Two Sources of Uranium at the Millennium Uranium Deposit, Athabasca Basin, Saskatchewan, Canada

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Summary

Renewed interest in nuclear energy has lead to increased uranium exploration to meet the demand for new uranium resources. The Athabasca Basin in northern Saskatchewan, Canada, hosts the world's highest grade unconformity-related uranium deposits. Uranium mineralization is hosted within the Athabasca Group above the unconformity and the crystalline basement rocks. The Athabasca Group-hosted deposits have been studied extensively for more than 30 years and multiple depositional models have been developed. The Millennium uranium deposit, located 35 km north of the Key Lake mine, occurs between two subparallel reverse faults. The zone between these two faults represents a dilational structure that increased the permeability of the basement rocks.

Uranium mineralization occurs in a variety of styles including (1) massive replacement, (2) fracture filling veins, (3) fine-grain aggregates associated with "mini" roll fronts, and (4) disseminated grains. Massive replacement uraninite is associated with chlorite whereas fracture filled uraninite is associated with euhedral quartz-carbonate veins. These two styles of uranium mineralization constitute the majority of the ore whereas fine-grain aggregate and disseminated uraninites are minor components of the ore. The disseminated grains are altered uraninite with galena, are associated with hematite and clay minerals, and are thought to be primary grains that were altered by a sulfur rich fluid. Massive and vein-type uraninites have low $\delta^{18}O$ values from -35‰ to -15‰, which are typical of oxygen isotopic values of uraninite from other uranium deposits in the Athabasca basin. Relict metamorphic and secondary euhedral quartz grains associated with vein-type uraninite have $\delta^{18}O$ values of 11.1‰ to 15.1‰ and 16.2‰ to 19.1‰ respectively. The low $\delta^{18}O$ values for uraninite and the high $\delta^{18}O$ values for quartz suggest that the original isotopic composition of both minerals have been modified by recent low-temperature meteoric waters.

The chemical Pb and isotopic $^{207}Pb/^{206}Pb$ ages of the massive (style 1), vein-type (style 2), and fine-aggregate (style 3) uraninite cluster at 1400-1200 and 1100-900 Ma. The ~1400 Ma ages coincide with the primary mineralization event for many of the uranium deposits (1550-1400 Ma) within the Athabasca Basin. The younger age group reflects lead loss associated with post depositional fluid events. However, unlike other uranium deposits from the Athabasca basin, disseminated uraninite (style 4) have $^{207}Pb/^{206}Pb$ ages from 1770-1650 Ma. These ages are older than the depositional age for the Athabasca sediments (~1710 Ma) and are similar to the ages from the Beaverlodge vein-type uranium deposits. These ages suggest that the basement rocks that host the Millennium deposit contained disseminated uraninite similar to fine-grain uraninite from the metasediments from the Karpinka Lake uranium prospect (50 km southwest of the Key Lake), suggesting that the basement rocks, in addition to the Athabasca Group rocks, can be a possible source of uranium. The $^{207}Pb/^{206}Pb$ age of the galena associated with style 4 uraninite is ~1400 Ma and reflects the time when the disseminated uraninite was reset during the primary mineralization event.

1.0 Introduction

The Athabasca Basin unconformity-type uranium deposits have been studied extensively for more than five decades. This research has led to the development of an accepted exploration model for unconformity-type uranium deposits within the Athabasca Basin, and similar Paleoproterozoic Basins in Canada and Australia (Kyser et al., 2000). However, the source of uranium for these deposits has remained controversial for decades (e.g., Jefferson et al., 2007).

The unconformity-type uranium deposits from the Athabasca Basin can be subdivided into Athabasca Group-hosted and basement-hosted deposits. The potential of the basement rocks, to host economic uranium mineralization has also been known for several decades and significant basement-hosted deposits within the Athabasca include, Rabbit Lake, Eagle Point, Sue C, and Dominique Peter (Roy et al., 2005). The Millennium deposit provides an opportunity to study the formation of these basement-hosted deposits. Therefore, the objectives of this study are to document and compare the geochronology of Millennium deposit with other unconformity-type uranium deposits from the Athabasca and identify the source of uranium.

2.0 Geology

The Millennium deposit is hosted in a package of pelitic-psammopelitic gneisses/schists, with minor intercalated calc-silicates, amphibolites, and pegmatites in the hanging wall of a major reverse fault. The pelitic-psammopelitic units that hosts "main zone" of uranium mineralization is situated between a faulted graphitic-cordierite pelite known as the "marker unit" and the reverse fault. Based on these observations the marker unit is interpreted as a potential reverse fault (Roy et al., 2005). The pelitic-psammopelitic gneisses/schists, with minor intercalated calc-silicates, amphibolites, and pegmatites situated between the marker unit and the reverse fault display increased brecciation, argillic alteration, and multiple generations of fracture filling veins. Based on these observations, it is inferred that a large dilational zone was created between the two sub-parallel reverse faults that increased the permeability of the basement rocks, which host the Millennium deposit. This enhanced permeability affected the entire suite of basement rocks between the two fault systems including the Fe^{2+} rich pelitic-psammopelitic units that host the majority of the uranium mineralization.

3.0 Petrography

Unmineralized samples show weak argillic alteration of the feldspars and micas within the various basement units. The pegmatite and the granitic units within the footwall of the Millennium deposit display a weak argillic alteration of the feldspar and mica, but the alteration is mainly focused along grain boundaries and fractures within each grain. The "Marker Unit" is composed of quartz, biotite, cordierite, and graphite and is weakly altered (cordierite porphyroblasts are altered to pinite). The pelitic-psammopelitic gneisses/schists are mainly composed of weakly altered biotite and quartz grains whereas the amphibolite is composed of hornblende and plagioclase.

For each weakly altered unmineralized unit there are highly altered equivalent units within the ore zone. The samples associated with uranium mineralization are highly altered and in many cases the original mineralogy cannot be identified without comparing them to similar units from the weakly altered and unmineralized samples. An example of this is represented by the highly altered amphibolite unit where the hornblende has been completely altered to clay and can only be identified by the remnant crystal shape and triple junctions formed between hornblende grains. In many cases, this unit was previously identified as a calc-silicate in drill core due to the intense hydrothermal alteration.

Uranium mineralization occurs in a variety of styles including (1) massive replacement, (2) fracture filling veins, (3) fine-grain aggregates associated with "mini" roll fronts, and (4) disseminated 10-50 μm-size grains. Style 1, massive replacement uraninite is associated with chlorite whereas style 2, uraninite veins are associated with euhedral quartz-carbonate veins. The fine-grain aggregate uraninite (style 3) and disseminated uraninite (style 4) are associated with hematite and clay minerals. Galena is associated with style 4 uraninite.

Massive replacement uraninite (style 1) is characterized by high Pb contents (10.13-16.23 wt% PbO), low Si and Ca contents (<3 wt% SiO_2, CaO) and very low Fe contents (<1 wt% FeO). The alteration of massive uraninite along fractures and grain boundaries are characterized by intermediate Pb contents (6.09- 8.57 wt% PbO), intermediate Si and Ca contents (4.02-6.17 wt% SiO_2, CaO) and low Fe contents (generally <1 wt% two points show 1.06 and 2.14 wt% Fe). Vein type mineralization (style 2) is characterized by high Pb contents (10.32- 15.44 wt% PbO), low Si and Ca contents (<3 wt% SiO_2, CaO), and very low Fe content (<1 wt% FeO). The vein-type mineralization shows alteration of uraninite to coffinite along fractures and grain boundaries. The altered vein uraninite is characterized by low to intermediate Pb contents (0.5-9.7 wt% PbO) intermediate Si and Ca contents (4.7- 6.4 wt% SiO_2, CaO) and low Fe content (<1 wt% FeO). The coffinite is characterized by very low Pb content (<0.05 wt% PbO), high Si and Ca contents (24.9-41.18 wt% SiO_2, 1.5-2.89 wt% CaO) and very low Fe contents (<1 wt % FeO). Fine-grain aggregates of uraninite (style 3) have been partially altered to coffinite. The fine-grain uraninites are generally characterized by very low Pb contents (0-4.1 wt% PbO), intermediate Si and Ca content (4.14-6.84 wt% SiO_2, 3.29-4 wt% CaO), and very low Fe content (<0.09 wt% FeO), whereas the coffinite is characterized by low Pb content (0-4 wt% PbO), high Si and Ca content (11.25- 17.47 wt% SiO_2, 2.08- 3.84 wt% CaO), and very low Fe content (<1 wt% FeO). Disseminated uraninites (style 4) are characterized by very low Pb content (<0.5 wt% PbO), intermediate Si and Ca content (3.31-4.31 wt% SiO_2, 1.72- 3.25 wt% CaO), and very low Fe content (<0.3 wt% FeO). Although style 3 and 4 uraninite are associated with similar clay and oxide alteration minerals, style 4 uraninite consistently has lower Pb, Si, and Ca contents relative to style 3 uraninite.

4.0 Fluid Inclusions and Stable Isotopes

Thin section petrography identified veins of euhedral quartz intergrown with style 2 uraninite. The euhedral quartz contains primary and secondary two phase (*liquid* + *vapor*) fluid inclusions. Freezing measurements identified two fluid compositions. Primary fluid inclusions are characterized by moderate salinities (5-15 wt% NaCl), and the secondary fluid inclusions are highly saline brines (22-24 wt% NaCl). Heating measurements were unsuccessful due to fluid inclusion decrepitating. Decrepitating temperatures for both the moderate and highly saline inclusions ranged from 200-225°C. In thin section, the inclusions displayed variable liquid to vapor ratios which are attributed leakage of the inclusion due to radiation induced damage of the quartz crystal.

The $\delta^{18}O$ values of uraninite from the Millennium deposit range from -25.9‰ to -15.7‰ for the massive replacement mineralization (style 1) and -23.0‰ to -18.5‰ for vein type mineralization (style 2). These values are within the range of $\delta^{18}O$ values obtained from other unconformity-type uranium deposits. Euhedral quartz grains have $\delta^{18}O$ values that range from core to rim between 16.2‰ and 19.1‰ whereas metamorphic quartz has $\delta^{18}O$ values from 11.1‰ to 15.1‰. Using quartz-water fractionation factor of Kawabe (1978) and uraninite-water fractionation factor Zheng (1991) the calculated equilibrium temperature for quartz rims-uraninite is ~ 43°C. Kotzer and Kyser (1993) and Fayek and Kyser (1997) suggest that the low $\delta^{18}O$ values of uraninites from unconformity-type uranium deposits are the result of the interaction between late stage low temperature meteoric water interacting with the uraninite and results in negligible modification of the chemical composition and texture. These data suggest that meteoric fluids affected the Millennium deposit similar to other basement and sandstone-hosted unconformity-type uranium deposits in the Athabasca Basin (Fayek and Kyser, 1997). Oxygen isotopic analysis of style 3 uraninite is in progress and the $\delta^{18}O$ values of style 4 uraninite are difficult to obtain because of the small grain size and the lack of a suitable Secondary Ion Mass Spectrometer (SIMS) standard. However, due to the rapid diffusion of oxygen through the uraninite structure (Fayek et al., in prep), it is unlikely that the $\delta^{18}O$ values of style 3 uraninite will be outside the range of values obtained for styles 1 and 2 uraninite from the Millennium deposit.

5.0 Geochronology

$^{207}Pb/^{206}Pb$ ages were calculated for all four styles of uranium mineralization. The $^{207}Pb/^{206}Pb$ ages of disseminated uraninite (style 4) are among the oldest reported for Athabasca basin uranium mineralization and range from 1750-1650 Ma. The $^{207}Pb/^{206}Pb$ isotopic compositions of galena associated with the style 4 uraninite are highly radiogenic and give ages from 1450-1400 Ma. The massive replacement (style 1), vein type (style 2), and fine-grain aggregate (style 3) uraninite give $^{207}Pb/^{206}Pb$ ages that cluster at 1400-1200 and 1100-900 Ma. These ages indicate either lead loss or recrystallization by post-depositional fluids. The oldest age group 1750-1650 Ma is similar to ages reported for uranium minerals from the Beaverlodge vein-type uranium deposits (e.g., Jefferson et al., 2007) whereas the ages of the galena are consistent with the ages reported for the main uranium depositional event at ~1550-1400 Ma that is considered to be responsible for the formation of unconformity-type uranium deposits in the Athabasca Basin (Alexander et al., 2005).

6.0 Source of the Uranium

Based on the petrography and $^{207}Pb/^{206}Pb$ ages of the uranium minerals there appears to be uranium mineralization at the Millennium deposit that pre-dates the Athabasca Basin sediments (~1710 Ma; Jefferson et al., 2007) and a main ore depositional event that is geochemically and geochronologically similar to mineralizing events associated with unconformity-type uranium deposits elsewhere in the Athabasca basin (Fayek and Kyser, 1997; Alexander et al., 2005).

Uraniferous metasediments are not uncommon in the Wollaston Group. The Karpinka Lake uranium prospect is an uneconomic deposit located approximately 30 km south of the Athabasca Basin and 50 km southwest of the Key Lake deposit. The deposit is hosted within graphitic metapelites of the Wollaston Group and uranium mineralization is comprised of small disseminated uraninite and brannerite associated with sillimanite in meta-arkoses. U-Pb ages for uraninite and brannerite range between 1770-1730 Ma (Williams-Jones and Sawiuk, 1985). While there is no genetic link between the Karpinka Lake uranium prospect and the Athabasca Basin unconformity-type uranium deposits, $^{207}Pb/^{206}Pb$ ages of 1750-1650 Ma obtained from the disseminated uraninite are comparable to the U-Pb dates obtained for uranium mineralization at the Karpinka Lake uranium prospect. Although it is not unusual to find uranium mineralization with similar ages in the Wollaston/Mudjatik Groups along the periphery of the

Athabasca basin (e.g., Beaverlodge, Rabbit L.) and Hecht and Cuney (2000) have suggested that monazite alteration in basement rocks can be a source of uranium associated with unconformity-type uranium deposits, the 1750-1650 Ma ages of uraninite from the Millennium deposit are the first documented pre-Athabasca ages from an unconformity-type deposit and establish the presence of a basement source for uranium mineralization which predates the primary mineralization events within the Athabasca Basin.

Fluid inclusion analysis suggests that a basinal brine was primarily responsible for the alteration of the basement rocks and deposition of the massive and vein-type uranium mineralization at the Millennium deposit. Subsequent to the main ore depositional event, several fluid events between 1450 and 900 Ma, likely related to distal tectonic events affected the U-Pb systematics of the uranium mineralization, including recent low-temperature meteoric fluids. Therefore, there are two possible sources of uranium at the Millennium deposit, the uraniferous basinal brines that leached uranium from the Athabasca sedimentary package and the uraniferous basement metasediments.

7.0 Acknowledgments

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