Applying the Concept of 'Holistic' Basin Analysis to Unconformity-related Uranium Prospects in Under-explored Paleoproterozoic Basins

Steve R. Beyer*, Kurt Kyser
Queen's University, Kingston, Ontario, Canada
beyer@geoladm.geol.queensu.ca

Eric E. Hiatt
University of Wisconsin – Oshkosh, Oshkosh, Wisconsin, USA

Chris Pettman, Ian Fraser
Uravan Minerals Inc., Calgary, Alberta, Canada

Terrence K. O'Connor
Cameco Corporation, Saskatoon, Saskatchewan, Canada

Introduction

Sedimentary basins of nearly all ages host economic petroleum and mineral resources. Exploration for the next generation of concealed, sedimentary-hosted mineral deposits that lack clear surface geochemical or geophysical anomalies, and the evaluation of under-explored or unproven basins will benefit from what has been termed 'holistic' basin analysis (Kyser, 2007; Kyser and Cuney, 2008). Holistic basin analysis integrates aspects of sedimentology and sequence stratigraphy, geochemistry, geochronology, and additional disciplines to determine how the basin evolved with respect to diagenesis and fluid composition, when major geological events that may have triggered fluid movement in the basin occurred, and what exploration strategies would be effective to discover a deposit. This methodology has recently been applied to the Paleoproterozoic Athabasca Basin, Canada (Cloutier et al., 2009; Alexandre et al., 2009) and McArthur and Mt. Isa Basins, Australia (Southgate et al., 2006; Kyser, 2007) that host uranium and base metal deposits, resulting in illumination of some of the critical factors necessary to produce economic mineralization.

In this study we apply the tools provided by holistic basin analysis to the Paleoproterozoic Thelon and Otish Basins, Canada, both of which are known hosts of unconformity-related uranium mineralization but until recently were relatively under-explored regarding these deposits. Renewed exploration in both basins, driven by improving market conditions for uranium, has necessitated the evaluation of historical uranium showings as to whether or not they represent legitimate unconformity-type uranium targets, and the development of guidelines to focus exploration, an important aspect in geographically isolated areas such as the Thelon and Otish Basins where the costs of exploration are high.

Methods

This research focused on the Boomerang Lake prospect in the western Thelon Basin, N.W.T., and the Camie River prospect in the southwestern Otish Basin, Quebec. Thirty-eight diamond drill cores intersecting over 8,000 meters of basinal sandstones were logged in detail (measured and described at the decimeter-scale), and outcrops at eleven localities were studied to develop a sequence stratigraphic framework for basinal strata in order to help assess the paleoaquifer vs. paleoaquitard properties of the strata (e.g. Hiatt et al., 2003). A paragenesis was developed for each basin by chemically characterizing and determining the relative timing of diagenetic, hydrothermal alteration, and ore minerals using electron microprobe analysis (EMPA) and standard optical and electron microscopy. The absolute timing of diagenetic and ore minerals was determined by U-Pb and Pb-Pb geochronology using laser ablation multi-collector inductively-coupled plasma mass spectrometry (LA-MC-ICPMS), and $^{40}Ar/^{39}Ar$ geochronology. Additionally, we employed a weak acid partial leach method in conjunction with high resolution

(HR)-ICPMS (Holk et al., 2003) as an exploration tool and to help develop exploration guidelines.

Principal Findings

Sedimentology and Sequence Stratigraphy

We recognize three lithofacies within Otish Group sandstones, and at least six depositional packages that display a northeastward increase in the proportion of braid plain/delta deposits, and a southwestward increase in the proportion of braided channel and bar deposits. Despite the variable occurrence of pore space-occluding features such as compaction and early diagenetic cements, the capability of the sediments in all three lithofacies to conduct uranium-bearing fluids to a site of mineralisation was good due to the absence of thick successions of aquitard-prone sediments such as early-cemented well-sorted quartz sands or mudstone.

We recognize five major lithofacies and several sub-lithofacies within Thelon Formation sandstones, and three lithofacies stacking patterns that represent deposition in alluvial fan, alluvial plain, and braided fluvial channel settings, respectively. Strata deposited in alluvial fan and alluvial plain environments contain aquitard-prone mudstone intervals, display variable compaction and early pore space occlusion, whereas strata deposited in braided fluvial channel settings contain negligible mudstones, display less compaction, and were capable of conducting chemically reactive peak diagenetic fluids to a better degree than the former strata. The aquitard-prone strata and underlying basement rocks, including the Boomerang Lake prospect, show mineralogical, isotopic, and geochronological evidence for the restriction of fluid flow during peak diagenesis and hydrothermal alteration.

Paragenesis

In the Otish Basin quartz cement overgrowths and later quartz and albite cement are all relatively early diagenetic phases that variably occlude primary and secondary porosity within Otish Group sandstones. Peak diagenesis occurred at temperatures around 250°C and is marked by the development of secondary porosity within sandstones that is filled primarily with fine- to medium-grained muscovite. Uranium mineralisation paragenetically follows muscovite and consists of uraninite and minor brannerite hosted by a basement fault zone near graphitic, sulphide-bearing metasedimentary rocks. Pyrite and galena in the host rocks were the reductant for oxidized uranium-bearing fluids based on petrographic observations. The estimated formation temperature of later coarse-grained chlorite and muscovite within Otish Group sandstones is 300-350°C and suggests the basin experienced greenschist facies metamorphism that post-dates diagenesis and mineralisation.

In the western Thelon Basin, basement rocks preserve a hematite + kaolinite + muscovite ± clinochlore assemblage produced during retrograde metamorphism and subaerial exposure prior to the deposition of Thelon Formation sandstones. A quartz + phosphate + pyrite mineral assemblage represents early diagenesis within Thelon Formation sandstones. Peak diagenesis is marked by the development of secondary porosity that is filled by kaolinite and muscovite. Braided fluvial channel strata remained open to hot (200-250°C) peak diagenetic fluids and host pervasive dickite that follows muscovite. We studied sandstone-hosted uranium mineralisation that formed during hydrothermal alteration and consists of micron-scale patches of the rare mineral tristramite ((Ca, U^{4+}, Fe^{3+})(PO_4, SO_4)•$2H_2O$). This is contrary to a previous study (Davidson and Gandhi, 1989) that reported pitchblende as the U-bearing mineral. Co-Ni-As sulphides and selenides, and sudoite are present in both sandstone and basement rock near uranium mineralisation and are also associated with hydrothermal alteration.

Stable Isotope Geochemistry

The range of $\delta^{18}O$ and $\delta^{2}H$ values of fluids in equilibrium with muscovite and chlorite (2.7 to 11.1 per mil, and -68 to -11 per mil, respectively, V-SMOW) in Otish Basin sandstones represents the influence of two temporally distinct fluids. The first was a basinal brine that has an isotopic composition consistent with that of evolved seawater which reacted with siliciclastic basinal fill during diagenesis. The second was a later metamorphic fluid that imparted high $\delta^{18}O$ values to later muscovite and chlorite during greenschist grade metamorphism.

Fluids in equilibrium with peak diagenetic kaolinite, dickite, and muscovite in Thelon Formation sandstones have $\delta^{18}O$ and $\delta^{2}H$ values that range from 6.7 and 9.4 per mil and -76 and -24 per mil, respectively, which is consistent with those of oxidizing, saline, and acidic basinal brines in other Proterozoic basins (Kyser and Cuney, 2008). These fluids penetrated the unconformity in some areas, based on the $\delta^{18}O$ and $\delta^{2}H$ values of kaolinite in 'paleoweathered' basement rocks, but were absent in other areas based on the preservation of poorly-crystalline kaolinite and illite that were formed from fluids with isotope ratios similar to those of meteoric waters. Hydrothermal alteration-related fluids in equilibrium with sudoite had relatively high $\delta^{18}O$ and $\delta^{2}H$ values consistent with those of basinal brines that interacted with basement rocks at low water/rock ratios. Fluid-poor conditions were a result of the hydrologic isolation of overlying aquitard-prone alluvial plain-associated strata during peak diagenesis.

Geochronology

LA-MC-ICPMS analyses of uraninite at Camie River revealed a significant proportion of common Pb contributed by pre-mineralisation, host rock sulphides. Analyses with the highest $^{206}Pb/^{204}Pb$ ratios (or the lowest amount of common lead) were used to estimate a $^{207}Pb/^{206}Pb$ age of ca. 1730 Ma for uranium mineralization at Camie River, similar to the ages reported by Höhndorf et al. (1987) for Camie River uraninite and for emplacement of the Otish Gabbro. One muscovite from Otish Group sandstones, and two muscovites from intensely altered basement rocks yield a $^{40}Ar/^{39}Ar$ plateau age of 1409 ± 29 Ma, and total fusion ages of 1528 ± 10 Ma and 1663 ± 9 Ma, respectively. The ages of both uraninite and muscovite indicate that the U-Pb and Ar isotopic systems in the area were not greatly affected by the ca. 1000 Ma Grenville Orogeny, despite the location of the area within tens of kilometers of the Grenville Front Tectonic Zone.

Three muscovite samples from Thelon Formation sandstones with paleoaquifer characteristics yield $^{40}Ar/^{39}Ar$ plateau ages of 1337 ± 4 Ma, 1340 ± 5 Ma, and 1302 ± 11 Ma. One muscovite from sub-Thelon basement rocks, and one illite from a basement fault zone yield $^{40}Ar/^{39}Ar$ plateau ages of 1738 ± 14 Ma and 1759 ± 7 Ma, respectively. The ages of basement muscovite and illite likely represent the age of pre-Thelon Basin subaerial exposure, indicating little interaction with later basinal fluids in the sampled zones. The ages of muscovite in these Thelon sandstones suggest the presence of basinal fluids for several hundreds of millions of years after basin formation, a testament to the high-quality paleoaquifers formed by a majority of the strata at Boomerang Lake.

Mobile Components

Near Camie River, highly radiogenic Pb was leached from nearly all sandstone and basement samples in a diamond drill hole that intersected basement-hosted uranium mineralisation, and in sandstone and basement samples straddling the unconformity in a diamond drill hole several kilometers away from the U-mineralisation. Few of these samples were supported by proportionally high leachable U (Fig. 1), meaning little of the Pb was produced *in situ*, and most of the radiogenic lead was transported to the sample by fluids that interacted with U–bearing minerals.

At Boomerang Lake, radiogenic Pb was leached from sandstone and basement samples enveloping the unconformity and near some basement fault zones. In nearly all cases the radiogenic Pb was supported by proportionally high leachable U (Fig. 1), and in many cases high Zr, Th, and LREE also accompanied the highly radiogenic Pb. A high proportion of this radiogenic Pb was likely a product of the breakdown of accessory and detrital U-bearing minerals such as zircon, monazite, and apatite during faulting, retrograde metamorphism, and subaerial exposure of the basement, and compaction and prolonged, intense diagenesis in the basin, and not a nearby uranium deposit.

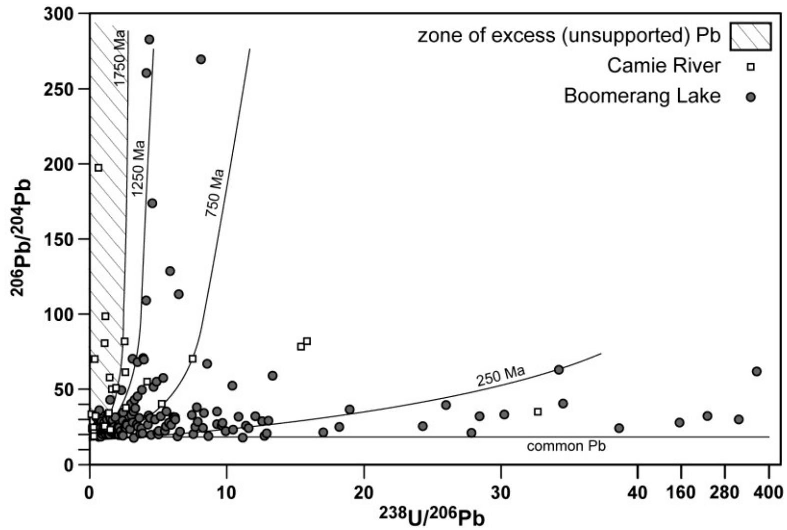

Figure 1 – Plot of $^{206}Pb/^{204}Pb$ vs. $^{238}U/^{206}Pb$ for weak acid leaches from Camie River and Boomerang Lake. Samples that fall into the hatched area to the left of the 1750 Ma U – Pb evolution curve have ^{206}Pb contents in excess of the amount of leachable uranium in the sample, which represents radiogenic Pb transported to a sample from a high-^{206}Pb source such as a uranium deposit (Holk et al., 2003).

Acknowledgements

This research was jointly funded by Uravan Minerals Inc., Cameco Corporation, and Natural Sciences and Engineering Research Council Collaborative Research Development grants.

References

Alexandre, P., Kyser, K., and Jiricka, D., 2009, Critical geochemical and mineralogical factors for the formation of unconformity-related uranium deposits: comparison between barren and mineralized systems in the Athabasca Basin, Canada: Economic Geology, v. 104, p. 413-435.

Cloutier, J., Kyser, K., Olivo, G.R., Alexandre, P., Halaburda, J., 2009, The Millennium Uranium Deposit, Athabasca Basin, Saskatchewan, Canada: An Atypical Basement-Hosted Unconformity-Related Uranium Deposit: Economic Geology, v. 104, p. 815-840.

Davidson, G.I., and Gandhi, S.S., 1989, Unconformity-related U-Au mineralization in the middle Proterozoic Thelon Sandstone, Boomerang Lake Prospect, Northwest Territories, Canada: Economic Geology, v. 84, p. 143-157.

Hiatt, E.E., Kyser, K., and Dalrymple, R.W., 2003, Relationships among sedimentology, stratigraphy, and diagenesis in the Proterozoic Thelon Basin, Nunavut, Canada: implications for paleoaquifers and sedimentary-hosted mineral deposits: Journal of Geochemical Exploration, v. 80, p. 221-240.

Höhndorf, A., Bianconi, F., and von Pechmann, E., 1989, Geochronology and metallogeny of vein type uranium occurrences in the Otish Basin area, Québec, Canada, *in* Metallogenesis of Uranium Deposits: Sci. Tech. Info. Publ. 775, IAEA (Int. At. Energy Agency), Vienna, p. 233–260.

Holk, G.J., Kyser, T.K., Chipley, D., Hiatt, E.E., and Marlatt, J., 2003, Mobile Pb-isotopes in Proterozoic sedimentary basins as guides for exploration of uranium deposits: Journal of Geochemical Exploration, v. 80, p. 297-320.

Kyser, K., and Cuney, M., 2008, Unconformity-related uranium deposits, *in* Cuney, M., and Kyser, K., eds., Recent and not-so-recent developments in uranium deposits and implications for exploration: Mineralogical Association of Canada Short Course, v. 39, p. 161-219.

Kyser, T.K., 2007, Fluids, basin analysis, and mineral deposits: Geofluids, v. 7, p. 238-257.

Southgate, P.N., Kyser, T.K., Scott, D.L., Large, R.R., Golding, S.D., and Polito, P.A., 2006, A basin system and fluid-flow analysis of the Zn-Pb-Ag Mount Isa-Type deposits of Northern Australia: Identifying metal source, basinal brine reservoirs, times of fluid expulsion, and organic matter reactions: Economic Geology, v. 101, p. 1103-1115.