

ACTINIDES IN GEOLOGY, ENERGY, AND THE ENVIRONMENT

Compositional variation and timing of aluminum phosphate-sulfate minerals in the basement rocks along the P2 fault and in association with the McArthur River uranium deposit, Athabasca Basin, Saskatchewan, Canada†

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ABSTRACT

The Athabasca Basin hosts world class uranium deposits, such as the McArthur River deposit. This paper presents the occurrence of aluminum phosphate-sulfate (APS) minerals in the metasedimentary rocks along the P2 fault, the main ore-hosting fault of the McArthur River deposit. It compares the APS minerals along the P2 fault with those outside the fault, examined in this study, and those from other deposits of the Athabasca Basin and from other Paleo- to Mesoproterozoic basins worldwide.

APS minerals are common along the P2 fault but rare outside of the P2 fault zone in the basement and along the unconformity between the Athabasca sandstones and the basement. The APS minerals along the P2 fault occur with sudoite (\pm illite, magnesiofioitite) and are zoned with Sr-, Ca-, and S-rich cores (solid solution between svanbergite, crandallite, and goyazite) and LREE- and P-rich rims (close to florencite composition). APS minerals in the Bleached Zone (altered rocks along the unconformity consisting predominantly of kaolin and illite) are Sr-, Ca-, and S-rich (high svanbergite component) and occur with kaolin. APS minerals in the Red-Green Zone (mingled red hematitic and green chloritic basement rocks below the Bleached Zone) occur with sudoite and clinocllore. They contain relict cores of LREE- and As-rich arsenoflorencite-(Ce) and rims of svanbergite-goyazite-crandallite solid solution.

The occurrence of svanbergite-crandallite-goyazite along the unconformity suggests their formation by relatively oxidizing fluids during diagenesis of the overlying sandstones. The relict cores of arsenoflorencite-(Ce) in the Red-Green Zone are interpreted to be the product of paleo-weathering before the deposition of the Athabasca sandstones. Florencitic APS minerals are found along the entire studied strike length (7 km) of the P2 fault, including the ore zone and non-mineralized areas, but are absent outside the fault zone. The florencitic APS minerals contain low SO_4^{2-} in the ore zone, suggesting relatively reducing conditions during their crystallization. Zoned APS minerals (with svanbergitic cores and florencitic rims) proximal to ore contain elevated U (up to 16 ppm). These features suggest that diagenetic, oxidizing, and uranium-bearing fluids traveled along the P2 fault and became relatively reduced, especially within the ore zone. It also suggests florencitic APS minerals are contemporaneous with uranium mineralization. The restricted occurrence of florencitic APS mineral along the P2 fault in the basement suggests their use in identifying fertile basement structures associated with uranium mineralization.

Keywords: Hydrothermal alteration, APS, uranium mineralization, florencite, svanbergite, arsenoflorencite, diagenesis, paleo-weathering, unconformity-type uranium deposits

INTRODUCTION

The Athabasca Basin hosts numerous large uranium deposits (Fig. 1), which are classified as unconformity-related uranium deposits. The prevalent model for mineralization was first proposed by Hoeve and Sibbald (1978) and modified later by many researchers (e.g., Alexandre et al. 2005; Derome et al. 2005; Richard et al. 2011; Mercadier et al. 2012). This model suggests that sea-water derived, uranium-bearing oxidizing brines (25–35 wt% eq. NaCl) precipitated uranium ore at the unconformity when it reacted with a reducing fluid of currently unknown origin. Many

deposits occur in the proximity of deformation zones in the basement and it is suggested that re-activated basement faults served as conduits for uranium-bearing fluids (Jefferson et al. 2007) or reducing basement fluids to reach the unconformity (McGill et al. 1993). The McArthur River deposit, the largest discovered high-grade (average grade of 16.46% U_3O_8 ; Bronkhorst et al. 2012) uranium deposit on Earth, is situated along the P2 fault, a 13 km long reverse fault constrained to graphitic metapelite below the Athabasca Basin. Although geophysical and structural studies have been carried out on the P2 fault (e.g., Hajnal et al. 2010), the exact role of the fault in the mineralization remains uncertain.

In the Athabasca and Thelon basins of Canada, aluminum phosphate-sulfate (APS) minerals (also known as aluminophosphate sulfate) spatially associated with uranium deposits have been reported (Quirt et al. 1991; Gall and Donaldson 2006;

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† Special collection papers can be found on GSW at <http://ammin.geoscienceworld.org/site/misc/specialissuelist.xhtml>.

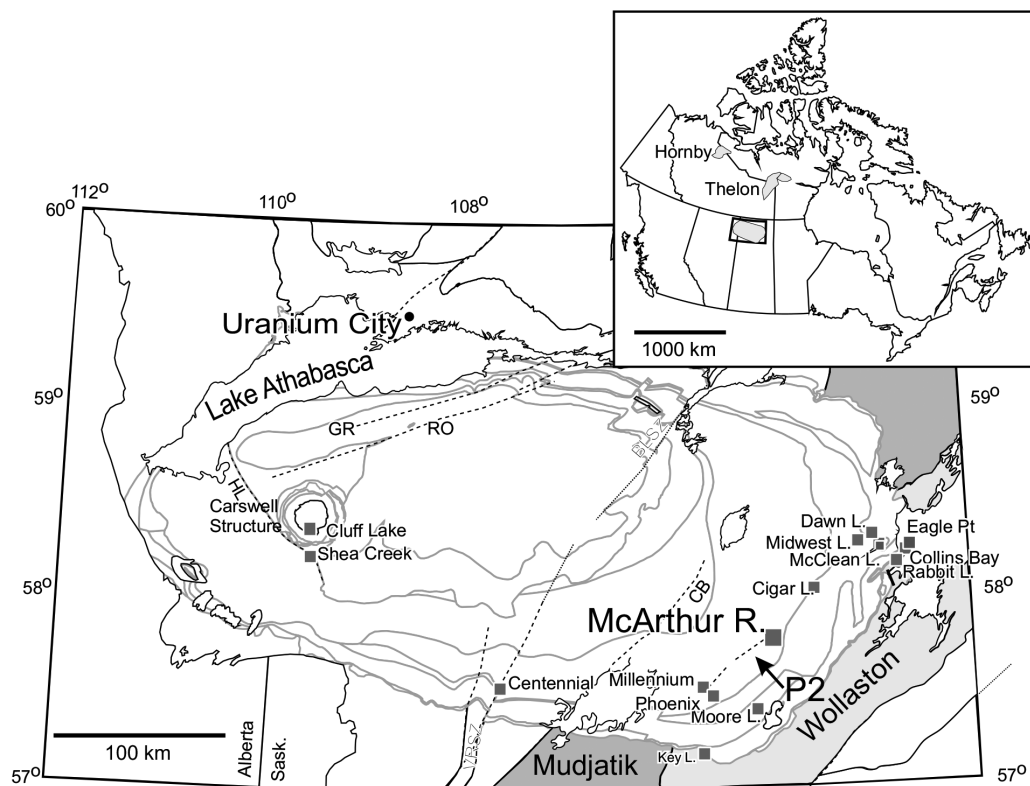


FIGURE 1. A map showing the location of the major uranium deposits (squares), including McArthur River deposit, and basement structures (dashed lines), including the P2 fault, in the Athabasca Basin (modified from Jefferson et al. 2007). The southeastern margin of the Athabasca Basin is underlain by the basement rocks of the Wollaston and Mudjatik Domains of the western Churchill Province. An insert shows the locations of the Athabasca basin relative to other two Mesoproterozoic sedimentary basins: Hornby and Thelon basins. Major shear zones: BB = Black Bay, BLSZ = Black Lake Shear Zone, CB = Cable Bay, GR = Grease River Shear Zone, RO = Robbilar, VRSZ = Virgin River Shear Zone.

Gaboreau et al. 2007; Riegler et al. 2014). APS minerals occur in various environments (Dill 2001) and form many solid-solution series with over 40 end-members (Jambor 1999; Stoffregen et al. 2000; Dill 2001). APS minerals have the general formula: $AB_3(XO_4)_2(OH)_6$, where A = mono-, di-, tri- or, more rarely, tetravalent cations (K^+ , Na^+ , Rb^+ , Ca^{2+} , Sr^{2+} , REE^{3+} , Th^{4+} etc.); B = trivalent cations (Al^{3+} , Fe^{3+}); and X = P^{5+} , S^{6+} , or As^{5+} . Since the incorporation of ions with different valences requires coupled substitution to accommodate charge balance, compositional zoning of APS minerals is commonly well preserved. This makes APS minerals excellent candidates for evaluating the chemical and physical characteristics of fluids from which they formed (Dill 2001; Beaufort et al. 2005; Gaboreau et al. 2005, 2007).

The focus of this paper is to present the occurrence and compositional variation of APS minerals in basement rocks along the P2 fault, discuss the role of the fault during mineralization and the timing of APS mineral formation with respect to uranium mineralization. In addition, the chemistry of APS minerals is compared with those along and outside of the fault zone in the basement, from other APS minerals studied in Athabasca Basin (within deposits or not), and from other Paleo- to Mesoproterozoic basins worldwide. The potential use of APS minerals in exploration for unconformity-related uranium deposits is also discussed.

GEOLOGICAL SETTING

Regional geology

The basement rocks in the eastern Athabasca Basin area are part of the Wollaston and Mudjatik Domains. The rocks of the Wollaston Domain consist of metapelite, metasediment, meta-arkose, calc-silicate, and quartzite (e.g., Annesley et al. 2005). They were metamorphosed under upper amphibolite to lower granulite conditions during the Trans-Hudson Orogeny (ca. 1.8–1.9 Ga; Lewry and Sibbald 1980; McKechnie et al. 2012). Abundant granitic pegmatite lenses intruded the metasedimentary rocks during peak metamorphism (Annesley et al. 2005; Jefferson et al. 2007).

Alteration immediately below the unconformity is laterally extensive and consists of a deeper Green Zone with sudoite (Al - Mg chlorite) and illite \pm Fe- Mg chlorite, a transitional Red-Green Zone with illite, sudoite, and hematite, an upper Red Zone with hematite and kaolin \pm illite, and, locally, there is Bleached Zone of kaolin and illite, immediately beneath the unconformity (Macdonald 1985; Quirt 2001; Adlakha et al. 2014). In addition to the Red-Green transitional Zone, the Red and Green Zones are mingled in places. The origin of these Zones has been in discussion. Macdonald (1985) considered them as the products of paleo-weathering before sandstone deposition, whereas Cuney et al. (2003) proposed their formation after the deposition of sandstones. Quirt (2001) and