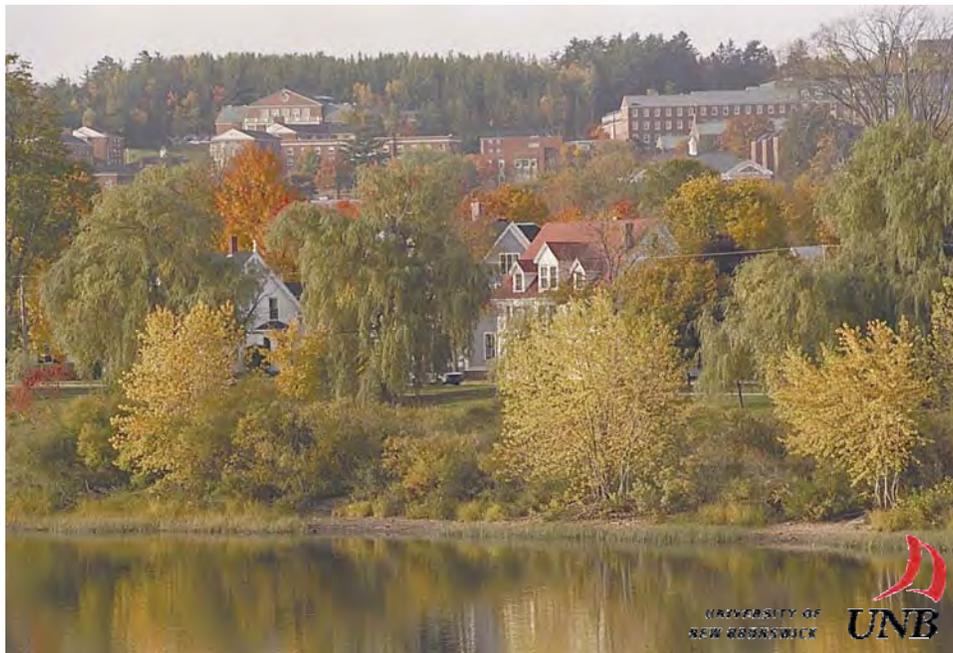




**PROCEEDINGS OF THE 24TH
INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM
FREDERICTON, NEW BRUNSWICK, CANADA**



JUNE 1ST-4TH, 2009

EDITED BY

DAVID R. LENTZ, KATHLEEN G. THORNE, & KRISTY-LEE BEAL



VOLUME I



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ISBN 978-1-55131-136-4

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**URANIUM DEPOSITS: GEOCHEMICAL EXPLORATION TECHNIQUES TO
CASE STUDIES**

EDITED BY:

**DAVID QUIRT
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Fraser Lakes Zones A and B, Way Lake Project, Saskatchewan: geological, geophysical, and geochemical characteristics of basement-hosted uranium mineralization

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ABSTRACT: The Fraser Lakes uranium showings (Fraser Lakes Zones A and B) were identified in 2008 by ground prospecting of airborne geophysical targets in the southern half of JNR Resources Inc.'s Way Lake property in northern Saskatchewan, Canada. The mineralized zones are proximal to a 5-kilometre-long folded electroromagnetic (EM) conductor comprised of Wollaston Group graphitic pelitic gneisses and uraniumiferous granitic pegmatites; some five kilometres east of the main Walker Lake EM conductive trend. Outcrop grab samples returned from 0.038 to 0.453% U₃O₈ and drill core samples returned mineralized sections with values from 0.012 to 0.552% U₃O₈.

KEYWORDS: *U-Th-REE mineralization, basement-hosted, unconformity-type, Hudsonian granitoids, Fraser Lakes*

INTRODUCTION

The Fraser Lakes uranium showings, part of JNR's Way Lake Project, are situated circa 25 km southeast of the southeastern margin of the Athabasca Basin, northern Saskatchewan, Canada (Fig. 1). These uranium showings (Fraser Lakes Zones A and B) were identified recently in 2008 by ground prospecting of airborne geophysical targets within the southern half of the Way Lake property. An ongoing drilling program is focusing on the widespread outcrops of uranium mineralization, referred to as the Fraser Lakes uranium showings.

The purpose of this paper is to document the occurrence, geology, geophysics, and geochemistry of the Fraser Lakes uranium showings.

GEOLOGICAL SETTING

Regional Geology

The Fraser Lakes uranium showings are located SE of the Athabasca Basin in the eastern Wollaston Domain, part of the eastern sub-Athabasca basement complex (Fig. 1).

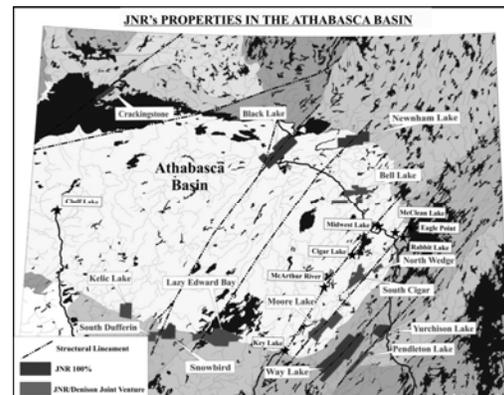


Fig. 1. Location of JNR's properties in the Athabasca Basin, including its Way Lake property on the SE margin (courtesy of JNR Resources Inc. Home Page).

The Athabasca Basin occurs within the southwestern part of the Churchill Structural Province of the Canadian Shield. The 100,000 km² basin is filled by an unmetamorphosed clastic sequence of the Mesoproterozoic (Helikian) Athabasca Group. The basin is underlain by an Archean/Paleoproterozoic basement complex that was strongly deformed and metamorphosed during the Hudsonian

Orogeny (Lewry & Sibbald 1977, 1980; Annesley *et al.* 1997, 1999, 2005).

The Wollaston and Mudjatik domains form two of the major subdivisions of the Cree Lake Zone (Lewry & Sibbald 1977), and also the eastern part of the western foreland of the Paleoproterozoic Trans-Hudson Orogen (i.e., part of the Hearne Province; Hoffman 1989, 1990; Bickford *et al.* 1990; Lewry & Collerson 1990). The present tectonic configuration resulted from the oblique collision of the Superior Province into the accreted Reindeer Zone and Hearne Province during the Hudsonian Orogeny (Fig. 2).

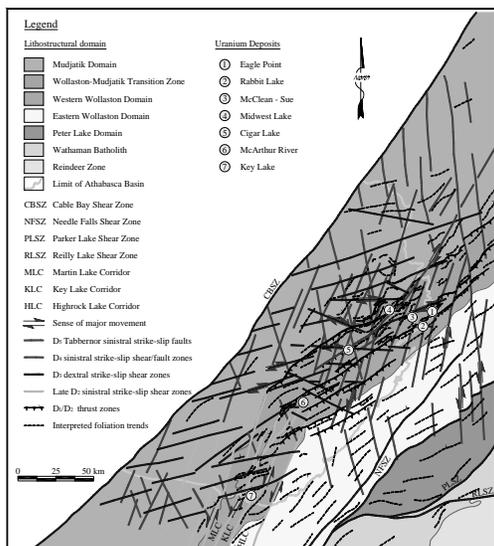


Fig. 2. Geological framework of the basement to the eastern Athabasca Basin, including the location of the major unconformity-type uranium deposits, from Annesley *et al.* (2005).

Local Geology

The Way Lake uranium project of JNR Resources Inc. is located 55 kilometres east of the Key Lake uranium mine in the Athabasca Basin of northern Saskatchewan. The property is underlain by a steeply-dipping, northeast-trending, highly folded sequence of intercalated Paleoproterozoic Wollaston Group metasediments and underlying Archean orthogneisses. In 2006, high-grade uranium mineralization was obtained from a previously identified massive pitchblende vein, now called the Hook

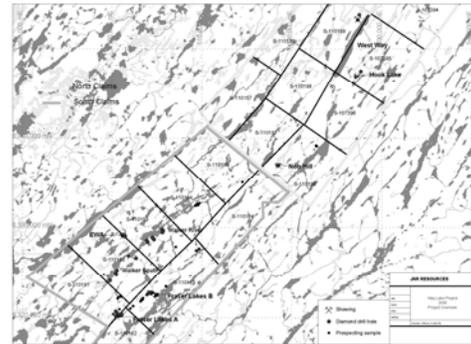


Fig. 3. The major uranium showings within the northern and southern parts of the Way Lake property, including the newly discovered Fraser Lakes zones A and B.

Lake showing (Fig. 3), where two grab samples yielded 40.1% and 48% U₃O₈ with significant Pb, REE, and Th enrichment, and anomalous B, Co, and V.

Within the Walker Lake area (Fig. 3, south-western part of the property), two major uranium showings (now called Fraser Lakes Zones A and B) were identified by airborne geophysics and ground prospecting. These mineralized zones are proximal to a 5-kilometre-long, folded EM conductor comprised of Wollaston Group graphitic pelitic gneisses and uraniferous granitic pegmatites and leucogranites.

A major prospecting campaign during the summer of 2008 identified significant uranium, thorium, and REE mineralization in several outcrops of granitic pegmatites and leucogranites, coincident with this conductive EM trend. These outcrops are estimated to be ~200-250 meters below a glacially eroded Athabasca/basement unconformity. The radioactive granitic pegmatites and leucogranites occur within a highly tectonized contact zone between Archean granitoids and basal Wollaston Group metasediments. This crustal melt shear zone (decollement) is folded around Archean granitic domes and is thickest within NE-plunging synformal and antoformal noses. These fold noses are interpreted to have been dilation zones with potential for brittle reactivation and associated fluid flow, alteration, and

mineralization after deposition of the Athabasca sandstones. The radioactive quartz-feldspar-biotite granitic pegmatites and leucogranites contain minor to trace amounts of uraninite, U-Th-REE-rich monazite, molybdenite, chalcopyrite, pyrite, and ilmenite. Locally, dark smoky quartz segregations and veins are noted.

The Fraser Lakes Zone B (Figs. 4 & 5) comprises numerous outcrop showings along the northern extent of this folded EM conductor, and is currently the more prospective of the two mineralized zones. Nearly 70 individual mineralized outcrop sites were identified over a 500-metre-wide by 1.5-kilometre-long area within an antiformal fold nose cut by an E-W dextral ductile-brittle cross-structure and younger NNW- and NNE-trending brittle faults. Over 70% of the grab samples taken from these sites assayed from 0.038 to 0.453% U₃O₈.

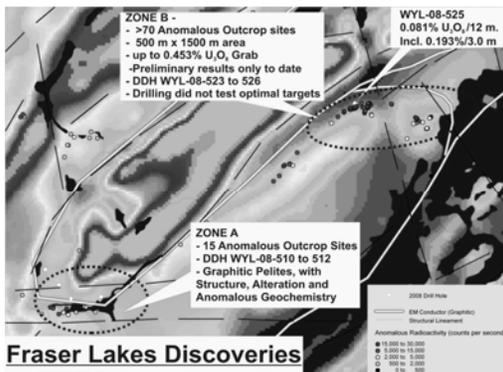


Fig. 4. Some highlights and details of the Fraser Lakes discoveries shown superimposed on the total field aeromagnetic image and a surface trace of the complexly folded EM conductor.

The B zone was tested by three drill holes (WYL-08-524 to 526) at the end of the 2008 program (Figures 4 and 5). Although they could not test the optimum target, namely the graphitic pelitic gneiss/granitic pegmatite contact that occurs beneath muskeg, all three intersected uranium and thorium mineralization, accompanied by rare-earth element enrichment and anomalous levels of pathfinder elements. The best results were from drill hole WYL-08-525, which

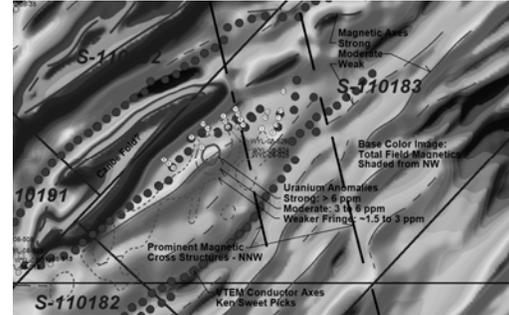


Fig. 5. Location of Zone B 2008 and 2009 drill holes (numbered dots) superimposed on the total field aeromagnetic image, airborne radiometric anomalies (contoured), and EM conductor picks (dark dots). Note the highly disrupted nature of the EM conductor picks in the vicinity of Zone B.

intersected numerous uraniumiferous intervals, mainly within granitic pegmatite. Of particular note was a 12.0-metre intersection from 77.50 to 89.50 metres down hole that returned 0.081% U₃O₈; including a 3.0-metre intercept of 0.193% U₃O₈ (true widths cannot be reliably estimated at this time).

Fraser Lakes Zone A uranium showings occur within a reactivated NE-plunging synformal fold nose, associated with Wollaston Group graphitic pelitic gneisses and leucogranites at the southern end of the EM conductor (Figs. 3 & 4). Seven holes (WYL-08-508 to 514) were drilled in this area, three of which intersected broad zones of significantly altered and structurally disrupted graphitic pelitic gneisses accompanied by anomalous levels of pathfinder elements, particularly copper, nickel, vanadium, bismuth, and zinc. Outcrop samples in the area contained up to 0.042% U₃O₈.

DISCUSSION AND CONCLUSIONS

The main results of this contribution can be summarized as follows:

- (1) The Fraser Lakes uranium showings (Fraser Lakes Zones A and B) were identified in 2008 by ground prospecting of airborne geophysical targets, and show characteristics typical of basement-hosted uranium deposits.
- (2) Outcrop radiometrics of the granitic pegmatites and leucogranites correlate

well with a high-resolution magnetic /radiometric survey over the Fraser Lakes and surrounding area.

(3) The large aerial extent of the airborne anomalies and the presence of U and Th in outcrop and within several boreholes clearly show that the Fraser Lakes area has a very high potential and likelihood of further uranium discoveries, including high-grade root zones.

In summary, the Fraser Lakes district has numerous similarities to nearby basement-hosted uranium deposits, such as Eagle Point and Millennium, and to U-Th-REE deposits found in the Grenville Province (Lentz 1991) and the Erzgebirge -Fichtelgebirge region, Germany (Förster 1998).

ACKNOWLEDGEMENTS

We thank JNR Resources Inc. for permission to publish.

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Geochemical controls on uranium precipitation in calcrete palaeochannel deposits of Namibia

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ABSTRACT: Palaeo-river channels containing calcrete are important potential hosts for economic uranium mineralization in many parts of southern Africa particularly Namibia. The main feature of these deposits are the dominance of the mineral Carnotite [$K_2(UO_2)_2(VO_4)_2 \cdot 3(H_2O)$] as the main uranium host in these channels. However other phases such as andersonite ($Na_2K_3UO_3(CO_3)_3(H_2O)_6$), liebigite ($Ca_2UO_2(CO_3)_3(H_2O)_{10}$), rutherfordine (UO_2CO_3), swartzite ($CaMgUO_2(CO_3)_3(H_2O)_{12}$), tyuyamunite ($Ca(UO_2)_2(VO_4)_2 \cdot 5-8H_2O$), and urancalcarite [$Ca(UO_2)_3(CO_3)(OH)_6 \cdot 6H_2O$] are also present in minor amounts. These minerals are associated with epigenetic calcite, dolomite, gypsum, palygorskite, and strontianite. Typically a complex stratigraphy of calcite as transported and epigenetic calcite can be observed in the deposits. Uranium precipitation can occur more than once in the paragenesis indicating carnotite can be dissolved and re-precipitated in the palaeochannel possibly in response to fresh alkaline groundwater. Clear evidence exists that carbonates, gypsum, and uranium minerals are precipitated interstitially in the granite dominated detrital that fills the channel. Grade in these channels is typically higher at shallow depth with often the highest grade being at surface indicating that evaporation may play a role in precipitating uranium. Mineral equilibrium calculations, based on known mineralogy and groundwater chemistry have been used to construct geochemical models to understand ore genesis and assist exploration for carnotite hosted calcrete deposits. Multiple phases of calcite and carnotite formation are indicated in mineral paragenesis and an explanation for this may be that there has been frequent re-working of the deposit by inflowing groundwater. In addition, high evaporation in the near surface environment generate conditions for another mechanism for carnotite formation. Species activities and mineral saturation have been determined. These demonstrate that for many of the deposits carnotite is close to saturation or is only weakly undersaturated demonstrating that recent or even seasonal dissolution and re-mobilization of uranium may occur in these deposits leading to wide hydrogeochemical halos for trace levels of uranium in groundwater around these deposits. However inherent difficulties in the analysis of trace levels of metals in high salinity groundwater typical of palaeochannels may limit application in exploration.

KEYWORDS: *uranium, hydrogeochemistry, geochemical modelling, Namibia*

INTRODUCTION

The discovery of the calcrete hosted surficial uranium deposits of Namibia demonstrated the presence of widespread uranium in calcrete filled palaeochannels (Hambleton-Jones 1984) and similar mineral deposits have been observed elsewhere in Southern Africa, USA and Australia (Carlisle 1978; Hambleton-Jones 1978; Mann & Deutscher 1978). The host rocks are typically lenticular bodies of alluvium, soil or detritus material cemented by calcite, gypsum, palygorskite, and other mineral phases. Uranium mineralogy is dominated by the mineral Carnotite [$K_2(UO_2)_2(VO_4)_2 \cdot 3(H_2O)$] as the main mineral in these channels. However other phases such as andersonite ($Na_2K_3UO_3(CO_3)_3(H_2O)_6$), liebigite ($Ca_2UO_2(CO_3)_3(H_2O)_{10}$),

rutherfordine (UO_2CO_3), swartzite ($CaMgUO_2(CO_3)_3(H_2O)_{12}$), tyuyamunite ($Ca(UO_2)_2(VO_4)_2 \cdot 5-8H_2O$), and urancalcarite [$Ca(UO_2)_3(CO_3)(OH)_6 \cdot 6H_2O$] are also present in minor amounts (Bowell *et al.* 2008). In Namibia the presence of authigenic gypsum in the surface calcrete increases with proximity to the Atlantic Ocean and this has been identified as an important factor in considering genesis of these deposits (Hambleton-Jones & Toens 1978). The genesis of carnotite-hosted calcrete deposits has been studied in both Namibia and in Australia and several mechanisms have been invoked; including evaporative controls weakening uranyl-carbonate species and decreasing pH close to the groundwater table (Mann & Deutscher 1978; Carlisle 1978), physical and chemical attenuation through

common ion effect and interaction with clay minerals and capillary driven diffusion mechanism similar to chemical dilatancy (Cameron *et al.* 2002). In order to determine the major geochemical controls on these deposits and the implications this may have for regional exploration geochemical modelling has been undertaken using groundwater chemistry from four deposits in Namibia.

GEOLOGY

The Namib Desert is underlain by bedrock complex of Late Proterozoic Damaran Belt unconformably overlying a 2 billion year old (Giga-annum or Ga) Mesoproterozoic basement complex of granite-gneiss (Kukla *et al.* 1991). The Damaran beds consist of metamorphosed arsenites and argillites of the Nosib Group overlain by pelitic rocks of the Swakop Group. Folding combined with regional granite intrusions occurred in the Pan African Orogeny (800 to 500 million years ago). Some of these orogenic granites are uraniumiferous. The sequence was intruded by both late to post tectonic 528Ma granites and most importantly by a series of post Karoo age (124-137Ma), anorogenic, peralkaline, slightly peraluminous, and topaz bearing granites with moderately elevated background uranium counts (e.g., Rössing; Basson & Greenway 2004). The latter younger granites (Spitzkoppe) are related to the break up of Gondwanaland (130 – 80Ma) and constitute the ultimate source rocks for Trekkopje Project mineralization, with background contents of 20-30ppm uranium in places.

Between 80 Ma and 50 Ma, the Namib rocks were eroded to a smooth peneplain (the Namib Unconformity). Namib Group Tertiary and Quaternary sedimentary debris was deposited in east-west to southwest trending paleochannels incised into Karibib marbles and schists on that Cretaceous age unconformity. From mid Tertiary to present, the central Namib region has maintained profoundly arid climatic conditions for the last 50 or more million years. Uplift initiated the post African erosion surface that filled valleys and channels with poorly sorted angular

material, with little evidence of chemical weathering or organic debris. Host rocks are paleo-channel deposits of cobbles, gravels, and local sands composed of the regional rock types. Calcrete formation is widespread throughout the region particularly in alluvium channels and paleoriver beds. The major calcrete channels in central western Namibia are shown in Figure 1.

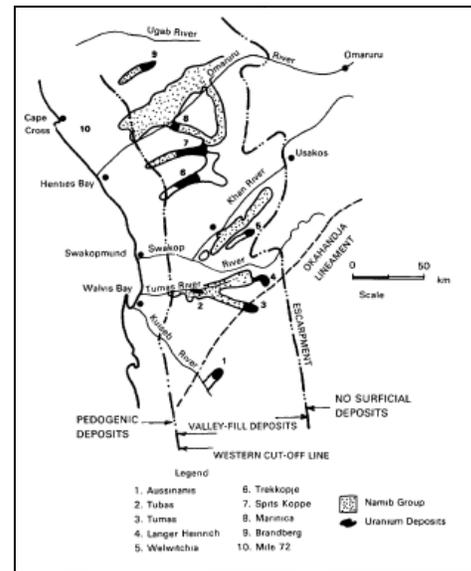


Fig. 1. Distribution of calcrete-hosted carnotite deposits in central Namibia (from Hambleton-Jones 1984).

HYDROGEOCHEMISTRY OF CARNOTITE HOSTED CALCRETE DEPOSITS

Data has been obtained from published sources and listed data held in the library of the Geological Survey of Namibia. This data has been used to assess the geochemical environment in the vicinity of channel fill and pedogenic uranium-bearing calcrete deposits. The data has been analysed by various methods and laboratories so direct comparison of the data has to be treated with caution. A summary table of the geochemistry of waters from each of the deposits is given in Table 1.

The deposit with the highest salinity is Mile 72, followed by Tubas, Trekkopje, and Langer Heinrich. The reason behind

Table 1. Hydrogeochemistry of representative groundwater analysis, Calcrete Uranium deposits, Namibia (average of available data).

Element	Trek-kopje	Langer Heinrich	Tubas	Mile 72
pH	6.62	7.8	7.57	7.81
Eh, mV	64	107	137	455
Carbonate mg/L	174	473	575	88.3
Sulfate mg/L	2090	2240	3250	1270
Chloride mg/L	6750	3000	6580	6790
Sodium mg/L	4110	970	2640	3070
Potassium mg/L	121	387	822	1160
Calcium mg/L	665	429	1460	890
Uranium mg/L	0.212	0.316	0.182	0.019
Vanadium mg/L	0.038	0.121	0.061	<0.005

this obviously can be related to distance from the sea with Trekkopje and Langer Heinrich the furthest from the coast, Tubas being 40 km and Mile 72 at the coast. Uranium is present in many of the groundwaters (Table 1). In terms of a correlation, a positive correlation can be observed for uranium with redox potential (Eh), high carbonate and lower sulfate and chloride, pH, and potassium in groundwaters (Fig. 2).

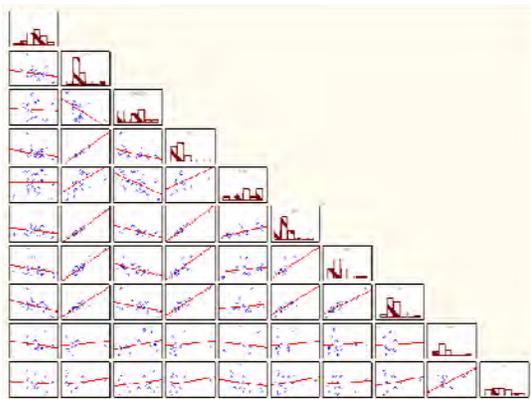


Fig. 2. Matrix plot for key groundwater parameters, calcrete-hosted carnotite deposits, Namibia.

GEOCHEMICAL CONTROLS

The speciation of uranium and vanadium has been determined for groundwaters from the calcrete-hosted carnotite deposits. These were completed in Geochemists Workbench v.7 using in-

program database supplemented by additional data from Gorman-Lewis *et al.* (2008). The chemistry of groundwater for Namibian calcretes promotes the stabilization of the species, $UO_2(CO_3)_2^-$ (Fig. 3) and for vanadium, $VO_2(OH)_4^-$.

The uranyl dicarbonate species is extremely stable in aqueous solutions but by evaporation can become sufficiently concentrated by evaporation to generate the low solubility mineral carnotite in the pH range 6 to 8, the natural range of pH values in the Namibian groundwaters.

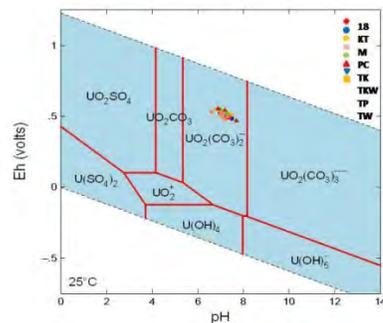


Fig. 3. Eh-pH diagram for the system U-H-O-S-Cl-C at 298 K.

At the prevailing pH in the Namibian groundwaters, the predicted solubility of carnotite is low and close to saturation. From one hole in the Tubas deposit, carnotite saturation is close to 0 and predicted to be over saturated around the water-table zone and in the near-surface upper 2m of the gypcrete. Where Eh is positive carnotite is predicted to be near-saturation. This indicates that carnotite accumulation at or above the regional water-table can occur by upward diffusion of uranyl carbonate species with possible precipitation due to nucleation on clay minerals or gypsum, as evidenced in the Tubas River.

MECHANISMS OF FORMATION

Understanding the formation of carnotite in calcrete is important with respect to not just understanding the formation of the deposits but also has implications for exploration of such deposits (Nash *et al.* 1981; Hambleton-Jones *et al.* 1984). A

number of mechanisms have been proposed to explain the precipitation of Carnotite in calcrete formations (Boyle 1984). These include reduction, sorption, uranyl complex dissociation, changes in redox state of constituent metals, evaporation, variation in CO₂ partial pressure, pH, mixing of different groundwaters and colloidal precipitation.

The source of uranium mineralization is erosion of uraniferous granites in the region followed by transportation of uranium in mildly oxidizing saline alkaline groundwater solutions in constricted drainages to semi-closed basins with variable evaporative conditions. The Quaternary erosion cycle was marked by uplift of coastal areas and marine regression with planation and incision of the post African erosion surface, with river valleys becoming younger towards the coast (Nash & McLaren 2003). This regional uplift across the Southern African subcontinent resulted in renewal of deposition of coarse sedimentary debris into incised drainage ways, creating the current drainage channels (Ringrose *et al.* 2005). Precipitation fluctuations in this period are believed to have effected uranium deposition, dissolution, and re-deposition.

In the fluvial-type deposits, such as Langer Heinrich or Trekkopje, most likely high carbonate fluids are responsible to mobilize uranium as uranium (VI) and deposition is in response to changes in a_{HCO₃}, pH, or redox similar to mechanisms proposed for Australian calcrete hosted carnotite deposits (Mann & Deutscher 1978b; Hartleb 1988). This form of carnotite is primarily due to remobilization of carnotite "upstream" and to de-complexing of uranyl-carbonates in waters of higher salinity. Uranium analyses and solubility indices suggest that the carnotite up stream is at present re-dissolving and that a different mechanism was primarily responsible for its original precipitation. The slow moving and upward welling groundwater undergo chemical and redox (reduction/oxidation state) changes allowing for precipitation of uranium as carnotite near surface. Carnotite occurs

within the margins of the "chemical delta" formed as the drainage system forms, as observed for trace-element distribution in modern inland deltas (Ringrose *et al.* 2005).

In zones close to or at the water table the primary driver for remobilization appears to be high salinity and evaporative driven chemical dilatancy such as in the shallow calcrete deposits, for example Mile 72. A possible comparative mechanism has been proposed by Cameron *et al.* (2002) to explain the development of surface geochemical anomalies in areas with a thick vadose zone. Results of soil and groundwater analyses from an integrated study at the Spence porphyry copper deposit in northern Chile, which is buried beneath 50 to 100 m of Miocene gravels, are consistent with the vertical movement of saline metal-rich groundwater along fractures (Cameron *et al.* 2002). Copper in groundwater is restricted to the mineralised area due to the tendency of Cu²⁺ released by oxidation of sulfides to adsorb to Fe hydroxide colloidal particles and coatings, whereas elements that dissolve as anions (e.g., As, Mo, Se, and Re), are dispersed widely. Field measurement of the conductivity of soil-water slurries showed two zones of salt (NaCl) enrichment, one directly over the deposit and the other 1 km away. Trenching of the soils in these zones revealed vertical fractures in the gravels, whereas trenching in a background area showed no fractures. The fracture zones appear to have formed by reactivation of basement faults. Elements present in the soils above the fracture zones are the same as those enriched in ground-water near the deposit and indicate redistribution of elements by ground-water movement to the surface during earthquakes, followed by evaporation and further redistribution by rain.

The correlation to calcrete-gypcrete deposits is that saline groundwater may mobilize uranium both laterally and vertically through cyclic diffusion and pumping in a similar, albeit on a smaller scale. This may occur in response to

recent marine transgression-regression episodes or even seasonally high salinity incursions in coastal groundwater.

Field measurements in sedimentary fluvial-type calcrete deposits also suggest that present-day groundwater in these areas may also display potential to both dissolve and precipitate uranium in the near surface. Chemical dilatancy and evaporation-driven diffusion that promote de-complexing, diffusion, and re-precipitation mechanisms are seen to play integral parts in the continued chemical re-working and modification of these calcrete-hosted carnotite deposits.

IMPLICATIONS FOR EXPLORATION

The development of relatively large, but weak geochemical halos associated with calcrete-hosted carnotite deposits can be utilized on a regional scale through the application of aerial radiometric surveys and in more detailed prospect level evaluation by direct geochemical analysis of groundwater coupled with borehole geology and down hole radiometric surveys. The proximity to such superficial deposits of uranium can be gauged by groundwater uranium content. In addition for blind deposits the development of a Carnotite Saturation Index has been applied in Australia as a more sensitive approach based on several parameters (Mann & Deutscher 1978). This index can be defined as;

$$CSI = \log \frac{[U][V][K]}{1.13 \times 10^4 [HCO_3]^{-2}}$$

Where uranium and vanadium concentrations are in µg/L and potassium and bi-carbonate are in mg/L. Where the CSI is equal to zero then groundwater chemistry and carnotite saturation are in equilibrium and the mineral has the potential to be present. The assessment of groundwater chemistry in the vicinity of calcrete-hosted carnotite deposits indicates that a wide geochemical halo exists and that this halo can be identified during exploration. In Australia direct analysis of groundwater and the CSI have been demonstrated as suitable methods for exploration. In Namibia, in reality although the approach may be useful for

higher grade deposits, such as Langer Heinrich, in reality the low uranium and vanadium chemistry in most groundwaters in proximity to calcrete-hosted carnotite deposits and difficulties in detecting trace levels of these metals will limit application. In addition for many of the Namibian deposits direct surface mapping of carnotite is possible for most of the known deposits so surface radiometrics and geological mapping will continue to provide a more cost-effective and reliable method of exploration for this class of deposit in Namibia and throughout Southern Africa.

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Variability of U and some trace elements in ferromanganese nodules of the Clarion-Clipperton zone (Pacific Ocean) and mechanism of their formation

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ABSTRACT: Marine geological exploration is able to provide accurate assessments of the metal content in seabed mineral deposits, which are considered as a new industrial type. Besides the relatively well-studied elements (Mn, Fe, Co, Ni, Cu, Zn, Pb, etc.), a number of economically important trace elements occur in deep-sea ferromanganese nodules, but they have been poorly studied in the past. Characteristic of U, Th, Ra, and Sr distributions in ferromanganese nodules, as well as adjacent bottom sediments from the Clarion-Clipperton region are given in this paper to get knowledge on their economic interest. These elements are not associated with the iron and manganese phases in ferromanganese precipitates and it is important to know possible mechanism of their concentration. The ferromanganese nodules have been formed in an open physicochemical system from an unsaturated ore components environment and only electrochemical mechanisms are possibly powerful enough to form these ore components at industrial scales.

KEYWORDS: *ferromanganese nodules, uranium, ore deposits*

INTRODUCTION

The ferromanganese nodules commonly are regarded as a new industrial kind of ore deposits due to high concentrations of Mn, Fe, Co, Ni, Cu, Zn, and Pb. In the recent past, we are seeing an increasing interest in the nodules as a possible source of many other elements, especially trace metals important for modern technologies. Many of the trace elements have been poorly studied in the past, due to analytical problems and lack of economic interest. For the element U, Th, Ra, and Sr only a few data are available, with mostly overestimated contents, caused by insufficient analytical capabilities and deficient sample treatments. We have therefore studied the distribution of these elements in the nodules and adjacent bottom sediments in order to estimate their possible source, relationship with common metals of the nodules, and assess their industrial importance. For these purposes we used our previous investigation (Guliy & Tysiachna 2008) of distribution and peculiarities of typical nodule components,

as well as their economic evaluation (Koschinsky 2008).

GEOLOGICAL SETTING

Regional Geology

The nodules studied have been dredged from a number of sites of the Clarion-Clipperton area of the Pacific Ocean floor between long. 137° and 138° W and lat. 12° and 13° N (Fig. 1). The Fe-Mn deposits are located between two famous faults – Clarion and Clipperton and they were the objects of several studies by a number of investigators.

Local Geology and Samples

The geology, textural characteristics of the nodules and bottom sediments, and descriptions of the substratum are summarized on site (Guliy 2004). Samples have been studied for its dimension, and mineralogical and chemical composition in accordance with their space distribution as well as age differences.

The nodules rest as a mono-disperse layer of potato-like balls on unconsolidated pelagic sediments down to 5500 m water depth.



Fig. 1. Location of studied area.

They have diameters of 2 to more than 8 cm. The substratum of the nodules is shark teeth, basalts, andesites, and more rare varieties of weathered volcanic rocks.

Nodules have an average population density of 12 kg/m² in high-quality fields, crust of 4 to 5 cm thickness show local coverages of 15 to 25 kg/m².

We studied two sites of samples. Firstly, the element's distribution in the ferromanganese nodules and adjacent bottom sediments has been investigated after undisturbed sampling by grabs. Secondly, dimension distribution of discoid, plate, and ellipsoid nodules, as well its fragments and crusts discovered after seagoing dredged samples.

Uranium, thorium, radium, and strontium spatial distribution within studied area turn out to be different: 1) a relatively similar pictures of U, Th, and Ra distributions (Fig. 2 – 4), and 2) a clear difference of distribution for Sr (Fig. 5). The greatest features in the spatial distributions of U, Th, and Ra appear in the northern-western and southern-eastern parts of the region (see Fig. 2 – 4).

Clear differences in spatial distribution of U, Th, Ra and Sr can reflect general differences in nature of these elements in the nodules.

We determined also another pictures of spatial distributions of U, Th, Ra and Mn, which are supported by negative values of correlation coefficients for these elements and Mn. At the same time, positive values of correlation coefficients for these elements and Fe (**rFe-U= 0.45**, **rFe-Th=**

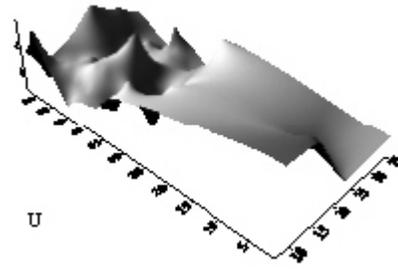


Fig. 2. Spatial distribution of U.

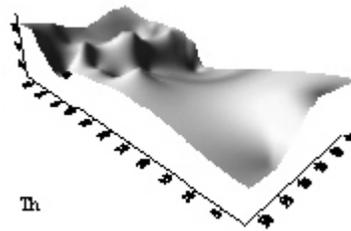


Fig. 3. Spatial distribution of Th.

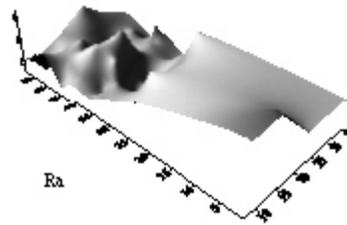


Fig. 4. Spatial distribution of Ra.

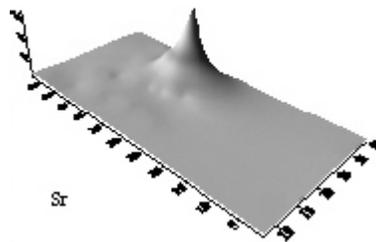


Fig. 5. Spatial distribution of Sr.

0.53, **rFe-Ra= 0.17**) give to us evidence of the close genetic relationships between these elements and Fe phases.

The characters of each element's distribution in ferromanganese nodules and adjacent sediments are different and

reflect differences in nature of ore components concentration. In general, according to obtained average compositions and calculated dispersions, the nodule matter is richer in uranium, thorium, and radium than the adjacent bottom sediment.

The ferromanganese nodules show a marked increase (up to 10 – 100 times) in manganese, cobalt, nickel, zinc, and copper concentrations (Guliy 2004). In contrast, the U and Th contents in the nodules show a weak increase (less than 2 times). Manganese, iron, cobalt, nickel, zinc, lead, and copper in the nodules are subdivided on the basis of character of their correlation into two main groups: Mn, Ni, Zn, Cu and Fe, Pb, and Co. However, our results do not show any strong correlation between these elements and U, Th, and Ra.

The main evidence for a different origin of the same components from the ferromanganese nodules and sediments is their marked difference in correlation coefficients for these materials. As we know from investigation of separate parts of sediments, the upper part of the sediment (darker) is rich in almost every metal due to a lot of small nodules. But, taking into consideration much lower concentration levels of metals in ocean water and sediments we can't accept two major hypotheses of nodule formation: (1) precipitation directly from ocean water, and (2) precipitation from pore solution during diagenesis. From this example we can see a paradoxical situation when from significantly metal-undersaturated solutions precipitate phases rich in some metals. So, the U, Th, and Mn, Fe, Ni, Co, Cu, Zn, and Pb contents and patterns in ferromanganese nodules and sediments studied lead to the idea that an electro-geochemical mechanism (adsorption & absorption) for ore component concentration.

CONCLUSIONS

This contribution can be summarized in such ways:

(1) Analysis of ferromanganese nodules from the Clarion-Clipperton zone show

contents of U, Th, Ra, and Sr similar to that from continental rocks.

(2) Results of U determinations show maximum values of U, Th, and Ra in the nodules, i.e., there is a chance to use these elements as additional economic components during future mining of seabed ferromanganese deposits.

(3) Obtained data show that the ferromanganese nodules have been formed in open physicochemical ore forming system from unsaturated seawater components. Ore elements could concentrate in solid phases in case if near bottom natural galvanic elements have been originated. It is suggested that electrochemical mechanisms are the main possible mechanism to enhance adsorption and absorption creating conditions for enhancing these important elements in seabed Mn-Fe nodules on a very scale.

ACKNOWLEDGEMENTS

We would like to thank P. Piven' and V. Gordienko for analytical support in this study.

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Mineralogical, geochemical, and geochronological constraints in the Double S Zone uranium deposit, Lac Turgeon Granite, north shore of the St. Lawrence Seaway, Quebec, Canada

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ABSTRACT: The Main Double S Zone is a system of uraniferous granite and granitic pegmatites occurring within the late tectonic Grenvillian Lac Turgeon granitic intrusion, which is hosted by metasedimentary units of the Grenvillian Wakeham Bay Group. Several episodes of U mineralization occur within this leucogranite and crosscutting pegmatitic dykes. The host leucogranite is similar to the pegmatite dykes in petrology, composition, and age. SEM-BSE images show uraninite and thorite/uranothorite are the major U-bearing minerals and are usually surrounded by chloritic minerals associated with radiation damage of the host phase with alteration. These uraniferous minerals also occur as inclusions in xenotime, monazite, and zircon and are associated with magnetite, rutile, and allanite. Some U minerals are secondary (non-magmatic) occurring within fractures. The granite has Rb (66-369 ppm), Nb (1.2-35 ppm), and Y (3.4-130 ppm) typifying syn-collisional, peraluminous (ASI = 1.15-1.26) granitic intrusions of S-type affinity, coupled with extensive fractionation into the (crustal) A-type granite field. Earlier dating by U-Pb concordia intercept indicates an age of primary U mineralization between 980 and 1000 Ma. The U-Th-Pb chemical monazite dating yield ages of 1028 ± 6 Ma and 981 ± 7 Ma, respectively for the granite and pegmatite.

KEYWORDS: uranium, granitic pegmatite, Lac Turgeon, Grenville Province, Quebec

INTRODUCTION

The uraniferous Main Double S Zone is located within the Lac Turgeon Granite, on the north shore of the St. Lawrence Seaway (North Shore Property) in eastern Quebec, approximately 9 km northwest of the town of Baie Johan Beetz.

Currently, Uracon Resources Limited owns claims to the Main Double S Zone, as well as two other mineralized zones (Middle Zone and TJ Zone) within the North Shore Property. These three zones combined contain a total inferred resource estimate of 154.9 million tonnes at an average grade of 0.012% U₃O₈ and contain 18.48 million kilograms (40.73 million pounds) of uranium using a 0.009% cut off (Uracon website). These resources outcrop at surface, are open at depth and along strike.

The deposit is also host to rare earth element mineralization, and porphyritic granitoids are noted to carry copper-gold and copper-molybdenum (Uracon).

GEOLOGICAL SETTING

Regional Geology

The uraniferous granitic pegmatites occur within the late tectonic Lac Turgeon granitic intrusion, which is hosted by metasedimentary units of the Grenvillian Wakeham Bay Group (Fig. 1).

The Wakeham Group (1.6-1.5 Ga) is the largest remnant of the sedimentary basins formed on the southeastern margin of Laurentia in Mesoproterozoic time. The Wakeham Bay Group consists of a north-trending synclinal basin about 3,885 km² in size of quartzites, schists, phyllites, marbles, and aluminous bands interlayered with metagabbro sills. Gabbroic and granitic rocks, such as the Turgeon Lake Granite have intruded and incorporated these units as xenoliths (Fig. 1). These volcanic rocks have a continental arc magmatic signature. The Grenville (1.08-0.98 Ga) orogeny is a major collisional event. It is associated with extensive crustal thickening and

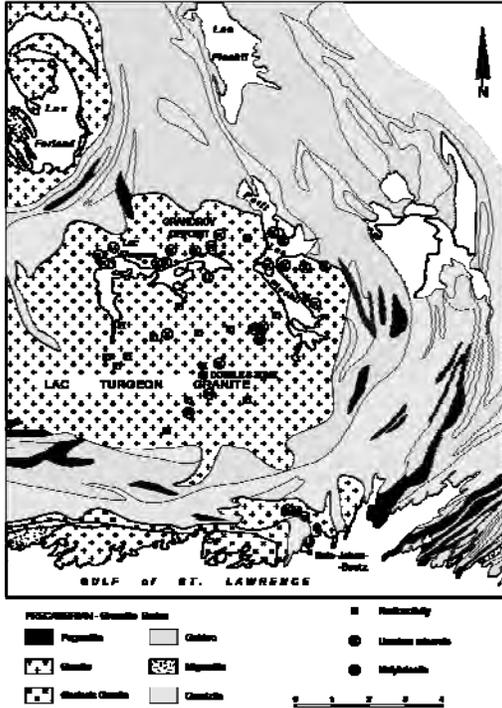


Fig. 1. Geology map of the Lac Turgeon Granite, Quebec. The Main Double S zone is indicated, along with several U occurrences, and the Grandroy deposit (modified from Cooper 1957).

tectonic extrusion, and led to widespread high-grade metamorphism (Ludden & Haynes 2000).

Local Geology

The mineralized Double S zone is a sequence of granitic pegmatite dykes and adjacent coarse-grained granites. At the surface, high radiometric signatures (1500-9000 c/s) in pegmatites and the surrounding granite are used to delineate the zone. The pegmatites range from low to very high radiometric signatures, and can have similar or distinct signatures from their host.

PETROLOGY

The granite outcrops are medium- to coarse-grained and have a hypidiomorphic granular texture dominated by rounded or interlocking quartz grains, and laths of pink, white, and perthitic feldspars.



Fig. 2. Photograph of a pegmatite dyke in host granite (SB-2670). The pencil tip points North.

Biotite and magnetite are also usually present and visible in hand specimen, muscovite may be present, and more rarely other oxides may be seen. Field estimates of modes ranged from 20-35 vol.% quartz, 15-35 vol.% plagioclase, 30-50 vol.% potassium feldspar, and 1-10 vol.% biotite. Accessory minerals include magnetite, muscovite, monazite, xenotime, zircon, apatite, epidote, ilmenite, titanite, allanite, molybdenite, and galena. The major U and Th minerals are uraninite and uranothorite.

The granitic pegmatites are composed largely of alkali feldspar, and to lesser amounts, quartz and plagioclase feldspar, and minor amounts of biotite and magnetite. The pegmatite bodies intrude the granite as dykes, lenses, and pods. The contact may be diffuse; the grain size may gradually grade into the other unit, making the contact difficult to determine. In sample SB-2670, the contact is sharp, but the granite coarsens at the contact and the pegmatite fines at the contact (Fig. 2). The contact may also be very distinct and it may be easy to trace to the edge of the outcrop or to where the intrusion terminates.

The layered quartzite occurs as xenoliths in the granite. The contact between the two units is sharp and discordant, and is locally undulatory. The xenoliths have rounded edges and range in size; xenoliths are very rare within the Main Double S Zone and do not contain U mineralization (e.g., 250-300 c/s).

MINERALIZATION

Uraninite is a common accessory mineral in the texturally homogeneous unzoned granitic pegmatite and peraluminous granite, and is present in both rock types in the Main Double S Zone.

Uraninite is associated with the following minerals: zircon, monazite, carbonaceous material (thucolite?), mica, feldspar, and with rare-earth-bearing minerals. It occurs in small distinct crystals or may be massive. Some grains are discoloured, especially in the centre, metamict, and fractured.

Although the general formula of uraninite is UO_{2+x} the naturally occurring mineral is partly oxidized ($x < 0.25-0.3$) and contains additional elements (Palache *et al.* 1944). The structural formula,

$(U^{4+}_{1-x-y-z}U^{6+}_xREE^{3+}_yM^{2+}_z v)O_{2+x-0.5y-z-2v}$, shows the common nonstoichiometric uraninite. The composition of the uraninite in the Double S zone ranges as follows: 63.88-81.15 wt% UO_2 , 5.2-9.74 wt% ThO_2 , 7.6-12.36 wt% PbO , 0.58-6.04wt% CaO , and 1.44-6.49 wt% Y_2O_3 , as well as up to 2.64 wt% rare-earth elements (REE) in its structure, with other trace elements.

GEOCHEMISTRY

The pegmatites of the Main Double S zone are classified as Mirolitic-REE class, NYF-A type pegmatites (Černý & Ercit 2005). The granites and pegmatites have a granitic composition (72-73 wt%

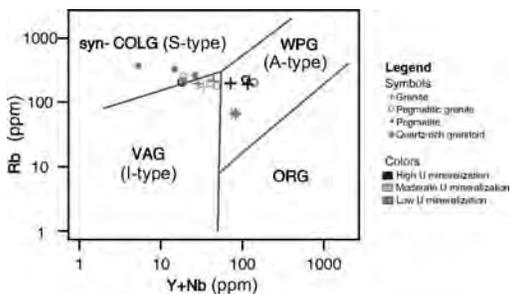


Fig. 3. Tectonic discrimination diagram of Rb versus Y + Nb from Pearce *et al.* (1984) and modified by Christiansen and Keith (1996) for syn-collision granites (syn-COLG), volcanic arc granites (VAG), within plate granites (WPG), and ocean ridge granites (ORG). The diagram suggests the granites and pegmatite were contaminated by a crustal component.

SiO_2), range from ferroan to magnesian (Fe^* of 0.71 to 0.91), mainly alkali-calcic (MALI of 2.26 to 10.75), and weakly peraluminous (ASI of 1.15 to 1.26).

Thorium (4 to 226 ppm) and U values (5 to 787 ppm) vary widely. Their U/Th ratios range from 0.14 to 23, but are typically <4.

Large variations in Zr/Hf (1.55 to 79.11), Nb/Y (0.04 to 0.97), and Nb/Ta (0.85 to 84.97) ratios, and moderate Rb/Sr (1.21 to 2.90) ratio reflect low-T crystal fractionation. The granite has Rb (66-369 ppm), Nb (1.2-35 ppm), and Y (3.4-130 ppm) typifying syn-collisional, peraluminous granitic intrusions of S-type affinity, with extensive fractionation into the (crustal) A-type granite field. This is consistent with their age and geologic setting.

GEOCHRONOLOGY

The Lac Turgeon Granite was previously dated at >980 Ma, based on a U-Pb concordia intercept (Rimšaitė 1982), and 948 ± 23 Ma from a whole-rock Rb-Sr isochron. It has an initial $^{87}Sr/^{86}Sr$ of 0.7090 ± 0.0043 (Fowler & Doig 1983); it is relatively young suggesting it has been partially reset or remained open.

Polished thin sections of the host mineralized granite, SB-2671, and pegmatite with minor mineralization, SB-2670B, were selected for U-Th-Pb chemical monazite dating using to the method of Montel *et al.* (1996).

Forty-nine analyses were taken of the

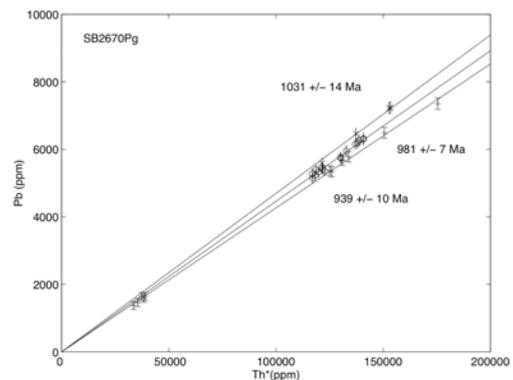


Fig. 4. Pb versus Th^* graph of a pegmatite intrusion (sample SB-2670) showing three age populations.

granite, SB-2671, showing two age populations: P1 of 1028 ± 6 Ma (n=23) and P2 of 946 ± 6 Ma (n=26). The populations can also be defined chemically; P1 has U>2500 ppm and P2 has U<2500 ppm. Although there is some overlap between the populations in Y, P1 generally has greater Y than P2.

Thirty-one analyses were taken of the pegmatite, SB-2670, showing three age populations: P3 of 981 ± 7 Ma (n=16), P4 of 939 ± 10 Ma (n=11), and P5 of 1031 ± 14 Ma (n=4, Fig. 4).

P1 and P5 represent the age of the granite, and agree with previous dating (Rimšaitė 1982). P3 represents the age of the pegmatite. P2 and P4 overlap and represent an event that reset monazite in both the granite and pegmatite, and corresponds to the age that Fowler & Doig (1983) obtained by whole-rock Rb-Sr methods.

Other pegmatites dating around the Grenville Orogeny are older, ranging from ca. 1000 to 1080 Ma (Easton 1986). Even with geologic constraints on the geochronologic data, pegmatites in the southwestern Grenville Province are dated to ca. 1020 to 1060 Ma (Lentz 1996).

CONCLUSIONS

The Lac Turgeon granite was generated at depth due to anatexis of the Wakeham Group, and is associated with high-grade metamorphism tectonically late in the Grenvillian orogeny. Since its age is younger than peak metamorphism, it likely corresponds to a period of adiabatic uplift. The pegmatites were likely derived from the same source as the Lac Turgeon granite, but represent a later stage of melt. Both display characteristics of an A-type source that has been generated from crust.

ACKNOWLEDGEMENTS

I thank Marc Simpson (Uracan) who helped with the sample collection, and provided Main Double S zone maps. Consul-Teck Exploration Incorporated hired me to do field work in the Double S zone. Funding for this project was

provided by Uracan Resources Limited and a NSERC Discovery grant to DL.

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Exploration strategies for Uranium deposits

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ABSTRACT: Although exploration strategies for uranium differ slightly for each deposit type, radiometrics, geophysics, and drilling are the major tools used. However, certain aspects common to all uranium deposits should be exploited to refine exploration. These include the timing of alteration and mineralizing systems, the nature of the fluids involved in each, the likely source of uranium, and the precipitation mechanism for the ore and alteration minerals. How these can be integrated into exploration is exemplified by comparing and contrasting results from unconformity-related and sandstone-hosted deposits.

KEYWORDS: *uranium, geochronology, basins, exploration, geochemistry*

INTRODUCTION

Exploration strategies for various types of U deposits vary depending on the type of deposit, but there are some general aspects critical to all types of U deposits. Although often considered academic, these should be part of advanced exploration efforts and include; (1) timing of the mineralizing and alteration processes, (2) nature of the fluids involved, (3) source of the U, and (4) the nature of an effective trapping mechanism. These aspects are often overlooked or trivialized relative to more classical aspects such as tectonic or structural setting.

(1) Timing of the mineralizing and alteration events is required in exploration so that the geologic, chemical and physical environment conducive to mineralization at the critical time in the evolution of an environment can be realized. Determining the age of U deposits is not straightforward (e.g., Chipley *et al.* 2005), but precise dating of uranium minerals and associated gangue minerals of known paragenesis, and integration of age data with other geologic factors render interpretation of geochronological data meaningfully for exploration. Without an idea of both the relative and absolute age of the mineralization, and both the alteration and

the host, strategies cannot evolve beyond prospector-driven exploration.

Effective exploration in any deposit requires detailed knowledge of the time-space relationships. For example, magmatic-related deposits form after advanced differentiation of peralkaline, post-orogenic parent magmas to allow extreme U enrichment in the latest magma intrusions and related magmatic fluids. In collision zones, U deposits related to peraluminous leucogranites require melting of the crust, which is facilitated by crustal thickening at an appropriate time during convergence. Metasomatic U deposits are associated with metamorphism during rapid uplift of an orogen, almost exclusively during the Proterozoic. Unconformity-related deposits require 75-100 m.y. after basin formation to allow chemical and thermal evolution of the fluids.

The timing of events that have subsequently affected the ores can also reveal when elements such as radiogenic Pb have been mobilized from the deposits and moved into the surrounding environment. These elements would elevate element concentrations in the surrounding environment, with gradients in concentrations as vectors to the deposits (Holk *et al.* 2003, Kister *et al.* 2004).

(2) Knowledge of the nature of the fluids involved, particularly their origin, temperature, pressure, oxygen fugacity, and chemical composition, is needed to identify the correct environment in which to explore. For example, most highly evolved alkaline intrusives do not host U deposits because they do not evolve to concentrate U in the last fluids, thereby necessitating evolution to magmatic fluids rich in U. Most areas of albitization do not host deposits because there was no reductant to trap the U. Diagenetic brines are involved in the genesis of unconformity-related uranium deposits, but most areas in basins with the appropriate geology and structure conducive to the ore-forming process are devoid of any significant U mineralization because reducing fluids were not present at the appropriate times in these areas. Most sandstone-hosted deposits occur in meanders of paleostreams where organic detritus could accumulate, but most such areas do not host ore because groundwaters either did not flow or did not carry U. Understanding why barren areas that should have ore, but do not, requires knowledge of the physical, chemical, and temporal characteristics of the fluids required to form various types of U deposits.

(3) The source of the U for many deposits is in units that have aberrantly high U contents, such as in volcanic glasses in the case of tabular deposits or in highly differentiated alkaline intrusions in the case of some magmatic-type deposits. Enrichment of U in the source region of basin-hosted deposits certainly increases the probability that a deposit could form (e.g., McNeal *et al.* 1981), as does the availability of U in the source region. Uraninite represents the most easily leachable U (sourced by oxidized fluids). Further, U is unlikely to be released from refractory minerals such as zircon unless they become metamict, which requires time. In sandstone-hosted deposits, unstable volcanic glasses with high U contents, mainly of peralkaline composition, make ideal sources because the U can be effectively mobilized.

(4) Trapping of U is a critical process for the generation of a deposit, with gradients in redox environments a necessity. For example, roll-front deposits best exemplify the gradients that occur in U mobilization and fixation. Deposits in the Paleoproterozoic Franceville Basin have characteristics very similar to unconformity-related deposits, but they occur at a redox boundary between oxidized sandstone and black shales within the basin. Unconformity-related deposits are normally associated with graphite, sulfide or a reducing fluid from the basement. For high temperature environments, such as the Rössing deposit, redox boundaries are represented by graphite-sulfide-rich metasediments. In these and other deposits, carbon appears to be an effective reductant, but there are alternatives such as sulfides and ferrous iron. Graphite, which is intimately associated with most unconformity-related deposits, is geochemically inert and therefore is unlikely to be an effective reductant unless it is modified to a more reactive form.

Although specific tectonic environments, structural settings and lithologies are required for all U deposit types, none of these are definitive indicators of mineralization because most of these settings, structures and lithologies do not host deposits. Thus, they are required for the deposits to form, but are not definitive indicators of mineralization. In effect, the only definitive indicators are geochemical, both in terms of U concentration and in the associated elements.

EXPLORATION STRATEGIES

With few exceptions, there is a paucity of published examples of exploration strategies for U, especially during the past 40 years. This would suggest that either there has been minimal advancement in exploration techniques or that this knowledge is resident in the geologists or companies that survived the drought in uranium exploration. The latter is unlikely given the time and personnel that have passed, and there have been advances in exploration for U other than drilling, but

these have been largely unnoticed. Differences and similarities in exploration strategies are conveniently illustrated by comparing how exploration is normally done for unconformity-related and sandstone-hosted deposits.

Unconformity-related deposits

Exploration for unconformity-related deposits is based firstly on Proterozoic red-bed basins overlying basement complexes and source regions characterized by high U contents. Given this criteria alone, there are nearly 200 basins that would qualify. Graphitic metasedimentary units within the basement complex are desirable, but not necessary, as exemplified by the Nabarlek deposit in the Northern Territory, Australia (Polito *et al.* 2004). Repeated brittle reactivations of ductile structures, normally from far field tectonic events, that may offset the basal unconformity and were foci for fluid flow are required.

Lithogeochemical and mineralogical haloes around unconformity-type uranium deposits can expand the size of drill targets (e.g. Quirt 1985). The ratio K_2O/Al_2O_3 can be useful in delineating hydrothermal illite distribution in the sandstone, and anomalously high boron haloes, corresponding to dravite alteration are also characteristic of these deposits, although dravite is not paragenetically related with the ore-forming process. Uranium, Ni, As, and Co are generally of more limited use because their haloes are restricted to a few tens of metres. The complexity of the basement lithology inhibits the use of individual elements as alteration guides other than in the intensely altered zone (Sopuck *et al.* 1983).

Clay minerals are ubiquitous up to hundreds of metres from hydrothermal U mineralization, and often there is zoning in the type of alteration minerals (Hoeve & Quirt 1984). These can be mapped with remote sensing that can detect in the visible and the middle-infrared sections of the electromagnetic spectrum (Earle *et al.* 1999). The two oxidation states of U and Fe have been proposed to map bleached

alteration zones associated with uranium mineralization using multispectral sensors like Landsat ETM+ (Rajesh 2008).

Lake water and sediment geochemistry and radiometric prospecting are significant tools in early regional exploration for U deposits in Canada (Cameron 1980). The development of anomalies in lakes is a two-stage process wherein U-rich detritus is transported down-ice from the mineralized source and then the metal is dispersed in solution from this detritus into the lakes. Ground-water samples collected from boreholes tens of metres from unconformity-related uranium mineralization have high levels of U, Ra, Rn, and He (Earle & Drever 1983). However, Rn and He distributions can be greatly affected by variations in permeability of the rocks and are frequently ineffective tools to detect buried mineralization (Butt & Gole 1985).

Biogeochemistry has been developed for uranium exploration during the 1980s (Dunn 2007). For example, spruce twigs indicate that tree roots can extract anomalous U from ground water and reflect deposits at 300m depth.

The mainstay of exploration geophysics for all types of U deposits is gamma-ray spectroscopy used in airborne surveys, down hole logging and on outcrops using hand held units. The former is normally collected as part of airborne magnetic surveys with magnetics used to reveal the general geology. Airborne gamma-ray spectrometry directly measures K, eU, and eTh, but only in near surficial material.

Improved magnetotelluric methods have detected deep conductors and shallow alteration zones in the search for deep unconformity-related deposits (Farquharson & Craven 2008). Clay-rich, quartz-corroded quartz-arenite has relatively low resistivity, whereas quartz-rich silicified zones are characterized by high resistivity. Although expensive, 3D seismic has been used to image details of basement topology and more favourable areas for drilling.

Sandstone-hosted deposits

Uranium ore deposits in the Grants

Mineral Belt, New Mexico, occur in fluvial sandstones in the Jurassic Morrison Formation where U is concentrated by dark gray to black humate derived from decaying vegetation. The ores vary greatly in size and shape, generally occur in clusters, and often are difficult targets for drilling. Exploration is done primarily by drilling, delineating favourable ground on a wide-spacing and then using closely spaced drilling in mineralized areas. Criteria for favourable areas includes the presence of a host sandstone, anomalous U contents, dark colour of host rock, presence of carbonaceous matter, and position of an area with respect to mineralized trends (Fitch 1979).

Analysis of groundwater can be a useful strategy for regional exploration for U in the reduced sediments in palaeochannels, although multi-element data are required. Lead isotopes can be used to confirm the groundwater interpretations (Dickson & Giblin 2007). If reduction of U by bacteria is an effective mechanism for formation of U deposits in palaeochannels, then microbial induced geochemical signals, such as carbon isotopes or enhanced mobile metals, should indicate favourable areas.

Geochemical detection of uranium deposits in sandstone-type deposits depends on the geochemical behavior of U and pathfinder elements (Rose & Wright 1980). Uranium is dispersed under oxidizing conditions but is immobile under reducing conditions. Adsorption on freshly precipitated Fe-oxides and certain types of organic matter also limits dispersion unless high concentrations of CO_3^{2-} or other complexers are present. Thorium accompanies U in most plutonic processes, but the two elements are separated under oxidizing conditions. Possible pathfinder elements associated with U in sandstone-type deposits include S, V, Mo, Se, As and at some deposits Cu, Ag, Cr, Pb, Zn, Ni, Co, Re, Be, P, Mn, and rare earths, plus He, Rn, and other radioactive decay products.

Most uranium deposits in sedimentary rocks are associated with geochemical provinces enriched in U and Th or with U-

rich intrusives or volcanic rocks, although the deposits may be separated by tens of kilometres from these U-rich source rocks. Weak regional U and Th anomalies in sediments containing U deposits may be present. Anomalies in U, Se, Mo, V, As, He, Rn, and other pathfinder elements in rock and in ground and surface waters can furnish geochemical guides to ore, as can thermoluminescence (Hochman & Ypma 1984), Pb, S and C isotopes, and textures of Fe and Ti oxides.

CONCLUSIONS

Because U deposits are geochemical anomalies, they are best discovered using strategies that integrate geochemistry as a significant part of the exploration repertoire. Exploration for U deposits, as with any type of deposit, requires the integration of geology, geophysics and geochemistry and must embrace new technologies and research results to be effective and competitive. Although "serendipity" will always be a factor, exploration must be more purposeful, especially as the need to find deposits undercover becomes more urgent. The last boom period was witness to limited success and in predominately brownfield areas. We should prepare ourselves for the next boom by refining models and finding key factors that promote formation of large deposits and the physical and chemical indicators of areas where deposits reside.

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Basement-hosted uranium oxides from Athabasca Basin: mineralogy, U/Pb dating, major and Rare Earth Element (REE) concentrations: comparison with U-oxides from deposits located in the vicinity of the unconformity

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ABSTRACT: The basement of the Athabasca Basin (Saskatchewan, Canada) is currently strongly explored for finding basement-hosted uranium deposits comparable to the Eagle Point deposits. However, few data are available on this type of deposit to compare them with deposits located in the vicinity of the unconformity. Recent results obtained by *in situ* analysis on three basement-hosted deposits are presented: the Millennium, Eagle Point, and P-Patch deposits. U/Pb isotopic ages of the best preserved uranium oxides are similar to ages obtained on deposits located in the vicinity of the unconformity (1340 Ma, 1275-1210 Ma, 1100 Ma, 770 Ma and 280 Ma) and they both have the same major-element composition. The Rare Earth Elements (REE) in basement-hosted uranium oxides have bell-shaped chondrite-normalized patterns, similar to those of the deposits located in the vicinity of the unconformity like McArthur River or Cigar Lake deposits. These results suggest that similar processes are involved for the formation of the two types of deposits (basement-hosted deposits and located at the unconformity).

KEYWORDS: Athabasca, uranium deposits, U-Pb dating, REE, basement-hosted

INTRODUCTION

Unconformity-type uranium deposits from the Athabasca Basin (Saskatchewan, Canada) represent the world-richest uranium ores with the McArthur River deposit as a prime example. They are mainly located close to the unconformity between a Paleo- to Meso-Proterozoic sedimentary basin, the Athabasca Basin, and an Archean to Paleoproterozoic metamorphic to plutonic basement. For several years, a new type of uraniferous mineralization, entirely located in the basement, has been drilled in the South-Eastern part of the basin. Few data are available for this type of deposit, limiting the comparison of their characteristics and possible genetic links with deposits located at the unconformity.

Hoeve & Quirt (1984) proposed two models for the dynamic of fluid circulation associated with the formation of unconformity-related deposits : (i) an "Ingress" type model for basement-hosted

deposits with the infiltration of a basin-derived U-bearing oxidized fluid into graphite-rich basement structure and precipitation of U by reaction with reduced basement lithologies, (ii) an "Egress" type model for unconformity-located deposits with the injection into the basin of a reduced basement-derived fluid precipitating uranium by mixing with the basin-derived U-bearing oxidized fluid. The REE patterns obtained for the uranium oxides from both deposits by Fayek & Kyser (1997) tend to support these two models.

The aim of this work is to further characterize the different generations of uranium oxide from three basement-hosted deposits: the Millennium, Eagle Point, and P-Patch with multiple micro-scale analysis techniques. The results will be compared to those previously obtained on uranium oxides from deposits located in the vicinity of the unconformity to evaluate the previously proposed ore formation models.

GEOLOGICAL SETTING

Regional Geology

The basement of the Athabasca Basin comprises Archean and Paleoproterozoic (Aphebian) rocks belonging to two structural provinces (Rae and Hearne) separated by the northeast-trending Snowbird tectonic zone (Hoffman 1990; Fig. 1). The two provinces consist of Archean granitoid gneisses, Aphebian platform metasedimentary rocks and mafic to felsic plutons (Annesley *et al.* 2005).

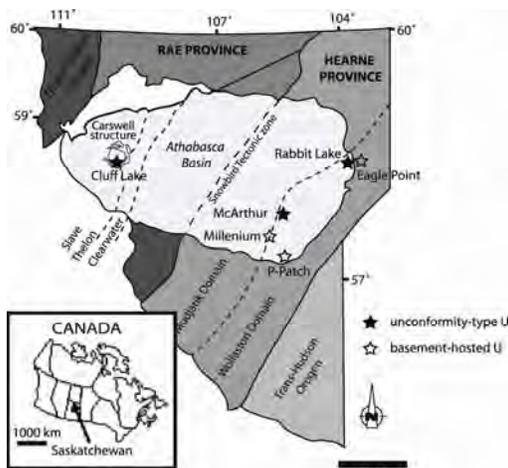


Fig. 1. Location of the Millennium, Eagle Point, P-Patch, and some of the main unconformity-type uranium deposits in Athabasca Basin (modified from Card *et al.* 2007)

The Athabasca sedimentary Basin consists of Helikian polycyclic, mature fluvial to marine quartz-rich sandstone deposited in a near-shore shallow shelf environment (Ramaekers 1990) with an estimated filling beginning at about 1700 to 1750 Ma (Armstrong & Ramaekers 1985). The estimate maximum thickness of the basin was 5 to 6 km from fluid inclusion studies (Pagel 1975).

RESULTS

Isotopic U/Pb dating of basement-hosted uranium oxides

For each deposit, the uranium oxides were carefully studied by SEM and EPMA to separate the different generations and

to select the less altered zones for isotopic U/Pb analysis.

Several U/Pb isotopic ages were determined by ion microprobe (Cameca IMS-3f) for the Millennium and Eagle Point deposits: 1340 Ma, 1275-1210 Ma, 1100 Ma, 770 Ma from Concordia diagrams (Fig. 2) and 278 Ma (²⁰⁷Pb/²⁰⁶Pb age).

Similar ages were obtained on Athabasca Basin deposits for mineralizations located in the vicinity of the unconformity or partly in the basement (McArthur River or Cigar Lake for example). The oldest ages obtained on uranium oxides from several deposits (i.e. Alexandre *et al.* 2009) have not been obtained in the present study. Such a feature could be linked either to lack of uranium deposition in the basement during this period or to the dissolution of the first U-oxides generations by later fluid circulation events.

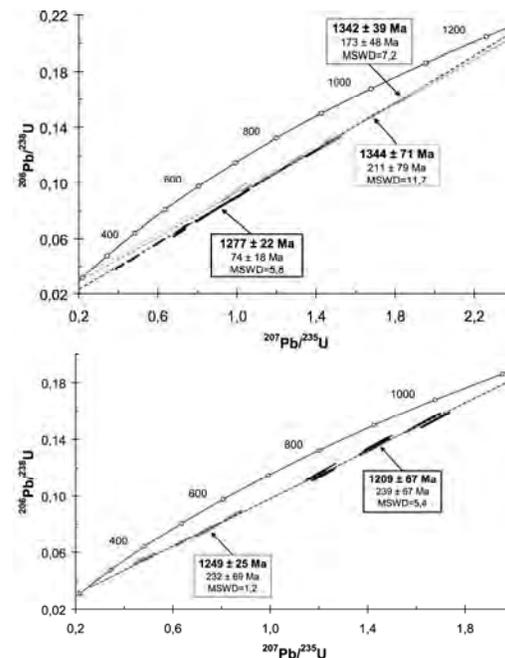


Fig. 2. U/Pb isotopic dating of different generations of uranium oxides from the Millennium (upper part) and Eagle Point (lower part) deposits.

REE abundances for basement-hosted mineralizations

Most uranium oxide generations which have been dated were also analyzed for

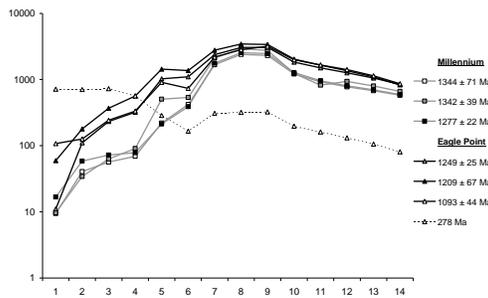


Fig. 3. Chondrite-normalized mean REE patterns of different generations of uranium oxides from the Millennium (square) and Eagle Point (triangle) deposits with their corresponding U-Pb isotopic age.

their REE contents by ion microprobe (Cameca IMS-3f) (Fig. 3).

The uranium oxides from the Eagle Point and Millennium deposits have bell-shaped REE patterns centred on Tb or Dy, typical of unconformity-related deposits (Pagel *et al.* 1987; Fayek & Kyser 1997; Bonhoure *et al.* 2007). All uranium oxides, from both deposits, presenting the oldest U/Pb ages (1340 Ma, 1275-1210 Ma, and 1100 Ma) have identical Heavy Rare Earth Elements (HREE) fractionation and abundance. Light Rare Earth Element (LREE) concentrations are identical between the different uranium oxide generations, from each deposit, whatever their U/Pb age but the LREE abundances differ between the two deposits. This difference is considered as reflecting the variability of the basement lithologies. However, the youngest uranium oxide generation (280 Ma) is strongly enriched in the lightest REE, but with the same bell-shaped pattern defined by the HREE.

REE abundance in uranium oxides from basement versus basin deposits

Uranium oxides studied by in-situ methods (Bonhoure 2007), Bonhoure *et al.* (2007), this study), from deposits located in the vicinity of the unconformity (Fig. 4) or in the basement have nearly identical REE abundance and fractionation (HREE/LREE>1).

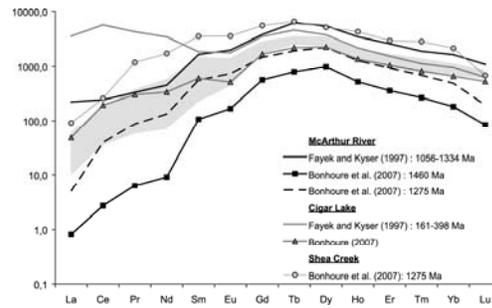


Fig. 4. Chondrite-normalized mean REE patterns of uranium oxides from deposits located near the unconformity (McArthur River, Cigar Lake and Shea Creek) and from basement deposits (grey zone, this study). Fayek & Kyser (1997): chemical age; Bonhoure (2007) and Bonhoure *et al.* (2007): U/Pb isotopic age.

For an equal isotopic age, and at the Athabasca Basin scale, uranium oxides located at the unconformity or in the basement have similar REE abundances.

CONCLUSION

This study has permitted us to obtain a large and systematic database of the geochemical characteristics and the ages of the different generations of uranium oxides from several basement-hosted deposits from Athabasca Basin.

The isotopic ages obtained for basement-hosted uranium oxides are identical to those published for uranium oxides located at the unconformity, indicating that the same fluid circulations, at a large scale, existed in both environments.

The chondrite-normalized REE patterns for basement-hosted uranium oxides are similar, except for a small variation of LREE abundances, indicating identical physico-chemical deposition conditions (T, pH, fluid composition) for the Eastern part of the Athabasca Basin basement. The previous REE distinction made between “Ingress” and “Egress” deposits (Fayek & Kyser 1997) is not confirmed by the present study, because both types have similar REE abundance and fractionations, indicating the similarity of the sources and the processes for both deposit types. Thus, these results suggest

reconsidering the previously “Ingress” and “Egress” models.

ACKNOWLEDGEMENTS

We thank Areva Resources Canada Inc and CAMECO for their assistance and for authorizing us to sample the mine sites. Areva NC is acknowledged for its financial support.

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Two contrasted types of Uranium mineralization in the "Cage" Uranium district, Nunavik, Quebec, Canada

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ABSTRACT: The CAGE district discovered in 2005 is located to the Northeast of the Canadian Shield, along the eastern margin of the Ungava Bay. The uranium showings are hosted by the Lake Harbour Group, a Paleoproterozoic metasedimentary sequence intruded by several pegmatoid generations at the end of the Torngat Orogen (1.87 – 1.77 Ga). Two contrasted types of uranium mineralization have been distinguished according to their geological setting, and mineralogical and geochemical characteristics, but both give the same U-Pb isotopic age on uraninite (1790 ±10 Ma):

(i) The first type occurs in impure dolomitic marbles and skarnoids. The mineralization consists in pure uraninite associated with enrichments in Ba, V, Zn, Pb, and S. REE patterns of uraninite present no or a positive Eu anomaly and a low global REE abundance. Organic matter and sulfides may have represented the initial uranium traps.

(ii) The second type is hosted by calc-silicate rocks (skarnoids or primary skarns) located in close vicinity of pegmatoid injections associated spatially with tremolite, scapolite, phlogopite, and calcite in veins. The mineralization consists in Th-rich uraninite and uranothorianite, characterized by REE patterns typical of magmatic uraninite. It is probably related to magmatic fluids expelled from pegmatites during a transtensive event at the end of the Torngat tectonic-magmatic cycle.

KEYWORDS: *Cage, marble, skarnoid, primary skarn, REE pattern*

INTRODUCTION

The Cage district was discovered during an exploration survey made in summer 2005 in northern Québec, by Claude Caillat (AREVA) and Serge Genest (Omegalpa). Two contrasted types of U mineralization have been recognized and are associated with marbles and "skarns s.l." of Lake Harbour Group: one is represented by Th-bearing uraninite and uranothorianite; the other by Th-free uraninite.

The aim of this study is to use mineralogical and geochemical tools for characterization of both types of uranium mineralization and possible identification of the U source(s).

GEOLOGICAL SETTING

The Cage district is located to the North-East of the Canadian Shield, along the eastern side of the Ungava Bay (Fig.1).

The Cage district belongs to the Core Zone of the south-eastern Churchill Province. This province represents a central terrane of reworked Archean gneiss and Paleoproterozoic intrusives and supracrustal rocks sandwiched between the Archean Nain and Superior cratons during Paleoproterozoic oblique collisions. The Torngat Orogen which welds the Core Zone to the Nain Craton in the East (1.87-1.82 main stage; 1.8-1.77 uplifting and associated pegmatites) and the New Quebec Orogen which welds the core zone to the Superior craton in the West (1.82-1.77) are formed during these collisions (Wardle et al., 2002).

REGIONAL GEOLOGY

The Core zone is divided into four lithostratigraphic units (Verpaelst *et al.* 2000):

1) the Kangiqsualujuaq Complex,

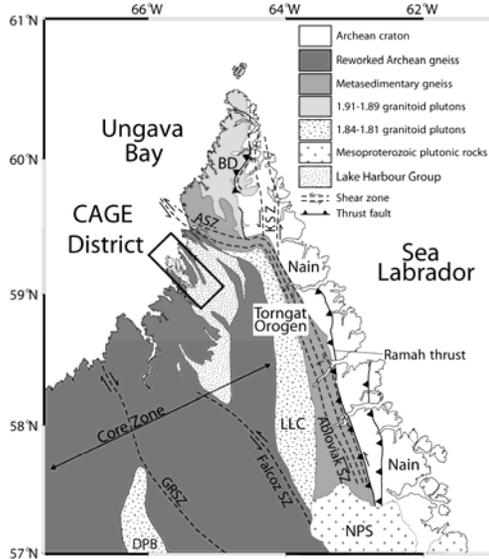


Fig. 1. Location map of the Cage District in northern Quebec within the Core Zone of the Churchill Province. KSZ-Komaktorvik Shear Zone; GRSZ-George River Shear Zone; NPS-Nain Plutonic Suite; DPB-De Pas Batholith; BD-Burwell Domain; LLC-Lac Lomier Complex (modified from Wardle *et al.* 2002).

comprising tonalitic and granitic orthogneisses crosscut by Archean granitoid plutons and dykes, remobilized during the Paleoproterozoic.

2) the Baudan Complex, corresponding to Archean granitic gneisses and diatexites, remobilized during the Paleoproterozoic.

3) the Lake Harbour Group, a Paleoproterozoic platform sequence of approximately 1 km thickness represented by calcitic and dolomitic marbles, paragneisses, calc-silicates rocks, quartzites, and metabasalts injected by several generations of pegmatites. The stratigraphic polarity is still not defined. Possible evaporites are proposed as the source for a Lapis Lazuli mineralization in extension of this Group in the Baffin Island (Hogarth & Griffin 1978).

4) the Nuvulialuk Mafic Suite, consisting in Proterozoic ultramafics and gabbros intruded as dykes and sills in the Lake Harbour Group.

Most U showings in the Cage District are located in marbles and "skarns s.l." belonging to the Lake Harbour Group.

Tectono-magmatic evolution

The tectonic study of the Cage district suggests that a continuum deformation linked to the Torngat Orogen is developed in the Lake Harbour Group and its Archean basement from early syn-foliation recumbent folds to late plurikilometric symmetric folds. N130°E is the average strike of these structures.

Towards the end of this tectonic evolution, a transtensive deformation (N130° dextral) is accompanied by the generation of U-Th enriched pegmatites along the marble/paragneiss contact, which apparently postdates a first generation of non radiogenic pegmatites associated with primary skarn.

URANIUM TH-FREE MINERALIZATION

This type of U mineralization is hosted in dolomitic marbles and skarnoids with Ca/Mg cationic ratios comprised between 0.7 and 1.1, without direct relationship with the pegmatite intrusions. Marbles are made of dolomite and variable amounts of forsterite and phlogopite, rarely K-feldspar. The skarnoids bear diopside and tremolite as major minerals and K-Feldspar, quartz, and scapolite (40%<Me<60%) as minors components. Skarnoids form elongated boudins within marbles bands, which can be followed over several kilometres along strike. In the dolomitic marbles and skarnoids, U mineralization is represented by very fine (<200µm) euhedral uraninite crystals as inclusions within carbonates and silicates, often rimmed by molybdenite.

High U contents are consistently associated with high Ba (as barite, Ba-rich K-feldspar and Ba-phlogopite, celsian, kampfite $Ba_{12}(Si_{11}Al_5)O_{31}(CO_3)_8Cl_5$), V (as coulsonite $Fe_{2+}V_{3+}2O_4$, V-Pyroxene), Zn (as sphalerite), S (as pyrite, pyrrhotite), Cu (as chalcopyrite), As (as arsenopyrite), and Sb (as ullmanite $NiSSb$). Non radiogenic galena cements this mineral assemblage. Graphite associated with uraninite has been identified in one marble occurrence.

REE patterns of the uranium oxides present a decreasing fractionation from the light to the heavy REE, with no or a

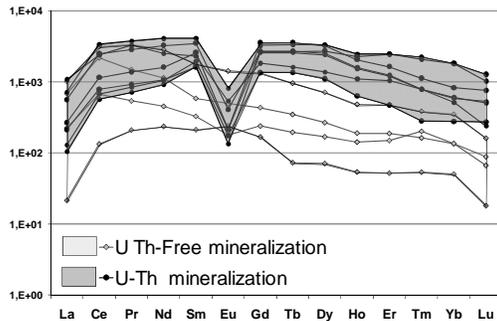


Fig. 2. Chondrite-normalized REE spectra measured on U-minerals of Cage district.

slightly positive Eu anomaly and a low global abundance of the REE (Fig. 2).

U-TH MINERALIZATION

The U-Th showings are located in primary skarn and skarnoid (diopsidite) developed at the contact with pegmatite injections or late migmatitic granite segregations, which are crosscut by infiltration skarns linked to late pegmatite injections at the end of the tectonic-magmatic cycle. Veins of tremolite, scapolite, and phlogopite are spatially associated with the U-Th mineralization, both being related to a late fluid infiltration. The U-Th mineralization seems associated with Fe-enrichment in host rocks.

The U-Th minerals are large (>mm) anhedral crystals of Th-rich uraninite or uranothorianite with lobate contours. High Y_2O_3 contents (0.56 ± 0.1 wt%) are also distinctive of the U-Th mineralization.

REE patterns of Th-rich uraninite and uranothorianite, are characterized by the high REE contents, a weak global fractionation, and a marked negative Eu anomaly (Fig.2), that are typical for magmatic uraninite, in particular those of the Rössing alaskite (Bonhoure 2007).

DISCUSSION

The most distinctive characteristics of the Cage district ore showings are the two contrasted types of uranium mineralization. Th concentration is one of the key geochemical parameters to discriminate both types of mineralization.

In marbles and skarnoids, the consistent U-Ba-Mo-Pb-V-Zn association and absence of Th, the rare occurrence of graphite, and the REE patterns in uraninite are evidences for a possible synsedimentary and/or diagenetic origin of the uranium and associated metals. This primary metal stock located in impure dolostone with possible evaporitic layers (as indicated by the presence of scapolite and kampfite in skarnoids) would have been more or less remobilized during regional metamorphism and tectonics.

Non-metamorphic equivalents of this Th-free mineralization may be sought in some rare limestone-hosted U-occurrences, such as the Jurassic Todilto lacustrine formation in the Grant Uranium Belt (Rawson & Richard 1980), the Cretaceous Toolebuc marine formation in Eromanga Basin (Ramsden 1982), the Mesoproterozoic Vempale marine formation in Cuddapah Basin (Sinha *et al.* 1989), and the Cretaceous Probeer marine formation in the Huab deposit (Hartleb 1988).

A late-metamorphic origin is proposed for the U-Th mineralization because of its spatial association with late pegmatites, its high contents in Th, REE, and Y contents and the typical magmatic REE patterns of the U minerals.

In terms of U-Th mineralogy and host rocks, the U-Th mineralization shares numerous similarities with U-Th-Mo-REE skarns of the Central Metasedimentary Belt of the Grenville Province (Lentz 1998) and uranothorianite rich Tranamaro pyroxenite of Madagascar (Moine *et al.* 1985). In these deposits the U-Th mineralization is related to hydrothermal fluids derived from pegmatite or granite intrusion related to syn-metamorphic partial melting. The different types of skarns could result either from recrystallization of impure siliceous limestones or marls recrystallization during regional metamorphism or from metasomatic reactions between the marbles and a hydrothermal fluid or magmatic intrusion.

The same U-Pb isotopic ages have been obtained for both types of Cage

mineralization at 1790±10 Ma, which corresponds to the uplift phase of the Torngat orogen (Wardle *et al.* 2002).

CONCLUSIONS

The two distinct types of mineralization at Cage could reflect the evolution of uranium from the initial trapping in epicontinental platform sediments to the remobilization by metamorphic processes in a collisional orogen:

1) Primary Ba-Mo-Pb-V-Zn and U-enrichment during sedimentary and (or) diagenetic phase possibly linked to reduction by organic matter.

2) During metamorphism, partial melting of metasediments, and possibly of the basement led to the formation of U-Th-rich anatectic melts and fluids, which have been trapped in “skarns s.l.” forming the second type of U-Th mineralization. During this event (1790±10Ma), local redistribution of the primary mineralization may also occur.

ACKNOWLEDGEMENTS

The authors acknowledge AREVA for the technical and the financial support of this study. We warmly thank all the Cage staff for its assistance during the field work.

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Applying Pb isotopes in unconformity-type uranium exploration

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ABSTRACT: Lead isotopes have been proposed as indicators of the fluid evolution of sedimentary basins and as guides for exploration of uranium deposits. In uranium exploration, the Pb isotope ratios provide information on timing of mineralization and element remobilization, and presence and timing of U and Pb migration on a regional basis and at drill hole scale. Sandstone distal to known uranium deposits has dominantly non-radiogenic Pb isotope ratios, while sandstone in the region around the uranium deposits often displays radiogenic Pb isotope ratios unsupported by the amount of U in the sandstone. Plots using the $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios show systematic trends useful in unconformity-type uranium exploration. Raw $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots do not provide information on 'excess Pb' content superimposed upon the original sedimentary/diagenetic Pb, but $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots adjusted for U content highlight those isotopic values that are unsupported by the amount of U in the sandstone.

KEYWORDS: Pb isotopes, unconformity-type uranium, sandstone, exploration

INTRODUCTION

Uranium oxides easily lose their radiogenic Pb and, in unconformity-type U deposits, part of this Pb has migrated significant distances from the deposits. Thus, the detection and interpretation of radiogenic Pb anomalies may be useful in exploration for these deposits. In particular, the Pb isotope ratios allow discrimination between potential sources of U, such as between U mineralization and background country rock. Several reports concerning the use of Pb isotopes in exploration for unconformity-type uranium deposits have been written since the late 1970s (Robbins & Gupta 1979; Kister, 2003; Holk *et al.* 2003; Kister *et al.* 2004; Carr & Rutherford 2005; Annesley *et al.* 2005).

This report concerns the application of Pb isotope geochemistry in the exploration for unconformity-type uranium deposits in the Athabasca Basin of northern Saskatchewan (Fig. 1). 2006 Pb isotope data from a number of current projects, several with U mineralization, will be discussed (Cigar Lake East, Close Lake, Midwest A, Wolly/McClean Lake, Cree-Zimmer project, and Shea Creek).



Fig. 1. Location map of deposits in the Athabasca Basin, northern Saskatchewan.

GEOLOGICAL SETTING

These unconformity-type deposits are located around the unconformity between the Helikian Athabasca Group sandstones and underlying Archean to early Proterozoic metamorphic basement (Hoeve & Sibbald 1978; Hoeve & Quirt 1984). The present sandstone cover ranges from 0 to ~1500 m in thickness and is dominantly composed of mature coarse-grained quartz arenite with a kaolin-illite clay matrix.

The deposits are localized at fault intersections, are associated with breccia zones, and are within clay mineral and silicification/desilicification host-rock alteration haloes. Mineralization can be found up to 40 m above and (or) below the unconformity. Basement-hosted mineralization can occur up to 200 m below the unconformity. The high-grade mineralization consists of massive to botryoidal pitchblende/uraninite replacements, veins, and impregnations, with varying amounts of Ni-Co-Fe arsenides, sulfarsenides, and sulfides.

ANALYSES

Approximately 100 g of each drill core sample of sandstone was crushed to -2 mm in a steel jaw crusher and ground to ~150 mesh in a motorized agate grinder.

Each sample was leached/digested using three methods:

1. Weak-acid partial leach - 0.5 g of ground sample material leached for 2 hours in 5 ml of 2% HNO₃ then diluted 10x with weak acid.
2. Aqua Regia partial digestion - 0.5 g of ground sample material digested in 2.25 ml of a 9:1 mixture of concentrated HNO₃:HCl then diluted 15x with deionized water.
3. Total digestion - 0.125 g of ground sample digested in a mixture of concentrated HF/HNO₃/HClO₄ until dry. Residue redissolved in dilute HNO₃ then diluted 8x with deionized water.

All leachates were analysed for ²³⁸U, ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, and ²³²Th using a Perkin Elmer Sciex Elan DRCII ICP-Mass Spectrometer.

Corrections were made on the ²⁰⁴Pb data for ²⁰⁴Hg interference using ²⁰²Hg, and a

procedural blank was analysed. Detection limits for the isotopes were 0.01 ppm for ²³⁸U, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, and ²³²Th, and 0.001 ppm for ²⁰⁴Pb.

RESULTS

Systematic trends in ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, ²⁰⁸Pb/²⁰⁴Pb, and ²⁰⁷Pb/²⁰⁶Pb ratios are observed in the data. The shallow uraniumogenic Pb trend in the ²⁰⁶Pb/²⁰⁴Pb-²⁰⁸Pb/²⁰⁴Pb plot (Fig. 2), with high ²⁰⁶Pb/²⁰⁴Pb ratio values, is consistent with elevated U/Th values, suggesting the presence of a high-priority target. This diagram also shows the effects of detrital Th-bearing minerals (e.g., Eastern Athabasca heavy mineral beds) on the Pb data and total gamma count data.

The features on the ²⁰⁷Pb/²⁰⁴Pb-²⁰⁶Pb/²⁰⁴Pb plot (Fig. 3) can be related to the timing of primary U mineralization and later remobilization.

Strongly anomalous ²⁰⁷Pb/²⁰⁶Pb ratio values correspond to elevated U values, but some samples do display low ratio values, suggestive of radiogenic signature, along with low U contents (Fig. 4).

Sandstone around the uranium deposits typically has radiogenic ²⁰⁶Pb/²⁰⁴Pb isotope ratios (>30) (Fig. 5), with Pb isotopic compositions that are unsupported by the amount of U in the sandstone. This is consistent with the introduction of this Pb

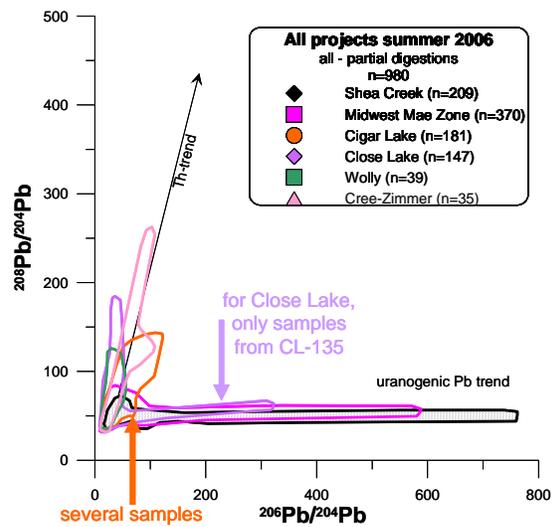


Fig. 2. ²⁰⁶Pb/²⁰⁴Pb-²⁰⁸Pb/²⁰⁴Pb plot.

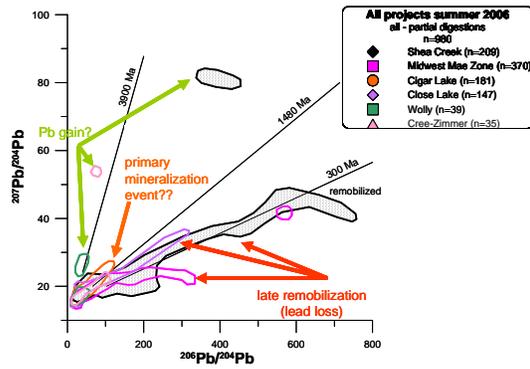


Fig. 3. $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ plot.

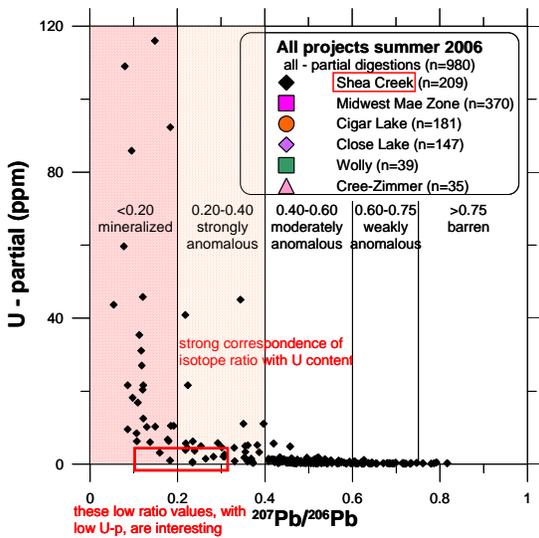


Fig. 4. $^{207}\text{Pb}/^{206}\text{Pb}$ ratio versus U-partial.

from the U deposits during post-mineralization fluid events. The presence of these radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ ratios show that the sandstone was permeable to late fluids.

The raw $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots (Fig. 6) illustrate the variations in the original Pb isotope data with depth down the drill hole. But they do not provide information on 'excess Pb' content superimposed upon the original sedimentary/diagenetic amounts by movement/transport of mineral deposit-related U through the sediments.

The adjusted $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots highlight those isotopic values that are unsupported by the amount of U in the sandstone, consistent with the introduction of these daughter isotopes from the U deposits during post-mineralization fluid

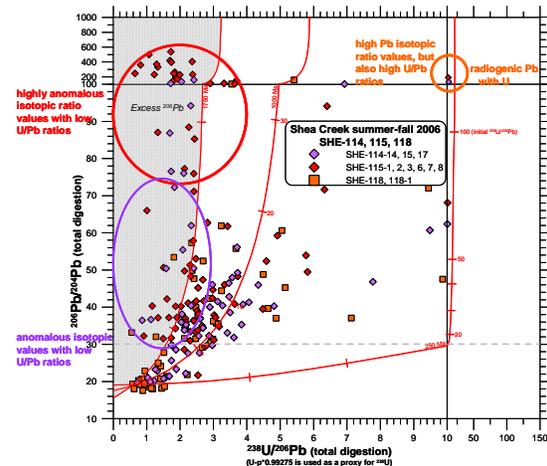


Fig. 5. $^{206}\text{Pb}/^{204}\text{Pb}$ ratio versus U/Pb ratio.

events.

CONCLUSIONS

Plots using the $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios show systematic trends useful in unconformity-type uranium exploration.

$^{206}\text{Pb}/^{204}\text{Pb}$ versus U/Pb plots provide information on Pb isotopic compositions that are supported or unsupported by the amount of U in the sandstone. This information is used in $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots to reflect 'excess Pb' contents.

Raw $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots do not provide information on 'excess Pb' content, but adjusted $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots highlight these unsupported isotopic values.

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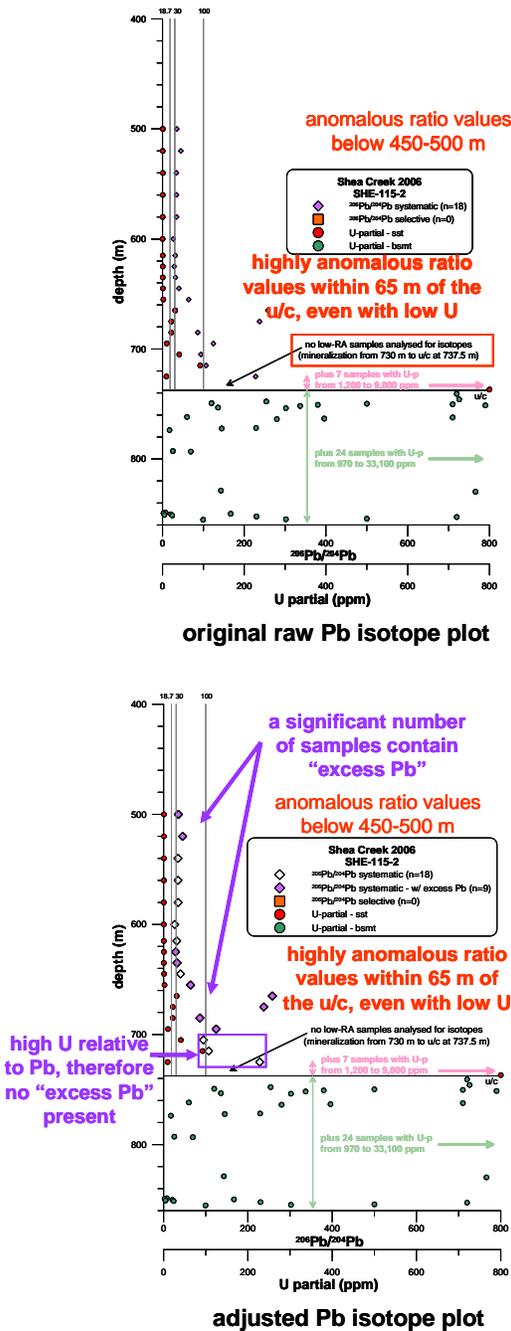


Fig 6. $^{206}\text{Pb}/^{204}\text{Pb}$ downhole plots - raw versus adjusted.

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Timing, chemistry, and implication of fluids in Canadian and Australian unconformity-related uranium deposits

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ABSTRACT: World class unconformity-related U deposits occur in the Proterozoic McArthur Basin (Northern Territory, Australia) and Athabasca Basin (Saskatchewan, Canada). Widespread pre- to post-ore silicifications in the vicinity of the deposits, allow proper observation of paragenetically well-characterized fluid inclusions. We used a combination of microthermometry, Raman microspectroscopy and Laser Induced Breakdown Spectroscopy (LIBS), to establish the physical-chemical characteristics of the main fluids having circulated at the time of U mineralization. The deduced salinities, cation ratios (Na/Ca, Na/Mg) and P-T conditions, led to the detailed characterization of a NaCl-rich brine, a CaCl₂-rich brine and a low-salinity fluid, and to the identification of mixing processes that appear to be key factors for U mineralization.

KEYWORDS: *uranium deposits, unconformity, silicifications, fluid inclusions, fluid mixing*

INTRODUCTION

Unconformity-related U deposits account for more than 33% of the world uranium resource due to their tremendous grade and tonnage. Most of them occur in the McArthur Basin (Northern Territory, Australia) and in the Athabasca Basin (Saskatchewan, Canada). The ore is commonly found close to the interface between Archaean to lower Proterozoic metamorphic and plutonic rocks, and unconformably overlying Proterozoic sandstones. Basement-rooted graphitic reverse faults are also important structural controls.

The most widely accepted models for the formation of unconformity-related U deposits involve the interaction of oxidizing diagenetic brines with a basement-derived reducing fluid, or alternatively with reduced basement lithologies (Hoeve & Sibbald 1978; Kotzer & Kyser 1995; Fayek & Kyser 1997). Uranium is thought to be leached by oxidizing diagenetic brines from accessory minerals either in the basin, or in the basement, or both, but evidence of U leaching are only found in the basement (Hecht & Cuney 2000).

Although fluids were described in previous fluid inclusion studies in Australian (Ypma and Fuzikawa, 1980; Wilde *et al.* 1989) and Canadian deposits (Pagel *et al.* 1980; Kotzer & Kyser 1995), no detailed fluid compositions are available and the following questions still remain: i) How many fluids have occurred in the vicinity of the unconformity-type U deposits? ii) At what P-T conditions have they circulated? iii) What are their major elements compositions? iv) Do they show evidence of mixing? v) What are their chronological and genetic relationships to U deposits?

METHODOLOGY

The precise determination of the composition of individual fluid inclusions in the H₂O-NaCl-(Ca,Mg)Cl₂ system from low temperature microthermometry is often limited by the difficulties in observing the melting of salt hydrates and by their common metastable behaviour. To add, the liquid phase can fail to nucleate any ice or hydrate during cooling down to -190°C.

Thus, when such problems appeared, we used Raman microspectrometry to identify the salt hydrates and to measure

the chlorinity of the aqueous phase (Dubessy *et al.* 2002), and Laser Induced Breakdown Spectroscopy (LIBS) to determine cation ratios Na/Ca and Na/Mg (Fabre *et al.* 1999).

FLUIDS FROM AUSTRALIAN DEPOSITS

The above methods were applied to fluid inclusions from the Jabiluka, Nabarlek, Caramal, South Horn and Ranger deposits. The results are presented in Derome *et al.* (2003) and Derome *et al.* (2007) and summarized here.

These studies revealed the occurrence of three distinct fluids: i) a NaCl-rich brine with about 10-19 wt.% NaCl, 4-11 wt.% CaCl₂, and 0-6 wt.% MgCl₂, ii) a calcium-rich brine with about 1-8 wt.% NaCl, 14-23 wt.% CaCl₂ and almost no detectable MgCl₂ iii) a low-salinity fluid with about 3-13 wt.% NaCl, 1-13 wt.% CaCl₂, and 0-0.6 wt.% MgCl₂.

Both NaCl and CaCl₂-rich brines are thought to have circulated at the base of the sandstones at minimal P-T conditions of 150 ± 20°C and 1250 ± 250 bars. The low-salinity fluid is slightly warmer and is thought to have circulated at depth before being injected at the base of the sandstones. The two brines and the low-salinity fluid were mixed and trapped at the favour of pressure decrease from lithostatic to hydrostatic regime at the time of U deposition.

FLUIDS FROM CANADIAN DEPOSITS

The above methods were applied to fluid inclusions from the McArthur River deposit. The results are presented in Derome *et al.* (2005) and summarized here.

This study revealed the occurrence of three distinct fluids: i) a NaCl-rich brine with about 25 wt.% NaCl, up to 14 wt.% CaCl₂, and up to 1 wt.% MgCl₂, ii) a CaCl₂-rich brine with about 5-8 wt.% NaCl, 20 wt.% CaCl₂, and up to 11 wt.% MgCl₂, iii) a low-salinity fluid with 6-9% NaCl, 2.5-5% CaCl₂ and 0-0.1% MgCl₂.

The NaCl-rich brine is thought to have circulated at P-T conditions of 220 ± 30°C and 1350 ± 150 bars, while the CaCl₂-rich brine is thought to have circulated at P-T

conditions of 110 ± 30°C and 700 ± 200 bars. Mixing between the two brines occurred during the pre-ore stage at 700 ± 200 bars after a pressure decrease from lithostatic to near hydrostatic conditions. The low-salinity fluid doesn't mix with brines and appears to be post-ore.

Ongoing studies on the Rabbit Lake, Shea Creek, Millennium, P-Patch and Eagle Point deposits give similar results. NaCl-rich, CaCl₂-rich brines and mixing trends between the two end-members are found in all deposits. Strictly basement-hosted deposits (Millennium, Eagle Point and P-Patch) share comparable fluid characteristics with classical unconformity-hosted deposits.

CONCLUSIONS

These studies identify three types of fluids in the Australian and Canadian deposits. In both cases, the NaCl- and CaCl₂-rich brines mixed with each other. The main differences between the two cases, is the mixing of the brines with a low-salinity fluid, which took place only in Australian deposits.

In both cases, the CaCl₂-rich brine is thought to have evolved from the NaCl-rich brine after fluid-rock interactions in the basement. The fault zones and the breccia bodies at the base of the basins represent active drainage zones where different fluid reservoirs were connected, and thus a highly favourable location for fluid mixing. Temperature and pressure changes, combined with the effects of fluid mixing, appear to be key-factors in the main stages of quartz cementation and U deposition in both Australian and Canadian deposits.

ACKNOWLEDGEMENTS

We gratefully thank the AREVA NC company for financial support and both the AREVA NC and CAMECO companies for providing samples.

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Petrological, geochemical, and isotopic evaluation of the Grenvillian uraniumiferous pink and white granitic pegmatites, Fort-Coulonge, Quebec

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ABSTRACT: The pink and white U- and Th-bearing granitic pegmatites of Fort-Coulonge Quebec were studied using petrology, geochemical analysis, and oxygen isotopes of quartz, feldspar, and biotite. Both pegmatites show some characteristics of NYF-type pegmatite and A-type granite, such as low CaO, MgO, and high Zr. For the oxygen isotope study, 21 mineral separates were obtained picking from 8 rock samples. The $\delta^{18}\text{O}$ values for the analysed minerals are within the general range of pegmatitic rocks, and the order of enrichment of ^{18}O quartz > feldspar > biotite is preserved in most cases. $\delta^{18}\text{O}$ values from quartz vary between 11.3-14.3‰, feldspar between 10.4-11.9‰, and biotite 7.0-8.3‰. The observed wide range of Δ quartz–biotite (+3 to +6‰) and Δ quartz–feldspar values (-0.6 to +3‰) could be the result of isotope exchange between minerals and magmatic fluids in an open system or of infiltration of a small quantity of external fluids.

KEYWORDS: uranium, pegmatite, oxygen isotope, Grenville Province, Quebec

INTRODUCTION

To date no economically viable uranium deposits have been identified in the Pontiac area of Quebec, although is noted for its high airborne radiometric background and presence of several occurrences of low-grade uranium mineralization. Therefore, a petrological and geochemical study of the uranium- and thorium-rich white to pink granitic pegmatites in the Fort-Coulonge area in southwestern Quebec, Canada was initiated to help build a better overview of the characteristics of these uraniumiferous pegmatitic systems.

GEOLOGICAL SETTING

The Grenville Province is a major structural province included within the Canadian Shield. The first two units of this Province are semi continuous, stacked belts: the Parautochthonous belt (PB) and the structurally overlying Allochthonous Polycyclic belt (APB) (Fig. 1). The Allochthonous Polycyclic belt and the Allochthonous Monocyclic belt (AMB) are two allochthonous units. After Carr *et al.* (2000) and Tollo *et al.* (2004), the Allochthonous Monocyclic belt is divided into three separate units: the Wakeham

terrane, the Composite Arc Belt, and the Frontenac-Adirondack-Morin Belt. The Composite Arc Belt is included in the Central Metasedimentary Belt in the tectonic subdivision of Wynne-Edwards (1972).

The Fort Coulonge area is located in the Central Metasedimentary Belt (CMB) in the western part of the Grenville Province about 100 km northwest of Ottawa, Canada. The Central Metasedimentary Belt consists of five units: Bancroft terrane, Elzevir terrane, Mont Laurier terrane, Frontenac terrane, and Adirondack Lowlands. The study area is located within the Mont Laurier terrane that is characterized by metasedimentary and metavolcanic rocks. Granitic, pegmatitic, tonalitic, or gabbroic intrusions of various dimensions and with variable degrees of metamorphism are common throughout the Mont Laurier terrane.

PETROLOGY

Two types of late orogenic granitic pegmatites are found in Fort-Coulonge, intruding ductily deformed and high-grade metamorphic rocks formed during the Proterozoic Grenvillian orogeny. The pink pegmatites are locally sheared, foliated or

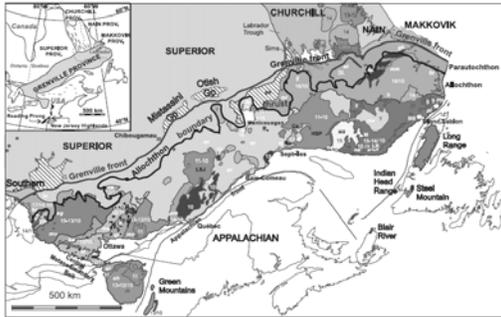


Fig. 1. Map of the geological subdivisions of the Grenville Province (modified after Corriveau *et al.* 2007).

zoned and are mainly quartz, two feldspars, biotite (5-10%), and magnetite (1-5%). Their grain sizes vary from aplitic to pegmatitic (2-5 cm). Hornblende is observed close to the mineralized zones and shows chlorite alteration. Graphic (Fig. 2) and granophyric quartz and K-feldspar intergrowths are common (Madore *et al.* 1994; Lentz 1996). The mineralized zones are mainly represented by uranothorite and zircon. The white pegmatites are unzoned (Fig. 3), vary in grain size from aplitic to pegmatitic (2-5 cm) and locally show graphic or granophyric texture. They contain mainly plagioclase and K-feldspar, both white, quartz, and biotite. Locally, the white pegmatites contain molybdenite or tourmaline as accessory minerals. The mineralized zones rich in U and Th of the white pegmatites contain uraninite, uranothorite or thorite usually located in biotite, K-feldspar, or rarely in apatite. Other accessory minerals that may contain U or Th are monazite, zircon, allanite, and xenotime.

GEOCHEMISTRY & GEOCHRONOLOGY

The pegmatites of the Fort-Coulonge area are classified as NYF pegmatite, AB-U subclass (Černý & Ercit 2005). The two types of pegmatite are peraluminous indicated by an $A/CNK > 1$ and have low CaO, MgO, TiO₂, and P₂O₅ (Fig. 4). All pegmatite samples contain high silica and alkali contents, with SiO₂ ranging from 63-80 wt.% and total K₂O+Na₂O varying from 5.1-10.2 wt.%. Thorium values (10-468 ppm) and U values (<1-613 ppm) vary

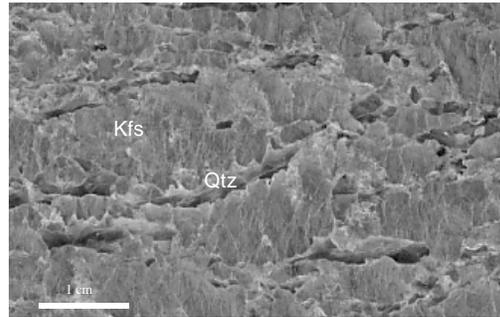


Fig. 2. Photograph of sample FC07-TJCR-258 showing graphic texture in the pink pegmatite.

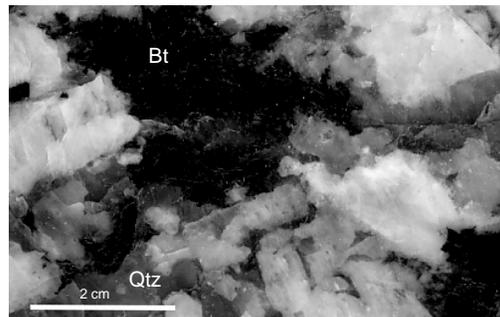


Fig. 3. Photograph of sample FC07-CR-Ch1 showing a pegmatitic texture in an unzoned white pegmatite.

widely. Their Th/U ratios range from 0.77 to 25, but are typically between 2 to 4 indicative of both extensive fractionation and magmatic hydrothermal processes. A total of six samples, four from the pink pegmatite and two from the white pegmatite show enrichment in total REE, with values between 530-712 ppm. Some mineralized white pegmatites have a very high La/Lu between 6280-8360, but with a mode closer to 300. The La/Lu ratio of the pink pegmatite is usually moderate to low, around 150. The white pegmatite has lower Sr values (155-254 ppm) compared to the pink pegmatite (199-659 ppm). The magma shows important crustal contamination, evident from the Rb-Ba-Sr systematics, where these pegmatites fall in the anomalous granite field. Their Nb-Y-Rb contents suggests that they are most likely to be of collisional origin and this is in agreement with them being associated with late orogenic processes (Lentz 1996) such as partial melting, magmatic coalescence, and quartz-

feldspar crystal fractionation leading to U-Th enrichment.

The multiphase pegmatitic intrusions were generated at depth due to anatexis associated with late high-grade metamorphism during the Grenvillian Orogeny. The pegmatites of the western part of the Grenville previously dated at 937 to 980 Ma using whole-rock Rb-Sr isochrons and at 1010 to 1060 Ma using U-Pb zircons, which are 30 to 80 Ma younger than the peak metamorphism at this level of the Ottawa phase of the Grenville orogeny and probably correspond to an uplift period. Recently, sample FC07-CR-Ch1, a white pegmatite was dated using CHIME U-Th-Pb on monazite. The weighted mean age is 1060 +/- 5 Ma and is similar to the ones obtained with previous U-Pb zircon dating.

OXYGEN ISOTOPE

Whole-rock $\delta^{18}\text{O}$ values can be acquired from homogenized rock samples, or from separates of individual rock-forming minerals. When $\delta^{18}\text{O}$ data of individual minerals are available, the oxygen isotope systematics of the rock-forming minerals can be evaluated in δ vs. δ plots (Gregory & Criss 1986).

For this study a total of 21 mineral separates were obtained by hand picking from 8 rock samples. Oxygen isotope analyses were measured using a DELTA^{plus}XP Stable Isotope Ratio Mass Spectrometer. The $\delta^{18}\text{O}$ values for the analysed minerals are within the general range of pegmatitic rocks, and the order of enrichment of ^{18}O quartz > feldspar > biotite is preserved in most cases. Only one sample shows a noticeable disequilibrium conditions with feldspar having $\delta^{18}\text{O}$ value higher than quartz and one sample shows apparent enrichment in $\delta^{18}\text{O}$.

In the δ - δ diagrams, plotted with a mineral which exchanges oxygen relatively slowly (quartz) on the horizontal axis and a mineral which exchanges oxygen relatively rapidly (feldspar, biotite) on the vertical axis, the data from the pink pegmatites shows vertical trends which is usually caused by open-system hydro-

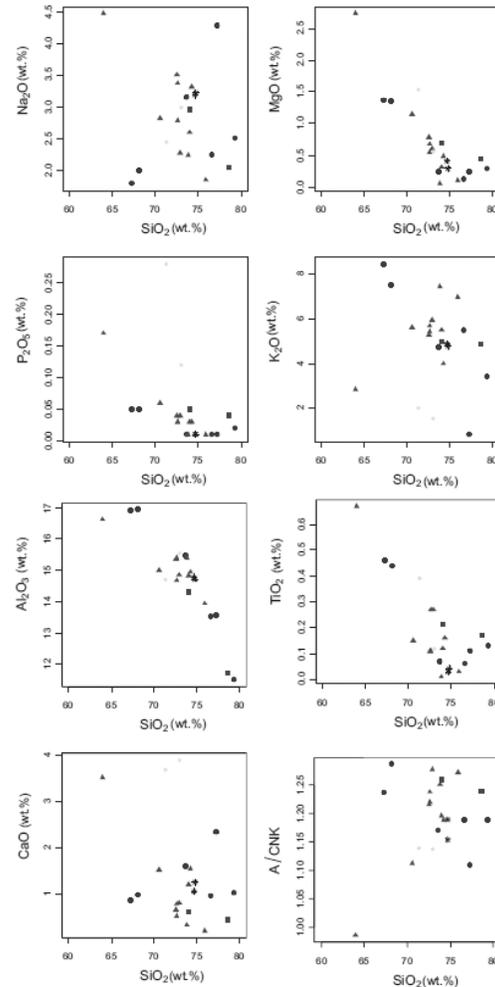


Fig. 4. Harker plots of SiO₂ wt.% vs Na₂O, MgO, Al₂O₃, P₂O₅, K₂O, CaO, TiO₂, and A/CNK. The symbols are: square for host rock, circle for white pegmatite, triangle for pink pegmatite, diamond for mineralized samples, and star for altered pegmatite.

thermal alteration (Gregory *et al.* 1989). The data from the quartz-feldspar diagram of the white pegmatites shows an array with a constant per mil difference (Δ) between the two minerals, indicative of constant temperature crystallization of minerals of different $^{18}\text{O}/^{16}\text{O}$ ratio (Harris *et al.* 1997). The observed wide range of Δ quartz-biotite (from +3‰ to +6‰) and Δ quartz-feldspar values (from -0.6‰ to +3‰) could be the result of isotope exchange between minerals and magmatic fluids in a system opened to fluid, or of infiltration of a small quantity of

external fluids. Harris *et al.* (1997) used the $\delta^{18}\text{O}$ data of quartz for distinguishing between S-type and I-type (or A-type) granites, as this mineral is generally less sensitive to alteration. The observed quartz $\delta^{18}\text{O}$ values from the Fort-Coulonge pegmatites range between 11.3 and 14.3‰, which is a bit higher than S-type granites. This is probably due to contamination with metasediments or hydrothermal alteration with a fluid having a high $\delta^{18}\text{O}$ value.

CONCLUSIONS

The geochemical analyses showed that the Grenvillian granitic white and pink pegmatites of Fort-Coulonge were affected by crustal contamination, which is characterized by high Rb and Th contents. Furthermore, the oxygen isotope data from the pink pegmatites shows vertical trends, which is usually caused by open-system hydrothermal alteration and the data from the quartz-feldspar diagram of the white pegmatites shows an array with a constant per mil difference (Δ) between the two minerals, indicative of constant temperature crystallization of minerals of different $^{18}\text{O}/^{16}\text{O}$ ratio. This supports the hypothesis that the pink and the white pegmatites of Fort-Coulonge haven't been influenced by the same fluids.

ACKNOWLEDGEMENTS

We thank Aldershot Resources Ltd. for providing funding for analyses and field work. This study was also financed through a NSERC Discovery grant to DL.

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Role of geochemistry in the search for Uranium deposits

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ABSTRACT: The behaviour of uranium, associated trace elements, and radon in surface and near-surface aqueous environments is discussed as it applies to the exploration for uranium deposits. Elemental dispersion and zoning will depend on composition, Eh, and pH of surface and near surface waters. Mobility is favored by oxidized conditions while uranium will be fixed under reducing conditions. Certain elements show a consistent zoning in deposits and can serve as pathfinders, however, because of its mobility under oxidizing conditions, uranium distribution in rocks, soils, and waters also can be used as vectors for deposits. Dispersion patterns will depend on hydrology, which is controlled by local structure and host rock porosity and permeability. Geochemical and radiometric exploration techniques can be useful as guides to ore when combined with mineral and alteration zoning, structural geology, and geophysical techniques.

KEYWORDS: *uranium, aqueous chemistry, redox equilibria, radon, hydromorphic dispersion*

INTRODUCTION

Exploration models applied to uranium deposits must be cost-effective and timely in order to be useful in the present day competitive environment. Economic uranium deposits take a wide range of forms in a variety of geologic terrains, and methods used must take into account the types of deposits sought. Geochemical methods should be just one component of a well-integrated exploration program, which includes geology, geophysics and radiometric surveys, both on a local and regional scale.

URANIUM GEOCHEMISTRY

The understanding of the geochemistry of uranium and its daughter elements, as well as useful pathfinder elements, in surface and near surface aqueous systems is paramount in the design of exploration models for economically recoverable deposits. This understanding should consider: 1) the mechanisms of uranium transport and deposition, and thus the petrogenesis of the deposits; 2) alteration assemblages typical of various types of deposits, and important in field recognition of mineralization; and 3) the hydromorphic dispersion of uranium and associated elements during secondary

processes, the interpretation of which is the focus of geochemical exploration.

In surface and near surface low temperature aqueous environments the behaviour of uranium is strongly controlled by the oxidation state, pH and the chemical composition of the solution because of its: 1) variable oxidation state (U^{4+} , and U^{6+} as UO_2^{2+}); 2) tendency to hydrolyze to dissolved species such as UO_2OH^+ ; 3) ability to form a large number of aqueous complexes (40) with a number of major and minor anions (OH^- , CO_3^{2-} , Cl^- , SO_4^{2-} , F^- , PO_4^{3-}); 4) tendency to adsorb on organic material and various oxyhydroxides; and 5) ability to form a large number of primary and secondary minerals (145). The latter may contain arsenic, selenium, vanadium, copper, molybdenum, and phosphate as essential components, and therefore some of these elements may serve as important pathfinders. These systems will be chemically open, therefore minor changes in pH and oxidation state will result in competition for uranium between solid phases, resulting in either precipitation or adsorption, and the aqueous phase, resulting in various soluble complexes.

Uranium most commonly is mobile in oxidized groundwaters as the uranyl

carbonate complex, and immobile in reduced fluids as the uranous state (Fig. 1). However, even under oxidized conditions, in the presence of As, Se, P, or V, uranium may be immobilized by the precipitation of various secondary minerals near neutral pH's as shown in Figure 2 for carnotite, $K_2(UO_2(VO_4)_2 \cdot 3H_2O$. These secondary minerals have characteristic spectral behaviour and thus constitute first order visual criteria in recognizing the presence of uranium mineralization. Interpretation of uranium dispersion patterns must consider the possibility of episodic changes in solution chemistry and aquifer composition, resulting in the progressive enrichment or depletion of uranium in space and time.

Figure 1 illustrates that in reduced aquifers uranium would not be mobile. It also shows that uranium can be precipitated well into the field of stability of hematite under oxidizing conditions. This common association between uranium mineralization and hematite needs to be taken into account in any exploration program.

INTERPRETATION

Geochemical data may be collected from the analysis of solids, both primary and secondary, the aqueous phase, either groundwater or streams, or in the case of decay products, the vapor phase. Sampling and analytical procedures should follow protocols typical of any survey employing geochemical methods, with attention paid to proper quality assurance and control issues. The design of a viable geochemical exploration program must include local background and threshold studies, particularly in areas where known uranium geochemical provinces occur.

Characteristics that complicate the interpretation of geochemical and radiometric data for uranium deposits include: 1) variable oxidation state of uranium and associated elements; 2) the variety of aqueous species possible; 3) the tendency for soluble uranium and

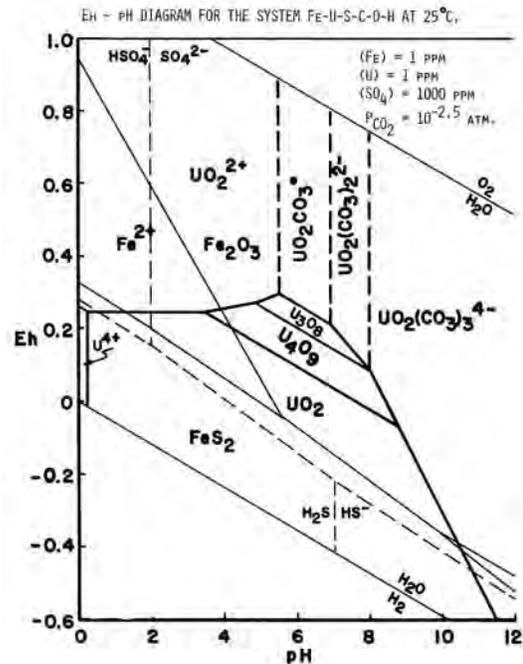


Fig.1. Eh-pH diagram for the system Fe-U-S-C-H₂O at 25 °C showing the mobility of uranium under oxidizing conditions, the relative stability of iron minerals, and the distribution of aqueous sulfur species. Heavy line represents the boundary between soluble uranium (above), and insoluble conditions (below), assuming 1 ppm uranium in solution.

associated elements to adsorb onto various oxides and clays; and 4) the contrasting behavior of uranium and decay products in the secondary environment. Eh, pH and fluid composition are important parameters in geochemical exploration programs. Additionally, the type of deposit targeted will also be important in the interpretation of geochemical data. For example, structurally-controlled deposits such as vein and unconformity-type will produce a dispersion pattern quite different from a sandstone-hosted deposit.

Depending on type, uranium deposits exhibit characteristic primary alteration and trace element zoning patterns, the latter commonly including, but are not limited to, elements exhibiting changes in oxidation state such as vanadium, selenium, molybdenum, arsenic, cobalt, and nickel (Fig. 3). It can be shown that

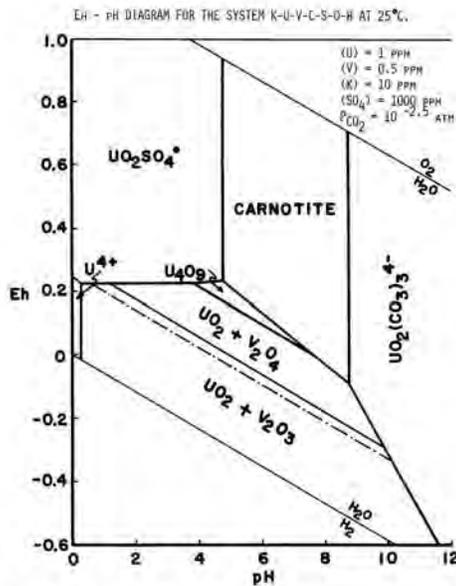


Fig. 2. Eh-pH diagram for the system K-U-V-C-S-H₂O at 25 °C showing the stability of secondary carnotite.

the order in which the elements occur away from the oxidized tongue is directly related to the order in which they precipitate as a result of decrease in Eh (reduction). Analytical data including anomalous amounts of more than one of these elements showing consistent spatial patterns may be useful in determining the type of deposit and the nature of dispersion.

Alteration assemblages may include primary chlorite, illite, smectites, and/or kaolinite, and various primary and secondary iron oxides, carbonates, and sulfides (Fig.1), any one of which may serve as indicators of fluid composition. Lithologic geochemical surveys rely on an understanding of these patterns to vector towards uranium deposits. The interpretation of hydromorphic geochemical surveys, including lake and stream sediment, and soil, depends on the mobility of uranium and associated elements in the surface and near surface environment.

RADIOMETRIC METHODS

The radioactive nature of uranium and associated daughter elements adds an additional dimension to geochemical

methods not typically available for other metallic commodities. The interpretation of radiometric surveys is affected by the degree of disequilibrium between uranium and decay products, which, in turn, depends on the relative mobility of parent and daughter nuclides and their half lives, such as helium, radium, radon, bismuth and lead. Radon and helium will be mobile and most easily detected in the vapor state. However, interpretation can be troublesome. The solubility of all gases in water will be directly proportional to pressure and inversely proportional to temperature. Therefore, interpretation of aqueous gas data will need to take into account both seasonal and diurnal atmospheric conditions. Because of the very low solubility of noble gases such as radon and helium in surface waters, they will be particularly sensitive to meteoric variations. During degassing of natural waters, as a result of groundwater discharge (during the sampling of wells) or in turbulent streams, trace gases will be quantitatively scavenged into the bubbles and pass out into the atmosphere.

Radon probably rarely reaches saturation in groundwater because of its transient nature. Radon (²²²Rn) is the decay product of radium (²²⁶Ra) with a half life of 3.8 days, which decays to polonium (²¹⁸Po, t_{1/2} = 3 min) and ultimately to lead, through alpha decay. The general rule is that after 10 half lives in a closed system the parent radon will be gone (38 days), so the parents of radon, radium or uranium, must be recharged in an open system. Even though radium has a significant half-life of 1600 years, it is very immobile under near surface conditions because it forms insoluble compounds. However, it probably does not reach aqueous saturation because it is readily adsorbed or co-precipitated with various secondary oxides, and may rarely migrate far from the site of uranium decay unless physically transported by stream flow. The contrasting mobility of uranium and these daughter elements suggests relying on total gamma eU determinations for estimation of uranium concentrations may

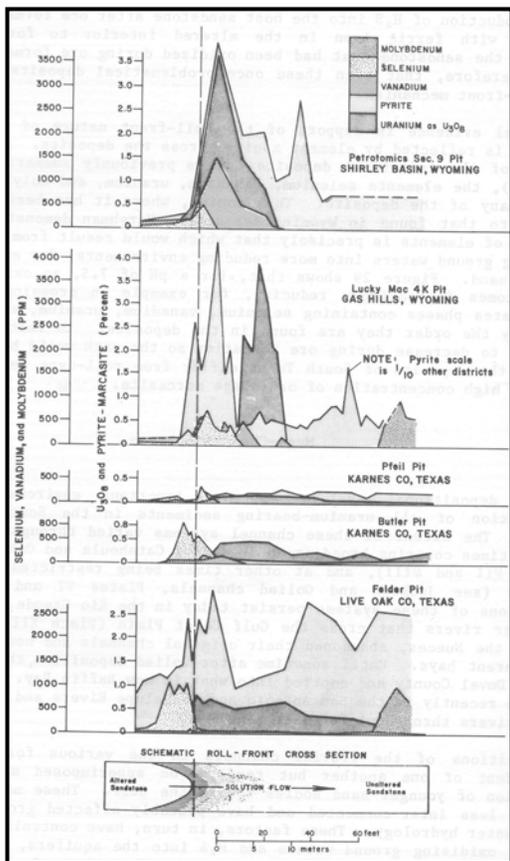


Fig. 3. Elemental and mineral zoning exhibited by selected roll-front uranium deposits. From Adams & Smith (1981) adapted from Harshman (1974).

be suspect, and more up-to-date instrumentation employing wavelength-specific techniques should be used.

Indirect methods have been suggested as viable exploration tools for uranium deposits by investigating radiation damage in minerals produced by radioactive decay processes. Botis *et al.* (2006) described the cathodoluminescence (CL) spectra in quartz in association with uranium mineralization in the Athabasca Basin of Saskatchewan. Hu *et al.* (2008) described the application of electron paramagnetic resonance (EPR) to investigate radiation damage in quartz also in the Athabasca Basin. They showed that radiation-damaged quartz occurred in alteration haloes surrounding known uranium deposits.

CONCLUSIONS

Because of the high mobility of uranium and daughter elements in surface and near surface environments, geochemical methods can be very useful in exploration programs for uranium deposits. However, geochemical surveys should not be used alone, but in conjunction with detailed geology, including, primary lithology, alteration zoning and structure, both pre- and post-mineralization. In hydrologic systems fluid flow is important and structures commonly define pathways that control element distribution during both primary mineralization and secondary dispersion. Pathfinder elements may be useful if their distribution is more widespread than uranium, particularly in hydrothermal deposits. However, because of its high mobility in the oxidizing environment, uranium and its daughter products may exhibit a wider secondary dispersion than associated trace elements, and therefore it may be best to analyze for uranium directly using chemical and/or radiometric methods using wavelength-specific instrumentation.

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Mobility of Uranium and Radon associated with uranium roll front occurrences in the Horton Group of the Windsor area, Nova Scotia, Canada

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Abstract: There are numerous uranium occurrences in the basin fill units of the Maritimes Basin and in the adjacent crystalline basement rocks in Atlantic Canada. The uranium occurrences in the Carboniferous Horton Group sedimentary strata are sandstone-hosted uranium roll fronts. Recent recognition of deeply weathered granitoids below the unconformity of the Horton Group on the Late Devonian South Mountain Batholith suggests a possible genetic link to regolith-related unconformity deposits as well. The roll fronts in the Horton Group sandstones are known primarily from drill core, however there is an excellent exposure of mineralized sandstone at Green Street, near Windsor, Nova Scotia. The rate and quantity of uranium and radon contributed to surface and groundwater by mineralized outcrops has been poorly documented in the past. Leaching experiments were undertaken using the mineralized sandstones and siltstones from the Green Street occurrence. All of the samples revealed significant uptake of uranium and radon into both distilled water and in samples mixed with natural rain water. These leaching experiments have important implications for the mobility of these elements in the environment and dispersion patterns in regards to geochemical exploration. Although this paper deals primarily with uranium and radon from occurrences in the Windsor area of Nova Scotia, the regional nature the Horton Group strata throughout eastern Canada would seem to imply that environmental issues related to the uranium mineralization might exist throughout the Maritimes Basin. This may be of particular note in areas that have elevated uranium occurrences within granitoid basement rocks adjacent to the Carboniferous basin fill.

Keywords: *uranium, radon, roll fronts, saprolites, mobility, Nova Scotia*

INTRODUCTION

The rate and quantity of radon and uranium contributed to waters exposed to mineralized outcrops and the subsequent mobility of these elements in the present day environment has not been previously documented. This paper presents the results from leaching experiments carried out on uranium-enriched Horton Group sandstones in the Windsor area of Nova Scotia. Understanding of these processes is important both to environmental and exploration geochemistry.

GENERAL GEOLOGY

The rocks and saprolites referred to in this paper are located primarily in southern Nova Scotia (Fig.1). Southern Nova Scotia forms the Meguma Terrane of the northern portion of the Appalachian

Orogen (Williams 1995). The Meguma Terrane is made up primarily of Cambro-Ordovician metasedimentary rocks of the Meguma Group and approximately one third of the terrane has been intruded by Late Devonian granitoid batholiths, the largest of which is the South Mountain Batholith (MacDonald 2001). These basement rocks are overlain by the sedimentary rocks of the Maritimes Basin.

The general stratigraphy of the Maritimes Basin consists of a late Devonian redbed and volcanic sequence referred to as the Fountain Lake Group, Mississippian clastic fluvial-lacustrine rocks of the Horton Group, Mississippian marine evaporite, clastic-carbonate sequence of the Windsor Group, the fine terrestrial clastics of the Mabou Group, the coal measures of the Cumberland Group, and the late

Carboniferous to Permian redbeds of the Pictou Group (Bell 1929). In the area surrounding the Bay of Fundy, there was also a Jurassic-Triassic sedimentary basin (Fundy Group) developed in which sandstones, shales, basalts and minor limestone were deposited. During the Cretaceous fluvial quartz sands and kaolin of the Chaswood Formation were deposited throughout the Maritimes, but only a few outliers have been preserved (Stea & Pullan 2001).

The Horton Group rocks of the Maritimes Basin are hosts to the best documented uranium occurrences (Quarch *et al.* 1981). The Horton Group can be divided into the upper arkosic Cheverie Formation and the lower Horton Bluff Formation.

URANIUM MINERALIZATION

The presence of anomalous levels of uranium, radium, and radon in the Carboniferous-aged Horton Group and underlying basement rocks of Atlantic Canada has been known for many years (Quarch *et al.* 1991; Fig. 1). The exploration model applied on the sandstone-hosted occurrences was that of a uranium roll-front similar to the deposits found in Texas and the western United States. However the recognition of deeply weathered granitoids below the unconformity of the Horton Group on the South Mountain Batholith suggests a genetic link to regolith-related unconformity deposits such as the Athabaska Basin of Saskatchewan may also be applicable.

There is no doubt of the presence of roll fronts in the Horton Group sandstones, however the source of the uranium within the system may be related to the weathered horizons beneath the Horton Group rocks and not exclusively the result of diagenetic change within the sandstones (Ryan & O'Beirne-Ryan 2007).

The granitoid rocks of the South Mountain Batholith in Nova Scotia contain numerous uranium deposits and occurrences. These deposits are interpret-

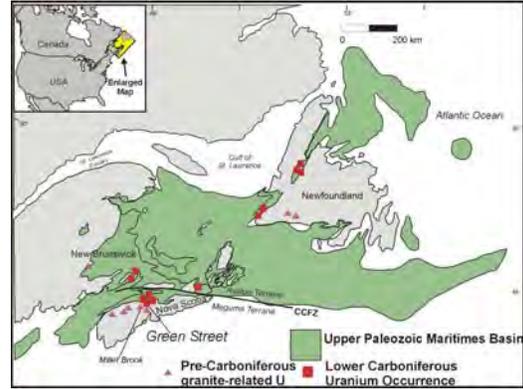


Fig. 1. Location of uranium occurrences in granitoids and the Horton Group in Atlantic Canada.

ed as having been formed due to fluid migration in the late stages of the granitoid emplacement and occur within shear and fracture zones of altered rocks either within the granitoids or as peribatholithic occurrences in the metasedimentary Meguma Group country rocks (Chatterjee 1983). These occurrences exhibit mineralogical evidence that they have been deeply weathered (Chatterjee 1983).

The uranium liberated by weathering of the granitic region must have been incorporated in the surface water and subsequently entered, as uranium-enriched groundwater, into the permeable sandstone and conglomerate aquifers of the Horton Group. Upon entering the sandstones of the Horton Group, the uranium-enriched oxygenated waters caused diagenetic reddening of the sandstone therefore liberating additional uranium into the water that travelled down dip until it reached a reduction-oxidation boundary where the uranium was deposited.

Uranium mineralization in the Windsor area is a typical sandstone roll-front type. The Green Street occurrence that is the focus of this study occurs in thick arkosic sandstones, siltstones, and pebbly conglomerates of the Cheverie Formation (Fig. 2). The occurrence is a remnant tail of a uranium roll front that has subsequently migrated down dip from the outcropping (Ryan & O'Beirne-Ryan 2007).

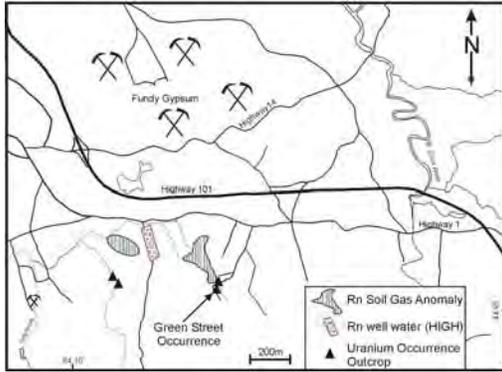


Fig. 2. Location of Green Street Occurrence and related radon soil gas and well water anomalies.

MOBILITY OF URANIUM AND RADON

The initial exploration and subsequent drilling in the Windsor area was sparked by the discovery of radon anomalies in the soil gas and well waters in the area (Quarch *et al.* 1981; Fig. 2). In addition, uranium and radium in well waters were weakly anomalous in the area. It is therefore not difficult to infer that these geochemical techniques are useful exploration tools for deposits of this type and that there are environmental issues related to uranium occurrences in the Horton Group.

A series of leaching experiments were carried out on mineralized sandstone and siltstone from the Green Street Occurrence (Parsons 2007). The samples were poorly consolidated and easily broken apart by hand and placed into the waters. The samples were placed in distilled water, stream water, and rain water at temperatures ranging from 5 to

Table 1. Total uranium in water analyses, leaching experiments using rainwater, Green Street Occurrence, near Windsor Nova Scotia (after Parsons, 2007).

Time	Mineralized sandstone	Mineralized siltstone
8 days	83,000 Bq/m ³	422,000 Bq/m ³
10 days	796,000 Bq/m ³	558,000 Bq/m ³
12 days	>1,000,000 Bq/m ³	>1,000,000 Bq/m ³

20⁰C. In addition to unshaken samples, duplicate samples were agitated at regular intervals for varying lengths of time and subsequently analyzed for uranium and radon. All of the samples demonstrated significant uptake of uranium into the water (Table 1; Parsons 2007). The uranium content of the water from the siltstone sample exceeded the Canadian Drinking Water Quality Guidelines of 20 µg/L. There are no guidelines for Radon in drinking water however the concentrations in the waters exceeded 1,000,000 Bq/m³ (Table 2; Finlayson 2008). Whereas the radon and uranium can easily be incorporated into the surface and groundwater and transported down slope (to the north) the anomalous radon in soil and well waters in the area can be attributed to the mineralized outcrops (Fig. 2).

Table 2. Radon uptake in unshaken distilled water at 20⁰C from mineralized Green Street samples (after Finlayson 2008).

Sample AP06-01	Sample AP06-04
Mineralized Sandstone	Mineralized Siltstone
16 µg/L Uranium	24 µg/L Uranium

Although this paper deals primarily with uranium and radon from occurrences in the Windsor area of Nova Scotia, the areal extent of the Horton Group strata throughout eastern Canada would seem to imply that environmental issues related to the Horton Group uranium mineralization might exist throughout the Maritimes Basin.

ACKNOWLEDGEMENTS

Funding for this project was provided by the Nova Scotia Department of the Environment and Labour and the Nova Scotia Department of Natural Resources.

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QA/QC, verification and integration of multisource data for the Novoveska Huta and Kuriskova deposits in Eastern Slovakia

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ABSTRACT: Novoveska Huta (NVH) and Kuriskova are uranium deposits in eastern Slovakia. They are located at the western end of the Carpathian Mountains. The Western Carpathian Mountain range of Eastern Europe is the result of the Variscan and Alpine multi-cycle collision orogenies and they host a number of uranium deposits. Kuriskova is near the town of Kosice in eastern Slovakia and NVH is approximately 65 kilometres west of Kuriskova. While Kuriskova has been explored since 1980, NVH has a much longer history including uranium production from open pit and underground mining. Uranium mineralization at both of these deposits is similar in style and character, occurring along the contact of meta-volcanic rocks and underlying meta-sedimentary rocks.

These deposits are currently being explored by Tournigan Energy Ltd. The NVH deposit has large amounts of historical data available. The challenge for the Tournigan team was to implement an efficient approach and method for data compilation and verification for integrating all of the different data types and to implement strict QA/QC procedures for more recent data collection and assaying. This paper summarizes the different types of historical data and the procedures and the QA/QC system that Tournigan adopted.

KEYWORDS: *Kuriskova, Novoveska Huta, Historical data, QAQC, Tournigan*

INTRODUCTION

The objective of data validation and verification, along with strict QA/QC procedures, is to ensure the quality of data for reliable mineral resource estimates.

Data collected, stored and validated is of no use unless it is stored in a meaningful way to ensure easy retrieval and presentation. Tournigan Energy Ltd. implemented these QA/QC procedures at an early stage on their projects, before stepping into detailed exploration and mineral resource estimates.

This paper highlights the procedures, QA/QC, and database management system implemented by Tournigan to ensure a reliable and secure data set. The effective QA/QC by Tournigan also helped to establish that Pressed Pellet and Borate Fusion XRF are a more accurate assaying method compared to ICP.

PROJECT GEOLOGY

The Kuriskova Uranium Deposit is located in the Kjsovska Hola region of the Volovec

Hills, which are a component of the Western Carpathian Range. The mountain range at Kuriskova is composed of mesozonal to epizonal metamorphic rocks known as the Gemericum tectonic unit of the Carpathian belt. There is a nearly continuous, 0.5 to 6.0 km wide and 80 km long zone of Permian rocks along the northern periphery of the tectonic unit in which there are numerous uranium occurrences.

The Novoveska Huta and surrounding area are part of the North Gemeric Syncline, which belongs to the Gemericum tectonic unit. The deposit itself is hosted in folded and faulted Permian age rocks. Active exploration in the area continues and is extending the limits of known mineralization.

EVOLUTION OF INDUSTRY STANDARDS

Prior to 1997, only a few QA/QC guidelines existed, and monitoring programs were not commonly conducted by mining companies. In 1997, the Toronto Stock Exchange and the Ontario

Securities Commission established the Mining Standards Task Force. One of the key recommendations, a Qualified Person (QP) concept, was developed.

In 2000, the CIMM adopted “Definitions and Guidelines” for “Standards on Mineral Resources and Reserves, which included a “Checklist for the Estimation of Mineral Resources” and “Exploration Best Practice Guidelines”. In early 2001, new mining disclosure standards were introduced by the Canadian Securities Administrators (CSA) under NI 43-101 (Standards of Disclosure for Mineral Projects), and its Companion Policy 43-101CP, and Technical Report Form 43-101F1.

DATA TYPES AND SOURCE

While Kuriskova has been explored since 1980, Novoveska Huta has information dating back to 1950. Kuriskova information is mainly older historical drill holes and the more recent holes drilled by Tournigan Energy Ltd. The Novoveska Huta data set includes channel samples from underground workings, underground drilling samples, surface drilling results (between 1950- 1990) and Tournigan drill holes from 2007 onwards.

Drill Holes information types				Number of holes	Year
Drill holes LH-NH-1 - 13 (Tournigan holes)				13	2006-2008
Historic holes	surface			106	1950-1990
Historic holes	underground	HP-xx (core)		20	1975-1982
Historic holes	underground	UP holes (no core)	composite	167	1982-1986
Historic holes	underground	Down holes (core)	composite	184	1982-1986
Radiometric channel				2010	1982-1986
Radiometric channel composite				71	1982-1986
				2571	

DATA VERIFICATION AND COMPILATION

The key tasks in working with historical data was

1. To verify the information was of good quality before proceeding.
2. Compilation of the data in one standard format, which can be imported into Datamine Studio for resource modelling
3. Creation of a secure database for preservation of historical data and storage of future data. The database needed to be easily accessible through the Internet for company personnel.

4. Verify disequilibrium.
5. Document QA/QC procedures for radiometric and geochemical analysis. Implement these procedures. Conduct internal audits to ensure procedure are in place and record actions taken for data that failed the checks.
6. Documenting of standard operating procedures for sampling, chain of custody, QA/QC, survey, logging, and data verification.

To start with, twinning of historical holes and underground raises was carried out to verify the reliability of geology, mineralization and survey information.

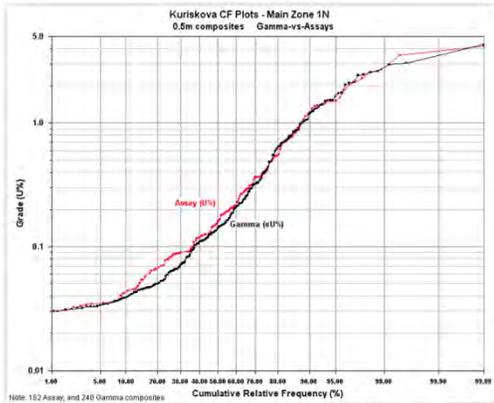
The documentation of all the available types of data in the archives was done and tabulated to decide which information could be verified. Tournigan incorporated only those holes in the database which could be verified from original documentation.

For the historical drill holes that have gamma-only eU data, Tournigan has verified the gamma log conversion data. This was done by randomly selecting 6 drill holes. Graphical logs were re-digitizing and then re-tabulated to create a data table of 0.1m eU% data. This was compared with data from the original 0.1m interval eU% data – essentially a double entry check of the data. For the historical gamma-only holes that have only graphical logs, all logs were digitized and output as 0.1m data tables, then re-plotted graphically and checked against the original plots.

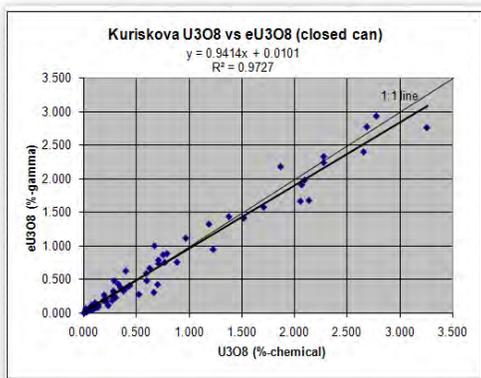
The recent drilling campaigns have essentially validated the mineralization reported by historical workers.

Documentation of radiometric calibration procedure from historical time until recent was discussed reviewed and documented. The results of parameters and software used in the past were verified by reproducing results.

Tournigan carried out closed can analysis to study the comparison of gamma versus assay data for Kuriskova. The general comparative distribution is shown in following CF plot.



Closed can analysis results in the following graph shows disequilibrium analysis done at Energy Lab (US) to verify disequilibrium.



Disequilibrium is the difference in grades, expressed as a ratio, of chemical U_3O_8 to gamma derived eU_3O_8 , as determined for the same sample volume.

Disequilibrium in uranium deposits relates to the chemical dissolution and re-deposition (usually by groundwater) of uranium prior to the time required for that uranium to generate the radiometric daughter products from the natural decay of uranium isotopes (U-238 and U-235)

The gamma logging procedure is indirect measurement of uranium and can be misleading if uranium has been remobilized and there has not been enough time at the original site of deposition for development of daughter products. The results of closed can analysis established the accuracy of

gamma data for historical as well as current drilling.

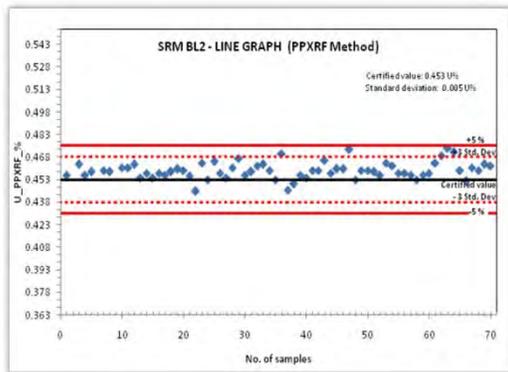
QA/QC FOR ASSAY DATA AND GAMMA DATA

In August 2007, Tournigan instituted a rigorous QA/QC program that is summarized in their corporate project reference manual (Tournigan Energy, 2007). The reference manual enumerates the sampling steps, chain-of-custody (sample management), QA/QC procedures performed, and reporting procedures. Once the samples are delivered to the labs, a dedicated Tournigan geologist tracks the samples, and reports all assay data completed as it is received.

Once initial analyses are completed, random samples are sent from SGS to ActLabs for check assays, to establish precision (repeatability) and analytical bias. Additionally, coarse sample rejects are chosen at random and sent to ActLabs for preparation and analysis, to check the accuracy and repeatability of the original sample preparation. A further check on SGS Lab precision is conducted by renumbering pulps and re-submission from ActLab to SGS for analysis. Tournigan monitors quality assurance by plotting and analyzing the data, as received, and activates re-assaying of sample batches that do not meet pre-determined standards.

Tournigan has done a sufficient amount of analyses by multiple methods ICP, pressed pellet-XRF (PP-XRF), and borate fusion bead and XRF (bf-XRF), to determine that pp-XRF provides the most accurate and precise analyses for uranium.

The following line graph on PP XRF and ICP demonstrate that PP XRF is a better method for the Novoveska Huta and Kuriskova ore types. As part of QA/QC for gamma data, two open holes are used for gamma relogging to obtain duplicate readings. The same drill holes are also relogged to establish accuracy of gamma measurement.



CREATION OF IN-HOUSE ONLINE DATABASE

Instead of implementing standard database packages, Tournigan decided to create their own database system based on .Net framework and SQL server. The salient features of this database are online remote access, multiple level security, documentation of any changes made to the database, compatibility with Datamine for easy updating and reduction of human entry errors, ease of use, inbuilt validations, automatic QC sample insert flags, automated QA graphs, no acceptance of assay data unless it passes QA/QC, automated e-mails to concerned parties in case of delays and the setting of flags for verified holes to be used in Datamine.

CONCLUSIONS

Integration of multi-type and multisource data is useful for any program using historical data. Integration and validation of all the available data types provides a number of real benefits including having a better understanding of the deposit with the more complete database. It also saves costs if historical data can be used rather than re-acquiring the data.

Strict QA/QC in each batch established PP XRF and BF XRF are the best means of sample analysis for the Kuriskova and Novoveska Huta deposits.

The result of all these processes and procedures creates a quality database which can be used to determine a reliable mineral estimate.

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A U-bearing hydrothermal vein system related to the strongly peraluminous, high heat producing North Pole Stream granitic suite, north-central New Brunswick Canada

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ABSTRACT: The Siluro-Devonian North Pole Stream Granitic suite (NPSG) is located in north-central New Brunswick and is cut by a late regional-scale wrench fault system. Magmatic fractionation produced at least four comagmatic differentiates, namely: biotite granite (oldest phase); biotite-muscovite granite; muscovite granite; and late quartz-feldspar porphyry (QFP) granitic dikes that crosscut all other phases of the pluton. Petrochemical data for the NPSG suggest that the muscovite granite is the most evolved phase in that it has A/CNK = 1.3-1.4, and very low TiO₂, Fe₂O₃T, MgO, CaO (0.04, 0.93, 0.12, 0.39 wt.%, respectively), Sr, Ba, Zr, Hf, Y and Σ REE (8, 22, 21, 1.2, 4, and 9.8 ppm, respectively); however, it is enriched in Rb, Sn, Nb, and Ta (546, 31, 50, and 8.6 ppm, respectively). The K (4.11 wt.%), U (30 ppm), and Th (5 ppm) contents are consistent with a high-heat producing (HHP) granite. Convection cells established in the NPSG and surrounding country rock near the HHP granite resulted in late fluid circulation and U leaching from the enriched granite, and localization of U vein formation in the adjacent wrench fault system.

KEYWORDS: *uranium, high-heat producing, specialized granite, Long Lake*

INTRODUCTION

The North Pole Stream granitic suite (NPSG) is located 31 kilometers northeast of Plaster Rock and underlies an area of approximately 500 km² in north central New Brunswick. This plutonic suite is a Siluro-Devonian, intrusive complex that was emplaced discordantly into Cambro-Ordovician metasedimentary rocks of the Miramichi Terrane (Fig. 1). The NPSG is crosscut by steeply-dipping wrench faults related to the Middle Devonian Acadian orogeny. All the wrench faults in the area postdate the oldest of the Devonian granites, and are truncated by younger Devonian and Carboniferous intrusions (Ruitenberg & McCutcheon 1982).

The granitic rocks of the NPSG are the youngest granitic rocks in the Long Lake area and are associated with several styles of mineralization: an early base metal (Zn, Cu, Pb) and granophile element (Mo, Sn, W, In) polymetallic vein system is associated with the emplacement of the NPSG (Fyffe & Pronk 1985), and later uranium vein mineralization, that resulted from

circulating meteoric fluids leaching uranium from the granites is associated with a late steeply-dipping wrench fault beneath Long Lake (Fig. 1).

GEOLOGY OF THE NORTH POLE STREAM GRANITIC SUITE

The NPSG mainly consists of four comagmatic differentiates, namely: biotite granite (oldest phase); biotite-muscovite granite; muscovite leucogranite; and late quartz-feldspar porphyry (QFP) granitic dikes (youngest phase). These phases are attributed to assimilation and fractional crystallization processes that modified an inward propagating solidification front and the dikes represent late stage magma that was intruded into the solidified carapace. The uranium and polymetallic styles of vein mineralization are genetically related to the muscovite leucogranite and QFP granitic dikes, respectively.

The NPSG primarily consists of biotite granite (Whalen 1993), that is generally pink to white, fine- to coarse-grained, and equigranular to K-feldspar porphyritic.

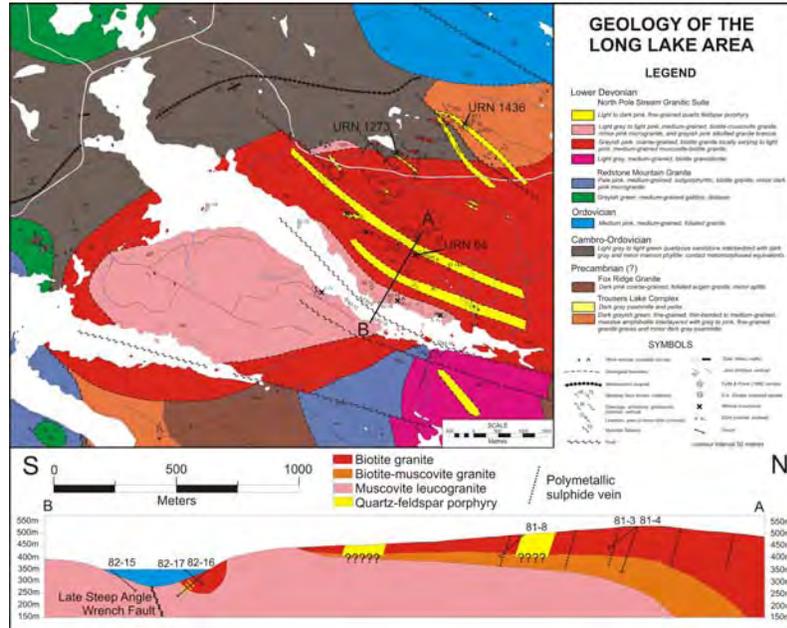


Fig. 6. General geology, mineral occurrences, and diamond drillhole locations in the Long Lake area with a cross section corresponding to the line A-B, illustrating the general geology beneath the surface (modified from Fyffe & Pronk 1985).

Biotite forms approximately 1 to 2 % of the rock, and is partly altered to chlorite.

The biotite-muscovite granite is a transitional phase between the biotite granite and the muscovite leucogranite. This two-mica granite is light-grey to light-pink, medium-grained, and equigranular; biotite and muscovite together account for approximately 3 to 4 % of the rock.

The muscovite leucogranite is found at the core of the pluton and, petrochemically, is the most differentiated. The leucogranite is pink, medium-grained, and equigranular with muscovite accounting for approximately 2 to 3 % of the rock.

The QFP granitic dikes are the youngest phase and crosscut the biotite granite. The polymetallic sulfide veins and mineralized breccias are parallel to the contacts of the QFP dikes and the biotite granite, implying that the sulfide mineralization and the QFP dikes are cogenetic. The dykes are green to pink and are comprised of subhedral to euhedral quartz, K feldspar, plagioclase, and minor biotite phenocrysts in an aphanitic quartzofeldspathic matrix. The

phenocrysts range from 2 to 3 mm and constitute approximately 50% of the rock.

AGE OF EMPLACEMENT OF THE NORTH POLE STREAM GRANITIC SUITE

A sample of biotite granite from 500 meters south of the study area has yielded a U-Pb monazite age of 417 ± 1 Ma, which has been interpreted as the emplacement age of the NPSG (Bevier & Whalen 1990a). Recent CHIME dating of monazite from the biotite-muscovite granite has yielded two dates, an older age of 421 ± 6 Ma (n=8) from U-, Y-, and Ca-rich monazite inclusions in quartz, and a younger age of 399 ± 16 Ma (n=12) from accessory U-, Y-, and Ca-poor monazite associated with zircon, apatite, and xenotime aggregates. In addition to monazite age dating, Ar-Ar dating of primary muscovite in the muscovite leucogranite has yielded an age of 406.1 ± 1.87 Ma (Fig. 2).

The quartz-hosted monazite inclusions pre-date the muscovite leucogranite and are in the same range as Bevier & Whalen's (1990a) U-Pb monazite age

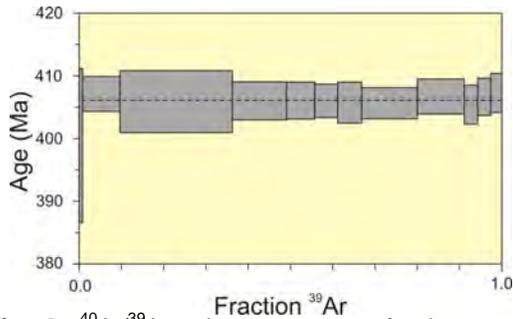


Fig. 2. $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra of primary muscovite from the muscovite leucogranite phase of the NPSG.

from the biotite granite, implying that the inclusions are inherited from an earlier phase in the crystallization history. The younger monazite age and the Ar-Ar age overlap, implying that the muscovite leucogranite crystallized much later than other parts of the pluton, i.e., during the terminal stages of crystallization of the NPSG.

GEOCHEMISTRY OF THE NORTH POLE STREAM GRANITIC SUITE

Existing petrochemical data for the NPSG suggest that it is a strongly peraluminous ($A/CNK = 1.3-1.4$), evolved 'I-Type to 'S-Type' granite, derived from a low degree of partial melting of supracrustal sedimentary rocks. With increasing magmatic fractionation, the NPSG shows increases and decreases in a number of major and trace elements (Table 1). Early monazite, xenotime, zircon, and apatite fractionation, due to the low solubility of these minerals in peraluminous low-temperature melts, resulted in strong Zr, Y, Hf, Th, and REE depletion. Increases in SiO_2 , Al_2O_3 , Na_2O , P_2O_5 , Rb, Nb, Ta, and U are due to fractional crystallization, and late-stage assimilation of the surrounding country rock by a melt derived from a very low degree of partial melting.

The two-mica granite and the muscovite leucogranite phases of the NPSG fall in the field of specialized granites on a Rb-Sr-Ba ternary variation diagram for granitic intrusions (Fig. 3). Based on the elevated uranium contents in these two phases, it is likely that the uranium at Long Lake was derived predominantly from them.

URANIUM MINERALIZATION

The two-mica granite and the muscovite leucogranite of the NPSG can be considered high-heat producing granites since they are abnormally enriched in the radioactive elements U (24 and 30 ppm, respectively), K (4.36 and 4.11 K_2O wt.%, respectively), and, to a lesser degree, Th (4 and 5 ppm, respectively). Fehn *et al.* (1978) showed that a granite of radius 17 km and a depth of 6.25 km, with a

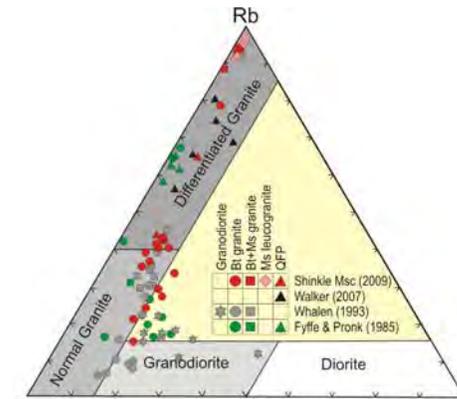


Fig. 3. Rb-Sr-Ba ternary variation diagram for rocks of the NPSG (after El Bouseily & El Sokkary 1975).

permeability of 0.5 mD and containing 15 ppm U, 57 ppm Th, and 4.0 wt.% K_2O could develop a U vein deposit of 10,000 tons in 2 Ma via heat generation from these radioactive elements and their daughter products producing local fluid convection of sufficient magnitude to develop hydrothermal uranium deposits long after cooling of the intrusion.

The uranium mineralization in the Long Lake area has been primarily intersected adjacent to a large northwesterly-trending wrench fault that underlies Long Lake. It is postulated that, post-crystallization of the NPSG, radiogenically-driven hydrothermal convection cells established in the NPSG and surrounding country rock drove oxidized meteoric fluids that leached uranium from the surrounding granites via the oxidation of uranium-rich phases such as uraninite and monazite. Post-oxidation, U was easily transported in

Table 1. Average concentration of selected elements for various phases of the NPSG

Element	Bt granite (n=16)	Bt-Ms granite (n=4)	Ms Leuco granite (n=5)	QFP granite (n=2)
SiO ₂ wt. %	75.12	77.12	76.68	75.87
Al ₂ O ₃ wt. %	16.01	16.21	17.14	17.77
TiO ₂ wt. %	0.25	0.06	0.04	0.16
Fe ₂ O ₃ T wt. %	2.01	0.97	0.93	1.73
MgO wt. %	0.72	0.13	0.12	0.64
CaO wt. %	1.28	0.69	0.39	0.32
Na ₂ O wt. %	3.35	3.91	4.28	0.75
K ₂ O wt. %	4.91	4.36	4.11	6.82
P ₂ O ₅ wt. %	0.09	0.25	0.28	0.04
Rb (ppm)	219	414	546	368
Sr (ppm)	75	5	8	47
Y (ppm)	25	5	4	27
Zr (ppm)	127	22	21	74
Nb (ppm)	19	37	50	25
Ba (ppm)	339	29	23	270
Hf (ppm)	3.6	1.0	1.2	2.2
Ta (ppm)	2.4	5.8	8.6	2.5
Th (ppm)	15	4	5	23
U (ppm)	9	24	30	13
ΣREE (ppm)	154.4	14.3	9.8	111.1

these circulating meteoric fluids and summarily deposited as pitchblende and hydrothermal uraninite after the hydrothermal fluids became reduced by sulfides formed along the wrench fault beneath Long Lake.

CONCLUSIONS

The muscovite leucogranite represents the upper part of a highly-fractionated magma chamber that underwent segregation into an upper phenocryst-poor residual liquid and a lower phenocryst-rich melt prior to its terminal stage of crystallization. A late, steeply-dipping

wrench fault crosscut and tilted the oldest granitic phase and brought the deep highly-evolved part of the NPSG into contact with the sulfide mineralization associated with the QFP dikes. High levels of heat generation from residual thermal energy and the decay of radiogenic elements and their daughter products established post-crystallization convection cells in the NPSG and surrounding country rock. Late-stage fluid circulation of oxygen-rich meteoric fluids along these convection cells resulted in leaching of uranium from the NPSG via the oxidation of uraninite and monazite, followed by deposition of pitchblende and hydrothermal uraninite along the wrench fault beneath Long Lake after the U-rich fluids were reduced by a fault-hosted sulfide mineralization.

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Diverse uranium mineralization in the Central Mineral Belt of Labrador, Canada: multiple styles and multiple questions

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ABSTRACT: Strong commodity prices in the last few years have led to a remarkable renaissance of uranium exploration in Labrador, focused in a complex and geologically diverse region known as the Central Mineral Belt (CMB). Potentially economic epigenetic U deposits are mostly hosted by supracrustal rocks of Paleoproterozoic and Mesoproterozoic age, and are difficult to place in the traditional pantheon of uranium deposit types. Recent exploration work implies that structural controls are important in some examples, but the relationships between mineralization and deformation remain far from clear. Geochronological data imply at least three periods of uranium mineralization between 1900 and 1650 Ma. It seems likely that the Labrador CMB represents a region in which U (and other lithophile elements) were repeatedly and sequentially concentrated by hydrothermal processes. The current exploration boom lends impetus for systematic research studies that may ultimately lead to refined genetic models that may be applicable elsewhere.

KEYWORDS: *Uranium, Labrador, Exploration, Epigenetic, Hydrothermal*

INTRODUCTION

Since 2005, Labrador has become an important area for uranium exploration in the Canadian Shield, second only to the Athabasca Basin of Saskatchewan. The unusual Michelin deposit is the largest undeveloped Canadian uranium deposit outside Saskatchewan, and one of the ten largest undeveloped uranium deposits in the world. The renewed exploration of the last few years led to new ideas and new discoveries, and views on the nature and genesis of mineralization are constantly changing. This contribution provides an historical overview, highlights the most significant exploration results, and discusses the known (or suspected) geological context of deposits, with emphasis on new geochronological results. The most recent overview of uranium mineralization in the CMB is provided by Sparkes & Kerr (2008).

GEOLOGICAL SETTING

Labrador (Fig. 1) contains sections of the Superior and North Atlantic Archean cratons, separated by a wide tract of Paleoproterozoic rocks assigned to the

Churchill Province. These are all bounded to the south by Paleoproterozoic and Mesoproterozoic orogenic belts of the Makkovik and Grenville Provinces. Uranium occurs in many parts of the territory, in a wide range of environments, but the most important examples are all located within the Central Mineral Belt (CMB), a loosely-defined area at the intersection of the Nain, Churchill, Makkovik and Grenville provinces (Fig. 1).

The CMB is defined mostly in terms of several Paleoproterozoic and Mesoproterozoic supracrustal sequences containing low-grade sedimentary and volcanic rocks, but it also includes voluminous plutonic suites and older (largely Archean) basement rocks. The CMB has a very complex evolutionary history and the timing of some important deformational and magmatic events lacks precise definition. Figure 2 provides a general summary of its geology and the setting of contained U mineralization.

The oldest supracrustal rocks are mafic volcanics and sedimentary rocks of the 2100-2000 Ma Moran Lake and Post Hill groups, believed to have formed as a

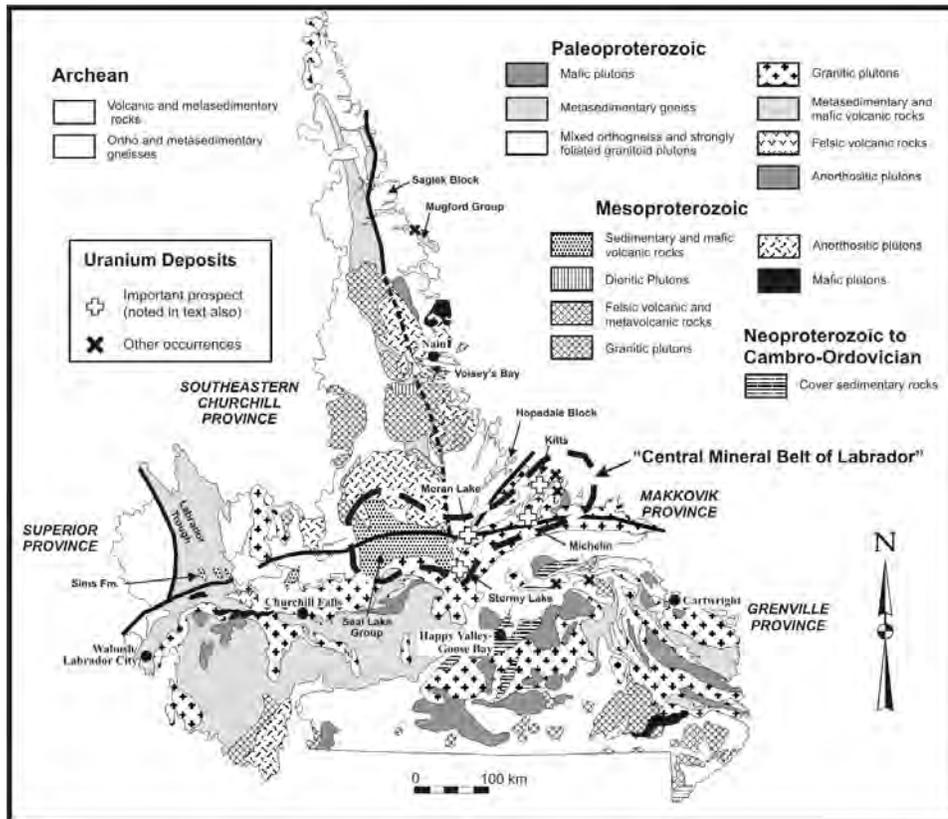


Fig. 1. The Central Mineral Belt of Labrador and its principal uranium occurrences.

passive margin sequence following rifting. These were variably deformed, and intruded by granitoid rocks prior to the deposition of the 1880 Ma – 1850 Ma Aillik Group, which is dominated by felsic volcanic and volcanoclastic rocks. Strong deformation during the main phase of the ca. 1800 Ma Makkovikian Orogeny affected all of the above, and this event also generated large volumes of syn- and post-tectonic granites. More local granitoid magmatism occurred ca. 1720 Ma. Voluminous magmatism occurred throughout the CMB at ca. 1650 Ma, forming the Trans-Labrador Batholith (TLB). The sedimentary and volcanic rocks of the Bruce River Group unconformably overlie the older Moran Lake Group, and their ca. 1650 Ma age implies that they are in part a carapace to the TLB. The youngest supracrustal sequences in the CMB are the ca. 1330 Ma alkaline volcanic rocks of the Letitia

Lake Group, and the overlying Seal Lake Group (ca. 1270 Ma), which includes varied (terrestrial) sedimentary rocks and mafic volcanics. The Seal Lake Group is well-known for its numerous Cu occurrences, and the Letitia Lake Group contains some rare-metal (Zr, Be, REE) occurrences. The southwestern portion of the CMB lies within the Grenville Province, and was affected by distal deformation related to the 1000-900 Ma Grenvillian orogenic event.

URANIUM MINERALIZATION

Uranium occurs throughout the CMB, but the most significant deposits are hosted by supracrustal sequences, notably in the Post Hill, Aillik and Bruce River Groups (Fig. 2).

In the Post Hill Group, the Kitts Deposit (~0.2 Mt at 0.7% U₃O₈) and related zones are hosted by graphitic to ferruginous, pelitic metasedimentary rocks. The same

unit locally hosts syngenetic (but barren) massive sulphides. Early models viewed the U as a syngenetic component of the protolith shales (Gandhi 1978), but subsequent work suggests that it is of epigenetic hydrothermal origin (Evans 1980). Reduction of fluids by carbon and sulphides provided a quasi-stratigraphic control on U precipitation. The relatively ductile host rocks lie within an important shear zone for which the timing of deformation relative to the mineralization is less clear. U-Pb ages from cross-cutting dykes, interpreted to be post-mineralization, indicate that uranium was deposited prior to ca. 1880 Ma, indicating that Kitts formed in a separate event from the ore-forming episode at Michelin.

In the Aillik Group, the most important uranium mineralization is hosted by felsic metavolcanic rocks. The largest deposit is Michelin, in which low grades (0.1 to 0.2% U₃O₈) are compensated by large size (44.5 Mt), continuity and structural predictability. The deposit as a whole is conformable with compositional layering, and was traditionally thought of as broadly syngenetic (Evans 1980; Gower *et al.* 1982). The mineralized zone has a remarkably consistent dip and plunge, and is now recognized to be part of an important regional shear zone. This has led to alternative models in which uranium is suggested to have been introduced syntectonically, connected with the development of the shear zone. However, the relationships between mineralization and deformation remain unclear.

Alteration at Michelin is dominated by intense soda metasomatism and potash depletion, coupled with locally intense hematization; much of the mineralization consists of fine-grained uraninite within sodium-rich silicates such as aegirine and arfvedsonite. The recently discovered Jacques Lake deposit, which is an important resource in its own right (about 17 million pounds U₃O₈), has many similarities to Michelin, although its metavolcanic host rocks are compositionally distinct. The age of the uranium mineralization in these deposits is

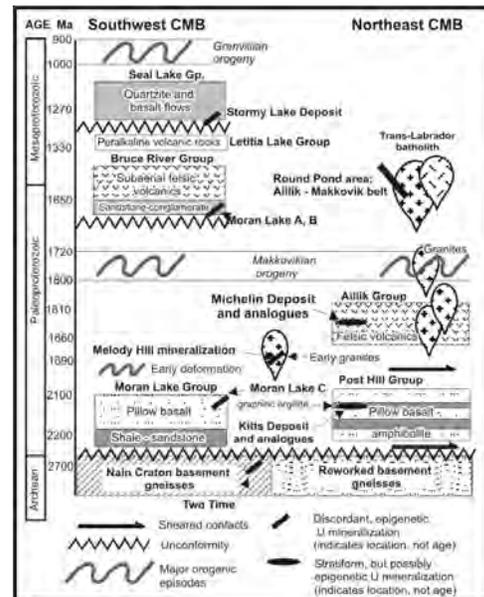


Fig.2. Simplified stratigraphic chart showing the settings of uranium deposits in the Central Mineral Belt of Labrador.

constrained by the age of the host rocks (ca. 1860 Ma) and the age of cross-cutting quartz-feldspar porphyry dykes (ca. 1800 Ma). Many aspects of the Michelin deposit are reminiscent of so-called “albitite” or “metasomatite” or “episyenite” deposits described from Europe, although it is considerably larger than any of these possible analogues.

Uranium deposits in the Moran Lake area present a different set of problems, in that they are hosted by two sequences differing in age by at least 150 Ma. The most widespread mineralization is hosted by mafic metavolcanic rocks of the Moran Lake Group, where it is associated with the development of iron carbonate-rich breccias and strong hematitic alteration. Unlike Kitts and Michelin, which essentially contain uranium alone, mineralization at Moran Lake contains associated Cu, V and Ag. The Fe-enrichment, coupled with the associated metals, invites comparison with IOCG-type settings, although these Labrador examples are uranium-rich rather than copper-rich. However, uranium mineralization is also present in closely

adjacent terrestrial sedimentary rocks of the ca. 1650 Ma Bruce River Group, which sits structurally below the older Moran Lake Group. This style of mineralization, hosted by sandstones and conglomerates, appears to be associated with redox boundaries in the sedimentary rocks, and it may have affinities with much younger sandstone-type uranium deposits. The relationships between these closely adjacent styles of uranium mineralization remain unknown, as do their absolute and relative ages; however, mineralization in the Bruce River Group must be younger than 1650 Ma. Uranium is also hosted by similar iron-rich breccia zones developed in Late Archean granodiorites, although these may be much younger than their host rocks. This deposit, known as Two Time, is one of the few truly new discoveries from the second wave of exploration in Labrador.

In addition to the examples listed above, uranium mineralization occurs in several other geological settings in and around the CMB, including within granitoid plutonic rocks and as possible syngenetic mineralization in felsic volcanic rocks of both the Aillik and Bruce River groups. Pegmatite-hosted uranium mineralization is also known in deeper-level reworked Archean basement terranes.

CONCLUSIONS

Uranium mineralization in the CMB is characterized by a diversity of style and host rocks, and it is naïve to suppose that a single genetic model can explain all its variations. Like many metallogenic provinces in which incompatible (or "lithophile") elements are important, the CMB of Labrador seems to represent an area in which U has been repeatedly and perhaps sequentially concentrated, and

then locally redistributed. The new geochronological data from the region indicate that there are at least three, and possibly four, periods of uranium deposition between about 1900 Ma and 1650 Ma. Much remains to be learnt about the timing and genetic origins of individual deposits, and the possibly connections between different styles of mineralization. The current exploration boom has reawakened interest in this area and its numerous metallogenic questions, and it is hoped that a growing research database from corporate data, university research projects and government geoscience will clarify some of these problems in the years to come.

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Harvey: a volcanic-hosted Uranium occurrence at the edge of the Maritimes Basin

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ABSTRACT: The late Devonian-early Carboniferous volcanic units of the Harvey Group west of Fredericton have received less attention than similar volcanic areas regarding their volcanic characteristics and potential for metallic mineral occurrences. Previous research and mineral exploration activity between the 1950s and 1980s typically focused on the search for Uranium mineralization and improved knowledge of the local volcanic stratigraphy.

Tripple Uranium Resources Inc. commissioned an airborne geophysical survey of the Harvey mineral property (including the Manners-Sutton occurrence) in early 2007 and identified several radiometric targets and geological structures, which were checked during the summer of 2007. Mapping during fieldwork led to a better understanding of the local geology and resulted in the identification of several substantially anomalous radiometric locations. These locations were further tested by commissioning a diamond drilling program during the fall of 2007.

Study of the drill-core, bore-hole geophysical data and IPC-MS multi-element geochemical assaying were combined with the airborne geophysics and historical work to produce a better understanding of the local geology and a model that would explain the various episodes of hydrothermal alteration observed at surface and on drill-core. The results of the study indicate that the geology in the drilling area is stratigraphically consistent yet characterized by multiple and overlapping hydrothermal alteration events.

KEYWORDS: *Harvey Group, Uranium, ignimbrite, volcanic centre, hydrothermal fluid*

INTRODUCTION

The wedge-shaped southwestern border of the Carboniferous age Maritimes Basin near Fredericton is rimmed to the south and to the west by late Devonian (and early Carboniferous?) volcanic units of the Harvey and Piskahegan groups. The southern edge volcanic and sedimentary rocks of the Piskahegan Group associated to the Mount Pleasant Caldera have been the subject of several studies and host the well known W-Mo and Sn-In Mount Pleasant Mine. However, less attention has been paid to the study of the predominantly volcanic rocks of the Harvey Group southwest of Fredericton, which may have a similar potential to Piskahegan Group to host economic mineral deposits. The Harvey Group hosts the Manners Sutton, York Mills, Harvey Station-Cherry Hill and Harvey Mountain-Acton mineral occurrences.

Previous exploration projects that took place between the 1950s and 1970s were

attracted by radon anomalies and anomalous Uranium concentrations in groundwater. These early projects identified hydrothermal alteration features in volcanic rocks, but were not thorough enough to identify the full potential of the local mineral occurrences and indicated that the presumed but as-of-then undiscovered Uranium mineralization style might be of the unconformity- or vein-type mineralization styles. Recent magnetic and radiometric airborne survey data combined with drill-core and geochemical analysis indicate that a more descriptive mineralization model is needed.

A magnetic and radiometric aerial survey was commissioned by Tripple Uranium Resources Inc. in early 2007 to gain a better understanding of the Harvey Group. Analysis and interpretation of the aerial survey results identified structural features and strong radiometric anomalies, which were prospected and mapped through the summer of 2007 and

resulted in the identification of several drill targets near the Manners Sutton mineral occurrence. During the fall of 2007 ten diamond drill-holes recovered 2,881m of drill-core, from which several hundred rock samples were taken and assayed by ICP-MS for major oxides and trace elements in order to study the rocks of the Harvey Group.

Analysis of drill-core combined with bore-hole logging and geochemical assay results point to the presence of several hydrothermal events, and that local stratigraphy of the Harvey Group consists of extensive laterally contiguous units which can be divided into 1) an upper assemblage of four ignimbritic and two volcanoclastic units and 2) a lower assemblage of mudstone with minor intermediate composition flow units. Assayed Uranium concentrations and radiometric bore-hole data indicate that Uranium is widely distributed in all units of the upper assemblage.

GEOLOGICAL SETTING

Regional Geology

The geology of the area consists of rocks from three time periods (Fig. 1): Silurian (Kingsclear Group), Devonian (Harvey Group) and Carboniferous (Mabou Group).

Kingsclear Group

This Silurian Group (418-424 Ma) has two formations associated with the Harvey area, Burtt's Corner Formation and Flume Ridge formation, both consisting predominantly of deep marine facies. The Burtt's Corner Formation is characterized by grey lithic wacke interstratified with dark grey, locally graptolite-bearing, siltstone and shale. The Flume Ridge formation consists of calcareous-argillaceous sandstone, siltstone, and shale.

Harvey Group

The Devonian (383-355 Ma) Harvey Group is approximately 200 metres thick and forms a narrow belt 16 km long by about 2 km wide (Beaudin *et al.* 1980). The Harvey Group consists primarily of

felsic volcanic rocks thrust over red conglomerate, sandstone and siltstone of the Early Carboniferous Shin Formation to the west and is unconformably overlain by the same rocks to the east (St. Peter 2000). The Harvey Group unconformably overlies the Late Silurian Kingsclear Group.

The Harvey Group consists of three units: Harvey Mountain, Cherry Mountain, and York Mills Formations. The upper Harvey Mountain formation consists of felsic volcanic rocks, typically flow-banded massive rhyolitic lava accompanied by ash-fall tuff. Rocks of the middle Cherry Mountain formation are characterized by the predominance of ash-fall and ash-flow tuffs at the top and volcanogenic sedimentary rocks at the base. The lower York Mills formation is a sequence of interbedded clastic, volcanogenic and minor volcanic rocks, that latter consisting of felsic volcanic-clast conglomerate, volcanogenic sandstone, siltstone and shale, felsic crystal lithic lapilli tuff and flow-banded rhyolite.

Mabou Group

The Shin Formation of the Mabou Group is Early Carboniferous in age and shows a fining-upward sequence of pebble to boulder conglomerate. The Minto Formation of the Pictou Group is from the Late Carboniferous and contains cross- and horizontal-bedded feldspathic and quartzose arenite and pebble arenite.

Local Geology

The earliest detailed description of the Harvey Group was by Kuan (1970), who proposed a twofold subdivision. Later descriptions by van de Poll (1972) and Pajari (1973) helped Beaudin *et al.* (1980) redefine the stratigraphic sequence in light of detailed mapping that was undertaken by Seru Nucleaire Limited as part of a Uranium exploration program on the Manners Sutton claims. Seru Nucleaire proposed that the Harvey Formation should be elevated to a group and suggested that it could be divided into three formations.

Payette & Martin (1986a, 1986b) described the chemistry and mineralogy of the volcanic rocks and of melt inclusions within the quartz-feldspar porphyry. Fyffe & Barr (1986) gave one chemical analysis for the Harvey volcanics in their comparative study of Carboniferous volcanic rocks in New Brunswick, and indicated that the analyzed Harvey sample is a subalkalic rhyolite of calc-alkalic affinity.

Diamond drilling of the Harvey area by Tripple Uranium Resources Inc. indicates that the local stratigraphy is characterized by extensive laterally continuous units, which can be divided into a 250 to 300 metres thick 'upper assemblage' of stacked ignimbritic and volcanoclastic units, and a 'lower assemblage' with approximately 130 metres of recovered core but unknown thickness (base not observed), consisting of red and grey mudstone with lenses of intermediate extrusive volcanic rocks. Identification and discrimination of distinct ignimbritic units near the top of the 'upper assemblage' was challenging due to sub-surface

weathering and also as a result of multiple, irregularly distributed episodes of hydrothermal alteration, including fluoridization, argillization, hematization, carbonatization and silicification. Positive field identification of ignimbritic units was aided by relatively consistent stratigraphy, the presence of distinct 'marker' lithological units and by analysis of the down-hole conductivity and background gamma radiation data from each borehole.

The ignimbrite units of the 'upper assemblage' are texturally very similar and display blocky textures and glass shards, indicating quick cooling at the basal depositional contact and at the exposed top, with a warmer 'core' that contains characteristic flattened pumice fragments. The base of one of the ignimbrite units is characterized by a distinct quenching texture with very well formed spherulitic nodules up to 10cm wide.

The alteration sequence in the ignimbrite units is assumed to have started with an early introduction of

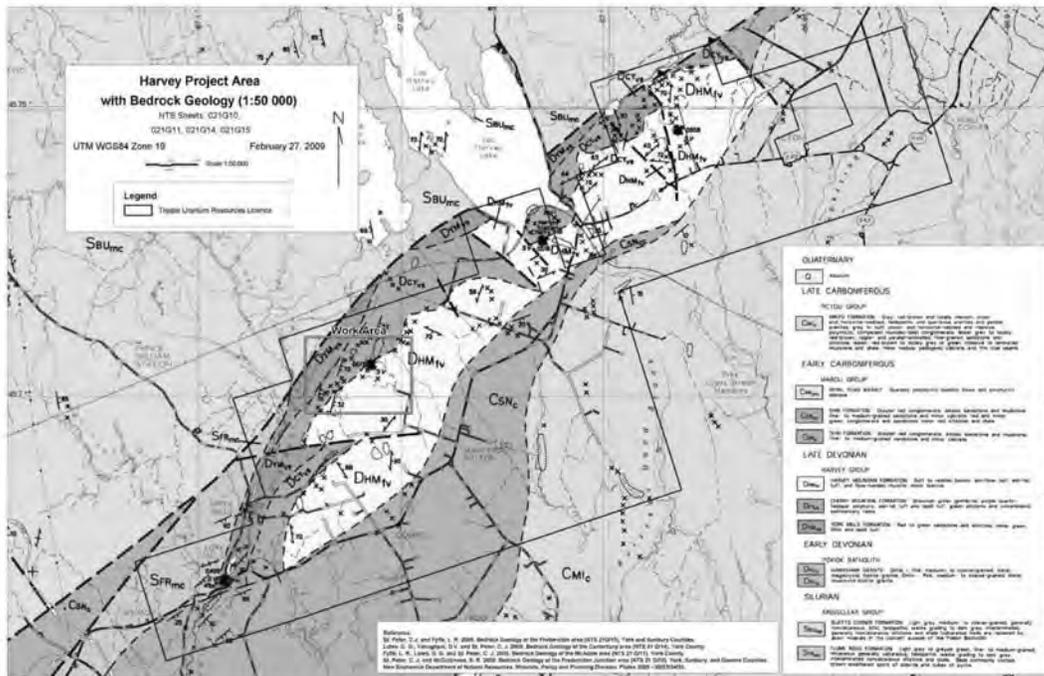


Fig. 1. Geological setting of the Harvey area.

fluorine-rich hydrothermal fluid that created the fluorite crystals, later altered to clay in places by subsequent, apparently multiple argillization +/- hematization +/- silicification events, and a late distinct siliceous alteration, which likely produced the widespread glassy appearance overprinting fluorite, clay and hematite observed in most of the drill-core. Strong localized silicification of the ignimbrite may be a result of interaction between meteoric/ground-water fluid and cooling of the pyroclastic unit.

The 'lower assemblage' consists predominantly of red mudstone, with narrow sections (5-20 cm) of reduction spots and entire sections (0.5 to 2 m) of grey reduced and pyritic mudstone becoming more common towards the base. Narrow (0.5 to 5 m) intermediate extrusive volcanic flows become more common towards the base of this assemblage, and display basal textures indicating that moisture and mudstone rip-clasts were acquired into the flow and that heat was supplied to the underlying mudstones, which produced narrow (< 5 cm) contact metamorphism bands of recrystallized mudstone.

Several sections of economic Uranium mineralization (>0.1% U₃O₈) were identified in drill-core. These appear to be associated to discrete stratigraphic horizons and to fault zones, of which the latter are strongly suspected to have acted as conduits of hydrothermal fluids.

CONCLUSIONS

Diamond-drilling of the Manners Sutton occurrence has substantially increased knowledge of the Harvey Formation stratigraphy and identified several distinct ignimbritic and volcanoclastic units. Analysis of drill-core and geochemical analysis of samples have supplied evidence for the presence of multiple hydrothermal alteration episodes. Ongoing analysis of data from geochemical assays and the airborne geophysical surveys will

help produce a hydrothermal alteration model and a better understanding on local Uranium mineralization.

ACKNOWLEDGEMENTS

We thank Steve McCutcheon and Malcolm McLeod of the New Brunswick Department of Natural Resources for their comments and suggestions, and Kathryn MacFarlane of Tripple Uranium Resources Inc. for GIS assistance.

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Deep-penetrating geochemical exploration for hidden sandstone-type uranium deposits in the Turpan-Hami basin, northwestern China

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ABSTRACT: The Turpan-Hami basin, covering an area of approximately 50 000 km² in northwestern China, has very good potential for sandstone-type uranium deposits. Recently, a sandstone-type uranium deposit was discovered at a depth of 300 m hosted in a Jurassic sequence composed of sandstone, mudstone, and coal beds. Conventional geochemical methods, based on coarse soil fraction sampling to avoid windblown sand dilution, are not effective to indicate the hidden deposits due to overburden concealing prospective bedrock sequences. A deep-penetration geochemical procedure, based on fine fraction sampling and selective partial leaching is effective to give signals from the hidden deposits and wide-spaced sampling of fine-fraction soils can provide a cost-effective powerful tool for delineation of regional targets of sandstone-type uranium in the basin. A wide-spaced sampling survey at a sampling density of approximately 1 / 100 km² was carried out throughout the whole basin. Samples were processed for analysis of 30 elements by ICP-MS. Three large geochemical anomalies have been delineated across the whole basin. One of the anomalies is consistent with the explored uranium deposit, and a new big deposit has been discovered by a follow-up exploration program at one of the delineated geochemical anomalies.

KEYWORDS: *deep-penetration, geochemistry, exploration, sandstone-type, uranium deposits*

INTRODUCTION

Traditional exploration for sandstone-type uranium deposits has centered on genetic models and radiometric methods (Morse 1969; Harshman 1970; Rubin 1970). However, these methods have become prohibitive for sandstone-type uranium deposits hidden at a depth of hundreds of metres (Riese *et al.* 1978). Radioactivity detectors are ineffective in regions where there is a relatively thin inactive overburden (Bowie *et al.* 1970).

Conventional regional soil geochemical surveys based on coarse fractions of soils (>20 mesh) to avoid windblown sand dilution for elemental contents failed to delineate uranium geochemical anomalies for blind sandstone-type uranium deposits in desert basin terrains in China.

The authors have set out to attempt to use deep-penetrating geochemical methods, based on fine-grained fraction sampling and selective leaching in exploration for hidden sandstone-type

uranium deposits and to delineate potential targets in large unexplored basins.

GEOLOGICAL SETTING

The Turpan-Hami basin covers an area of approximately 50 000 km² in Xinjiang, northwestern China. The west part of the basin, located in Turpan, is the lowest area of China mainland, with an elevation of -154 m. The region is extremely arid with the average annual rainfall of less than 15 mm.

The region is substantially covered by regolith sediments, which conceal prospective bedrock sequences. The regolith sediments include windblown sand, alluvial gravels, and caliche horizons. Commonly, the vertical profile of the regolith sediments consists of surface lag or loosely windblown sand underlain by weakly cemented sands and dense caliche-cemented sediments with gypsum.

Miocene sandstone overlying Jurassic sedimentary rocks occur in the Turpan-Hami Basin. Sandstone-type uranium

Table 1. Concentrations and percentage of various uranium forms in regolith over Shihongtan Uranium deposit, Xinjiang

Samples	contents (ppb)					Percentage(%)			
	WEM	AEM	OCM	FMM	T	WEM/T	AEM/T	CM/T	FMM/T
SHT34P0	53.8	954.6	381.3	35.5	2392.5	2.3	39.9	15.9	1.5
SHT34P1	26.7	407.9	228.4	26.4	1712.2	1.6	23.8	13.3	1.5
SHT32P0	57.8	976.9	378.2	47.7	2444.3	2.4	40.0	15.5	1.9
SHT32P1	22.2	331.7	203.4	28.3	1856.8	1.2	17.9	10.9	1.5
Average	40.1	667.8	297.8	34.5	2101.5	1.9	30.4	13.9	1.6

WEM-water extractable U, AEM-adsorbed and exchangeable U, OCM-U occluded in carbonate, FMM-U adsorbed in coatings of Fe-Mn oxides (FMM), T-total U.

deposits are hosted in the Jurassic sandstone rocks.

SAMPLING AND CHEMICAL ANALYSIS

Samples were collected from the weakly cemented sandy clay-rich horizon of soils at a depth of 15-30cm and sieved to -120 mesh in the field.

The samples were ground to a grain size less than 200 mesh (74 μ m) by using high-alumina ceramic or agate mills. The samples were processed for total analysis by 4 acids and selective leaching of water extractable metals (WEM), adsorbed and exchangeable metals (AEM) in clays, occluded metals in carbonate (OCM), and adsorbed metals in coatings of Fe-Mn oxides (FMM) (Wang 1998). Elements are determined by ICP-MS.

RESULTS

Variations of uranium over the deposit

Table 1 shows that Uranium is largely present as adsorbed and exchangeable forms in clays, which make up average 30.4% of the total contents in the soils over a known uranium deposit, Xinjiang.

Figure 1 shows that concentrations of U and associated elements such as Mo, La, Ce, Au, and Th tend to increase in fine fraction of soils over the uranium deposit. This is due to the fact that U complexes $[UO_2]^{2+}$ are easily adsorbed by clays.

Figure 2 shows that U and Mo in -120 mesh fraction of soils give good indication to uranium deposit at the depth of 300m.

Fine fraction samples can give very good indications to concealed uranium deposits.

Regional geochemical survey

Wide-spaced sampling was carried out in an area of approximately 150 000 km² at density of one sample per 100 km² (Wang *et al.* 2007). Soil samples were collected from the weakly cemented sandy horizon at a depth of 20-30cm. The soil samples were subjected to total analysis and selective leaching of mobile metals. Elements were determined by ICP-MS.

Three geochemical provinces of U and Mo were delineated in the Turpan-Hami Basin (Fig. 3). The westernmost one contains the Shihongtan large sandstone-type uranium deposit. Sandstone-type uranium deposits are characteristic by coexisting U and Mo anomalies. The east one at Hami area is was selected for follow-up exploration and a big deposit was found by drilling program.

CONCLUSIONS

(1) The uranium tends to concentrate in the fine fractions of soils in which clays can adsorb uranium complex compounds $[UO_2]^{2+}$ transported from uranium deposits.

(2) Sandstone-type uranium deposits are characteristic by coexisting uranium and molybdenum anomalies.

(3) Sampling of fine-grained fractions of soils (-120 mesh) from the cemented clay-rich horizon at a depth of 15-30 cm are

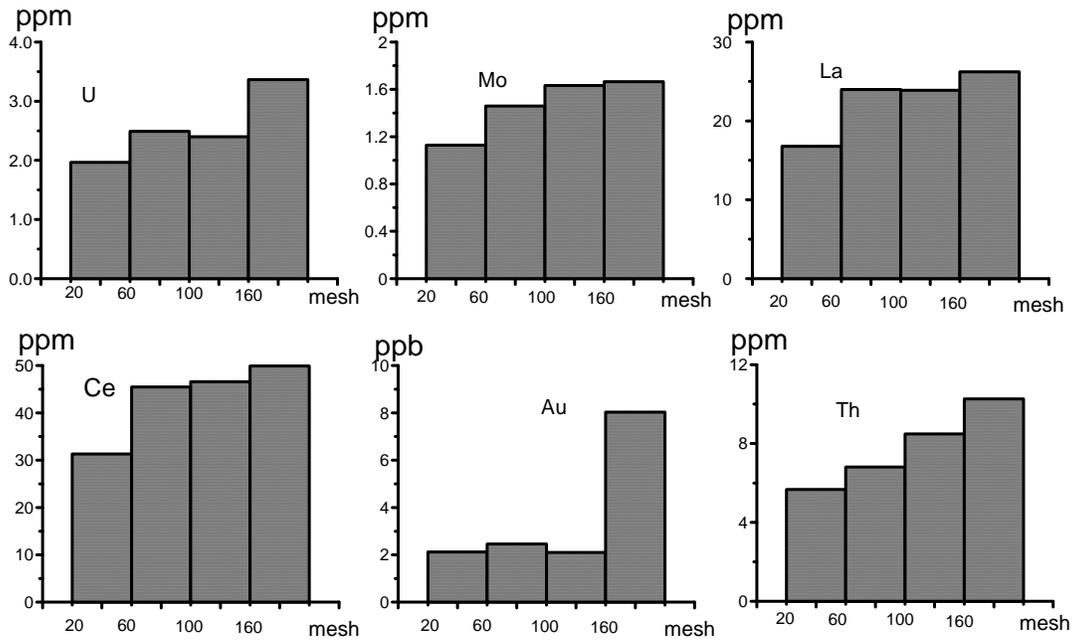


Fig. 1. Bar graphs showing the concentrations of various elements in different size fractions of soil over the Shihongtan sandstone-type uranium deposit.

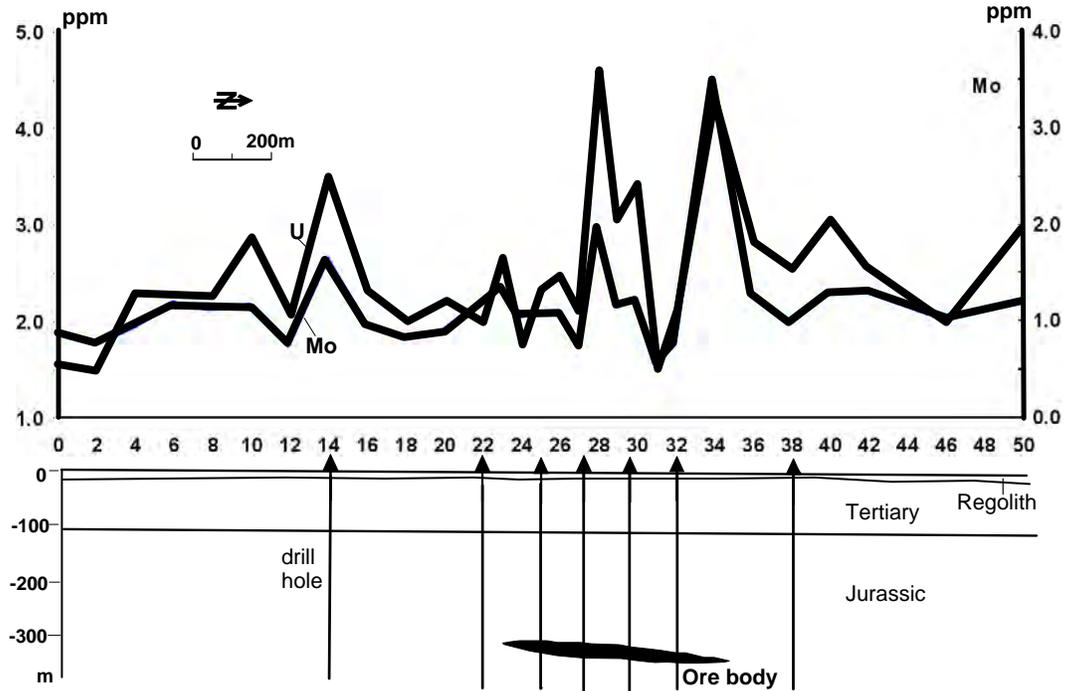


Fig. 2. Uranium and molybdenum anomalies over the Shihongtan uranium deposit.

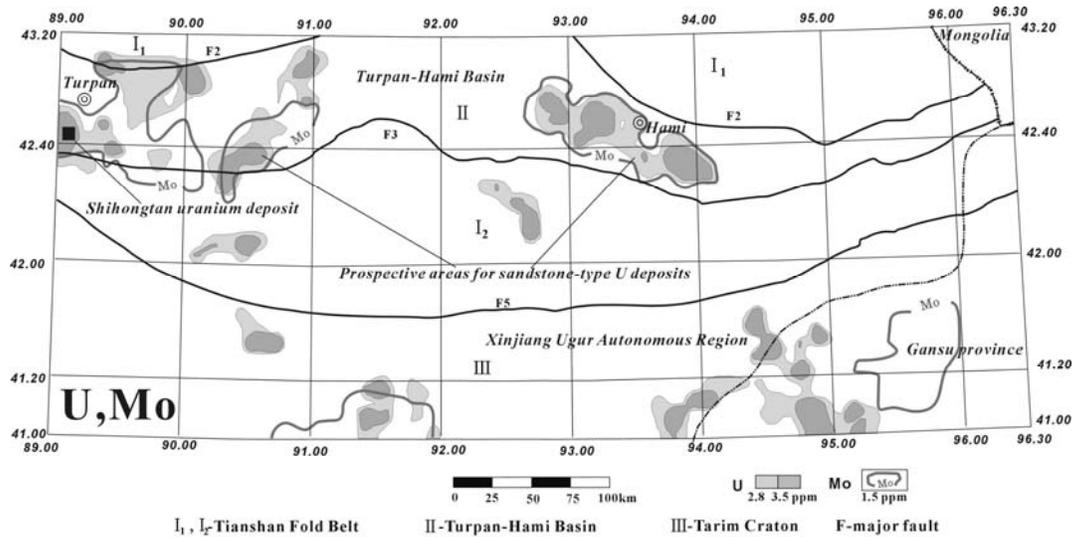


Fig. 3. Uranium geochemical provinces delineated by wide-spaced sampling.

effective both in local and regional exploration for sandstone-type uranium deposits in desert basins.

ACKNOWLEDGEMENTS

Thanks are given to the Ministry of Science and Technology of the People's Republic of China and the China Geological Survey for the financial support (projects Sinoprobe04, 2007AA06Z133, and 2007CB411406).

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Vectoring potential of multi-element chemistry in unconformity-associated uranium deposits: major and trace element signatures of the McArthur River Uranium Deposit, Saskatchewan, Canada.

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ABSTRACT: McArthur River, the world's largest high-grade uranium deposit discovered to date, is located in the Athabasca Basin, Saskatchewan, Canada. Multidisciplinary investigations of the McArthur River deposit have identified key features of the unconformity uranium deposit model from which ongoing exploration has benefitted. Historically, geochemical investigations of this area has been typically restricted in the past to drill core analysis of a suite of five "pathfinder" elements (U, Pb, Ni, Cu, and B), and to the use of short-wave infrared identification of dominant clay species. These investigations have identified broad anomalous uranium halos and refined the known distribution of clay species around this deposit. However, the identification of zones of economic mineralization within these relatively large halos remains problematic. Modern multielement geochemical analysis methods have been recently applied in an attempt to further refine our geochemical models of these deposits and improve our targeting of economic mineralization. Exploration-relevant results of this study have included the identification of 1) multielement signatures associated with mineralization and alteration and 2) the relative spatial distribution of these elements for application in exploration for unconformity-associated uranium deposits.

KEYWORDS: *uranium, geochemistry, unconformity-associated, Athabasca Basin.*

INTRODUCTION

The McArthur River Uranium Deposit, located in northern Saskatchewan, Canada, is the largest high-grade uranium deposit found to date, and is arguably the most valuable deposit of any type or commodity in the world. Exploration for unconformity-associated deposits like McArthur River has utilized geological, geophysical, and geochemical models and techniques to assist with targeting prospective areas. Multielement geochemistry techniques have been recently adopted in the McArthur River area, and have displayed potential for refining the exploration model for unconformity-associated uranium deposits.

GEOLOGICAL SETTING

The McArthur River Uranium Deposit lies in the eastern portion of the Athabasca Basin and within the Churchill Structural Province of the Canadian Shield. The deposit straddles the unconformity between the quartz arenite - rich Late Paleoproterozoic Athabasca Group and

Early Paleoproterozoic metasedimentary/ Archean granitoid basement rocks of the Wollaston Domain. The deposit is also spatially associated with a post-Athabasca Group reverse fault (known as the P2 fault), a feature that occurs within and sub-parallel to a group of graphite-bearing Early Paleoproterozoic metasedimentary units.

The deposit currently consists of eight significant zones of mineralization occurring at vertical depths ranging from 500 to 600 metres. As of December 31, 2007, the deposit contains publically quoted uranium proven (486,500 metric tonnes at 17.38%) and probable reserves (280,000 metric tonnes at 26.33%) totalling 766,500 metric tonnes of ore at an average grade of 20.66% U₃O₈ (Cameco 2008 Business Review).

CURRENT EXPLORATION

METHODOLOGIES

Current exploration for unconformity-associated uranium deposits in the Athabasca Basin rely upon the integration

and comparison of geological, geophysical, and geochemical information relative to the unconformity-associated exploration model (e.g., Jefferson *et al.* 2007).

Key components of the model used in exploration for these deposits include: 1) the presence of an angular unconformity between a Paleoproterozoic sandstone basin and older graphite-bearing metasedimentary and plutonic basement rocks, 2) post-Athabasca Group structural disruption, and 3) the presence of mineralization and mineralization-related hydrothermal alteration.

Due to a lack of outcrop, an abundance of transported overburden, and significant target depths, past exploration has relied heavily on diamond drilling to test electromagnetic conductors. These EM conductors are presumed to have been caused by faulted graphitic basement units at and beneath the Athabasca Group-Basement unconformity. Once the EM conductors have been intersected by drilling, follow-up geological evaluation, clay alteration speciation, and trace-element chemistry of drill core is typically utilized to assist with vectoring exploration towards the location of potential mineralization.

Clay speciation analysis, dominated by the use of short-wave infrared techniques, highlights variations in the clay alteration associated with these deposits. The presence of a key species, such as illite, may be locally significant, but absolute amounts of each clay relative to alteration intensity are typically unattainable from these types of analyses.

The historic use of trace-element geochemistry around the McArthur River Uranium Deposit has primarily focussed on a limited suite of elements, including uranium, lead, nickel, copper, and boron. At McArthur River, uranium is distributed around the main deposit to significant distances (100's of meters) in the overlying Athabasca Group (McGill *et al.* 1993), yet variations in the uranium content of this halo is typically restricted to 1-3 parts per million with little spatial variation, restricting one's ability to vector

into the deposit. Lead is a product of the radioactive decay of uranium, and typically displays a similar distribution to that of uranium. Nickel and copper are common components of unconformity-associated uranium deposits, but their distribution is usually restricted proximally to the main deposits. Boron contents confirm the presence of dravite, an alteration phase that often shows a general spatial association with uranium deposits.

Multielement Geochemical Modelling

In order to refine the geochemical model for unconformity-uranium deposits, whole-rock multielement geochemistry was determined in drill holes from the north end of the McArthur River Uranium Deposit. These data were used to assist with refining the geochemical signatures of mineralization and alteration associated with the deposit, and to define the spatial distribution of these features to assist with deposit vectoring. As a result of this review, several basic geochemical associations related to uranium through a series of geochemical processes have been identified and spatially modelled.

Reduction-oxidation processes, which are the dominant control for uranium mobility and deposit formation, are also responsible for elevated molybdenum and vanadium contents observed associated with mineralization.

Radioactive decay of the two main isotopes of uranium produces significant contents of the lead isotopes ²⁰⁶Pb and ²⁰⁷Pb. The total amount and age of uranium combined with the differences in decay rate of the two uranium isotopes leads to the production of distinct ²⁰⁷Pb/²⁰⁶Pb lead isotope ratios uniquely related to mineralization (e.g., Gulson 1986; Holk *et al.* 2003).

Several elements from the multielement suite are associated with alteration and clay chemistry. Due to the relative cleanliness of the Athabasca Group sandstones, anomalous contents of aluminium, magnesium, potassium, lithium, and boron, along with loss-on-ignition, provide measures of the amount and type of alteration present. These data

can also assist with refining our understanding of the spectral clay results in these areas.

The relative spatial distribution of the mineralization- and alteration-related geochemical signatures can be useful in vectoring toward uranium mineralization (Fig. 1).

A distal uranium halo (1 ppm) extends over 500 metres from the deposit towards surface, indicating the presence of mineralization. Significant changes in the uranium content are not observed until within approximately one hundred metres of mineralization, where partial digest uranium values begin to increase significantly.

Anomalous values of lithium, ²⁰⁷Pb/²⁰⁶Pb, and molybdenum (and other process-related elements) are observed within the distal uranium halo, and appear to represent intermediate and perhaps proximal halos enveloping mineralization. Local enrichments are also observed associated with structural features distal or intermediate to the main zone of mineralization, the trend of which may be useful for vectoring into the deposit.

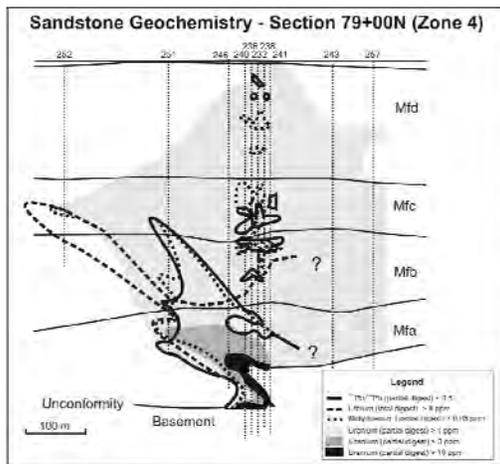


Fig. 1. Cross-sectional distribution of uranium, molybdenum, lithium, and ²⁰⁷Pb/²⁰⁶Pb lead isotope ratios around mineralization at Zone 4, P2 North, McArthur River.

CONCLUSIONS

Exploration for unconformity-associated uranium deposits is dependent upon the effective integration of geological,

geophysical, and geochemical information as well as exploration models. The McArthur River Uranium Deposit is one of the most economically significant examples of an unconformity-associated uranium deposit, and is an ideal model for the review of the multielement chemistry associated with such a deposit. Several major and trace element signatures associated with alteration and mineralization have been identified (e.g., Li, Mo, ²⁰⁷Pb/²⁰⁶Pb), and the relative distribution of these signatures may be integrated with geological and geophysical information to highlight the presence and location of uranium mineralization in unconformity-associated uranium deposits.

ACKNOWLEDGEMENTS

Cameco Corporation, AREVA Resources Canada, and UEM Inc. are gratefully acknowledged for their support of this work and their permission to present it here. Numerous members of the Cameco Exploration team contributed to the collective product, and the staff of the McArthur River Exploration Team are especially thanked for their logistical assistance in the collection of the material analyzed.

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Broad-based physicochemical paragenetic aspects of primordial uranium deposits of endogenic origin

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ABSTRACT: Many U deposits have an endogenic origin connected with magmas of a very wide in composition from nepheline-normative and carbonatite to different granitoid types. We concluded that all U-bearing granitoids belong to alkali magmatic types whose transmagnetic fluids (Korzhinskii's term) participate in formation of U-containing and proper U ore deposits. These fluids extract U from crustal and terrigenous rocks by oxidation into transportable complexes. At the same time crustal rocks fuse giving rise granitic magmas of alkalic affinity specialized in both U and rare metals. The generally oxidizing nature of transmagnetic fluids result in the mobility of U (and other metals) and subsequent precipitation occurring at reducing barriers, such as rocks containing graphite, free carbon, sulfides, and quartz-rich rocks.

KEYWORDS: *alkali magmas, transmagnetic fluids, endogenic deposits, uranium*

INTRODUCTION

It is well known that the overwhelming majority of U deposits form as the result of two key processes – first endogenic (hypogene hydrothermal) and later supergene enrichment ones. We'll only view the processes of the former group.

PRINCIPLE METHOD OF OUR POINT OF VIEW

We base on progress of Korzhinskii's ideas of physicochemical analysis of mineral parageneses of natural rocks (Korzhinskii 1959) and participation of transmagnetic fluids (dense superheated gases and solutions) in magmatism (Korzhinskii 1952) and other endogenic processes. The active role of these fluids in endogenic ore formation is developed by I.A. Zotov (1980, 1989; Korzhinskii *et al.* 1984) and A.A. Marakushev (1999) (e.g., Marakushev *et al.* 2006).

MAIN FACTORS CONTROLLING FORMATION OF PRIMODIAL ENDOGENIC U-MINERALIZATION OF DEPOSITS

Magmatic factor

Many U deposits indisputably are

connected to alkalic magmas of re-activated tectonic structures (often depressions) of ancient platforms. The typical high relative Th and U concentrations of such magmatic rocks support such point of view. Nevertheless some U deposits probably have maternal granitic magmas, which have no obvious signs of high alkalinity like the presence of alkalic dark colour minerals. But some granites of this group, such as charnockites and rapakivi varieties, contain mineral parageneses (K-spar+hypersthene in the former and K-spar+olivine in the latter) of high alkali conditions according to Korzhinskii's criteria (Korzhinskii 1946). Often U productive granitic complexes of unclear alkalinity contain leucogranite and alaskite (mono-spar) phases and facies, which are also indicators of magma evolution in high alkali environments (Zotov 2006). By the way early connection of U deposits with alkali magmatism was proposed by A.A. Marakushev (1999, p. 205-215).

Transmagnetic fluids

The reason for the similarity of Th-U and rare-metal ore mineralization between silica-undersaturated (nepheline-

normative) and silica-saturated (granitic family) magmas is not simple, since the former group magmas are generated in mantle conditions and granitoid magmas – in the crust. Straightforward relations between them are not known, but the latter ones obviously are generated under influence of the heat of the mantle magmas. Alkali basalt magmas possibly are parental for both groups of magmas. The exact mechanism of transfer of rare-metal specialization of alkali basalts to spatially and temporally associated (bimodal) granitoid magmas remains enigmatic, but questions of volatile transfer mechanisms are needed. The radical change in understanding of the role of volatiles was developed by D.S. Korzhinskii (1952), who formulated the concept of transmagmaic fluid flow that naturally develops from crystallizing magmas; he postulated that such fluids can percolate into and even through magmatic liquids (melts) as free supercritical overheated gases. Since transmagmaic fluids would be in chemical equilibrium with the parental magmas and eventually evolve from those consolidating magmas, the evidence for these fluids can typically be found in the exocontacts of these magmatic bodies. The magmatic fluids chemically and thermally react with the wall rocks causing metasomatic and metamorphic changes in them. This *magmatic stage* metasomatism differs from the more widespread post-magmatic metasomatism in that the former does not react with the parental magmatic rocks, whereas the derivative metasomatites are cut by magmatic veins that contain their xenoliths. During 1954-1984 in Russia there have been comprehensive studies of magmatic stage metasomatites of all natural magma types, which completely confirms Korzhinskii's concept. At the same time it was found that although all magmatic bodies always contained evidence of transmagmaic fluid flow, their activity (or better fluid volumes) was greatly variable not only from one magmatic massif and complex to another, but even within one magmatic body; the later regularity is evidence that there is

fluid movement through crystallizing magmas. These studies also show that the great majority of magmatic massifs are characterized by minimal fluid flow such that they do not influence magma evolution. Fluid flow interaction is only most evident in ore-bearing intrusions (Korzhinskii 1962). Korzhinskii (1952) noted the sublithospheric source of transmagmaic fluid, which probably originates in the athenosphere (Zotov 1989).

Later (Zotov 1980, 1989; Korzhinskii *et al.* 1984; Marakushev *et al.* from 2002 up to 2006), it was shown that transmagmaic fluids are able to transport ore metals whose portion may be predominant in endogenic deposits as for example in Pt-Pd-Cu-Ni sulfide deposits (same ref.), apatite deposits of alkali (Zotov 1989) and alkali-carbonatite (Seredkin *et al.* 2004) magmatic massifs. This concept is essentially useful as an application for understanding of genesis of big endogenic ore deposits (Zotov 1980).

The role of transmagmaic fluids in genesis of U endogenic deposits

It was proposed above that endogenic U deposits seem to be produced by a wide variety of alkalic magmas, which are usually accompanied by active (great volume) reaction of transmagmaic fluids. Additional evidence of it is the widespread occurrence of apatite in amounts up to 60 vol.% in many deposits. Our early studies of different types of primary apatite deposits (Zotov 1989; Seredkin *et al.* 2004) have shown that they indisputably were formed by transmagmaic fluids of alkali magmas, which serve as good conductors for K-P compounds of the fluids producing K-metasomatism (finitization) of exocontact rocks. Ca-rich lithofacies of the latter play a role as barriers for P mobility resulting in deposition as apatite mineralization. Thus apatite mineralization of many U deposits confirms participation of transmagmaic fluids of alkali magmas in their formation.

At the same time it is quite obvious that most mantle material cannot be the source of uranium, because it was not

found in critical amounts in any mantle xenoliths. Hence transmagnetic fluids sequester their uranium from the crust. Transmagnetic fluids derived from alkalic magmas are good solutions for leaching uranium from crustal rocks, via transformation into transportable oxidized uranyl complexes. This is related to the relatively high oxidation environment in alkali magmas (nepheline-normative and carbonatitic ones) at depth and remain incompatible in these magmas with oxidized iron contained in rock-forming minerals – aegerine and alkali amphiboles. Most likely, complexing is related to high activity of fluorine and not just oxygen fugacity, although transmagnetic fluids must also be characterized by high oxidation potential.

It is obvious that the action of such fluids on crustal rocks invoke oxidation of uranium transforming it in mobile complexes. At the same time uraniumiferous terrigenous rocks may partially melt giving rise to derivative crustal anorogenic granitoid magmas of alkalic affinity that may accompany contamination (including U) of primary mantle alkalic magmas, which initiated these crustal fusion processes.

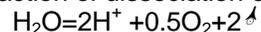
Formation of Primary Endogenic U Concentrations of the Deposits

The high oxidized character of U-bearing magmatic ore-forming systems determines both their metallogenic specialization and conditions of deposition of their ore load including U.

The ore mineralization should be deposited in or near U-bearing intrusion. According to the concepts described, ore productive magmatic bodies are to be characterized by active action of transmagnetic fluids, which should be expressed by wide-spread metamorphism, magmatic stage metasomatism, and magmatic replacement phenomena along intrusion exocontacts. Contamination by wall rock materials is also a typical feature of such intrusions.

The ore formation itself is connected with the oxidation state of ore-bearing fluids for which reducing mediums are

favourable as chemical reaction barriers for ore precipitation. Such a reductant role can be associated with graphitic, free carbon, sulfidic, and other reduced iron-rich rocks. Quartz-rich rocks also show reducing properties under hydrothermal influence due to oxidation-reduction interaction of components of hydrothermal solutions and the rocks (Korzhinskii, 1963). Reaction of dissociation of water



show inverse dependence of acidity ($\text{pH} = -\log[\text{H}^+]$), and reduction potential (μ) at constant oxygen fugacity ($f(\text{O}_2)$), which is reliable for leucocratic or quartz-rich rocks. Dilution of silica of the latter provoke decrease of activity of all acids due to lowering of activity coefficient (ν) of acidic components. Hence when hydrothermal fluids come in to quartz-rich rocks, the reduction potential is supposed to increase causing precipitation of U and high-charged ore elements, especially rare metals.

These factors of U ore deposition can be demonstrated by the following examples. In deposits of "Unconformity" type from the Athabasca basin, the uranium localizes in graphite-containing layers, which are used as favourable prospecting signs as at the MacArthur River deposit. In deposits of the El'kon U ore region spreading of brannerite streaks is limited by zones of pyrite-containing K-spar metasomatites. We should be reminded that the giant Olympic Dam U deposit initially was prospected and explored as copper-sulfide sandstone. Lastly, there is the enormous group of Proterozoic deposits where U-TR and Au-U mineralization is localized in quartz-pebble conglomerate layers (Dahlkamp 1991) and Witwatersrand with its mineralized conglomerate-like polymictic breccia with quartz rounded fragments (70-80 vol.%) and pyrite is between them. Some U deposits (including the big Tulukai one) of Strel'tsovskoe ore field (Russia) are localized in Si-rich felsites.

CONCLUSIONS

This contribution is summarized as

follows:

(1) primary uranium mineralization of endogenic U deposits are related to the production of a wide variety of alkalic magmas;

(2) transmagnetic fluids (first supposed by D.S. Korzhinskii in 1952) derived from mantle alkalic magmas are postulated to be involved in the leaching and (or) melting of U; the derivative alkalic crustal affinity of the granitic magmas are a related product of heat advection from advecting mantle magmas;

(3) the oxidized state of the U-bearing transmagnetic fluids under discussion explains the typical precipitation of U in the reducing rocks with graphite, free carbon, sulfide, other reduced Fe-rich rocks, and quartz-rich rock varieties;

(4) such conditions and origin of U-containing fluids can also explain the valuable rare-metal components typifying many U deposits.

ACKNOWLEDGEMENTS

We express our gratitude to D.S. Korzhinskii, who supported the research developed here from the first steps.

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