-western Sudan, has been identified as a region with very high natural background radioactivity. This elevated natural radiation is attributed to the high concentrations of 238 U and 232 Th series and 40 K in the geological formations. Mining activities (uranium and gold) may take place soon, which could increase the radiation hazard to the public. The authors' aim was to investigate the distribution of 238 U and 232 Th in fingernails and whole blood in relation to its intake via drinking water by the Nuba people who live in the area. Water, fingernails and blood samples were analysed for 238 U and 232 Th using inductively coupled plasma mass spectrometry. The results of some analyses of water supplies revealed uranium concentrations higher than the World Health Organization guidance level (15 µg/L) for drinking water. Analysis of body tissues showed that both 238 U and 232 Th were better reflected in fingernails than in blood, and thus may serve as biomonitors for uranium and thorium intake in the area. The generated data represent a valuable baseline for the decision makers to consider prior to the onset of mining activities.

ADVANCED TECHNOLOGIES FOR SUSTAINABLE EXPLOITATION OF URANIUM-BEARING MINERAL RESOURCES IN FINLAND

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Abstract

Efficient metal recovery from complex polymetallic and low-grade large-tonnage mineral resources is a major challenge, both metallurgically and in ensuring compliance with environmental and social legislation and expectations. In recent years, several exploration and mining projects in Finland have focused on the exploitation of uranium-bearing polymetallic deposits, in which the primary targeted commodity includes gold, nickel, cobalt and other base metals, as well as rare earth elements. Mineral parageneses and the relationship between these metals and the deportment of uranium of ores must be carefully documented in order to develop an optimum flowsheet for processing. Our current research is aimed at combining this mineral characterization with the development and demonstration of new techniquess for the effective recovery of uranium from process and mine waters, even at low concentrations. These approaches cover the utilization of different bisphosphonate adsorbents, hybrid materials of nanoporous silicon carbide frameworks and bisphosphonates. and biological/bioelectrochemical uranium reduction.

We have selected several metallogenically diverse uranium-bearing deposits in Finland, representing sedimenatry hosted and metamorphosed, Au-Co-U deposits and intrusive-related Rare Earth Element mineralization. In addition to microscopic (Mineral Liberation Analyser, Electron probe micro-analyzer, Scanning Electon Microscope, Micro-Computed Tomography) and isotopic (Laser Ablation-Inductively Coupled Plasma Mass Spectometry) mineralogical characterization we perform a range of laboratory-scale bulk leaching experiments at the GTK Mintec processing plant. Both process waters and minewaters collected from dormant open pits are being tested for selective recovery and isolation of not only uranium, but also other metals, with the aim of integrating these bisphosphonate and biosorption techniques into processing flowpaths, for metal recovery and environmental management. Bench-scale experiments have demonstrated the effectiveness of both the biosorption of activated sludge and bisphosphonates and hybrid derivative materials in adsorption of uranium from solution, even at very low concentrations, with the additional advantage of allowing rapid and efficient recycling and reuse of sorbent materials.

MODERN URANIUM OPEN PIT GRADE CONTROL

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Abstract

The Langer Heinrich mine resource definition work was based around radiometric logging of drill holes and this has been carried through to mining grade control. The resource model is an Multiple Indicator Kriging estimation with a variance adjustment based on expected mining parameters. Due to the large block size of 50 m x 50 m, infill to 12.5 m x 12.5 m to allow for detailed mine planning is undertaken. This intermediate stage is designed to provide accurate information for mine planning and scheduling for a forward 12-month period and significantly reduces the risks associated with mining a highly variable and nuggety deposit.

The blast hole logging process is a one-man operation using logging equipment installed on a small four-wheel drive vehicle. This allows easy access to close spaced blast holes without the risk of damaging hole collars. The data is downloaded at the end of each shift and is processed to an equivalent uranium grade value using software developed on site. The resulting uranium values are then used to define grade control blocks via conditional simulation software. All material of ore grade is hauled to the run of mine pad via a radiometric discriminator system to add a final level of selectivity to the mining process.

COORDINATED RESEARCH PROJECT ON URANIUM/THORIUM FUELLED HIGH TEMPERATURE GAS COOLED REACTOR APPLICATIONS FOR ENERGY NEUTRAL AND SUSTAINABLE COMPREHENSIVE EXTRACTION AND MINERAL PRODUCT DEVELOPMENT

F. REITSMA, P.H. WOODS International Atomic Energy Agency, Vienna, Austria

Abstract

Around the world, the demand for mineral commodities is growing strongly and high grade, easily extractable resources are being depleted. Thermal processes are often the most appropriate for production from low grade and some unconventional mineral resources; these in turn depend on the availability of large amounts of energy. These thermal mineral extraction processes are usually cleaner and generate lower quantities of wastes than current chemical processes. The availability of affordable and responsibly produced energy would, in many cases, also add value through the production of higher end products, thereby improving the overall economics of the project.

Thermal processes using high temperature nuclear heat could be a more sustainable and environmentally friendly alternative to heat generated by other means and conventional chemical processes. Many mineral deposits contain low concentrations of uranium and thorium; these could be recovered and used as, or be the equivalent of, fuel in reactors. The IAEA's Coordinated Research Project generates basic data on the availability and characteristics of various potentially suitable mineral resources and process residues, and conducts conceptual and pre-feasibility studies on appropriate thermal processes in which uranium/thorium fuelled high temperature gas cooled reactors provide the required energy.

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ASSESSMENT OF THORIUM AND ASSOCIATED RESOURCES: PHILIPPINE INITIATIVES

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Abstract

The exploration for thorium in the Philippines has always been regarded as secondary to uranium and even a subsidiary activity to the exploration for rare earth elements. With 70% of the country having been covered by reconnaissance geochemical surveys, the potential areas for thorium have been identified as the Ombo and Erawan coastal areas of north-western Palawan Island, which contain radioactive heavy minerals. Mineralogical examination of these heavy minerals from panned concentrates of beach and stream samples showed major medium- to coarse-grained euhedral brown–reddish allanite (74.0–81.8%) and minor fine-grained subhedral yellow monazite (2.4–11.6%).

Field gamma ray spectrometric measurements in Ombo and Erawan showed thorium contents varying in the ranges 2.2-770.5 ppm and 8.6-388.5 ppm, respectively. Thorium values by gammametric analysis in panned heavy beach and heavy stream sediment samples showed values for Ombo and Erawan varying in the ranges 0.93-1.28% and 0.76-1.15%, respectively. Xray fluorescence analysis for rare earth elements in both the panned heavy mineral stream and beach samples gave various ranges of values for lanthanum (3.00-12.24%), cerium (5.00-21.07%), praseodymium (0.04-1.71%), neodymium (2.00-6.51%) and yttrium (0.03-0.21%).

HARMONY - THE FUTURE OF ELECTRICITY AND NUCLEAR DELIVERING ITS POTENTIAL

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Abstract

Nuclear power is in demand globally and growing at its fastest rate in 25 years, with new countries and new designs coming on line for the first time. However, to meet climate and development goals nuclear must grow faster still. Harmony is the nuclear industry's vision for the future of electricity and sets the goal of building 1000 GWe of new capacity and providing 25% of global electricity in 2050.

What might be the consequences for fuel supply of such a nuclear programme? The 1250 GWe of nuclear capacity envisaged in 2050 would require about 200,000 tU annually, assuming similar fuel efficiencies to current reactors, and it would require nearly 4.5 million tU of cumulative consumption up to 2050. Sufficient uranium resources exist in the world to allow such a rapid expansion: the 2016 edition of the 'Red Book' identifies over 10 million tU of conventional and unconventional resources. More could undoubtedly be discovered with scaled-up exploration programmes. Of course, a very rapid expansion of the mining sector would also be needed to supply such an industry.

REGULATIONS FOR THE DIVERSIFICATION OF PARTNERS AS PART OF THE SECURITY OF SUPPLY POLICY

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Abstract

In the current uranium industry environment, ensuring a stable and sustainable natural uranium and uranium fuel supply is becoming crucial. This objective can be achieved through the mandatory diversification of uranium suppliers' portfolio. Some countries and utilities experience such constraints because of some regulations in their arrangements with strategic counterparties. As an example of this, for some utilities working in the market, the natural uranium supplier portfolio is diversified by means of their own corporate policies, for example, where they allow not more than 10% of their requirements to be fulfilled by uranium producers with a single mining source and not more than 20% of their requirements procured from the producers with more than one sustainable mine. Given the prevailing situation in the market and the international political situation, as well as ensuring the stability of fuel supplies for such sensitive facilities as nuclear power plants, it seems advisable to introduce international rules on the mandatory diversification of supplies of natural uranium and uranium fuel to fulfil the needs of energy companies.

IAEA COORDINATION GROUP FOR URANIUM LEGACY SITES (CGULS): STRATEGIC MASTER PLAN FOR THE ENVIRONMENTAL REMEDIATION OF URANIUM LEGACY SITES IN CENTRAL ASIA

M. ROBERTS, M. KINKER International Atomic Energy Agency, Vienna, Austria

Abstract

Uranium mining and processing activities have been carried out in Central Asia since the mid-1940s, particularly in the mountainous areas above the Syr Darya River and the Ferghana valley, where the borders of the Kyrgyz Republic, Kazakhstan, Tajikistan and Uzbekistan intersect. Many of these activities ceased in the 1990s, leaving numerous sites containing uranium and other hazardous and radioactive wastes in populated areas. Left unremediated, these uranium legacy sites (ULS) pose a hazard to future generations.

To move forward CGULS developed and is implementing a Strategic Master Plan (SMP) for environmental remediation of ULS in Central Asia. The SMP sets out a strategy for adoption and a master plan for implementation for the remediation these ULS. The SMP addresses three main activities:

- 1. Systematic and comprehensive studies to assess the current status of each ULS and to propose appropriate and effective remediation solutions.
- 2. Remediation solutions implemented according to international standards and good practice.
- 3. Countries develop the capacity to implement remediation projects and assume long term stewardship of the remediated sites.

The first step of site evaluation and remediation solutions design is underway; the next step, the actual implementation of the remediation work, requires additional funding.

TECHNOLOGICAL UPGRADING BY RECYCLING EFFLUENTS GENERATED AT A URANIUM METAL PRODUCTION PLANT, INDIA

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Abstract

India's uranium production plant has been assigned to produce uranium metal for differing and important domestic requirements. In the plant, diuranates and other oxides are processed through several unit operations to produce uranium metal where three process effluents are generated in tonnage quantities. Among the three effluents, two are nitrate-bearing radioactive wastes (effluents (N)) and another is fluoride-bearing radioactive effluent (effluent (F)). Waste disposal norms and regulations are becoming increasingly more stringent. In response to this stipulation, efforts have been made to develop suitable a methodology for recycling the wastes and also for 'polishing' the generated wastes to make them suitable for disposal. Suitable technologies have been developed for treating and recycling the effluents (N) and reducing waste generation and these have been demonstrated for reuse in the same plant. Developed technology has been utilized to treat the fluoride effluent (F) and the zero discharge principle has been achieved. The developmental study describing treatment and recycling of ammonium nitrate waste generated in the ammonium diuranate precipitation process has been challenging. This presentation will describe the insight gained from these developmental studies and also demonstrate the upgrade of uranium metal production technology in India with respect to waste recycle schemes.

USING NUCLEAR TECHNOLOGY FOR DETECTION AND DETERMINATION OF MINERALS AND FOR PREPARING STANDARD REFERENCE MATERIAL

H. SAYED Sudan Atomic Energy Commission, Khartoum, Sudan

Abstract

The contribution of the mining sector to Sudan's economy is approximately 4%. At present, the only resources mined in Sudan are gold, chrome, salt and building materials, the latter being mainly cement raw materials. In order to ensure future availability of resources and expand Sudan's inventory of economically important minerals, action needs to be taken. More efficient and economic methods of exploration and extraction of raw materials need to be developed. Effective production methods must be used that provide energy and raw materials. This also has a bearing on relevant nuclear and analytical techniques such as X ray fluorescence and neutron activation analysis. These analytical techniques will be used for this study, along with inductively coupled plasma mass spectrometry, as these have great potential to improve the efficiency of the results of raw material analysis. Since the main task of the Sudanese Atomic Energy Commission is to promote the safe use of nuclear energy through its application in nuclear analytical techniques in the exploration, extraction and treatment of metallic or non-metallic elements, uranium minerals are considered to be the most important focus for investigation.

INVESTIGATION OF THE GEOLOGICAL PROCESSES WHICH CONTROL THE GENESIS OF UNCONFORMITY-TYPE URANIUM DEPOSITS USING PARALLELIZED NUMERICAL SIMULATION ON A SUPERCOMPUTER

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Abstract

Uranium deposits of the Athabasca Basin, Canada, and the Alligator Rivers region, Australia, are located near subhorizontal unconformities between polydeformed/metamorphosed Archaean–Palaeoproterozoic rocks and overlying essentially undeformed Proterozoic sedimentary strata. Most deposits are associated with basement rooted faults, although the location of uranium mineralization with respect to the unconformity is quite variable. Athabasca Basin deposits occur at, above or below the unconformity. Conversely, all discovered deposits in the Alligator Rivers region occur below the unconformity. Conceptual models for these deposits invoke sandstone sourced oxidized fluids moving down into the basement (basement mineralization), or basement sourced reduced fluids moving up into the sandstone (sandstone mineralization). The movement is driven by topography, deformation or thermal buoyancy. This study focuses on deformation driven flow, using numerical simulation to explore fluid flow controls. The model is subjected to horizontal shortening and fluid flow directions are explored by varying fault dip, shortening direction, strain rate, basement rock strength, or permeability. Over 300 finite-element simulations were performed using the MOOSE simulation framework. The results indicate that shallow fault dip, high strain and fault-perpendicular shortening favour downward flow, whereas steep fault dip, low strain, and low-angle-to-fault shortening favour upward flow. These results are used to predict new mineralization targets.

LONG TERM TRENDS FOR GLOBAL URANIUM EXPLORATION

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Abstract

The global search for uranium started in earnest at the end of World War 2 and continues through to today. Over the intervening seven decades, a total of \$72 billion (in constant 2017 US Dollars) has been spent exploring for uranium. This has led to the discovery of over 1230 deposits (where uranium is the primary metal) containing a total of 11.1 Mt of U. This equates to an average unit discovery cost of US\$6.49 per Kg U.

The paper looks at when, where and who found these deposits. It also assesses the trend over time in the location of these discoveries, unit discovery cost, metres drilled per discovery, deposit style and the average size.

Data has also been compiled on how many of these deposits that have successfully been developed into mines, and the associated time delay between discovery and development. It is noted that, in recent decades, the conversion rate has been getting progressively slower and lower. This, combined with the current low uranium prices, has adversely affected the amount of exploration carried out. This is also of serious concern to end-users – as it raises the issue of whether (or not) the industry is able to find and deliver sufficient metal to meet its requirements in the longer term.

In practice, the uranium market will balance itself through the pricing mechanism. Higher prices will stimulate higher levels of exploration activity (and the amount of metal found). Higher prices will also enable existing projects to be economically developed.

Given the above, and assuming that the historical discovery and conversion performance trends continue into the future, estimates were made of the likely amount of uranium that could be found and developed over the next 20 years under a range of different demand and price scenarios. Depending on the scenario chosen, the author estimates that the uranium price needs to rise to \$156 or \$252/kg U (equal to \$61 to \$99 per lb of U_3O_8) for the industry to be in-balance in the longer term.

AN INTERNATIONALLY STANDARDIZED REPORTING TOOL TO UNDERSTAND THE SUSTAINABLE DEVELOPMENT PERFORMANCE OF URANIUM MINING AND PROCESSING SITES

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F. HARRIS Rio Tinto, Brisbane, Australia

Abstract

The World Nuclear Association has developed an internationally standardized reporting tool to understand the sustainable development performance of uranium mining and processing sites (referred to as the 'Checklist'). The goal is to achieve widespread agreement on a list of topics and indicators (for example, environment, health and safety, corporate social responsibility) for common use in demonstrating producers' adherence to sustainable development performance. Accompanying guidelines have also been prepared to support its use and completion. The Checklist is designed to draw on producers' existing reporting, supplemented by additional information required to achieve comprehensive supply chain risk management.

The Checklist has been developed to align with the Association's policy document on Sustaining Global Best Practices in Uranium Mining and Processing: Principles for Managing Radiation, Health and Safety, and Waste and the Environment. It has been prepared in cooperation with experts from some of the Association's member organizations.

It is anticipated that the Checklist will be reviewed over the next year to ensure that it accounts for any recent developments and feedback from user testing.

CONCEPTUAL MODEL OF THE FRACTURED AQUIFER OF THE URANIUM MINE IN CAETITÉ, BRAZIL: IMPLICATIONS FOR UNDERGROUND WATER FLOW

L. SILVA

National Security Cabinet — Federative Republic of Brazil,

J. CAMPOS University of Brasilia,

Brasilia, Brazil

Abstract

The area studied is that located in the uraniferous district of Lagoa Real in Brazil. The region is set in a semiarid climate context, with a water deficit for all months of the year and a high aridity index. Groundwater represents the main supply source, considering that most surface water sources are temporary and only flow during rainy periods. The main aquifer system present in the region is fractured and the presence of groundwater flow occurs through the discontinuities of the rock, where the rock mass corresponds to the set formed by the rock matrix and all its discontinuities (fractures, foliations and discordances). In this sense, the main purpose of the study was to develop a conceptual model for the aquifer system, through the geotechnical characterization of discontinuities, as these structures control the secondary porosity of the host medium. Hydrochemical data complement those data on the physical characterization of the behaviour interpreted for the aquifer. The aquifer system is unconfined, however, and presents points of stagnation of flow forming compartments without communication with the surrounding areas. Results have shown that discontinuity distribution was not a dominant factor over the chemical parameters. The composition of the rock was revealed as the most important factor.
WORLD NUCLEAR ASSOCIATION 2017 FUEL REPORT

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Abstract

The World Nuclear Association has published reports on nuclear fuel demand and supply at two-year intervals since 1975. The 2017 report is the 18th edition in the series and looks at scenarios for uranium demand and supply to 2035.

'The Nuclear Fuel Report' considers three scenarios (Lower, Reference and Upper); the projections are based on assumptions of electricity demand growth, nuclear economics, public acceptance, government policies and electricity market structure within each country.

From 2000 until the Fukushima accident in March 2011, successive editions of The Nuclear Fuel Report projected increasing nuclear capacity. But since the Fukushima accident, the reports have reduced nuclear capacity projections year-on-year, with a corresponding reduction in uranium requirements. The extensive range of mining projects that were developed over 2000-2010 have largely fallen away in the light of historically low uranium prices.

The World Nuclear Association believes that nuclear energy can make a greater contribution to clean and reliable electricity generation and presents a vision for the future, called 'Harmony'. In this vision, 25% of global electricity in 2050 would be provided by nuclear energy. We can be confident that sufficient uranium resources exist in the world to allow such a rapid expansion.

AN INTEGRATED CAPACITY BUILDING APPROACH TO URANIUM PRODUCTION CYCLE MILESTONES FOR REGIONAL ASIA PACIFIC TECHNICAL CO-OPERATION

SYAHRIL International Atomic Energy Agency, Vienna, Austria

Abstract

The Asia-Pacific region is the major consumer of mineral raw materials including uranium and other its associated mineral resources materials. However, production of the required raw materials which are required for many sectors including energy production and agro-industries are not sufficient to meet the demand. This is many due to predominantly low grade, unconventional and relatively technologically difficult to process mineral ore available in the region. Radioactive and associated mineral resources that could be extracted as co or by product far outweighs the conventional mining projects in the region. But the regional capacity to address challenges in economic, environmental and social returns and formulate a well-defined project through the life-cycle is found lacking. Creating a base line capacity and knowledge management platform to address the deficiency in those areas will greatly assist IAEAMember States in the region. The IAEA through the Technical Cooperation regional project RAS2019 – "Conducting the Comprehensive Management and Recovery of Radioactive and Associated Mineral Resources" provides capacity building in core technology in uranium production, feasibility and macro-economic aspect of uranium production, facilitate exchange of information and good practices, and also provide opportunities for dissemination of research and development results through publication and participation in international conferences.

A RISK BASED APPROACH TO URANIUM MINING REHABILITATION

K. TAYLER Department of the Environment and Energy, Darwin, Australia

Abstract

The Supervising Scientist is established to protect the environment from the effects of uranium mining in northern Australia, including overseeing the operation and closure of the Ranger uranium mine. Ranger has operated since 1980 and is surrounded by the dual World Heritage listed Kakadu National Park. Uranium milling operations at Ranger must cease by 2021, with rehabilitation work to be completed by 2026. A risk based programme of assessment and research has been developed by the Supervising Scientist Branch to ensure the protection of the environment throughout the decommissioning and rehabilitation process, between now and 2026. This presentation will provide details of the risk assessment and planning work undertaken by the Supervising Scientist Branch to systematically identify the knowledge needed to ensure environmental protection and the project work required to address these needs, align these with the mine rehabilitation schedule and inform the regulatory assessment process.

URANIUM POTENTIAL IN GREENLAND: AN UPDATE

K. THRANE Geological Survey of Denmark and Greenland Copenhagen, Denmark

Abstract

The uranium potential in Greenland is considered to be relatively high, with several known uranium occurrences. In 2016, a workshop on the assessment of the uranium potential in Greenland was held. Three uranium deposit types were chosen for the assessment: intrusive, sandstone hosted and unconformity-related. The main conclusion of the workshop was that the intrusive and unconformity-related deposits have the highest probability of having formed uranium deposits in Greenland. Existing evidence from airborne radiometric and drainage surveys, combined with field investigations, points to South Greenland as being the most prospective region for additional hidden or unrecognized intrusive type uranium occurrences. Highest ranked tracts are the Mesoproterozoic Ilímaussaq and Motzfeldt alkaline igneous intrusions. In addition, both the Central Domain and the Southern Domain of South Greenland were ranked as having a high potential for containing undiscovered intrusive deposits. Favourable geological settings for unconformity-related uranium mineralization have been identified. The highest ranked tracts comprise the two Mesoproterozoic basin formations that rest unconformably on Palaeoproterozoic or Archaean basement, namely the Eriksfjord Formation in South Greenland and the Thule Supergroup in North Greenland.

FOUNDATIONAL FUELS OF THE 21ST CENTURY: EVOLVING SOCIO-ECONOMICS OF SUSTAINABLE ENERGY SYSTEMS

H. TULSIDAS United Nations Economic Commission for Europe, Geneva, Switzerland

Abstract

The last few years saw the end of the commodity super-cycle, the gradual fall in oil and gas prices, the carbon crunch and the wide-ranging revolution that is going on in technology, often termed Industry 4.0. Rapid digitization, which is taking over all areas of the industry and society, including transportation, means that energy in general will be increasingly electric. How the electricity will be produced, stored, distributed and utilized will depend on the acceleration of this change and the bare realities of economics. Three fuels assume importance as foundational fuels in this scenario - natural gas, uranium and renewable resources. This paper will discuss the socio-economics of energy transformation, the comparative advantages and disadvantages, especially focusing on the role of nuclear energy in the post Paris Agreement era.

DEVELOPMENT, EVOLUTION AND IMPLEMENTATION OF ENVIRONMENT PROTECTION STANDARDS FOR URANIUM MINING IN THE AUSTRALIAN TROPICS

K. TURNER Department of the Environment and Energy, Darwin, Australia

Abstract

The Ranger uranium mine is surrounded by the dual World Heritage Listed Kakadu National Park. Kakadu is recognized for its significant cultural and environmental attributes. Owing to this, the Ranger mine is subject to very stringent environmental protection standards. These standards are developed and overseen by the Government of Australia through its Supervising Scientist Branch, which is part of the Department of the Environment and Energy. For 40 years, the Supervising Scientist Branch has undertaken site specific monitoring and research into the impacts of uranium mining on the sensitive environment surrounding the Ranger mine site. The collected data were used to derive site specific water quality compliance objectives that have helped to ensure the protection of the environment from the effects of mining operations. The data are now being used to develop closure criteria for the rehabilitation of the Ranger site, which is scheduled to be completed by 2026. This presentation will provide an overview of the Supervising Scientist Branch's monitoring and research programmes and demonstrate how the collected data have been used to ensure protection of the environment throughout the operation and after the rehabilitation of the Ranger uranium mine.

COAGULATION OF COLLOIDAL SILICA FROM URANIUM LEACH SOLUTIONS FOR IMPROVED SOLVENT EXTRACTION

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Abstract

Colloidal silica generated in the leaching process by contacting clays and concrete with sulphuric acid has caused operational problems in solvent extraction at Cameco's Key Lake uranium mill throughout its history. This colloidal silica stabilizes the aqueous continuous emulsions created in solvent extraction, resulting in increased solvent losses and operational downtime. Silica coagulation was investigated in 2014 by using POLYSIL RM1250, a polyethylene glycol coagulant. Laboratory results showed excellent clarification of the process solution, but subsequent mill trials were unsuccessful. In 2015, the problem shifted from optimizing solution clarity to measuring the changes in phase separation performance under both organic and aqueous continuous mixing with varying POLYSIL doses. This analysis showed aqueous continuous separation performance was equivalent to organic continuous separation performance at doses approaching 300 ppm, significantly higher than anything previously tested. A follow-up pilot study confirmed the laboratory results, but also discovered an inverse relationship between acid concentration and separation time, suggesting less acid would be required in the mill process. A mill trial with POLYSIL RM1250 was performed in 2017 with doses varying in the range 170–300 ppm. The mill trial was successful in reducing solvent consumption by 85% and overall acid and lime consumption by 7%.

URANIUM RECOVERY FROM ACID MINE DRAINAGE TREATMENT RESIDUE – CALDAS, BRAZIL CASE

R. VILLEGAS, M. MARTINS DIAS, C. H. TEIXEIRA CARVALHO, H. TAKUJI FUKUMA Brazilian Nuclear Energy Commission, Poços de Caldas, Brazil

Abstract

The generation of acid mine drainage on mining areas, an effluent generated due to the presence of a sulphide minerals (usually pyrite, FeS₂) in contact with oxygen and water, is a significant environmental problem. The Osamu Utsumi Mine, the first uranium mine in Brazil, located in Caldas, Minas Gerais, which ceased operations in 1995, presents this environmental issue. The acid solution is produced from the waste rock piles and leaches residual metals, including uranium. This effluent is treated continuously with lime and the residue, an alkaline mud, is deposited into the mine pit. This alkaline mud contains uranium and rare earths and several projects are being carried out in order to recover these products. This paper presents the comparison between efforts on developing acid and alkaline leaching processes to extract and to concentrate uranium liquor from this residual material. As the uranium concentration in the residue ranges from 1800-3000 mg/kg U₃O₈ (~1500 – 2500 mg/kg U), this recovery is interesting not only from the economical point of view but also from the environmental one, as the material could be deposited in a safer way during the mine closure process.

GEOLOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE JILING NA-METASOMATISM URANIUM DEPOSIT, GANSU, CHINA.

K. WANG, X. LIU, W. LIU, J. PAN East China University of Technology, Nanchang, China

Abstract

The metasomatite-related uranium deposit type hosts the second largest uranium resource repository in all deposit types. The type is widely distributed in Australia, Brazil, Russian, and Ukraine, but rarely presents in China. The Na-metasomatism-related uranium deposit in the Jiling area, northwest Chin,a was selected to investigate its genesis. The petrology indicates that late-magmatic albitization was followed by chlorite alteration of biotite and feldspar. The major uranium minerals are uraninite and brannerite. A large amount of uranium minerals occur in fractures in the newly formed albite and chlorite, indicating the main mineralization stage occurred later than albitization and chloritization. The geochemistry reveals that the Jiling granitoids belong to A-type granitoids and generated by mingling between the crust- and mantle-derived magmas. The high Th/U ratios (2.76 to 10.63) of the Jiling granitoids can provide uranium for mineralization. Compared to the fresh granitoids, the mineralized granitoids display high Na, U, low K, Si contents, and Light/Heavy Rare Earth Element ratios. H, O, and C isotopes reveal that the CO2 originated from the mantle, and water in hydrothermal fluid from mixing between magmatic hydrothermal and meteoric water. Pb isotopes reveal that the uranium may derive from the host granitoids.

PROSPECTIVITY ANALYSIS OF THE MOUNT ISA REGION (QUEENSLAND, AUSTRALIA) FOR METASOMATITE-TYPE URANIUM

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M. BRUCE Thunderbird Metals, Melbourne

Australia

Abstract

Results of quantitative mineral resource assessment (QMRA) and mineral prospectivity analysis (MPA) for metasomatite-type (albitite-type) uranium deposits in the Mount Isa region of Queensland, Australia, are discussed. The study illustrates the process of using a geological model and various input data to define areas prospective for undiscovered uranium resources. The approach was fundamentally knowledge-driven and required use of geological judgment in choosing appropriate input layers, in assigning fuzzy membership values and in deciding the most appropriate methods of combining the input layers. The prospectivity mapping was successful in that known deposits, particularly larger examples, fall within pixels categorized as highly prospective. Ultimately, however, the success of the approach will need to be judged by the success of ongoing mineral exploration in areas deemed to have prospectivity.

A comparison of regional and detailed studies illustrates the scale dependency of the input parameters, with some input layers being appropriate for the regional analysis but not for the more detailed one. Prospectivity maps generated by the fuzzy gamma and vectorial fuzzy logic techniques are similar. The latter technique may, however, provide better discrimination of areas prospective for large (rather than medium or small) deposits. A further benefit of this technique is that there is no need to produce intermediate combinations of input layers and no necessity for a gamma parameter. This results in a simplified process and makes subsequent applications of the technique more repeatable and comparable.

This work also used MPA as the basis for defining a prospective tract which was the input for QMRA. A global regression model of total ore tonnage estimated undiscovered ore tonnage for the entire Mt Isa North tract at 83 Mt.

TAILINGS AND WASTE MANAGEMENT AT THE KENTICHA TANTALUM MINE SITE

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Abstract

Tantalum mining is a major source of radioactive waste in Ethiopia, with U-238, Th-232 and K-40 average concentration in the solid waste of 110, 15 and 0.6 kBq/kg, respectively. It is clear that nations cannot reduce pollution from waste by reducing the nation's growth. This economic growth should be developed in a sustainable way. The generation of radioactive waste due to tantalum mining in the country needs to be regulated and managed in an efficient manner in order to comply with the health, environmental and safety regulations.

The regulations are enforced in order to avoid hazardous radiation exposure of workers in the industry, the public in general and to protect the environment. The regulatory body has enacted an extensive radiological monitoring programme at the Kenticha mine sites and tailings dam to measure the radiation exposure of people living close to the mine by measuring radionuclides dispersed by surface water, groundwater and atmospheric pathways. This has been achieved by testing water samples from effluent, soil and cereals from the environment and converting these measurements into radiation exposure estimates. The radiation dose estimates have been lower than the annual public dose limit of 1 mSv.

DEPLOYING TECHNOLOGY AND MANAGEMENT OF SUSTAINABLE URANIUM EXTRACTION PROJECTS

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Abstract

Through its Technical Cooperation programme, the IAEA is supporting a major, four-year interregional project on deploying technology and management of sustainable uranium extraction projects. Fifty-two of the IAEA's Member States are involved, from 2016-2019 inclusive. This project is in continuation of an interregional project on supporting uranium exploration and production that was active during 2012 - 2013. The main activities are Workshops and Training Courses held in the Member States, with both general and specialized topics in the themes of the project, and to provide inputs that can help leverage the value-addition of the uranium value chain and build business models that adaptive to a wide range of local conditions. At the half-way point, the activities of the project are summarized and the activities for the last two years are set out, which have been refined based on feedback from the participants and the specialized experts who have assisted the IAEA.

OVERVIEW OF URANIUM HEAP LEACHING TECHNOLOGY IN CHINA

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Abstract

With the merits of low power, reagent and water consumptions and low operational cost, heap leaching of uranium ores has become the most widely used technological process for natural uranium production in China. Of the proved uranium reserves in China, hard rock resources of low uranium grade comprise the largest proportion. These resources are mainly located in southern China and suitable for processing by heap leaching. The study of heap leaching of uranium ores has been emphasized in the past decades in the country and some technical achievements have been made and already applied in commercial production. The current status of the application of uranium heap leaching in China is discussed in this paper and includes such details as ore characteristics and technological processes for typical processing mills and some new technologies, developed and applied. Some existing problems in practical operation are also discussed.

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