International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018)

Contribution ID: **120** Type: **ORAL**

The ultimate origin of uranium provinces

Monday, 25 June 2018 16:00 (20 minutes)

INTRODUCTION

The global distribution of mineral deposits on the Earth shows that some areas concentrate large resources (with high endowment), whereas others are almost devoid of any resource. This has led [1] to introduce for the first time the term "metallogenic province". The first definition of a uranium province was proposed by [2]: "Economic uranium deposits resulted from original inhomogeneity's of uranium distribution in the Earth's crust that commonly persisted through long periods of time, and through a combination of orogenic, metamorphic, and sedimentary processes produced rocks with enriched uranium contents. The initial enriched uranium domain was successively remobilized and concentrated into new enrichments of one or more magnitudes above normal background forming uranium ore deposits". The nature, origin, evolution, and distribution of U provinces, and the characteristics of some of the major U provinces will be presented. The delineation of such provinces is of major importance for U exploration and the evaluation of the potential resources of such areas.

IS AN ANOMALOUS METAL ENRICHMENT NECESSARY TO GENERATE ORE DEPOSITS ?

A controversy exists about the necessity of an initial metal enrichment in the source rocks to generate ore deposits. Following [1], the term "metallogenic province" was defined by [3] simply, as a domain on the Earth with an unusual abundance of ores of a particular metal or type (e.g. Cu province of Chile. But, several authors, such as [4], [5], [6], similarly to [2] propose that metallogenic provinces are associated to a previous metal enrichment in the Earth's crust or even in the mantle, and this idea has led to the concept of geochemical provinces, regional geochemical specialization, or metal domain. This concept has been further precized by [7] with the introduction what he called the "basic theorem" of metallogeny: "The concentrations of a metal appear at the intersection of a metal domain (actually a volume capable of reaching down to the mantle), bearing during very long periods of time (permanency and heritage) a metal potential (that is the primordial metallotect), and of other metallotects, acting as revealers of this potential". The term "metallotect" was in fact introduced first by [8] and defined as "any geological feature or phenomenon associated with lithology, paleogeography, structure, geochemistry, etc. which has contributed to the formation of a mineral concentration". However, a metallogenic province cannot be simply assimilated to a geochemical province for which the definitions is highly variable [9] and ore forming processes are not considered.

Conversely, other authors such as [10], propose that hydrothermal ore deposits of Cu, Pb, Zn or Ba, with crustal abundances higher than 10 ppm, do not require any pre-concentration in the crust for their formation. The main parameters controlling ore deposit formation would be the availability of a large volume of fluids able to extract and transport the metals and then to deposit them thanks to an efficient trapping mechanism. Similarly, [11] defends that Sn deposits result purely from a progressive concentration of the metal during magmatic processes from an inital average crustal Sn content. However, this model has been contradicted by [12] taking as example the Sn-W deposits of Western Europe, for which they propose their derivation from the partial melting of Sn-W enriched pelites. The source enrichment is related to intense chemical weathering of continents and to their fragmentation leading to the accumulation metal-rich sediments at the margin of fragments of those continents. The ore deposits within a single belt may be of different type and may be formed recurrently.

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

SELECTIVE URANIUM ENRICHMENT OF SPECIFIC CONTINENTAL CRUST SEGMENTS

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

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

At about 2.3-2.2 Ga, the oxygen level in the atmosphere was high enough [18], for meteoric water, containing dissolved CO2, in contact with U, to pass it into solution as uranyl carbonate complexes. The U was dissolved from U-oxides having crystallized in highly fractionated U-rich granite, from metamict U-rich silicate minerals in plutonic or sedimentary rocks, from devitrified U-rich volcanic acidic glasses, and uraninite accumulated in the pre-2.2 Ga paleoplacers.

Rise of oxygen in the atmosphere and oceans was sustained by high organic carbon burial, within the sediments (black shales), especially in marginal sea environments, and occurred during the so-called "Shunga event"[19], which have permitted the trapping of large quantities of U, mobilized by oxygenated meteoric water, in the reduced post-2.2 Ga epicontinental platform sediments. These Early Paleoproterozoic sedimentary units have represented a huge U reservoir for the formation of a variety of U deposits during the following tectono-thermal events. Typical examples are the FB Formation in the Franceville basin in Gabon, the upper Zaonezhskaya Formation, north of Onega Lake in Russia, and metamorphosed equivalents such as the Wollaston belt in northern Saskatchewan, Canada, and the Cahill Formation in the Northern Territory, Australia, all associated with significant U deposits.

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

A WELL CHARACTERIZED URANIUM PROVINCE: THE ATHABASCA U PROVINCE (AUP)

Five to six steps of U enrichment have been characterized in the AUP. The Archean basement mainly consists of U-poor magnetite bearing tonalites, but locally potassic orthogneisses with high U contents are known. For example at Key Lake, high-K granitic gneisses have in average 6.8 ppm U with 4.1 ppm leachable [21]. Then, the decisive step of U enrichment in the AUP occurred during the Upper Paleoproterozoic with the U enrichment in the epicontinental platform sediments of the Wollaston-Mudjatik belt consisting of carbonaceous schist, metacarbonate and calc-silicate rocks, micaschist, feldspathic quartzite, para-amphibolite, and

metaevaporites.

The next important step of U reconcentration during the Paleoproterozoic has occurred in the Eastern part of the Athabasca Basin basement with the formation of abundant leucogranites and anatectic pegmatites during the Hudsonian Orogeny (ca 1.8 Ga). They occur as syn- to late-orogenic plutons, sheets, dykes, and stockworks deriving from the partial melting of the U-rich lithologies of the Wollaston- Mudjatik belt metasediments [22]. They are variably enriched in U, Th, Zr, and REE (e.g., Parslow and [23]; Mercadier et al., 2013) [1]. The U content of these pegmatites in generally in the order of some tens to hundreds of ppm but may reach several thousands of ppm. For example, the Charlebois Lake pegmatoids represent a sub-economic resource with 17,500 tU at about 600 ppm U. During Paleoproterozoic, a new input of U is represented by the emplacement of large amounts of high-K calc-alkaline granitoids in the western part of the Athabasca basement [24]. They belong to the southern extension of the Taltson Belt. In the eastern part of the Athabasca basement a U-rich potassic porphyritic granite, is reported in the Wheeler River district [22] and in the Eagle Point Mine [25]. A further Paleoproterozoic stage of U reconcentration, prior to Athabasca Basin deposition, led to the formation of the late Hudsonian (1.8 Ga) vein and episyenite type U-deposits (e.g. Beaverlodge) [26]. 25,939 tU were mined from the Beaverlodge area [27].

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

THE URANIUM PROVINCES OF THE WORLD

Numerous U provinces are known in the world but the successive steps of U enrichment within these provinces are not always well characterized and their geographic extension is highly variable and sometime difficult to define. The history of many U provinces starts during the Archean (e.g. South Africa, or Athabasca U Provinces), whereas others are relatively young (e.g. the mid-European U Province and the Central Asian U Super-Province), some have a relatively small geographic extension (e.g. the Athabasca or the Central Ukrainian U Provinces, whereas others are very large (e.g. the Central Asian U and the Karoo Super-Provinces). A map of the most important U provinces is provided in the new edition of the World Uranium Map [31].

REFERENCES

[1] LAUNAY, L., (de) Traité de métallogénie. Paris, 3 volumes (1913).
[2] KEPPLER, M.R., WYANT, D.G., Uranium provinces, in Geology of uranium and thorium: Proceed. Internat. Conf. Peaceful Uses of Atomic Energy, Geneva, August 1955. 6 (1956) 217-223.
[3] HAWKES, H.E., WEBB, J.S., Geochemistry in mineral exploration: Harper & Row, N.Y. (1962).
[4] ROUTHIER, P., Les gisements métallifères : principes de recherche. Masson, Paris, 2vol. (1963).
[5] SCHUILING, R.G., Tin belts on the continents around the Atlantic Ocean. Econ. Geol. 62 (1967) 540-560
[6] BRADSHAW et al. Exploration Geochemistry: A series of seven articles reprinted from Mining in Canada and Canadian Mining Journal. Barringer Research Ltd, Ont. (1972).
[7] ROUTHIER, P., Où sont les métaux pour l'avenir? Les provinces métalliques. Essai de métallogénie globale. Masson, Paris (1980).
[8] LAFFITTE et al., Cartographie mètallogénique, métallotecte et géochimie régionale. Bul. Soc. Fr. Minér. Crist, 88 (1965) 3-6.
[9] REIMANN, C., MELEZHIK, V., Metallogenic provinces, geochemical provinces and regional geology - what causes large-scale patterns in low density geochemical maps of the C-horizon of podzols in Arctic Europe ? Appl. Geoch, 16 (2001) 963-983.
[10] SKINNER, B.J., The many origins of hydrothermal mineral deposits. In: H.L. Barnes (Editor), Geochemistry of Hydrothermal Ore Deposits. John Wiley and Sons, New York (1979) 1-21.
[11] LEHMAN, B. Tin granites, geochemical heritage, magmatic differentiation. Geol. Rdsch. 76 (1982) 177-185.
[12] ROMER, R.L., KRONER, U., Phanerozoic tin and tungsten mineralization—Tectonic controls on the distribution of enriched protoliths and heat sources for crustal melting. Gond. Res. 31 (2016) 60-95
[13] JAIRETH, S., HUSTON, D. Metal endowment of cratons, terranes and districts: Insights from a quantitative analysis of regions with giant and super-giant deposits. Ore Geol. Rev. 38 (2010) 288-303
[14] WHITE W.M., Geochemistry, in: Geochemistry of Solid Earth. Chapter 11: The Mantle and Core. Wiley-Blackwell Edit. (2012).
[15] YAMASHITA et al., U on the Moon: Global distribution and U/Th ratio. J.G.R.L. 37 (2010).
[16] CUNEY, M., Evolution of uranium fractionation processes through time: driving the secular variation of uranium deposit types. Econ. Geol., 105 (2010) 449 –465.
[17] CARROUÉ et al., Uranium concentration processes in Archaean batholiths, sources of the oldest uranium deposits. Goldschmidt Conf. Abst., Montréal, Canada. Min. Mag. (2012) 1549.

[18] LYONS et al., Rise of oxygen in Earth's early ocean and atmosphere. Nature 506 (2014) 307-315
[19] HANNAH et al., Re-Os geochronology of shungite: A 2.05 Ga fossil oil field in Karelia [abs.]: Goldschmidt Conference, 2008, Vancouver, B.C., Canada, Abstracts, A351. (2008)
[20] ZHAO et al., Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth-Sci. Rev. 59 (2002) 125–162.
[21] HÖHNDORF et al, Age determination of basement units in the Key Lake area, Saskatchewan, Canada. IAEA Tech. Com. Meeting on U Resources and Geology of North America. IAEA Tech. Doc. 500 (1989) 381-409.
[22] ANNESLEY I., MADORE, C., Leucogranites and pegmatites of the sub-Athabasca basement, Saskatchewan: U protore? In Mineral Deposits: Processes to Processing (Stanley, C.J. et al., eds.), Balkema (1999) 297-300.
[23] PARSLOW, G.R., THOMAS, D.J. Uranium occurrences in the Cree Lake Zone, Saskatchewan, Canada. Min. Mag. 46 (1982) 163-171.
[24] BROUAND, M., et al., Eastern extension of the Taltson orogenic belt and eastern provenance of Athabasca sandstone: IMS 1270 ion microprobe U/Pb dating of zircon from basement plutonic rocks and from overlying sandstone (Canada). Proc Int. Conf. Uranium Geochemistry, Nancy (2003).
[25] CLOUTIER et al., Geochemical, isotopic, and geochronologic constraints on the formation of the Eagle Point basement-hosted uranium deposit, Athabasca Basin, Saskatchewan, Canada and recent remobilization of primary uraninite in secondary structures. Mineral. Dep. 46 (2011) 35-56
[26] RUZICKA, V., Vein uranium; & Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geol. Surv. Canada, Geology of Canada. 8 (1996).
[27] JEFFERSON et al., Unconformity-associated uranium deposits of the Athabasca Basin, Saskatchewan and Alberta, in Goodfellow, W., ed., Min. Dep. Canada, Spec. Publ. 5 (2007) 273-305.
[28] HOEVE, J., QUIRT, D., Mineralization and host-rock alteration in relation to clay mineral diagenesis and evolution of the middle-Proterozoic Athabasca Basin, northern Saskatchewan, Canada; Sask. Res. Counc., Tech. Rep. 187 (1984) 187p.
[29] FAYEK, M., KYSER, T.K., Characterization of multiple fluid events and rare earth element mobility associated with formation of unconformity-type uranium mineralization from the Athabasca Basin, Saskatchewan, Canada. Can. Miner. 35 (1997) 627-658.
[30] CUNEY, M., et al., What parameters control the high grade - large tonnage of Proterozoic unconformity related U deposits from the Athabasca? Proc Int. Conf. U. Geochemistry, Nancy (2003)
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, World Distribution of Uranium Deposits. IAEA-TECDOC (to be published in 2018).

Country or International Organization

Université de Lorraine, CNRS, CREGU, GeoRessources, FRANCE

Primary author: Dr CUNEY, Michel (CNRS - GeoRessources - CREGU - Universite de Lorraine)

Presenter: Dr CUNEY, Michel (CNRS - GeoRessources - CREGU - Universite de Lorraine)

Session Classification: Applied Geology and Geometallurgy of Uranium and Associated Metals

Track Classification: Track 3. Applied geology and geometallurgy of uranium and associated metals