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A SHALLOW-BURIAL MINERALIZATION MODEL FOR THE UNCONFORMITY-RELATED URANIUM DEPOSITS IN THE ATHABASCA BASIN

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Abstract

The unconformity-related U deposits associated with the Proterozoic Athabasca Basin are among the largest and richest U deposits in the world. The conventional genetic model suggests that mineralization occurred under deep-burial (>5 km), diagenetic-hydrothermal conditions at normal geothermal gradients (~35°C/km). Based on regional geochronostratigraphic and ore geochronological data, it is inferred that, at the time of primary U mineralization (≥ ca. 1540 Ma), the burial depths of the unconformity surface were likely <~3 km. The elevated fluid pressures (up to 1,500 bars) used to support the deep-burial model were probably overestimated due to misinterpretation of accidentally entrapped halite crystals as daughter minerals in fluid inclusions. The elevated fluid temperatures (180°–250°C) estimated from fluid inclusion and clay mineral geothermometry from both mineralized and barren areas, which were interpreted to have resulted from deep burial at normal geothermal gradients at the time of mineralization, may be alternatively explained by local or basin-scale elevation of geothermal gradients at the time of mineralization, followed by continued burial and/or temporarily increased thermal gradients after mineralization. The shallow-burial mineralization model can better explain the geologic characteristics of the unconformity-related U deposits, including development of pervasive clay alteration halos, breccia zones, and dissolution vugs locally filled with drusy quartz, as well as evidence of fluid boiling recorded by fluid inclusions. The modified model emphasizes the importance of combined basinal (development of brines) and deep-seated geodynamic factors for large-scale U mineralization. Recognition of these factors is important for U exploration in the Athabasca Basin and similar basins elsewhere.

Introduction

The Proterozoic Athabasca Basin in northern Canada hosts a large number of world-class, high-grade (typically >1%, up to ~20% U), and large-tonnage (up to ~200,000 t U) U deposits and represents one of the most important U-producing systems in the world (Jefferson et al., 2007; Kyser and Cuney, 2015). These deposits are generally referred to as "unconformity related" because the mineralization typically occurs close to the unconformity between basinal sediments and the underlying crystalline basement (Jefferson et al., 2007; Kyser and Cuney, 2015), although some orebodies extend down to ~1 km below the unconformity (Cox et al., 2017). The deposits are generally considered to have formed from basinal brines under diagenetic-hydrothermal conditions (Pagel, 1975; Hoeve and Sibbald, 1978; Pagel et al., 1980; Hoeve and Quirt, 1984; Kotzer and Kyser, 1995; Derome et al., 2005; Richard et al., 2011, 2013, 2014, 2016; Mercadier et al., 2012). Based on a study of fluid inclusions in quartz overgrowths in sandstones from the Athabasca Basin, Pagel (1975) estimated that the fluid pressure and temperature at the base of the basin once reached 1,500 bars and 220°C, which correspond to a burial depth of ~5.7 km, assuming lithostatic fluid pressure and a rock density of 2.65 g/cm^3, resulting in a geothermal gradient of ~35°C/km. Subsequent fluid inclusion and clay mineral geothermometric studies suggested that the basal part of the Athabasca Basin, including the mineralized areas and barren areas, commonly underwent temperatures between 180° and 250°C, which were generally taken to support the notion that the unconformity-related U deposits in the Athabasca Basin were formed under deep burial conditions at normal geothermal gradients (Hoeve and Quirt, 1984; Kotzer and Kyser, 1995; Derome et al., 2005; Cloutier et al., 2009; Richard et al., 2016).

However, an examination of regional geochronostratigraphic data (Ramaekers et al., 2007), together with recent uraninite age dating (see references cited in next section) and the interpreted evaporitic seawater origin for the mineralizing fluids (Richard et al., 2011, 2013, 2014; Mercadier et al., 2012), suggests that primary U mineralization in the Athabasca Basin likely took place before maximum burial of the basin, at depths significantly shallower than previously thought. This paper presents evidence in favor of a shallow-burial mineralization environment, examines problems with the conventional diagenetic-hydrothermal model with respect to depth of mineralization, and discusses various factors affecting the revised model and its implications for exploration.

Geochronostratigraphic Constraints on Depths of Mineralization

The preserved strata in the Paleo- to Mesoproterozoic Athabasca Basin are divided into four major unconformity-bounded sequences comprising, from bottom to top, (1) Fair Point Formation, (2) Smart/Read and Manitou Falls

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formations, (3) Lazenby Lake and Wolverine Point formations, and (4) Locker Lake, Otherside, Douglas, and Carswell formations (Fig. 1; Ramaekers et al., 2007). Most of the units at present consist of fluvial quartz arenitic sandstone, with the exception of the Fair Point Formation (debris flows), Wolverine Point Formation (marginal marine mudstone/siltstone/sandstone), Douglas Formation (marine mudstone/siltstone/shale), and Carswell Formation (marine stromatolitic carbonates with siliciclastic interbeds). The current thickest stratigraphic section (~1.5 km), located in the east-central part of the basin, comprises strata from the Read to Otherside formations (Fig. 1). Adding a maximum thickness of 300 m for the Douglas Formation and 500 m for the Carswell Formation (Ramaekers et al., 2007) on top of the Otherside Formation, the minimum depth of the deepest part of the basin from the top of the Carswell Formation to the basal unconformity would be ~2.3 km (Fig. 1). Toward the margin of the basin, at current depths of <500 m, where many discovered U deposits are located, the stratigraphic thickness from the top of the Carswell Formation to the basement would be <1.5 km (Fig. 1). Based on decompaction-compaction simulations (Chi et al., 2013), a present stratigraphic thickness of 2.3 and 1.5 km would be decompacted to an original thickness of 3.2 and 2.7 km, respectively, at the end of deposition of the Carswell Formation (Fig. 1).

The sedimentation in the Athabasca Basin is inferred to have started after ca. 1720 to 1710 Ma (Jeanneret et al., 2017). A zircon U-Pb age of 1644 ± 13 Ma has been reported from locally reworked tuff layers in the Wolverine Point Formation (Rainbird et al., 2007), and U-Pb ages of 1.64 to 1.61 Ga have been reported for diagenetic fluorapatite in the Smart, Manitou Falls, and Wolverine Point formations (Cumming et al., 1987; Rainbird et al., 2003; Davis et al., 2011). An Re-Os isochron age of 1541 ± 13 Ma has been obtained for carbonaceous shales of the Douglas Formation (Creaser and Stasiuk, 2007). Subsequently, the strata in the Athabasca Basin were intruded by the 1267 ± 2 Ma Mackenzie diabase dikes (LeCheminant and Heaman, 1989), the 1165 ± 17 Ma Douglas River diabase dike (Bleeker and Chamberlain, 2015), and the 1109 ± 2 Ma Moore Lakes diabase-gabbro intrusion (French et al., 2002). Therefore, the age of sedimentation in the Athabasca Basin is bracketed between ca. 1720 and ca. 1267 Ma.

A large number of U-Pb ages of uraninite and some Ar-Ar ages of illite alteration related to U mineralization have been obtained for U deposits in the Athabasca Basin, ranging from ca. 1590 to 60 Ma (Fig. 2). Since uraninite is prone to isotopic resetting, many of these ages likely reflect U remobilization and, thus, Alexandre et al. (2009) suggested that the ca. 1590 Ma age represents the primary U mineralization event across the Athabasca Basin. However, the 1590 Ma age is from minor prospects and the maximum U-Pb ages obtained from uraninite in the largest U deposits (e.g., McArthur River and Cigar Lake) are less than ca. 1540 Ma (Fig. 2). It is also worth noting that xenotime (more robust than uraninite for dating) from the Maw zone rare earth element (REE) deposit, interpreted to be coeval with U mineralization in the region based on paragenetic constraints (Rabiei et al., 2017) and the fact that unconformity-related U deposits are generally enriched in heavy rare earth elements (HREEs) + Y (Normand, 2014), yielded a U-Pb age of 1547 ± 14 Ma (Rabiei et al., 2017). Based on these discussions and the regional geochronostratigraphic data, it is inferred that, within analytical uncertainty, the most important primary U mineralization event in the Athabasca Basin may have taken place at ca. ≥1540 Ma.

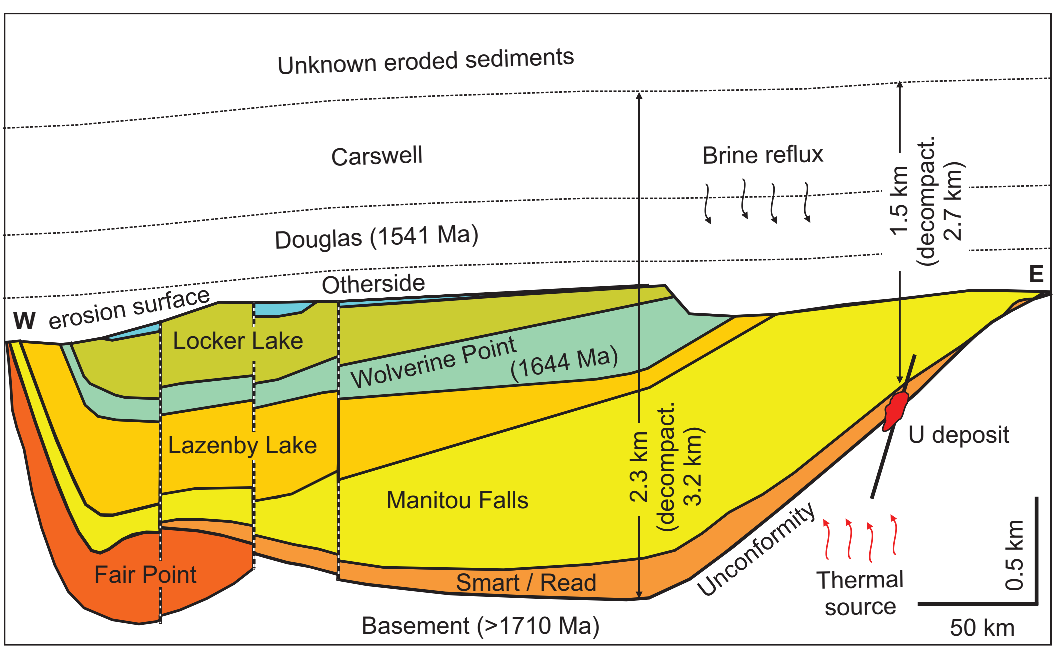

Fig. 1. Cross section of the Athabasca Basin showing the stratigraphic units of the remnant basin and inferred eroded strata (modified from Ramaekers et al., 2007). The depths of the basin at the end of the deposition of the Carswell Formation (the inferred time of primary U mineralization) are shown for the deepest part of the basin and in the middle of the marginal part of the basin, where many major U deposits are located.

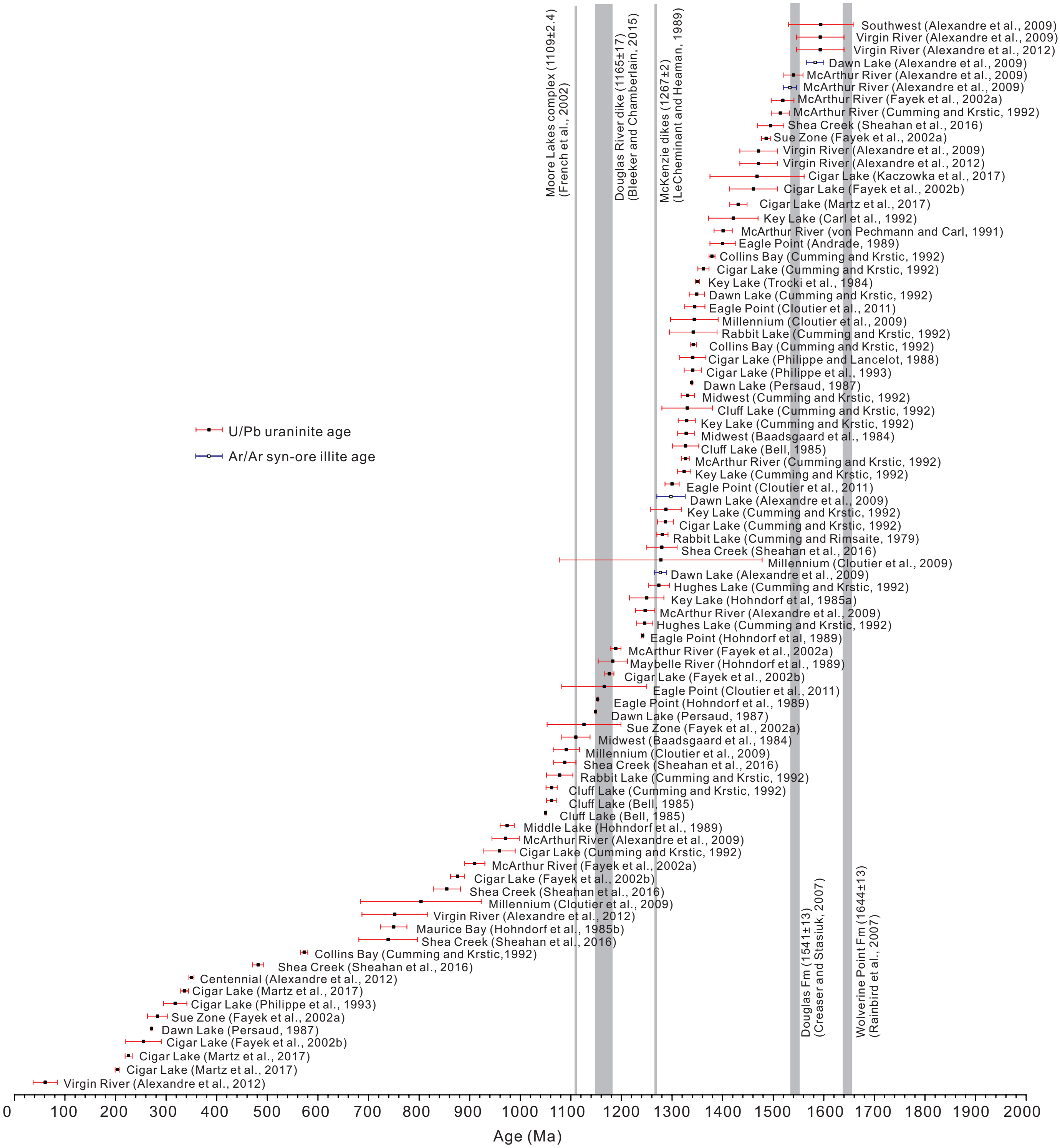

Fig. 2. A compilation of U-Pb ages of uraninite and Ar-Ar ages of illite associated with U mineralization in the Athabasca Basin. Also shown are the ages of a few stratigraphic units of the Athabasca Basin and magmatic events that affected the basin.

Halogen and noble gas geochemistry of fluid inclusions (Richard et al., 2011, 2013, 2014) and boron isotope signatures in tourmaline associated with U mineralization (Mercadier et al., 2012) support derivation of the ore-forming fluids from evaporitic seawater. The majority of the Athabasca Basin sediments were deposited in continental environments, except for parts of the Wolverine Point, Douglas, and Carswell formations (Ramaekers et al., 2007). Although no evaporite horizons have been found in the preserved Athabasca strata, the presence of gypsum pseudomorphs and solution-collapse breccias in the stromatolitic dolomite of the Carswell Formation provides evidence that evaporites likely developed during the deposition of the Carswell Formation (Hendry and Weathley, 1985). The age of the Carswell Formation is unknown but may be close to that of the underlying Douglas Formation (1541 ± 13 Ma; Creaser and Stasiuk, 2007), based on their transitional contact (Ramaekers et al., 2007).

Taking into consideration the geochronostratigraphic data and analytical uncertainties, it is inferred that the most important primary U mineralization event took place during the deposition of the Carswell Formation. As discussed above, by the end of the Carswell Formation deposition, the maximum depth of the Athabasca Basin is estimated at 3.2 km, and mostly <2.7 km for the marginal parts of the basin (Fig. 1). Therefore, most of the unconformity-related U deposits are inferred to have formed at depths less than ca. 3 km.

Discussion

The proposed shallow burial model (<3 km) for U mineralization in the Athabasca Basin contradicts the deep-burial hypothesis invoked in the conventional diagenetic-hydrothermal mineralization model (>5 km), which has been widely accepted (see Jefferson et al., 2007; Kyser and Cuney, 2015). It is therefore important to discuss relevant problems with the conventional model, how the revised model may reconcile with data that were used to support the conventional model, and whether the revised model can better explain the geologic characteristics of the deposits. Various uncertainties and factors that may affect the shallow-burial model are also discussed.

An important support for the deep-burial hypothesis is the high fluid pressures (1,500 bars) interpreted from a study of fluid inclusions in quartz overgrowths in the Athabasca Basin (Pagel, 1975). This pressure estimation was based on the assumption that the dissolution temperature of halite (which is present in some fluid inclusions) represents the trapping temperature, and that the corresponding pressure on the isochore of the fluid inclusion represents the trapping pressure (Pagel, 1975). However, halite-bearing fluid inclusions are uncommon in quartz overgrowths in the Athabasca Basin, and fluid inclusion assemblage (FIA) analysis suggests that the halite crystals more likely represent an accidentally entrapped solid rather than being daughter mineral (Chu and Chi, 2016). Misidentification of accidentally entrapped solids as daughter minerals can lead to significant overestimations of fluid pressure (Becker et al., 2008). Furthermore, to obtain fluid pressures as high as 1,500 bars in the basin would necessitate invoking a lithostatic pressure system, as was assumed in Pagel (1975). However, a lithostatic fluid pressure system is difficult to develop in sandstone-dominated sedimentary basins with slow sedimentary rates such as the Athabasca Basin (Chi et al., 2013, 2014a). If the fluid pressure regime was hydrostatic in the Athabasca Basin, as suggested by Chi et al. (2013, 2014a), a fluid pressure of 1,500 bars would correspond to a burial depth of 15 km, which would result in an unrealistically low geothermal gradient.

Another problem with the deep-burial concept is that it simplistically links high fluid temperatures (180°–250°C) with deep burial, implying that the mineralizing fluids were at temperatures similar to those of the ambient rocks and that the mineralization took place at maximum burial. Hoeve and Quirt (1984) invoked local heat anomalies induced by graphitic lithologies in the basement as a driving force of fluid flow, but the mineralization was nevertheless considered to occur in deep-burial environments. If a shallower burial environment is invoked during mineralization, as discussed above, the high fluid temperatures recorded in the rocks across the basin (e.g., Hoeve and Quirt, 1984; Chu and Chi, 2016) may be explained by two alternative mechanisms. One mechanism is that the Athabasca Basin was subjected to deep burial after the primary U mineralization at normal geothermal gradients, and another is that the basin underwent thermal event(s) causing basin-scale abnormal geothermal gradients. Such regional thermal events may be related to the ca. 1644 Ma tuffaceous rocks in the Wolverine Point Formation (Rainbird et al., 2007), ca. 1540 Ma basalt in the Kuungmi Formation in the Thelon Basin farther to the north (Chamberlain et al., 2010), ca. 1267 Ma Mackenzie dikes (LeCheminant and Heaman, 1989), ca. 1165 Ma Douglas River dike (Bleeker and Chamberlain, 2015), and ca. 1109 Ma Moore Lakes intrusion (French et al., 2002; Fig. 2). Other potential thermal events may include those related to the regional-scale, seismic "bright reflector," which extends for more than 160 km in the eastern Athabasca region at a present depth of ~8 km and probably represents a deep-seated magma sill (Mandler and Clowes, 1997; Hajnal et al., 2007), and the newly discovered carbonatites in the basement of the Athabasca Basin in the Patterson Lake area (Card and Noll, 2016), but the timing of the magmatic emplacements remains unknown. Although a magmatic event of the same age as the Kuungmi basalt in the Thelon Basin has not been identified in the Athabasca Basin and surrounding areas, the coincidence of the drastic change in depositional environment at the time of Douglas deposition (ca. 1541 Ma) in the Athabasca Basin with similar change occurring in the Thelon Basin (Lookout Point Formation carbonate overlying the Kuungmi Formation) suggests that similar deep-seated geodynamic processes were operating underneath the two basins at the same time. In fact, thermal events do not have to be manifested as magmatism, as elevated geothermal gradients can be developed in tectonically active, amagmatic environments (Bruhn et al., 2010; Rau and Forsyth, 2011). The Athabasca region was interpreted to be part of a rifting system at ca. 1550 Ma that eventually led to the breakup of the Nuna supercontinent (Ramaekers et al., 2017), and it is possible that regional geothermal gradients significantly higher than 35°C/km were once developed in the region.

The above two mechanisms, like the conventional deep-burial concept, assume that the elevated temperatures recorded in the mineralized areas and the ambient environments were related to the same burial conditions or thermal events. However, it is possible that the U mineralization systems represent local heat anomalies—i.e., the ore-forming fluids were significantly hotter than the ambient host rocks, as is considered by some authors to be a requirement to qualify as hydrothermal systems (White, 1957; Machel and Lonnee, 2002). Thus, the temperatures of the ambient rocks surrounding individual U deposits at the time of mineralization may have been normal, e.g., ~110°C for a depth of 2.5 km (assuming a normal geothermal gradient of 35°C/km and a surface temperature of 20°C). Such low background temperatures may be represented by the lower end of the spectrum of fluid inclusion homogenization temperatures reported from several deposits (e.g., Derome et al., 2005; Richard et al., 2016; Rabiei et al., 2017). The local heat anomalies may be related to fluid channeling along major structures linked with deep-seated heat sources, but the nature of the heat sources and the hydrodynamic conditions for the thermal advection remain to be investigated.

The shallow-burial mineralization model proposed in this paper more appropriately explains the geologic characteristics of the unconformity-related U deposits than the deep-burial model. The development of pervasive clay alteration halos and breccia zones and dissolution vugs locally filled with drusy quartz (Hoeve and Quirt, 1984; Quirt, 2003; Jefferson et al., 2007; Kyser and Cuney, 2015) typically occurs in ore systems developed at shallow crustal depths (e.g., epithermal deposits; Simmons et al., 2005). Fluid inclusion assemblages consisting of liquid-dominated, vapor-dominated, and vapor-only inclusions have been found in ore-stage quartz in several U deposits in Proterozoic basins in northern Canada and interpreted to indicate fluid boiling (Chi et al., 2017; Liang et al., 2017). While vapor-dominated and vapor-only inclusions were reported in earlier studies of U deposits in the Athabasca Basin (Dubessy et al., 1988; Derome et al., 2005), their significance in terms of fluid boiling was not recognized until recently (Chi et al., 2014b). Although fluid boiling or immiscibility can be caused by "flash vaporization" during seismic fracturing at depth (Weatherley and Henley, 2013), the low concentrations of nonaqueous volatiles in the vapor phase (Chi et al., 2017; Liang et al., 2017), as also observed in REE deposits that may be genetically linked with unconformity-related U deposits (Rabiei et al., 2017; Richter et al., 2018), are more consistent with boiling systems associated with epithermal-style mineralization (Wilkinson, 2001; Simmons et al., 2005). The low fluid pressures associated with boiling (Chi et al., 2017; Liang et al., 2017) are better explained by the suction pump model typical of epithermal-style systems (Sibson, 1987; Sibson et al., 1988), in which a fluid pressure regime fluctuates between hydrostatic and subhydrostatic, rather than between lithostatic and hydrostatic as is ascribed to fault valve-controlled fluid flow (Sibson, 1987; Sibson et al., 1988) and the conventional deep-burial concept of unconformity-related U mineralization (e.g., Derome et al., 2005).

Nevertheless, it must be pointed out that there are some controversies and uncertainties on certain aspects of research related to the model proposed in this study, which warrant further discussion and clarification, although the main conclusions remain unchanged. Firstly, although several studies on halogen and noble gas compositions of fluid inclusions (Richard et al., 2011, 2013, 2014) and boron isotopes of tourmaline associated with U mineralization (Mercadier et al., 2012) point to a seawater evaporation origin of the ore-forming fluids, depleted hydrogen isotopes of tourmaline appear to suggest a meteoric origin of the fluids (Adlakha et al., 2017). The boron isotope data may be alternatively interpreted as resulting from incorporation of boron in fluid during dissolution of carbonate or evaporitic rocks and preferential removal of ^{10}B by the crystallization of illite and kaolinite (Adlakha et al., 2017). However, an alternative interpretation of the depleted hydrogen isotopes in the tourmaline may be contribution of hydrocarbons in mineralization, as proposed by Hoeve and Sibbald (1978). Another complication is that, in addition to the potential development of evaporites in the Carswell Formation and in stratigraphically higher units, it has been proposed that evaporites may have been developed in the Wolverine Point Formation as well (Ramaekers, 2013; Ramaekers et al., 2017). However, the involvement of brines from the Wolverine Point Formation would implicate a mineralization depth even shallower than we propose here, so the above uncertainties or controversies do not affect the general conclusion that mineralization occurred at shallow depths.

Secondly, nothing is known about the total thickness of the Carswell Formation before erosion, and the possibility of evaporite strata being present above the currently preserved 500 m of Carswell strata cannot be ruled out. Likewise, no definitive information is available about what strata exactly lie below the Douglas Formation (Hoeve et al., 1985) and, therefore, the possibility that some pre-Douglas strata may have been eroded cannot be discounted. Furthermore, it is unknown whether or not the location of thickest sedimentation during deposition of the Carswell Formation was located near the preserved basin edge or elsewhere and, therefore, there is the possibility that the depth of burial near the preserved basin edge is similar to that in the preserved basin center. Nevertheless, the cross section shown in Figure 1, with 800 m of combined Douglas and Carswell formations being evenly added on top of the preserved strata, represents the best stratigraphic reconstruction that can be done based on available data. Although the exact depths of burial of the basal unconformity during mineralization are difficult to determine, they are likely much shallower than invoked in the conventional model.

Finally, given the wide range of uraninite U-Pb ages (Fig. 2), it has been suggested that there were multiple U mineralization events (e.g., Ramaekers et al., 2017) and, thus, it is possible that some mineralization may have taken place under deep burial conditions after deposition of the Carswell Formation. We interpret the spectrum of uraninite U-Pb ages as being a result of uraninite remobilization and isotopic resetting from a primary accumulation of uraninite (the first major mineralization event), as has also been suggested in some previous studies (e.g., Alexandre et al., 2009; Martz et al., 2017). The oldest uraninite U-Pb ages reported for a given deposit, such as the giant Cigar Lake deposit (1461 Ma, Fayek et al., 2002b; 1430 Ma, Martz et al., 2017; 1468 Ma, Kaczowka et al., 2017), may still be younger than that of the primary mineralization event. Geochronological data using more robust methods, such as xenotime U-Pb dating (Rabiei et al., 2017), are required to determine the age of the major primary mineralization. The main reason for not interpreting the multiple younger uraninite U-Pb ages as representing multiple mineralization events is that no distinct hydrothermal systems corresponding to different U-Pb ages have been found to overprint the main orebodies. In other words, although there may have been multiple thermal-fluid activities after the major primary mineralization, these events probably did not bring any significant additional amounts of U into the preexisting deposits (Martz et al., 2017), as such mineralization events would have been accompanied by macroscopically recognizable overprinting geologic features, in addition to resulting in younger U-Pb ages.

Implications for Exploration

The shallow-burial mineralization model implies that the unconformity-related U deposits in the Athabasca Basin did not form in an environment involving only the basin and immediate surroundings, but are rather controlled by a combination of basinal and deep-seated geodynamic factors. Recognition of these factors is important for U exploration.

The Athabasca Basin is endowed with unusually high grade and large tonnage U deposits. Almost all the unconformity-related U deposits are associated with reactivated basement faults (see Jefferson et al., 2007; Kyser and Cuney, 2015). The accumulation of large amounts of U in limited areas requires channeling of large amounts of uraniferous fluids through the sites of mineralization, which requires a robust driving force (Hoeve and Quirt, 1984; Raffensperger and Garven, 1995; Chi et al., 2013; Li et al., 2016, 2017). Although it has been shown that the deformation processes related to faulting can be an important driving force of fluid flow related to the unconformity-related U mineralization (Cui et al., 2012; Li et al., 2017, 2018), such processes alone may not be sufficient to form the large U deposits, as individual faulting events are relatively short-lived. On the other hand, fluid convection driven by thermal gradients, which has also been proposed for fluid flow related to the unconformity-related U mineralization (Raffensperger and Garven, 1995; Li et al., 2016), may not be effective without the permeability enhancement caused by faulting. A combination of the two processes may be required for the large-scale U mineralization. Based on the discussions above, we propose that both faulting and thermal convection near the sites of mineralization may be linked to a common, deep-seated geodynamic process through deep-rooted faults. Although most of the reactivated basement faults hosting the unconformity-related U deposits do not appear to extend to great depths (e.g., McArthur River area, Gyorfi et al., 2007; David Thomas, pers. commun., 2017), it is remarkable that major U deposits in the Athabasca Basin are distributed along certain deformation corridors, such as the Wollaston-Mudjatik transition zone in the eastern Athabasca Basin (Jefferson et al., 2007; Kyser and Cuney, 2015) and the Patterson Lake corridor in the southwestern part of the Athabasca Basin (Card and Noll, 2016). These regional deformation zones likely played a critical role in connecting the shallow-extended faults near the unconformity with deep-seated heat sources and providing sustainable driving forces for fluid flow, leading to large-scale U mineralization.

While deep-seated geodynamic processes may be essential for driving fluid flow around the sites of mineralization, as discussed above, development of basinal brines is critical for U dissolution and transport (Hoeve and Quirt, 1984; Komninou and Sverjensky, 1996; Richard et al., 2012). Moreover, the reflux of brine from the upper part of the basin (Fig. 1) may have enhanced fluid convection due to fluid density contrast (Koziy et al., 2009). The timing of the deep-seated geodynamic process and basinal brine development may be a determining factor for the formation of large unconformity-related U deposits. Before deposition of the Douglas and Carswell formations, the predominantly fluviodeltaic sediments in the Athabasca Basin were likely characterized by low-salinity fluids that have limited U-leaching capability and, therefore, little U mineralization may have occurred even if there was a deep-seated mechanism driving fluid circulation in the basin. Conversely, after the Carswell Formation, U contained in various source rocks may have already been extracted by the action of passing brines and, therefore, little additional U may have been brought to the preexisting U deposits even if various fluid flow mechanisms were still operating in the basin. Thus, it appears that simultaneous development of basinal brines and deep-seated geodynamic processes at the time of Douglas and Carswell deposition, as manifested by the drastic change in depositional environment in both the Athabasca and Thelon basins and occurrence of basalt in the Thelon Basin around that time, provided the best condition for large-scale U mineralization. Based on these analyses, it is proposed that, for future U exploration in the Athabasca Basin and similar basins elsewhere, attention should be paid to deep-rooted major structures and their relationships with secondary structures near the unconformity. Much more study is required to understand the nature of the deep-seated geodynamic processes, especially at the time when brine was actively developed in the basin.

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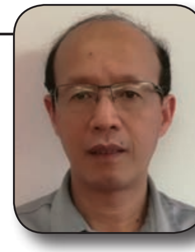

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