

# The Millennium Uranium Deposit, Athabasca Basin, Saskatchewan, Canada: An Atypical Basement-Hosted Unconformity-Related Uranium Deposit

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## Abstract

The Millennium uranium basement-hosted unconformity-related deposit is one of the most recent discoveries of basement-hosted deposits, and may hold as much as 46.8 million pounds (18,000 metric tonnes U) at an average grade of 4.53 percent U<sub>3</sub>O<sub>8</sub>. The alteration zone associated with the deposit is atypical, as it consists predominantly of muscovite rather than the chlorite and muscovite commonly found in the other basement-hosted deposits of the Athabasca basin.

The preore stage consists of early minor clinocllore alteration at temperatures of about 275°C, interpreted to result from retrograde metamorphism of the basement rocks prior to the deposition of the Athabasca basin. This clinocllore event is followed by an extensive 1Mc muscovite alteration of the basement rocks by Na-K-Fe-rich basinal brines at temperatures of about 250°C, creating up to 25 percent void space in the basement rocks. Subsequently, a weak chamoisite alteration resulted from Fe-Mg-Ca-rich fluids with temperatures of about 300°C that evolved from reactions between the basinal brines and the basement rocks. Ore stage uraninite has an extrapolated chemical age of 1590 Ma and is contemporaneous with synore 1Mc muscovite and iron oxide deposited at temperatures near 250°C from fluids with similar  $\delta^{18}\text{O}$  but lower  $\delta\text{D}$  values to preore basinal fluids. The low  $\delta\text{D}$  values indicate postdepositional exchange of H isotopes with Cenozoic fluids. Postore alteration consists of dravite and sudoite precipitated from Mg-Ca rich fluids, from the same evolved basinal brines that precipitated preore chamoisite, at temperatures of about 185°C, filling voids created during the preore stage. Our results indicate that the pre- and synore minerals were formed dominantly by basinal fluids, with no contribution from basement fluids, which differ from some other basement-hosted deposits in the Athabasca basin where basement-derived fluid influx was more significant.

Several U-Pb and Ar-Ar resetting events recorded on preore muscovite and on uraninite are coincident with fluid flow induced by distal orogenies, remobilizing radiogenic Pb from the deposit. The radiogenic Pb remobilization events were not widespread as the presence of radiogenic Pb is restricted to basement rocks proximal to the deposit and along the unconformity.

## Introduction

PALEOPROTEROZOIC sandstone- and basement-hosted unconformity-related uranium deposits in the Athabasca basin, Canada, account for about one-third of the global stock of uranium (McGill et al., 1993; Krasenberg, 2004; Kyser and Cuney, 2008). There are two general end-member types of unconformity-related deposits: those hosted primarily in the sandstone above the unconformity (sandstone-hosted or egress-style) and those that occur in the metamorphic basement rocks below the unconformity (basement-hosted or ingress-style; e.g., Jefferson et al., 2007; Kyser and Cuney, 2008). In general, alteration associated with basement-hosted deposits consists of an outer illitic halo, an inner illitic-chloritic halo, and a core containing most of the uranium mineralization (e.g., Fayek and Kyser, 1997; Thomas et al., 1998; Alexandre et al., 2005). Zones of silicification and dravitzation are commonly observed above the mineralized zones (Thomas et al., 1998) and hydrothermal assemblages in sandstone units overlying basement-hosted deposits include quartz, kaolinite, illite, chlorite, and dravite (McGill et al., 1993). Basement-related mineralization in most cases is in close proximity to graphitic units related with pre-Athabasca basin steeply to moderately dipping fractures and breccias, which may extend down to 400 m into the basement (Thomas et al., 1998). Mineralization typically occurs as disseminated

and massive uraninite, with an average grade of 1 to 3 percent U<sub>3</sub>O<sub>8</sub>, although McArthur River has a much higher average grade of 14 percent U<sub>3</sub>O<sub>8</sub> (Thomas et al., 1998).

Two distinct models have been proposed to explain the source of uranium in basement-hosted deposits. One model suggests that the source of uranium is mainly from uranium-rich phases, such as apatite, zircon, and monazite from the sandstones of the Manitou Falls Formation. In this model, uranium is leached from these minerals by basinal oxidizing fluids and transported downward into suitable structural traps such as at fracture zones and faults in the basement, and then deposited by reaction with reducing rock types or by mixing with reducing fluids of basement origin (e.g., Wilson and Kyser, 1987; Kotzer and Kyser, 1995; Fayek and Kyser, 1997). However, Hecht and Cuney (2000) and Derome et al. (2003) propose that the source of uranium is monazite from the metamorphic basement rocks and that uranium is leached from these phases by basin-derived oxidizing brines, and then precipitated below or at the unconformity by mixing with reduced fluids of unknown origin or by interacting with Fe-bearing rocks.

The Millennium deposit, which was discovered in 2000 by Cameco Corporation (Roy et al., 2005; Fig. 1), occurs on a major post-Athabasca Group sandstone structural trend in the eastern Athabasca basin, in close proximity to a graphitic horizon at a depth of 650 m from the surface and 100 m below the unconformity (Roy et al., 2005; Figs. 2A, B, 3A).

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Present indicated resources are 46.8 million pounds (18,000 t U) at an average grade of 4.53 percent  $U_3O_8$  (Thomas, 2002; Roy et al., 2005). The mineralization at Millennium is situated in the footwall of a major reverse fault and is broadly strata bound, although several styles of mineralization are observed (Fig. 3A). The mineralization is essentially monometallic, with Pb and V contents increasing with uranium enrichment (Roy et al., 2005). Manitou Falls Formation sandstones above Millennium have the typical alteration observed in the sandstone above other basement-hosted deposits, with an envelope of illite, chlorite, kaolinite, dravite, and dickite (McGill et al., 1993; Roy et al., 2005). The most striking feature at Millennium is the mineralogy of the alteration envelope that surrounds the deposit, as it is composed mainly of illite, which is atypical of most basement-hosted deposits in which chlorite and illite are the dominant alteration minerals (Fig. 3B). Minor amounts of chlorite, dravite, kaolinite, and fine-grained hydrothermal quartz occur throughout the alteration zone of the Millennium deposit.

In this paper, we report detailed petrographic, mineralogical, and isotopic data from the Millennium deposit to constrain the mechanisms responsible for the formation of this atypical alteration zone and the uranium mineralization. Based on these results, we propose a model for the genesis of the deposit, with implications for exploration of similar deposits.

### Geology

The Millennium deposit is situated in the Paleoproterozoic Athabasca basin, at 45 km from its eastern margin, 35 km southwest of the McArthur River deposit, and 35 km north of the Key Lake deposit (Fig. 1). The deposit is hosted in basement rocks in the transition zone between the Archean and

Paleoproterozoic rocks of the Wollaston Domain and the Mudjatik Domain, both belonging to the Cree Lake Mobile zone of the Hearne province (Hoffman, 1988; Tran et al., 2003; Fig. 1).

The Wollaston Domain is a northeast-trending fold and thrust belt that is fault bounded to the east by the Peter Lake Domain and to the west by the Mudjatik Domain (Money, 1968; Fig. 1). Three main groups of rocks are distinguished (Lewry and Sibbald, 1977): (1) 2800 to 2950 Ma Archean granitic, granodioritic, and tonalitic orthogneisses and subordinate metamorphic rocks (Annesley et al., 2005), (2) unconformably overlying ~1920 Ma high-grade Paleoproterozoic graphitic and nongraphitic pelitic, psammopelitic, and psammitic gneisses, subordinate metaquartzite, calc-silicates, and amphibolites, as well as rare BIF of the Wollaston Group (Lewry and Sibbald, 1980; Tran et al., 2003), (3) 1810 to 1840 Ma deformed granitoids, minor gabbros, and pegmatites (Annesley et al., 2005).

The Mudjatik Domain is a northeast-trending fold and thrust belt that is fault-bounded to the east by the Wollaston Domain and to the west by the Virgin River Domain (Money, 1968; Fig. 1). It is composed of rocks similar in composition to the Wollaston Domain; however, it is dominated by granitoid gneisses derived in part from in situ migmatization and anatexis (Lewry and Sibbald, 1980) and contains a larger volume of late, peraluminous granite (Roy et al., 2005).

The Wollaston-Mudjatik transition zone is characterized by a structurally complex zone made up of elongated Archean granitoid domes (mega-boudins), thrust- and strike-slip structures, and related duplex structures (Annesley et al., 2005). The boundary is defined on the basis of lithological changes in the Archean basement, lithofacies changes in the Wollaston

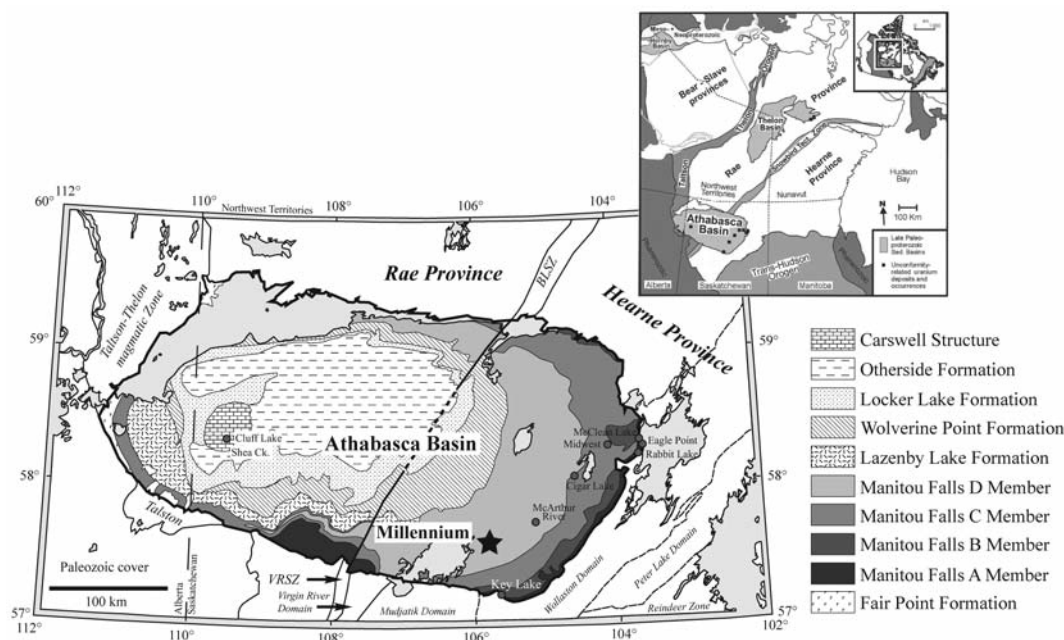


FIG. 1. Simplified geologic map of the Athabasca basin in northern Saskatchewan, Canada. The major lithotectonic units of its basement (provinces and their domains) are indicated in italics. Also shown is the position of the Millennium deposit (star) and major unconformity-related uranium deposits (circle). BLSZ = Black Lake Shear Zone; VRSZ = Virgin River Shear Zone. Modified after Sibbald and Quirt (1987).

Group, and changes in types of Hudsonian intrusive rocks. The boundary is a major anastomosing northeast-trending transcurrent shear zone associated with a thermotectonic front, and is defined as a transitional zone from thick-skin tectonics in the Wollaston Domain to thin-skin tectonics in the Mudjatik Domain (Annesley et al., 2005).

The rocks of the Wollaston and Mudjatik domains were complexly deformed and metamorphosed to amphibolite facies by the Trans-Hudson orogen, which reached peak metamorphism at ca. 1800 to 1820 Ma (Lewry and Sibbald, 1980; Kyser et al., 2000). Subsequent rapid uplift initiated the formation of the Athabasca basin at maximum age of 1750 Ma, as recorded by K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages (Burwash et al., 1962; Kyser et al., 2000; Alexandre et al., 2009), and at a minimum age of 1620 to 1640 Ma obtained on early diagenetic fluoroapatite (Rainbird et al., 2003). The Athabasca basin formed as a series of three northeast-southwest-oriented subbasins, with the easternmost Cree subbasin hosting the majority of the uranium deposits (Armstrong and Ramaekers, 1985; Kyser et al., 2000), and sedimentation continued until the deposition of the carbonaceous marine shale of the Douglas Formation at ca. 1540 Ma (Creaser and Statiuk, 2007).

Sediments of the Athabasca basin consist of sequences of Paleoproterozoic and Mesoproterozoic polycyclic, mature fluvial to marine quartz sandstone, collectively referred to as the Athabasca Group. These were deposited in a near-shore shallow shelf environment (Ramaekers and Dunn, 1977; Ramaekers, 1990). The Athabasca Group in the eastern part of the Athabasca basin is made up exclusively of the Manitou Falls Formation, which consists of coarse to fine-grained, hematite-rich conglomerates along thin stratigraphic horizons, indicating oxidation of heavy mineral layers and silty sandstones filling (Ramaekers, 1990). Ramaekers et al. (2007) proposed a revised stratigraphy of the Athabasca Group introducing newly recognized Smart Formations in the western Athabasca and Read Formation in the eastern Athabasca, which replace the A Member of the Manitou Falls Formation. Ramaekers et al. (2007) also subdivide the Manitou Falls Formation, introducing the Warnes Member (MFw), Raibl Member (MFr) and Bird Member (MFb), that are the equivalent of the Manitou Falls B Member, but are attributed to the Karras deposystem for the Warnes Member, Moosonee deposystem for the Raibl Member and the Ahenakew deposystem for the Bird Member. To be consistent with past publications and industry practices, this paper follows the original stratigraphy proposed by Ramaekers (1990) and will refer to the Read Formation as the Manitou Falls A Member and the Warnes, Raibl, and Bird members of the Manitou Falls Formation as the Manitou Falls B Member.

The Manitou Falls Formation and underlying basement are cut by a series of mafic dikes known as the McKenzie dike swarms (Cumming and Kristic, 1992), dated at  $1267 \pm 2$  Ma from U-Pb date from baddeleyite (LeCheminant and Heaman, 1989). They range from 1 m to several hundred meters wide, and are controlled by tensional trends associated with left-lateral movement along the ancient Hudsonian faults (Hoeve and Sibbald, 1978; Sibbald and Quirt, 1987).

The Millennium deposit is located within Paleoproterozoic metasedimentary basement rocks of the Wollaston-Mudjatik

transition zone at a depth ranging from 600 to more than 750 m from the surface, and from 100 to more than 150 m below the sandstone-basement unconformity (Figs. 1, 2A, B, C, 3A). The deposit is interpreted to lie along the northwest-trending limb of a Z-type parasitic fold structure associated with the east limb of a larger, regional, north-plunging synformal fold that closes to the south-southwest (Thomas, 2002). The mineralization is located between two reverse faults and is essentially stratabound (Fig. 3A). The footwall reverse fault, known as the Mother fault, is filled with preore quartz, and the hanging wall reverse fault is associated with a cordierite-graphite metapelitic gneiss unit closely associated with the mineralization (Fig. 3A). Basement rocks consist of graphitic metapelitic schists and gneisses and lesser metacalcic pelitic rocks that have been intruded by numerous pegmatitic and granitic rocks (Fig. 3A; Thomas, 2002). They are overlain by the Paleoproterozoic Athabasca Group which consists of 500 to 700 m of diagenetically altered A, B, C, and D members of the Manitou Falls Formation (Ramaekers, 1990; Roy, 2005) cut by fractures and faults. The mineralization is hosted within the metapelitic gneisses and is overprinted by extensive illite alteration (Roy et al., 2005; Fig. 3B). The alteration pattern was interpreted by Thomas (2002) to reflect a zonation from distal saussuritization (plagioclase retrogression) and sericitization, through a more proximal zone of chloritization into a central zone of increasing illitic and dravite alteration. In contrast, other major basement-hosted deposits are characterized by a small outer illitic halo, a large inner chloritic halo and a core containing most of the uranium mineralization (e.g., Fayek and Kyser, 1997; Thomas et al., 1998; Alexandre et al., 2005).

Uranium mineralization consists predominantly of uraninite with minor amounts of coffinite (Roy et al., 2005) and occurs in a variety of styles, including massive foliation-controlled replacement, uraninite matrix in breccias, irregular fracture-controlled infillings and thin vein-type uraninite, bleblike aggregates and thin discordant uraninite veinlets and rims around fragments or quartz veins (Thomas, 2002). Massive replacement type is the dominant style of mineralization, whereas fracture infilling and vein-type are less well developed (Thomas, 2002). Textures in breccia-hosted mineralization suggest a progression from simple fracture-controlled, through more complex hydraulic fracturing, and finally into corrosive solution breccias characterized by progressive rounding and embayment of clasts (Thomas, 2002). Width and grade of the ore zones are variable with grades ranging between 1 and 4 percent U over 20 to 30 m (Roy et al., 2005).

### Methodology

A total of 84 samples were taken from 15 drills holes delineating a north-south transect in the Manitou Falls Formation sandstone and a east-west transect in the Manitou Falls Formation sandstone and underlying basement (Figs. 2A, B, 3A). Polished thin sections of all samples were examined using conventional transmitted and reflected light microscopy to determine mineral paragenesis. All samples were analyzed with a portable infrared mineral analyzer (PIMA) in order to conduct preliminary identification of the hydrous minerals. The samples were crushed and sieved, and clay minerals were extracted from the coarsest crushed fraction (>1.4 mm) by

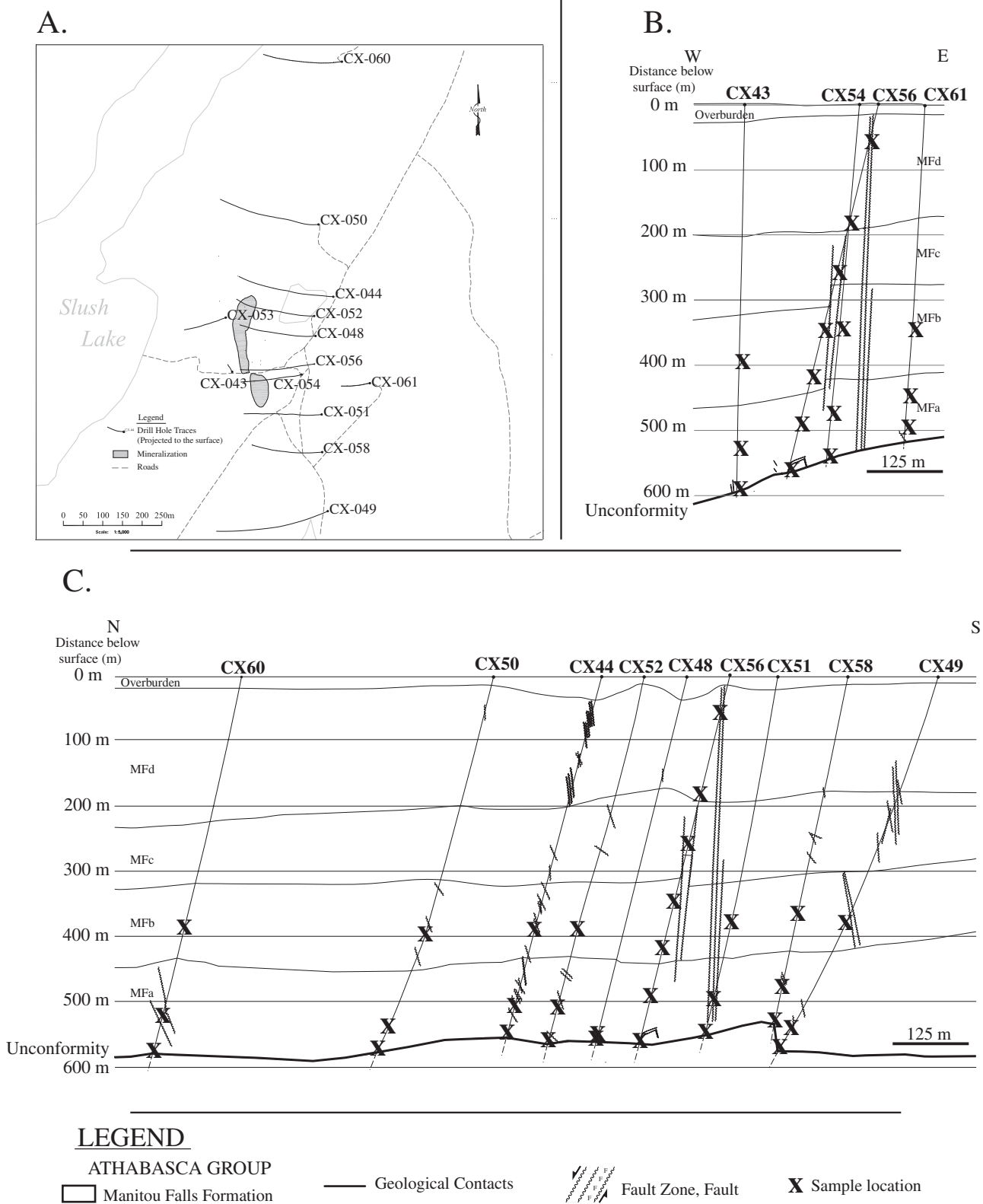


FIG. 2. (A) Schematic plan view of the orebodies of the basement-hosted Millennium deposit with the location and orientation of the drill holes sampled, (B) and (C) schematic cross sections of lithology and structure of the Manitou Falls Formation above the basement-hosted Millennium deposit. Also shown is the location of the drill holes sampled and samples taken.

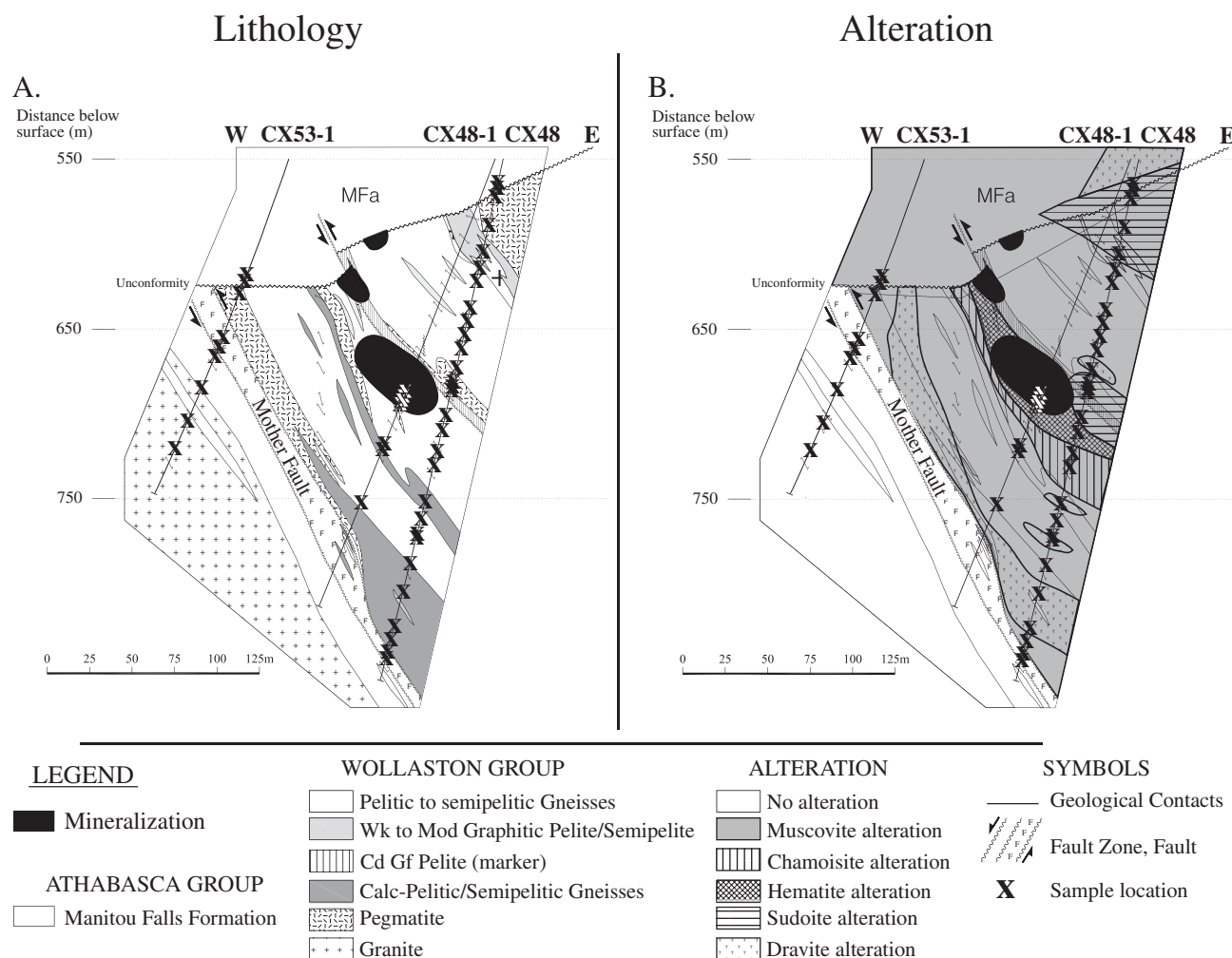


FIG. 3. (A) Schematic cross section of lithology, structure, and orebodies and (B) alteration of the basement-hosted Millennium deposit based on detailed logging of three drill cores and compilation of drill cores logged by Cameco Corp. (modified from Roy et al., 2005). Also shown is the location of the drill holes sampled and samples taken.

ultrasound disintegration. X-ray diffraction (XRD) analyses were performed on all size fractions of the mineral separates obtained from ultrasound disintegration (<2, 2–5, and >5  $\mu\text{m}$ ) using a Seimens X-Pert at Queen's University, Kingston, Canada. The <2- $\mu\text{m}$  pure monomineralic and mixed clays separates were selected for stable isotope analyses and 2 to 5  $\mu\text{m}$  pure monomineralic separates of muscovite were analyzed by  $^{40}\text{Ar}/^{39}\text{Ar}$  techniques. Chemical compositions of alteration minerals were determined by electron microprobe analyses (EMPA) using a Camebax MBX electron microprobe equipped with 4 wavelength dispersive X-ray spectrometer (WDX) at Carleton University, Ottawa, Canada. Analyses are accurate to 1 to 2 percent relative for major elements (>10 wt %), 3–5 percent relative for minor elements (>0.5 – <5.0 wt %). As detection limit is approached (<0.1 wt %), relative errors approach 100 percent. The compositions of chlorite and muscovite were used to estimate their temperatures of formation. The chemical composition of chlorite and muscovite was used to estimate temperatures of formation based on tetrahedral site occupancy (Cathelineau, 1988) and are accurate to within 30°C.

For stable isotopes, oxygen was extracted using the  $\text{BrF}_5$  method of Clayton and Mayeda (1963) and  $\delta^{18}\text{O}$  values were measured using a dual inlet Finnigan MAT 252 isotopic ratio mass spectrometer. Hydrogen isotope compositions were determined using a TC/EA Thermo Finnigan and a DeltaPlus XP Finnigan Mat mass spectrometer. O and H isotope compositions are reported in the  $\delta$  notation in units of per mil relative to the standard V-SMOW. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values were reproducible to  $\pm 0.2$  and  $\pm 3$  per mil, respectively. Oxygen isotope fractionation factors used throughout this paper are those proposed by Wenner and Taylor (1971) for water-chlorite, O'Neil and Taylor (1969) for water-muscovite, and Fayek and Kyser (2000) for water-uraninite. Hydrogen isotope fractionation factors used are those proposed by Marumo et al. (1980) for water-chlorite and Vennemann and O'Neil (1996) for water-muscovite. In previous studies, the water-illite fractionation factor was used instead of water-muscovite. Hydrogen water-illite fractionation factors of Yeh (1980) used in previous studies were calibrated in the Texas Gulf Coast and used a natural diagenesis progression from kaolinite to smectite to illite-smectite to illite. The illite chemical composition from

the Texas Gulf Coast varies between 2 to 6 percent  $K_2O$  and 2 to 6 percent  $FeO$  (Awwiller, 1993) and is different from the chemical composition of the white mica present in the Athabasca, where  $K_2O$  generally varies between 8 and 10 percent and  $FeO$  is usually <1 percent (Wilson and Kyser, 1987; Kotzer and Kyser, 1995; Alexandre et al., 2005). Moreover, Vennemann and O'Neil (1996) pointed out that  $Fe$  content has the strongest effect on the fractionation of hydrogen-mineral, wherein the water-mineral fractionation factor increases with decreasing  $Fe$  content. The  $\delta D$  values of the fluids are 38 per mil higher at 250°C using the muscovite-water fractionation factors relative to those using illite-water. Therefore, we prefer the muscovite-water fractionation factor of Vennemann and O'Neil (1996), as the  $Fe$  content is closer to what is observed in muscovite from the Athabasca basin.

U-Pb isotope ratios were determined using LA-HR-ICP-MS (Chipley et al., 2007), using a Finnigan MAT ELEMENT HR-ICP-MS and a NEPTUNE HR-MC-ICP-MS, both equipped with a high-performance Nd:YAG New Wave UP-213 laser ablation system at the Queen's Facility for Isotope Research (QFIR). Ablation of uraninites was achieved on polished thin sections using a 35- to 40- $\mu m$  spot size with 35 to 40 percent laser power at a frequency of 2 Hz. The gas (argon in all cases) flows were as follows: cooling gas, 15 l/min; auxiliary gas, 1.0 l/min; sample carrier gas, 1.0 l/min. A low mass resolution of 350 (defined as the ratio of mass over peak width at 5% of the signal height) was used. For each sample,  $^{204}Pb$ ,  $^{206}Pb$ ,  $^{207}Pb$ ,  $^{235}U$ , and  $^{238}U$  were measured and corrections for common  $Pb$  were made scan-by-scan to each spot. No corrections were made to the  $^{238}U/^{235}U$  ratios as they were near the 137.88 natural ratio.

$^{40}Ar/^{39}Ar$  dating was performed on two pure monomineralic separates of muscovite using the 2- to 5- $\mu m$  size fraction. Plateau ages were calculated using not less than 70 percent of the gas released and three consecutive steps that overlap in their  $1\sigma$  error margin, whereas pseudoplateau ages are defined by 30 to 70 percent of the gas released. The  $^{40}Ar/^{39}Ar$  dating was performed at the Noble Gas Laboratory, Pacific Centre for Isotopic and Geochemical Research, University of British Columbia. Mineral separates were wrapped in aluminum foil and stacked in an irradiation capsule with similar-aged samples and neutron flux monitors (Fish Canyon Tuff sanidine (FCs), 28.02 Ma (Renne et al., 1998)). The samples were irradiated at the McMaster Nuclear Reactor in Hamilton, Ontario, for 90 MWH, with a neutron flux of approximately  $6 \times 10^{13}$  neutrons/cm<sup>2</sup>/s. Analyses ( $n = 45$ ) of 15 neutron flux monitor positions produced errors of <0.5 percent in the  $J$  value. The mineral separates were step-heated at incrementally higher powers in the defocused beam of a 10W  $CO_2$  laser (New Wave Research MIR10) until fused. The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, as well as interfering  $Ar$  from atmospheric contamination and the irradiation of  $Ca$ ,  $Cl$ , and  $K$  (isotope production ratios:  $(^{40}Ar/^{39}Ar)_K = 0.0302 \pm 0.00006$ ,  $(^{37}Ar/^{39}Ar)_{Ca} = 1416.4 \pm 0.5$ ,  $(^{36}Ar/^{39}Ar)_{Ca} = 0.3952 \pm 0.0004$ ,  $Ca/K = 1.83 \pm 0.01(^{37}Ar_{Ca}/^{39}Ar_K)$ .

Forty-one Manitou Falls Formation sandstones and 14 basement samples were analyzed for leachable  $Pb$  and  $U$  isotopes and leachable trace elements. Samples were crushed and then leached following the technique of Holk et al. (2003). The 0.50- to 1.40-mm crushed fraction was used and about 0.5 g of sample and 5 ml of 0.02 M  $HNO_3$  were loaded into a polyurethane tube, placed in an ultrasonic bath for 120 min and centrifuged. One gram of the liquid was diluted with 100 g of 1 percent  $HNO_3$  spiked with  $^{115}In$  and the  $Pb$  isotope ratios and trace element concentrations were measured using a Finnigan MAT ELEMENT high-resolution ICP-MS. The  $Pb$  and  $U$  isotope ratios were calculated using the signal intensities (counts/s) in low-resolution mode and have an average uncertainty of ca. 1 percent based on repeat analyses. Corrections were made for interferences from  $Hg$  and mass fractionation was monitored using  $Tl$  in the solutions and externally with in-house and NIST  $Pb$  isotope standards (NBS 981, normal  $Pb$  and NBS 983, radiogenic  $Pb$ ). For each sample,  $^{201}Hg$ ,  $^{202}Hg$ ,  $^{204}Pb$ ,  $^{206}Pb$ ,  $^{207}Pb$ ,  $^{208}Pb$ ,  $^{235}U$ , and  $^{238}U$  were measured, blank subtracted, and  $^{204}Pb$  was corrected for  $^{204}Hg$  interference using  $^{202}Hg$ . Concentrations were corrected for instrument drift and matrix using  $^{115}In$  as an internal standard and external calibration for element concentrations and blank subtraction.  $^{206}Pb/^{204}Pb$  ratios greater than 30 were considered radiogenic.

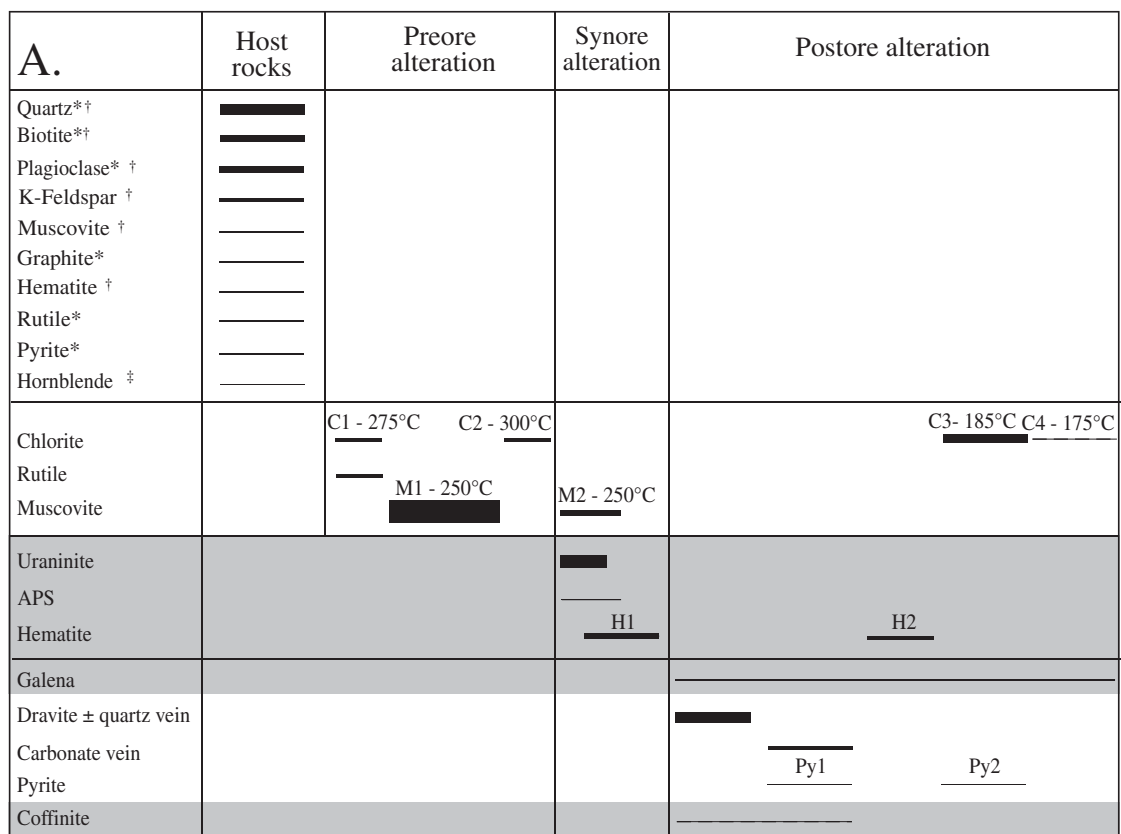
### Paragenesis of Alteration Minerals

Mineral paragenesis for the sub-Athabasca basement and the Manitou Falls Formation sandstones based on textural relationships are shown in Figure 4A and B, respectively. Three main stages of alteration were recognized in the basement (preore, synore, and postore) and four main stages of alteration were recognized in the basin (diagenesis, early and late hydrothermal alteration, and late alteration).

### Basement alteration

Detailed basement host-rock descriptions by Roy et al. (2005) described 10 stratigraphic units consisting of metapelitic to metasemipelitic to metacalcpelitic gneisses associated with minor graphite, a cordierite-graphite metapelitic gneiss unit, granites, pegmatites, and minor amphibolites (Figs. 3A, 4A). Mineral assemblages in the metapelitic to metasemipelitic gneisses consist of fine-grained quartz, plagioclase, biotite, rutile, and minor amount of graphite (Fig. 5A). Metacalcpelitic gneisses contain the same assemblage as metapelitic to metasemipelitic gneisses with the addition of carbonate minerals. The cordierite graphitic metapelitic gneiss consists of fine-grained cordierite, graphite, quartz, plagioclase, biotite, and rutile. The granite and pegmatite units consist of medium- to coarse-grained quartz, plagioclase, potassium feldspar, muscovite, and biotite. One small layer of amphibolite (~1.5 m) was identified and consists of hornblende and plagioclase.

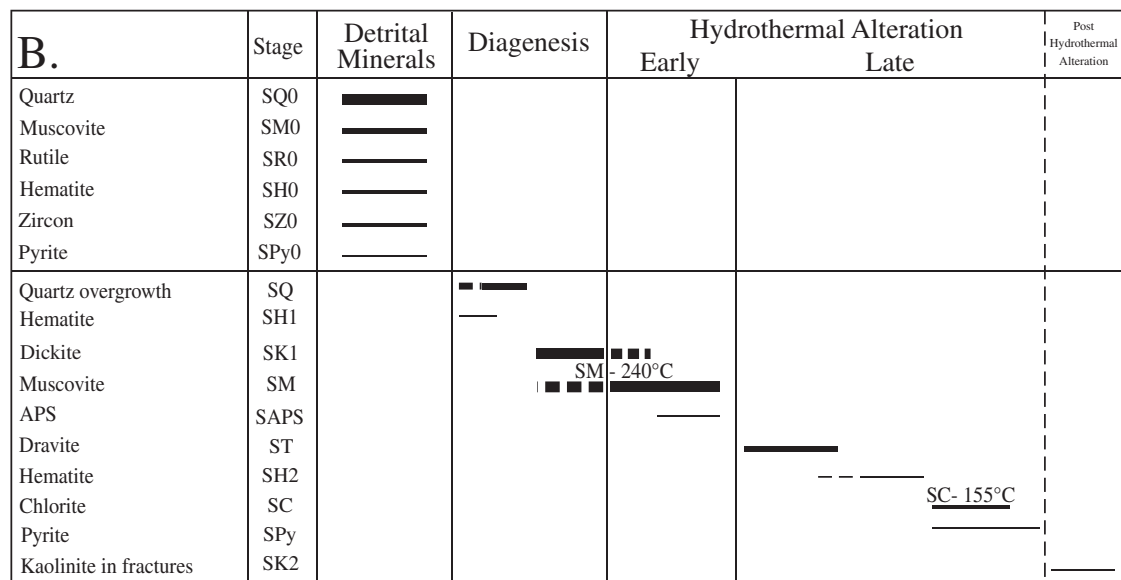
Early preore alteration of the metamorphosed basement metapelitic assemblages is characterized by C1 chlorite alteration of fine- to medium-grained (0.5–10 mm) biotite within the metapelites (Figs. 4A, 5B) and recrystallization of rutile needles present within the biotite crystal to rutile aggregates in the chlorite crystal (Fig. 5B). This relationship is only observed in the distal alteration zone, which is >75 m from the



████████ In ore zone

Relative timing →

\* Pelites † Granite and pegmatite ‡ amphibolite



Relative timing →

FIG. 4. General mineral paragenesis for (A) basement rocks and (B) Manitou Falls Formation sandstones of the Millennium deposits. Three main alteration stages for the basement rocks include pre-, syn-, and postore alteration and four main stages for the Athabasca Group sandstones include early, peak, and late diagenesis and late alteration. The thickness of the lines indicates the relative abundance. Dashed lines indicate uncertainty in the position. Also shown is the primary mineral present in pelitic rocks (\*), granites and pegmatites (†) and amphibolite (‡). Temperatures associated with the different alteration minerals are derived from their chemistry and are accurate to within 30°C (see text for detailed explanation).

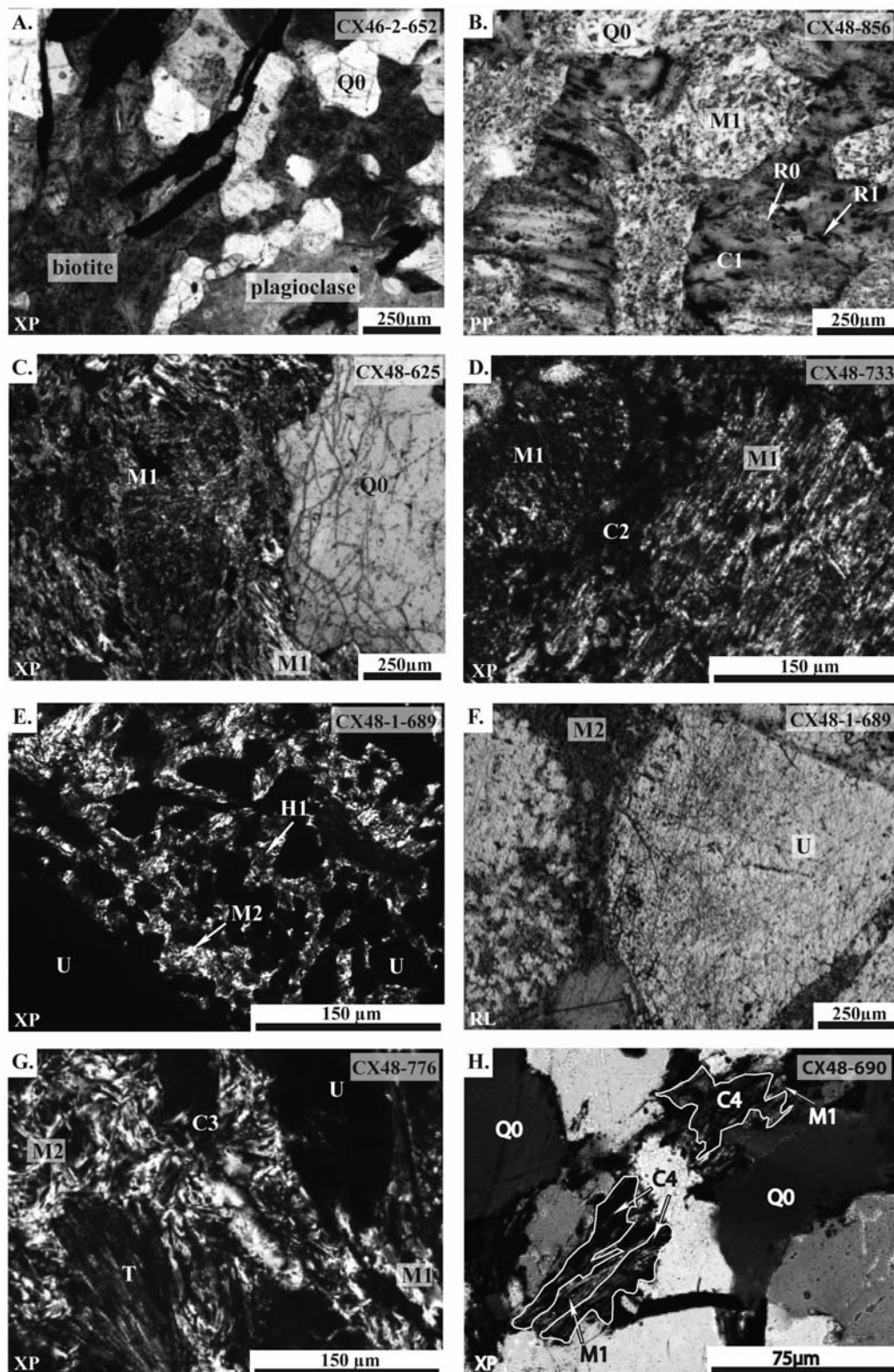


FIG. 5. Photomicrographs of typical basement rock mineral phases from pre-, syn- and postore. (A) fresh metapelite sample containing biotite, quartz, and plagioclase. (B) Preore C1 chlorite altering biotite and rutile (R0) to R1 rutile crystals. (C) Preore M1 muscovite alteration within metapelite. (D) Preore C2 Fe-rich chlorite altering preore M1 muscovite. (E) Massive uraninite (U) and associated synore M2 muscovite and H1 iron oxide. (F) Massive uraninite (U) showing a fine mottled and speckled appearance and associated synore muscovite (M2). (G) Postore dravite (T) crosscutting synore M2 muscovite being altered by C3 chlorite. (H) Postore chlorite (C4) altering preore muscovite (M1). PP = plane-polarized light, XP = cross-polarized light, RL = reflected light.

ore zone. Subsequently, these assemblages were overprinted by pervasive M1 muscovite alteration, creating medium- to fine-grained anhedral muscovites (Figs. 4A, 5C). This muscovite alteration is observed proximal to the mineralization, but extends into the distal alteration zone up to 100 m from the ore zone. Prior to synore alteration is minor replacement of M1 muscovite to dark green C2 chlorite in the footwall of the fault associated with the cordierite-graphite metapelitic gneiss unit (Fig. 5D).

Synore alteration of the basement rocks consists of zones of massive uraninite 5 to 10 m below the cordierite-graphite metapelitic gneiss unit of the hanging-wall fault (Figs. 3A, B, 4A, 5E) and zones of disseminated uraninite in the hanging wall of the Mother fault (Fig. 5F). Uraninite has a finely mottled and speckled appearance, forms euhedral (Fig. 5E), colloform, or anhedral grains (Fig. 5F), and is typically zoned in reflected light and backscattered electron images. Lower reflectivity or porous zones, particularly those in close proximity to the rims of the uraninites, are interpreted to indicate recrystallization during postore alteration stages. Uraninite is spatially associated or rimmed with medium- to coarse-grained (10 to 300  $\mu\text{m}$ ), anhedral to euhedral M2 muscovite and fine-grained H1 hematite (Fig. 5E, F). Some rare fine-grained euhedral aluminium phosphate-sulfate (APS) minerals occur with the disseminated mineralization within M2 muscovite aggregates.

Postore alteration is characterized by the occurrence of minor dravite as fine-grained acicular dravite aggregates (50–300  $\mu\text{m}$ ) and as veinlets of dravite  $\pm$  quartz (50–500  $\mu\text{m}$ )

overprinting the pre- and synore assemblages throughout the alteration zone (Fig. 5F). Locally, brecciated zones 25 to 40 m wide containing a matrix of fine-grained dravite occur in the hanging wall of the Mother fault (Fig. 3B). Small amounts of acicular coffinite (Fig. 6A) rim uraninite crystals in the ore zone and are interpreted to have formed between the dravite and later calcite precipitation. Minor amounts of thin (50–300  $\mu\text{m}$ ) calcite  $\pm$  Py1 pyrite veins cut the dravite aggregates and veinlets and H2 hematite partially replaces H1 hematite. Fine-grained C3 chlorite (5–100  $\mu\text{m}$ ; Fig. 5F) with minor Py2 pyrite occurs in corroded zones filling the voids created by prior alteration, and is one of the late phases. Locally, C4 chlorite has altered, medium-grained M1 muscovite in the fault associated with the cordierite-graphite metapelitic gneiss unit and is interpreted to have been formed during the late postore stage based on geothermometric results.

#### *Alteration of Manitou Falls Formation sandstones*

The earliest diagenetic textures preserved in the sandstones are thin veneers of red-brown SH1 hematite and poorly to well-developed syncompaction SQ1 quartz overgrowths on detrital SQ0 quartz grains followed by fine-grained SK1 dickite (Figs. 4B, 7A, B, C). Fine-grained SM muscovite (Fig. 7A, B, C) occurs, filling corroded zones in quartz overgrowths, characteristic of early hydrothermal alteration minerals throughout the Manitou Falls Formation sandstones and indicative of significant water/rock ratios (Wilson and Kyser, 1987; Kotzer and Kyser, 1995). Minor amounts of fine-grained euhedral APS minerals (SAPS) are observed to have

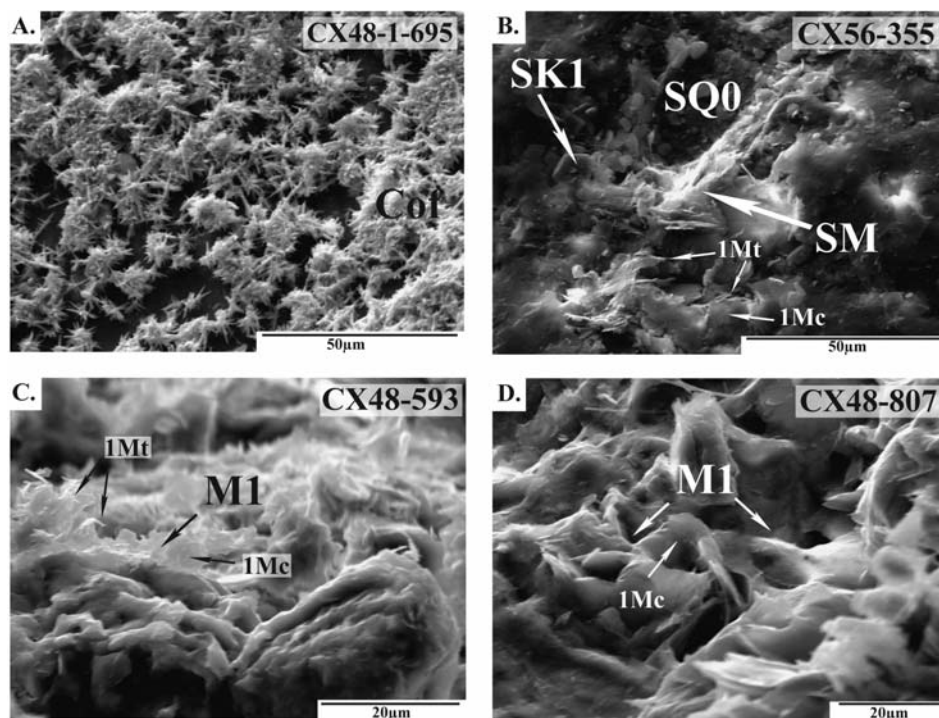


FIG. 6. Secondary electron scanning electron microscope microphotographs of (A) Basement uraninite alteration to acicular coffinite (Cof). (B) Detrital quartz (SQ0), peak diagenesis muscovite (SM) and peak diagenesis dickite (SK1) of Athabasca Group sandstone, with peak diagenesis 1Mc muscovite showing overgrowth of the 1Mt polytype. (C) Basement preore muscovite (M1) close to the unconformity having the 1Mt polytype. (D) Basement preore muscovite (M1) below the ore zone having the 1Mc polytype.

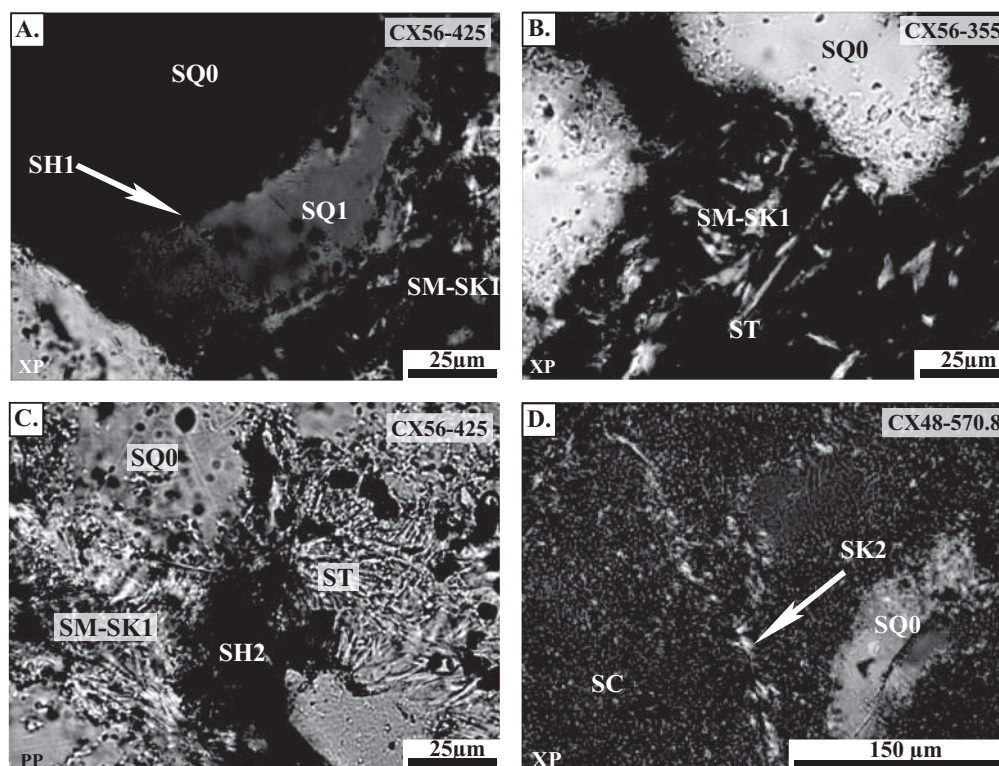


FIG. 7. Photomicrographs of typical Athabasca Group sandstones mineral assemblages from early, peak and late diagenesis and late alteration. (A) SH1 hematite highlighting the boundary between detrital quartz (SQ0) and SQ1 quartz overgrowth. SM muscovite and SK1 dickite are altering SQ1 quartz overgrowth. (B) Peak diagenesis muscovite (SM) and dickite (SK1) being crosscut by dravite (ST). (C) Hematite (SH2) crosscutting dravite (ST) and peak diagenesis muscovite (SM) and dickite (SK1). (D) Late diagenesis chlorite (SC) crosscut by late kaolinite (SK2).

crystallized simultaneously with early hydrothermal alteration SM muscovite. SK1 dickite and SM muscovite are partially replaced by needle-shaped ST dravite near the unconformity (Fig. 7C), which is interpreted to have formed during late hydrothermal alteration. Dravite occurs in minor amounts in all areas, except near the unconformity in drill hole CX56, where it is the only alteration mineral present in the sandstones interstices. Locally, SH2 hematite occurs in embayments in the margins of late hydrothermal alteration tourmaline (Fig. 7C). Late SPy pyrite and fine-grained SC chlorite (Fig. 7D) are observed close to the unconformity, with the latter partially replaced along microfractures by fine-grained posthydrothermal alteration SK2 kaolinite (Fig. 7D).

#### Crystal Chemistry of the Alteration Minerals

Preore alteration C1 chlorites are Mg-Fe-Al chlorite with a calculated structural formula of  $\text{Mg}_{5.92}\text{Fe}_{4.20}\text{Al}_{2.54}(\text{Si}_{5.92}, \text{Al}_{2.08})\text{O}_{20}(\text{OH})_{16}$  (Table 1), reflecting the composition of a clinocllore chlorite. This chemical composition is consistent with formation temperatures near 275°C, based on site occupancy (Cathelineau, 1988). Preore alteration C2 chlorites have distinctly different chemical compositions than C1 chlorite, with a calculated structural formula of  $\text{Mg}_{2.78}\text{Fe}_{6.65}\text{Al}_{2.36}(\text{Si}_{5.73}, \text{Al}_{2.27})\text{O}_{20}(\text{OH})_{16}$  (Table 1), corresponding to the composition of a chamoisite chlorite with formation temperatures near 300°C. Postore chlorites C3 have a calculated average chemical formula of  $\text{K}_{0.08}\text{Mg}_{3.45}\text{Fe}_{1.16}\text{Al}_{5.06}(\text{Si}_{6.61}, \text{Al}_{1.39})\text{O}_{20}$

$(\text{OH})_{16}$  (Table 1), corresponding to the composition of a sudoite chlorite with formation temperatures near 185°C. Postore chlorites C4 are similar in composition to C3 chlorite with a calculated structural formula of  $\text{Mg}_{2.80}\text{Fe}_{0.22}\text{Al}_{6.19}(\text{Si}_{6.48}, \text{Al}_{1.52})\text{O}_{20}(\text{OH})_{16}$  (Table 1), corresponding to the composition of a sudoite chlorite with formation temperatures near 175°C. Late hydrothermal alteration SC chlorites in the Manitou Falls Formation are similar in composition to C3 and C4 chlorites in the basement with a calculated structural formula of  $\text{Mg}_{3.09}\text{Fe}_{0.09}\text{Al}_{6.23}(\text{Si}_{6.82}, \text{Al}_{1.18})\text{O}_{20}(\text{OH})_{16}$  (Table 1), corresponding to a composition of a sudoite chlorite with formation temperatures near 155°C.

When plotted on a molar Al-Mg-Fe ternary diagram (Fig. 8), C1 and C2 chlorites plot on the Fe-Mg side of the diagram. These compositions are similar to those of biotite in the basement rocks and probably reflect an inherited chemistry from the altered minerals or alteration fluids that equilibrated with the metamorphic basement rocks prior to chlorite alteration. The C1 chlorite has a similar composition to preore chlorites reported by Alexandre et al. (2005) for Dawn Lake, McArthur River, and Rabbit Lake basement deposits, whereas C2 chlorites have higher Fe contents (Fig. 8). Such differences in the chemical composition between the C1 and C2 chlorites might be attributed to the different chemistry of the altered minerals that locally fixed the chemistry of the alteration fluid. C3, C4, and SC chlorites plot close to the postore chlorite field from Dawn Lake,

TABLE 1. Average Chemical Composition (in wt % and 1σ), Temperatures of Formation, and Average Structural Formulas of Various Muscovite and Chlorite Phases from the Millennium Deposit

|                                                         | SiO <sub>2</sub> | TiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Cr <sub>2</sub> O <sub>3</sub> | FeO        | MnO       | MgO        | CaO       | Na <sub>2</sub> O | K <sub>2</sub> O | SUM        | Temp. (°C) | Average half structural formula                                                                                                                         |
|---------------------------------------------------------|------------------|------------------|--------------------------------|--------------------------------|------------|-----------|------------|-----------|-------------------|------------------|------------|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| Early hydrothermal alteration muscovite (SM)<br>(n = 8) | 47.5 ± 1.3       | <DL              | 32.2 ± 0.7                     | <DL                            | 0.7 ± 0.1  | <DL       | 1.2 ± 0.5  | 0.1 ± 0.1 | <DL               | 9.1 ± 0.5        | 91.0 ± 1.6 | 240        | K <sub>0.80</sub> Mg <sub>0.12</sub> Fe <sub>0.04</sub> Al <sub>1.86</sub> (Si <sub>3.26</sub> ,Al <sub>0.74</sub> )O <sub>10</sub> (OH) <sub>2</sub>   |
| Late hydrothermal alteration sudoite (SC)<br>(n = 5)    | 38.4 ± 1.3       | <DL              | 35.4 ± 0.6                     | <DL                            | 0.6 ± 0.2  | <DL       | 11.7 ± 1.6 | 0.1 ± 0.1 | <DL               | —                | 86.5 ± 2.3 | 155        | Mg <sub>0.09</sub> Fe <sub>0.09</sub> Al <sub>6.23</sub> (Si <sub>16.82</sub> ,Al <sub>1.18</sub> )O <sub>20</sub> (OH) <sub>16</sub>                   |
| Preore alteration muscovite (M1)<br>(n = 9)             | 50.5 ± 1.3       | <DL              | 33.3 ± 1.7                     | <DL                            | 0.6 ± 0.5  | <DL       | 1.8 ± 0.8  | 0.1 ± 0.1 | <DL               | 9.7 ± 0.7        | 96.2 ± 0.9 | 250        | K <sub>0.80</sub> Mg <sub>0.17</sub> Fe <sub>0.03</sub> Al <sub>1.82</sub> (Si <sub>3.27</sub> ,Al <sub>0.73</sub> )O <sub>10</sub> (OH) <sub>2</sub>   |
| Synore alteration muscovite (M2)<br>(n = 4)             | 50.1 ± 1.3       | <DL              | 32.7 ± 1.4                     | <DL                            | 0.9 ± 0.4  | <DL       | 1.7 ± 0.6  | 0.2 ± 0.1 | <DL               | 8.9 ± 1.2        | 94.8 ± 0.5 | 250        | K <sub>0.75</sub> Mg <sub>0.17</sub> Fe <sub>0.03</sub> Al <sub>1.83</sub> (Si <sub>3.29</sub> ,Al <sub>0.71</sub> )O <sub>10</sub> (OH) <sub>2</sub>   |
| Preore alteration clinocllore (C1)<br>(n = 1)           | 28.0             | <DL              | 18.5                           | <DL                            | 23.7       | <DL       | 15.7       | <DL       | <DL               | <DL              | 86.3       | 275        | Mg <sub>0.92</sub> Fe <sub>0.08</sub> Al <sub>2.54</sub> (Si <sub>15.92</sub> ,Al <sub>0.08</sub> )O <sub>20</sub> (OH) <sub>16</sub>                   |
| Preore alteration chamoisite (C2)<br>(n = 3)            | 25.6 ± 0.7       | <DL              | 17.5 ± 0.4                     | <DL                            | 35.5 ± 0.9 | 0.5 ± 0.1 | 8.3 ± 0.6  | <DL       | <DL               | <DL              | 87.5 ± 0.8 | 300        | Mg <sub>0.78</sub> Fe <sub>0.65</sub> Al <sub>2.36</sub> (Si <sub>15.73</sub> ,Al <sub>0.27</sub> )O <sub>20</sub> (OH) <sub>16</sub>                   |
| Postore alteration sudoite (C3)<br>(n = 4)              | 35.8 ± 2.1       | <DL              | 29.6 ± 2.7                     | <DL                            | 7.4 ± 3.8  | <DL       | 13.8 ± 1.2 | 0.4 ± 0.4 | <DL               | 0.4 ± 0.4        | 87.5 ± 0.8 | 185        | K <sub>0.08</sub> Mg <sub>0.43</sub> Fe <sub>1.16</sub> Al <sub>5.06</sub> (Si <sub>16.61</sub> ,Al <sub>1.39</sub> )O <sub>20</sub> (OH) <sub>16</sub> |
| Postore alteration sudoite (C4)<br>(n = 2)              | 36.1 ± 1.1       | <DL              | 36.4 ± 0.6                     | <DL                            | 1.6 ± 0.3  | <DL       | 11.9 ± 0.4 | <DL       | <DL               | <DL              | 86.3 ± 1.6 | 175        | Mg <sub>0.80</sub> Fe <sub>0.22</sub> Al <sub>6.19</sub> (Si <sub>16.48</sub> ,Al <sub>1.52</sub> )O <sub>20</sub> (OH) <sub>16</sub>                   |

Notes: Paragenesis of all phases analyzed is shown in Figure 4; the variation of calculated temperatures is ±30°C; see text for more discussion; n indicates the number of individual analyses on which the average was calculated; <DL = concentration lower than the detection limit; late hydrothermal alteration sudoite figures (SC) were corrected for their muscovite content

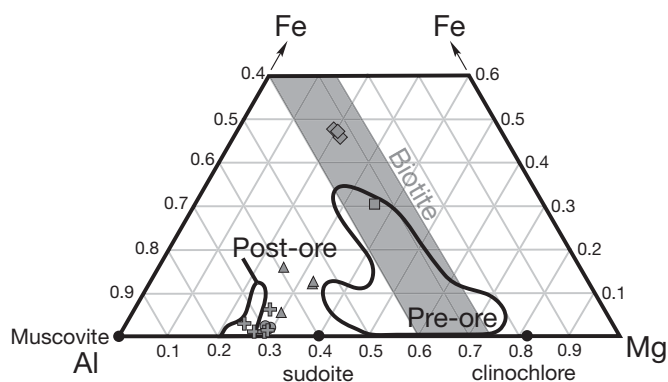


FIG. 8. Al-Mg-Fe ternary diagram for SC (cross) late diagenesis, C1 (diamond) preore, C2 (square) preore, C3 postore (circle) and C4 (triangle) postore chlorites from the Millennium deposit, plotted as a function of molar proportions (Bailey, 1980). The black solid lines delineate the field of preore and postore basement-derived chlorite from Dawn Lake, McArthur River, and Rabbit Lake basement-hosted deposits (Alexandre et al., 2005). Also shown are the compositions of biotite, muscovite, clinocllore, and sudoite.

McArthur River, and Rabbit Lake basement deposits (Alexandre et al., 2005).

Preore M1 muscovites have similar crystal chemistry to synore M2 muscovite. Calculated structural formula for preore M1 muscovites is  $K_{0.80}Mg_{0.17}Fe_{0.03}Al_{1.82}(Si_{3.27},Al_{0.73})O_{10}(OH)_2$ , with K varying from 0.72 to 0.89, and is  $K_{0.75}Mg_{0.17}Fe_{0.03}Al_{1.83}(Si_{3.29},Al_{0.71})O_{10}(OH)_2$  for synore muscovite, with K varying from 0.65 to 0.89 (Table 1). Temperatures derived from the crystal chemistry of M1 and M2 muscovites are similar at 250°C (Table 1). The crystal chemistry of the preore and synore muscovites are analogous to those reported by Alexandre et al. (2005) for preore and synore illites at Dawn Lake, McArthur River, and Rabbit Lake, suggesting that the fluids responsible for the alteration of the basement rocks that formed the pre- and synore muscovites were consistent throughout the eastern part of the Athabasca basin. Early hydrothermal alteration SM muscovites in the Manitou Falls Formation sandstones have a similar crystal chemistry to the pre- and synore muscovite (M1, M2) in the basement, with calculated structural formulas of  $K_{0.80}Mg_{0.12}Fe_{0.04}Al_{1.86}(Si_{3.26},Al_{0.74})O_{10}(OH)_2$  with K varying from 0.71 to 0.85 and formation temperatures near 240°C (Table 1).

XRD data from preore M1 and synore M2 muscovites in the basement and SM muscovite from the Manitou Falls Formation sandstones indicate the presence of 2 polytypes within the Millennium alteration system (Fig. 9). SM muscovites from the Manitou Falls Formation sandstones and preore basement M1 muscovites up to 25 m below the unconformity are dominated by the 1Mt polytype (Figs. 6B, C, 9), while preore M1 and synore M2 muscovites deeper than 25 m below the unconformity are dominated by the 1Mc polytype (Figs. 6D, 9). 1Mc muscovites are rigid micrometer-scale lath-like shaped crystals (Fig. 6D), whereas 1Mt muscovites are thin, submicrometer, “hairy-shaped” crystals growing on the edge of 1Mc muscovites (Fig. 6B, C). These polytypes are similar to those observed in the Manitou Falls Formation at the Shea Creek deposit by Laverret et al. (2006), where the 1Mc polytype was dominant in the lower part of the sandstones and the 1Mt polytype was dominant close to the sandstone-basement

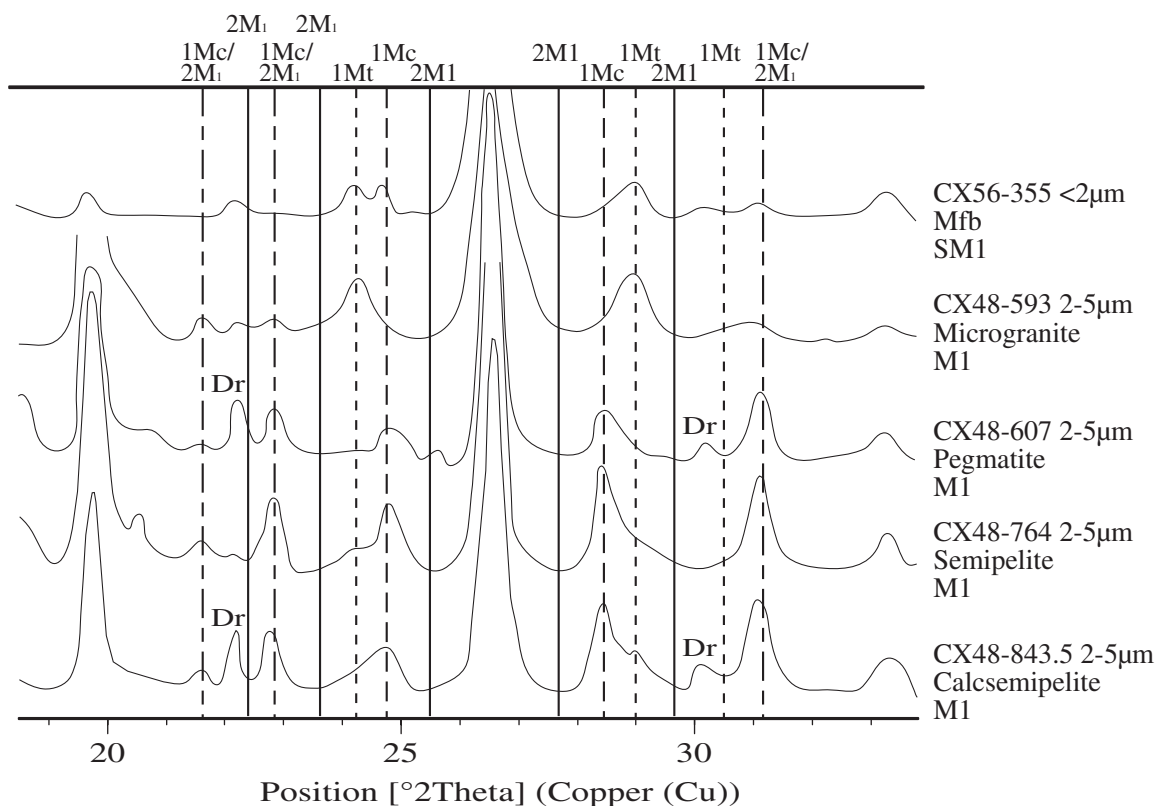


FIG. 9. XRD profiles of 2 to 5 and <2  $\mu\text{m}$  muscovites separates from early hydrothermal alteration (SM) from the Athabasca basin and preore muscovites (M1) from the basement of Millennium, showing 1Mc polytype as the main polytype in the basement and 1Mt as the main polytype close to the sandstone-basement unconformity. Major peak position for 1Mc, 1Mt, and 2M<sub>1</sub> muscovite polytypes are also shown (Drits et al., 1993).

unconformity and around brittle structural features. Laverret et al. (2006) interpreted the 1Mc polytype in barren areas to be related to muscovite alteration from diagenetic brines and the 1Mc and 1Mt polytype in the mineralized area to be related to the reinjection of basinal brines that interacted with the basement rocks into the overlying sandstone. At Millennium, the 1Mc muscovite polytype is the dominant alteration mineral in the basement rocks, which we interpret to be related to pre- and synore muscovite alteration from diagenetic brines. The 1Mt muscovite polytype is observed growing from the edge of the 1Mc muscovites, as is the case at Shea Creek, which would imply that this 1Mt polytype is related to late postmineralization alteration fluids.

Synore basement APS minerals (APS) vary from 9.50 to 10.66 percent SrO, 1.95 to 2.20 percent CaO, 2.70 to 3.84 percent La<sub>2</sub>O<sub>3</sub>, 4.37 to 6.02 percent Ce<sub>2</sub>O<sub>3</sub>, 1.16 to 1.56 percent Nd<sub>2</sub>O<sub>3</sub>, 4.70 to 10.29 percent SO<sub>3</sub>, 22.44 to 24.72 P<sub>2</sub>O<sub>5</sub>, 0.11 to 4.27 percent FeO and 29.22 to 34.56 percent Al<sub>2</sub>O<sub>3</sub> with minor amounts of F, BaO, and ThO<sub>2</sub> (Table 2). The calculated average structural formula is Sr<sub>0.45</sub>Ca<sub>0.17</sub>LREE<sub>0.30</sub>(Al<sub>2.87</sub>Fe<sub>0.11</sub>)(PO<sub>4</sub>)<sub>1.54</sub>(SO<sub>4</sub>)<sub>0.35</sub>(OH)<sub>6</sub>, corresponding to goyazite composition. Early hydrothermal alteration basin APS mineral (SAPS) chemical compositions are similar to synore APS chemistry in the basement rocks at Sr<sub>0.44</sub>Ca<sub>0.18</sub>LREE<sub>0.28</sub>(Al<sub>2.91</sub>Fe<sub>0.11</sub>)(PO<sub>4</sub>)<sub>1.53</sub>(SO<sub>4</sub>)<sub>0.29</sub>(OH)<sub>6</sub> (Table 2), also corresponding to a goyazite composition.

The concentration of uranium in uraninite varies from 50.2 to 77.4 percent U (Table 3) and Pb contents also vary, ranging from 0.2 to 23.1 percent Pb. Other elements present within the uraninite structure include Ca (0.37–3.62%), Si (0.10 to 4.74%), Fe (0.09 to 4.74%), Ti (0.03 to 0.19%), V (0.03 to 0.75%), and O (11.58 to 16.70%) (Table 3), consistent with micron-scale becquerellite and coffinite alteration after uraninite.

#### Isotopic Compositions of the Minerals and Fluids Involved in the Deposit

Stable isotopic compositions were determined for basement preore M1 and synore M2 muscovites, preore C2 and postore C3 chlorite, basin early hydrothermal alteration SM muscovite and late hydrothermal alteration SC chlorite (Table 4, Fig. 10).

##### Basement preore M1 muscovite and C2 chlorite

Measured  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values of nine preore M1 muscovites vary from +10.2 to +13.7 per mil for  $\delta^{18}\text{O}$ , and –66 to –52 per mil for  $\delta\text{D}$ . These values are similar to those reported in previous studies of the Manitou Falls Formation (Kotzer and Kyser, 1995), but the  $\delta\text{D}$  values are distinct from those that produced early muscovite in basement host rocks in the Key Lake (Wilson and Kyser, 1987), McArthur River and Rabbit Lake deposits (Alexandre et al., 2005), where  $\delta\text{D}$  are

TABLE 2. Chemical Composition (in wt %) of Aluminum Phosphate-Sulfate (APS) Phases from the Millennium Deposit

|                                                 | F<br>(%) | BaO<br>(%) | CaO<br>(%) | FeO<br>(%) | SrO<br>(%) | PbO <sub>2</sub><br>(%) | ThO <sub>2</sub><br>(%) | UO <sub>2</sub><br>(%) | SO <sub>3</sub><br>(%) | Al <sub>2</sub> O <sub>3</sub><br>(%) | La <sub>2</sub> O <sub>3</sub><br>(%) | Ce <sub>2</sub> O <sub>3</sub><br>(%) | Pr <sub>2</sub> O <sub>3</sub><br>(%) | Nd <sub>2</sub> O <sub>3</sub><br>(%) | V <sub>2</sub> O <sub>3</sub><br>(%) | P <sub>2</sub> O <sub>5</sub><br>(%) | Total<br>(%) |
|-------------------------------------------------|----------|------------|------------|------------|------------|-------------------------|-------------------------|------------------------|------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|--------------------------------------|--------------------------------------|--------------|
| <u>Early hydrothermal alteration APS (SAPS)</u> |          |            |            |            |            |                         |                         |                        |                        |                                       |                                       |                                       |                                       |                                       |                                      |                                      |              |
| CX53-1-664_01                                   | 0.53     | 1.09       | 1.98       | 0.16       | 10.59      | 0.26                    | 0.23                    | <DL                    | 4.70                   | 30.46                                 | 2.70                                  | 4.37                                  | 0.30                                  | 1.28                                  | <DL                                  | 23.31                                | 82.27        |
| CX53-1-664_02                                   | 0.71     | 0.63       | 2.02       | 4.27       | 9.64       | <DL                     | 0.03                    | <DL                    | 10.29                  | 29.22                                 | 2.87                                  | 4.96                                  | 0.38                                  | 1.45                                  | 0.02                                 | 22.44                                | 89.33        |
| CX53-1-664_03                                   | 0.46     | 0.36       | 2.18       | 0.15       | 9.85       | <DL                     | 0.09                    | <DL                    | 5.50                   | 33.33                                 | 3.70                                  | 5.62                                  | 0.28                                  | 1.33                                  | 0.02                                 | 24.72                                | 87.95        |
| CX53-1-664_04                                   | 0.44     | 0.41       | 2.20       | 0.22       | 9.50       | 0.02                    | 0.05                    | 0.13                   | 5.05                   | 31.41                                 | 3.51                                  | 5.68                                  | 0.52                                  | 1.56                                  | 0.05                                 | 23.05                                | 85.10        |
| CX53-1-664_05                                   | 0.56     | 0.56       | 1.95       | 0.11       | 10.08      | <DL                     | 0.03                    | 0.05                   | 5.77                   | 33.33                                 | 3.84                                  | 5.72                                  | 0.45                                  | 1.26                                  | <DL                                  | 23.30                                | 87.54        |
| CX53-1-664_06                                   | 0.71     | 1.00       | 1.95       | 0.15       | 10.66      | <DL                     | 0.11                    | <DL                    | 5.50                   | 34.56                                 | 3.35                                  | 5.17                                  | 0.30                                  | 1.40                                  | 0.04                                 | 23.39                                | 88.72        |
| CX53-1-664_07                                   | 0.86     | 0.80       | 2.07       | 0.28       | 9.96       | 0.02                    | 0.09                    | <DL                    | 5.17                   | 34.42                                 | 3.41                                  | 6.02                                  | 0.37                                  | 1.16                                  | <DL                                  | 24.00                                | 88.91        |
| <u>Synore APS (APS)</u>                         |          |            |            |            |            |                         |                         |                        |                        |                                       |                                       |                                       |                                       |                                       |                                      |                                      |              |
| CX53-1-622.5_01                                 | 0.94     | 0.73       | 2.06       | 5.01       | 6.11       | <DL                     | 0.53                    | <DL                    | 6.46                   | 29.92                                 | 4.70                                  | 6.38                                  | 0.42                                  | 1.01                                  | <DL                                  | 22.94                                | 87.61        |
| CX53-1-622.5_02                                 | 0.84     | 0.57       | 2.22       | 2.72       | 8.25       | <DL                     | 0.85                    | <DL                    | 4.31                   | 32.90                                 | 3.51                                  | 6.53                                  | 0.41                                  | 1.98                                  | <DL                                  | 22.36                                | 87.87        |
| CX53-1-622.5_03                                 | 0.92     | 0.86       | 2.16       | 2.82       | 7.32       | <DL                     | 0.89                    | <DL                    | 4.14                   | 30.41                                 | 4.00                                  | 6.05                                  | 0.45                                  | 1.14                                  | 0.03                                 | 23.14                                | 84.72        |
| CX53-1-622.5_05                                 | 0.90     | 0.82       | 2.18       | 2.85       | 7.08       | <DL                     | 0.68                    | 0.07                   | 3.93                   | 30.34                                 | 4.39                                  | 6.18                                  | 0.62                                  | 1.05                                  | 0.01                                 | 22.80                                | 84.49        |
| CX53-1-622.5_04                                 | 1.11     | 0.78       | 2.32       | 2.70       | 7.30       | 0.01                    | 0.79                    | 0.02                   | 4.30                   | 30.47                                 | 3.70                                  | 6.19                                  | 0.26                                  | 1.17                                  | 0.03                                 | 21.37                                | 83.03        |
| CX53-1-622.5_06                                 | 0.72     | 0.55       | 1.83       | 1.40       | 9.25       | 0.03                    | 0.10                    | 0.03                   | 4.53                   | 28.47                                 | 2.66                                  | 5.17                                  | 0.51                                  | 1.33                                  | 0.02                                 | 21.53                                | 79.68        |
| CX53-1-622.5_07                                 | 0.52     | 0.37       | 1.82       | 0.64       | 9.04       | <DL                     | 0.27                    | <DL                    | 4.31                   | 26.90                                 | 2.38                                  | 4.63                                  | 0.42                                  | 1.69                                  | <DL                                  | 20.66                                | 77.29        |
| CX53-1-617.5_01                                 | 0.64     | 0.70       | 1.91       | 1.13       | 10.84      | 0.02                    | 0.45                    | <DL                    | 4.64                   | 30.73                                 | 1.80                                  | 4.27                                  | 0.20                                  | 1.20                                  | 0.01                                 | 21.36                                | 81.69        |
| CX53-1-617.5_02                                 | 0.75     | 0.65       | 1.97       | 1.62       | 9.99       | <DL                     | 0.32                    | <DL                    | 4.92                   | 28.96                                 | 1.69                                  | 4.04                                  | 0.47                                  | 1.06                                  | 0.04                                 | 19.52                                | 79.18        |
| CX53-1-617.5_03                                 | 0.60     | 0.50       | 1.68       | 1.10       | 6.57       | <DL                     | 0.38                    | 0.14                   | 3.27                   | 25.62                                 | 1.57                                  | 2.90                                  | 0.18                                  | 0.92                                  | 0.04                                 | 13.92                                | 69.12        |
| CX53-1-617.5_04                                 | 0.74     | 0.75       | 2.29       | 1.31       | 10.39      | <DL                     | 0.70                    | <DL                    | 5.27                   | 30.72                                 | 2.60                                  | 4.05                                  | 0.14                                  | 1.19                                  | 0.01                                 | 21.91                                | 83.29        |
| CX53-1-617.5_05                                 | 0.91     | 0.72       | 2.01       | 1.10       | 10.71      | 0.04                    | 0.95                    | 0.01                   | 5.42                   | 30.47                                 | 1.74                                  | 4.33                                  | 0.39                                  | 1.59                                  | 0.01                                 | 21.92                                | 82.74        |
| CX53-1-617.5_06                                 | 0.64     | 0.59       | 1.96       | 0.91       | 9.51       | 0.01                    | 0.68                    | 0.04                   | 5.41                   | 27.58                                 | 1.77                                  | 3.76                                  | 0.35                                  | 1.61                                  | 0.03                                 | 19.61                                | 76.86        |
| CX53-1-617.5_07                                 | 0.61     | 0.69       | 1.55       | 0.69       | 10.05      | <DL                     | 0.23                    | 0.20                   | 4.34                   | 25.98                                 | 1.85                                  | 3.78                                  | 0.29                                  | 1.61                                  | <DL                                  | 20.59                                | 72.92        |
| CX53-1-617.5_08                                 | 0.62     | 0.63       | 1.61       | 0.65       | 10.31      | 0.01                    | 0.14                    | 0.05                   | 4.62                   | 28.06                                 | 1.90                                  | 3.89                                  | 0.26                                  | 1.81                                  | <DL                                  | 21.08                                | 76.05        |
| CX56-425_01                                     | 0.67     | 0.64       | 1.97       | 0.51       | 10.52      | <DL                     | 0.30                    | <DL                    | 4.61                   | 31.98                                 | 2.13                                  | 4.48                                  | 0.50                                  | 1.43                                  | <DL                                  | 23.23                                | 83.58        |
| CX56-425_02                                     | 0.95     | 0.99       | 2.77       | 0.91       | 9.28       | 0.01                    | 0.38                    | <DL                    | 3.69                   | 31.17                                 | 2.19                                  | 4.95                                  | 0.25                                  | 1.22                                  | <DL                                  | 24.02                                | 84.35        |

Notes: Paragenesis of all phases analyzed is shown in Figure 4; see text for more discussion; <DL = concentration lower than the detection limit; APS compositions have been corrected for their muscovite content

TABLE 3. Uraninite Average Chemical Composition and Calculated Chemical Age from the Millennium Deposit

|                | U    | Pb   | Si  | Fe  | Mg  | Ca  | Ti  | V   | O    | Total | Chemical age |
|----------------|------|------|-----|-----|-----|-----|-----|-----|------|-------|--------------|
| CX48-1-684.5-3 | 69.8 | 2.3  | 1.5 | <DL | <DL | 0.3 | 3.8 | 0.4 | 14.3 | 92.4  | 197          |
| CX48-1-684.5-5 | 71.1 | 4.0  | 0.9 | 0.2 | <DL | 0.4 | 2.3 | 0.2 | 13.0 | 92.2  | 341          |
| CX48-1-684.5-7 | 74.7 | 6.6  | <DL | 0.2 | <DL | 1.3 | 0.0 | <DL | 11.8 | 94.9  | 519          |
| CX48-1-684.5-8 | 72.5 | 8.8  | <DL | 0.2 | <DL | 1.1 | 0.1 | <DL | 11.8 | 94.8  | 702          |
| CX48-1-684.5-9 | 75.1 | 4.7  | <DL | <DL | <DL | 1.4 | 0.0 | 0.2 | 11.7 | 93.4  | 372          |
| CX48-1-689-1   | 72.9 | 7.3  | <DL | 0.2 | <DL | 1.1 | 0.4 | <DL | 11.9 | 94.0  | 584          |
| CX48-1-689-2   | 74.1 | 6.2  | <DL | <DL | <DL | 1.2 | 0.3 | <DL | 11.8 | 94.0  | 493          |
| CX48-1-689-3   | 75.4 | 5.5  | <DL | <DL | <DL | 1.4 | 0.2 | 0.2 | 11.9 | 94.6  | 433          |
| CX48-1-689-4   | 71.2 | 10.8 | <DL | <DL | <DL | 0.8 | 0.1 | <DL | 11.8 | 95.1  | 865          |
| CX48-1-689-5   | 71.1 | 11.1 | <DL | <DL | <DL | 0.8 | 0.1 | <DL | 11.8 | 95.2  | 883          |
| CX48-1-689-6   | 74.4 | 6.4  | <DL | <DL | <DL | 1.2 | 0.1 | <DL | 11.7 | 94.2  | 506          |
| CX48-1-689-7   | 76.4 | 0.8  | 1.8 | 0.3 | <DL | 0.9 | 0.1 | 0.3 | 13.2 | 93.8  | 67           |
| CX48-1-689-8   | 73.9 | 7.5  | <DL | <DL | <DL | 1.1 | 0.1 | <DL | 11.8 | 94.6  | 591          |
| CX48-1-689-9   | 73.8 | 7.1  | <DL | <DL | <DL | 1.2 | 0.2 | <DL | 11.8 | 94.4  | 566          |
| CX48-1-689-10  | 73.7 | 7.3  | <DL | <DL | <DL | 1.1 | 0.2 | <DL | 11.8 | 94.3  | 581          |
| CX48-1-689-11  | 73.4 | 8.6  | <DL | <DL | <DL | 1.0 | 0.2 | <DL | 11.8 | 95.1  | 680          |
| CX48-1-689-12  | 74.3 | 6.7  | <DL | <DL | <DL | 1.2 | 0.2 | <DL | 11.9 | 94.7  | 533          |
| CX48-1-689-13  | 73.2 | 8.5  | <DL | <DL | <DL | 1.0 | 0.1 | <DL | 11.8 | 95.0  | 674          |
| CX48-1-689-14  | 74.5 | 8.0  | <DL | <DL | <DL | 1.1 | 0.2 | <DL | 12.0 | 96.1  | 626          |
| CX48-1-689-15  | 74.6 | 7.4  | <DL | <DL | <DL | 1.2 | 0.3 | <DL | 12.1 | 95.9  | 579          |
| Average        | 73.3 | 6.4  | 0.4 | 0.1 | <DL | 1.0 | 0.6 | 0.2 | 12.2 | 94.1  |              |
| ±1σ            | 1.9  | 2.9  | 0.6 | 0.1 |     | 0.4 | 1.1 | 0.1 | 0.8  | 0.9   |              |

Note: <DL = concentration lower than the detection limit

TABLE 4. Measured Mineral  $\delta^{18}\text{O}$  and  $\delta\text{D}$  and Calculated  $\delta^{18}\text{O}$  and  $\delta\text{D}$  Values for Fluids in Equilibrium with Alteration Minerals and Uraninite from the Millennium Deposits

| Sample no.                                   | Fraction size | Mineral          |                       | Water            |                       |
|----------------------------------------------|---------------|------------------|-----------------------|------------------|-----------------------|
|                                              |               | $\delta\text{D}$ | $\delta^{18}\text{O}$ | $\delta\text{D}$ | $\delta^{18}\text{O}$ |
| Early hydrothermal alteration muscovite (SM) |               |                  |                       |                  |                       |
| CX49-385                                     | <2            | -50              | 11.3                  | -20              | 6.1                   |
| CX56-499.5                                   | <2            | -61              | 7.0                   | -31              | 1.8                   |
| Late hydrothermal alteration sudoite (SC)    |               |                  |                       |                  |                       |
| CX48-567.1                                   | <2            | -53              | 9.3                   | -9               | 5.5                   |
| CX54-598                                     | <2            | -48              | 15.9                  | -4               | 12.1                  |
| CX56-186.5                                   | <2            | -64              | 13.9                  | -20              | 10.1                  |
| CX60-596                                     | <2            | -48              | 13.4                  | -4               | 9.6                   |
| Preore muscovite (M1)                        |               |                  |                       |                  |                       |
| CX48-593                                     | <2            | -65              | 13.1                  | -35              | 8.3                   |
| CX48-607                                     | 2-5           | -50              | 11.8                  | -20              | 7.0                   |
| CX48-625                                     | <2            | -66              | 11.8                  | -36              | 7.0                   |
| CX48-688                                     | <2            | -53              | 13.7                  | -23              | 8.9                   |
| CX48-704.5                                   | <2            | -55              | 10.2                  | -25              | 5.4                   |
| CX48-764                                     | 2-5           | -61              | 10.3                  | -31              | 5.5                   |
| CX48-807.5                                   | 2-5           | -52              | 10.1                  | -22              | 5.3                   |
| CX53-1-629                                   | <2            | -56              | 10.3                  | -26              | 5.5                   |
| Preore chamoisite (C2)                       |               |                  |                       |                  |                       |
| CX48-733                                     | <2            | -54              | 7.1                   | -29              | 7.0                   |
| Synore muscovite (M2)                        |               |                  |                       |                  |                       |
| CX48-1-684                                   | -             | -89              | 11.4                  | -59              | 6.6                   |
| CX48-1-689                                   | -             | -94              | 12.6                  | -64              | 7.8                   |
| CX48-1-695                                   | -             | -104             | 10.2                  | -74              | 5.4                   |
| Uraninite                                    |               |                  |                       |                  |                       |
| CX48-1-689                                   |               | -12.9            |                       |                  |                       |
| CX48-1-695                                   |               | -8.6             |                       |                  |                       |
| CX56-3-680.5                                 |               | 9.8              |                       |                  |                       |
| CX56-3-711                                   |               | -0.8             |                       |                  |                       |
| Postore sudoite (C3)                         |               |                  |                       |                  |                       |
| CX48-713                                     | <2            | -55              | 8.1                   | -13              | 5.4                   |
| CX53-1-686                                   | <2            | -57              | 11.5                  | -15              | 8.8                   |

Notes: The temperatures used to calculate the fluid values are derived from the crystal chemistry of the clay minerals; the variation of the individual O and H analyses are  $\pm 0.2$  and  $\pm 3$  per mil; see the text for more details

higher. Using the formation temperature of 250°C for M1 muscovite obtained from the mineral chemistry (Table 1), the calculated  $\delta^{18}\text{O}$  values for the fluid in equilibrium with this muscovite range from +5.3 to +8.9 per mil, while the  $\delta\text{D}$  fluid values range from -36 to -20 per mil (Fig. 10; Table 4).

Measured  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values of one preore C2 chlorite gives a calculated  $\delta^{18}\text{O}$  value of +7.0 per mil and  $\delta\text{D}$  of -29 per mil for the fluid in equilibrium with this chlorite (Fig. 10; Table 4), similar to preore M1 muscovite in the basement. This fluid value is similar to those reported by Alexandre et al. (2005) for preore chlorite at Dawn Lake, McArthur River and Rabbit Lake deposits.

#### Synore M2 muscovite and uraninite

Synore M2 muscovites have  $\delta^{18}\text{O}$  values from +10.2 to +12.6 per mil, similar to preore M1 muscovite, but lower  $\delta\text{D}$  values, averaging -96 per mil. Using the formation temperature of

250°C for M2 muscovite obtained from the mineral chemistry (Table 1), the calculated  $\delta^{18}\text{O}$  values for the fluid in equilibrium with this muscovite vary between +5.4 and +7.8 per mil. The  $\delta\text{D}$  values of the fluids average -104 per mil (Fig. 10; Table 4), and reflect preferential exchange of hydrogen isotopes with more recent fluids moving along fractures in the mineralized zone as fluids with such low values were not present in the basin except recently (Wilson and Kyser, 1987; Kotzer and Kyser, 1995).

Measured  $\delta^{18}\text{O}$  values of four uraninite samples vary from -12.9 to +9.8 per mil (Table 4). Using the  $\delta^{18}\text{O}$  values and temperatures of the fluids that formed the synore M2 muscovites, pristine uraninites should have  $\delta^{18}\text{O}$  values near -4 per mil (Fayek and Kyser, 2000). The large variation in  $\delta^{18}\text{O}$  values of the uraninites at Millennium is interpreted to result from variable degrees of uraninite alteration, with high values reflecting alteration during incorporation of Ca, Si, and Fe to secondary uranium minerals, whereas low values reflect exchange of the uraninites with relatively recent  $^{18}\text{O}$ -depleted fluids that percolated along faults and fractures (Kotzer and Kyser, 1993; Fayek and Kyser, 2000). The low  $\delta^{18}\text{O}$  values in uraninites are attributed to recent fluids, as the Athabasca basin slowly migrated to higher latitudes since its formation (Ramaekers and Dunn, 1977), where meteoric waters with lower  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values are expected.

#### Basement postore C3 chlorite

Two postore C3 chlorites have  $\delta^{18}\text{O}$  values of +8.1 and +11.5 per mil and  $\delta\text{D}$  values of -57 to -55 per mil. Using formation temperatures of 185°C for C3 chlorites obtained from the mineral chemistry (Table 1), the calculated  $\delta^{18}\text{O}$  values for the fluid in equilibrium with these chlorites are +5.4 and +8.8 per mil, and the D fluids values are -15 and -13 per mil (Fig. 10; Table 4). The  $\delta\text{D}$  values are higher than the fluids associated with the postore chlorite at McArthur River (Alexandre et al., 2005), which range from -80 to -31 per mil. The values for the fluids that equilibrated with the C3 chlorites also have higher  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values than those for the fluids that produced the chlorite alteration in the gneissic host rock of the Key Lake deposit in the southwest Athabasca basin (Wilson and Kyser, 1987), where  $\delta^{18}\text{O}_{\text{FLUID}}$  ranged from +0 to +4.1 per mil, and  $\text{D}_{\text{FLUID}}$  was from -61 to -30 per mil.

#### Basin SM muscovite and SC chlorite

SM muscovites from early alteration of the Manitou Falls Formation sandstones above the deposit have  $\delta^{18}\text{O}$  values of +7.0 and 11.3 per mil and  $\delta\text{D}$  values of -61 and -50 per mil. These values are similar to pre- and synore muscovites in the basement and to reported values in previous studies of the Manitou Falls Formation (Kotzer and Kyser, 1995). Using formation temperatures of 240°C for SM muscovite obtained from the mineral chemistry (Table 1), the calculated  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values for the fluid that formed SM muscovite is +1.8 and +6.1 per mil for  $\delta^{18}\text{O}$  and -31 and -20 per mil for  $\delta\text{D}$  (Fig. 10).

SC chlorites from late alteration of the Manitou Falls Formation sandstones above the deposit have  $\delta^{18}\text{O}$  values between +9.3 and +15.9 per mil and  $\delta\text{D}$  values of -64 and -48 per mil. Using formation temperatures of 155°C for SC chlorite obtained from the mineral chemistry (Table 1), the calculated  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values for the fluid that formed SC

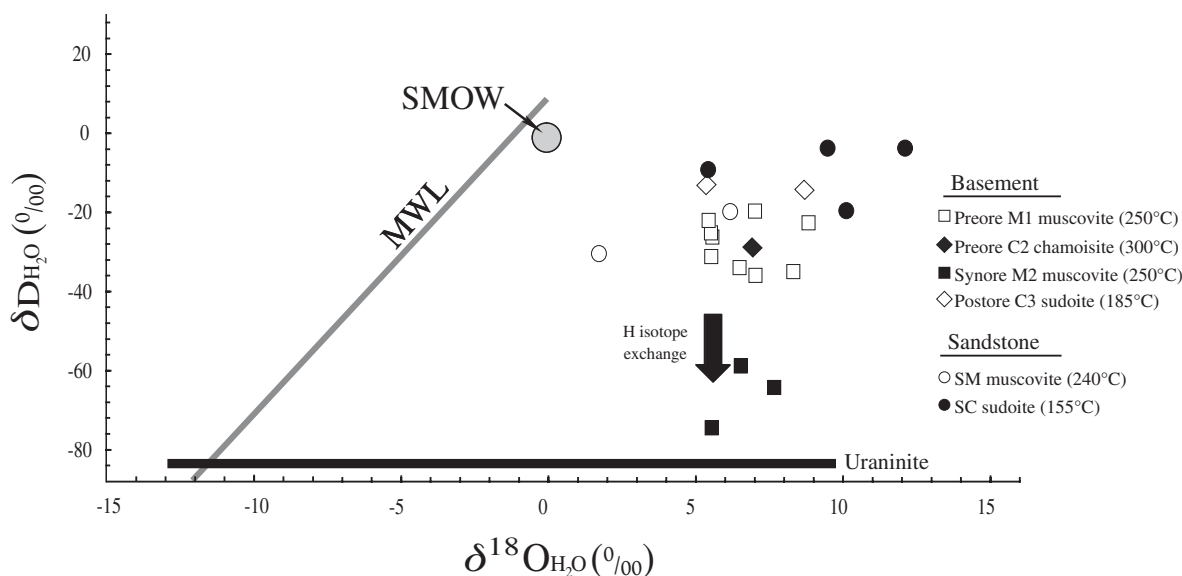


FIG. 10. Calculated  $\delta D$  and  $\delta^{18}O$  values of fluids in equilibrium with clay minerals from various alteration stages from basin and basement and  $\delta^{18}O$  values of uraninite at the Millennium deposit (Table 4). Also shown are the meteoric water line (MWL), the isotopic composition of standard modern ocean water (SMOW), and the effect of preferential exchange of H isotopes with modern fluids.

chlorite are +5.5 and +12.1 per mil for  $\delta^{18}O$  and -20 and -4 per mil for  $\delta D$  (Fig. 10).

#### Timing of Fluids That Have Affected the Millennium Deposit

Chemical U-Pb ages derived from the composition of uraninite vary from 67 to 702 Ma, suggesting variable recrystallization and Pb loss. There is a decrease in the chemical age with an increase in Ca, Fe, and Si contents of the uraninites (Fig. 11) and since alteration is expected to result in a decrease in radiogenic Pb, the age of formation of the uraninite in the Millennium deposit can be estimated by extrapolating the chemical U-Pb ages to the age when the concentration of the secondary elements (Ca, Fe, and Si) were negligible in the uraninite (Alexandre et al., 2005). Regression to zero

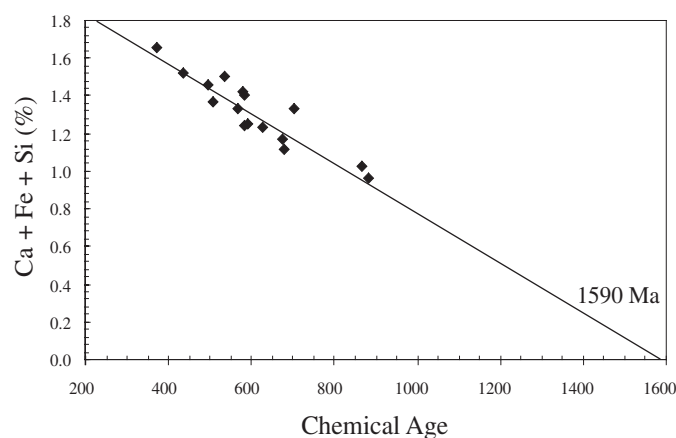


FIG. 11. Plot of Ca+Fe+Si contents in uraninites (Table 3) as a function of chemical date. Regression to 0 percent Ca+Fe+Si gives a chemical uraninite age of 1590 Ma.

content of these elements in the uraninites corresponds to 1590 Ma (Fig. 11), which is the same as the initial formation age that Alexandre et al. (2009) proposed for all the unconformity-related deposits in the Athabasca basin.

U-Pb isotope compositions of several uraninite grains analyzed by LA-HR-ICP-MS and LA-HR-MC-ICP-MS (Table 5) show significant resetting of U-Pb isotope systems (Fig. 12A). This resetting is also evident from the finely mottled and speckled appearance of uraninite grains under reflected light and backscattered electron imaging (Fig. 5F). Almost all uraninite grains have near-zero-age lower intercepts (Fig. 12A), reflecting major recent Pb loss. The  $^{206}Pb/^{207}Pb$  dates range between  $131 \pm 30$  Ma and  $1421 \pm 7$  Ma (Fig. 12F),  $^{206}Pb/^{238}U$  dates range between  $166 \pm 7$  Ma and  $1212 \pm 102$  Ma, and  $^{207}Pb/^{235}U$  dates range between  $263 \pm 9$  Ma and  $1135 \pm 1$  Ma ( $1\sigma$ ) (Table 5).

U-Pb upper intercept correspond to dates of  $1344 \pm 48$  Ma,  $1278 \pm 200$  Ma,  $1091 \pm 26$  Ma, and  $804 \pm 120$  Ma and a lower intercept near 0 Ma (Fig. 12B-E), which are similar to the dominant Pb-Pb dates recorded by the uraninites at Millennium (Fig. 12F). Similar dates for these upper intercept with the most frequent Pb-Pb isotope dates indicate episodes of partial resetting that occurred after the main mineralization event, the most dominant being near 1100 Ma (Fig. 12D) and coincident with the Grenville orogeny (Hoffman, 1990; Mosher, 1996).

Preore muscovite samples from the basement have disturbed  $^{40}Ar/^{39}Ar$  spectra with pseudoplateau  $^{40}Ar/^{39}Ar$  dates of  $1425 \pm 8$  Ma and  $1435 \pm 8$  Ma from 41 percent of the gas released (Fig. 13A). Both samples analyzed show a limited amount of superficial  $^{40}Ar^*$  loss (Fig. 13A) that should not affect the dates. A cumulative probability diagram for the two samples indicates a main date near 1430 Ma, defined by 60 percent of the steps and corresponding to the pseudoplateau ages, and a secondary date defined by 15 percent of the steps near 1390 Ma (Fig. 13B).

TABLE 5. Isotopic Data and Apparent Ages for Uraninite from the Millennium Deposit

| Analytical method                                                                | Sample no.       | <sup>206</sup> Pb/<br><sup>204</sup> Pb | com. Pb*<br>(%) | <sup>207</sup> Pb/<br><sup>235</sup> U | ±1σ    | <sup>206</sup> Pb/<br><sup>238</sup> U† | ±1σ    | R‡     | <sup>207</sup> Pb/<br><sup>206</sup> Pb | ±1σ    | Apparent ages ( ±1σ, Ma) <sup>°°</sup> |       |                                     |       | Disc.††<br>(%) |     |    |
|----------------------------------------------------------------------------------|------------------|-----------------------------------------|-----------------|----------------------------------------|--------|-----------------------------------------|--------|--------|-----------------------------------------|--------|----------------------------------------|-------|-------------------------------------|-------|----------------|-----|----|
|                                                                                  |                  |                                         |                 |                                        |        |                                         |        |        |                                         |        | <sup>206</sup> Pb/ <sup>238</sup> U    | Error | <sup>207</sup> Pb/ <sup>235</sup> U | Error |                |     |    |
| <i>Theoretical ratio for pure non-disturbed uraninite with an age of 1590 Ma</i> |                  |                                         |                 |                                        |        |                                         |        |        |                                         |        |                                        |       |                                     |       |                |     |    |
| HR-ICP-MS                                                                        | CX48-1-684_01    | <sup>206</sup> Pb <DL                   | 0.00            | 3.7870                                 | -      | 0.2798                                  | -      | -      | 0.0982                                  | -      | 1590                                   | 656   | -                                   | 1590  | -              | 0   |    |
|                                                                                  | CX48-1-684_01    | 67878                                   | 0.01            | 1.4672                                 | 0.0687 | 0.1402                                  | 0.0083 | 0.479  | 0.0778                                  | 0.0028 | 747                                    | 428   | 8                                   | 1119  | 141            | 41  |    |
|                                                                                  | CX48-1-684_07    | <sup>206</sup> Pb <DL                   | 0.00            | 1.1149                                 | 0.0602 | 0.1103                                  | 0.0060 | 0.511  | 0.0805                                  | 0.0036 | 758                                    | 377   | 6                                   | 1035  | 176            | 33  |    |
|                                                                                  | CX48-1-684_A02   | 118241                                  | 0.02            | 1.4695                                 | 0.0102 | 0.1374                                  | 0.0016 | 0.519  | 0.0805                                  | 0.0005 | 534                                    | 66    | 2                                   | 823   | 26             | 42  |    |
|                                                                                  | CX48-1-684_A03   | 303161                                  | 0.01            | 1.0903                                 | 0.0174 | 0.1073                                  | 0.0019 | 0.910  | 0.0756                                  | 0.0004 | 902                                    | 111   | 2                                   | 1152  | 22             | 32  |    |
|                                                                                  | CX48-1-684_A05   | 123807                                  | 0.02            | 0.5887                                 | 0.0130 | 0.0696                                  | 0.0025 | 0.7645 | 0.0636                                  | 0.0008 | 433                                    | 83    | 3                                   | 726   | 50             | 40  |    |
|                                                                                  | CX48-1-684_A06   | 97959                                   | 0.02            | 1.3114                                 | 0.0096 | 0.1257                                  | 0.0014 | 0.493  | 0.0780                                  | 0.0005 | 639                                    | 62    | 1                                   | 1021  | 27             | 37  |    |
|                                                                                  | CX48-1-684_A07   | 115748                                  | 0.02            | 1.1137                                 | 0.0239 | 0.1141                                  | 0.0026 | 0.090  | 0.0738                                  | 0.0004 | 557                                    | 17    | 602                                 | 24    | 827            | 23  | 33 |
|                                                                                  | CX48-1-684_A08   | 91641                                   | 0.02            | 1.2501                                 | 0.0139 | 0.1207                                  | 0.0025 | 0.061  | 0.0770                                  | 0.0009 | 722                                    | 89    | 835                                 | 3     | 1108           | 49  | 35 |
|                                                                                  | CX48-1-684_E01   | 161921                                  | 0.01            | 1.5423                                 | 0.0077 | 0.1502                                  | 0.0013 | 0.415  | 0.0760                                  | 0.0004 | 636                                    | 49    | 736                                 | 1     | 1149           | 19  | 45 |
|                                                                                  | CX48-1-684_E02   | 87044                                   | 0.02            | 1.0774                                 | 0.0139 | 0.1077                                  | 0.0014 | 0.005  | 0.0753                                  | 0.0003 | 797                                    | 89    | 907                                 | 1     | 1143           | 14  | 30 |
|                                                                                  | CX48-1-684_E03   | 168165                                  | 0.02            | 1.3739                                 | 0.0096 | 0.1304                                  | 0.0011 | 0.780  | 0.0797                                  | 0.0003 | 637                                    | 62    | 692                                 | 1     | 1054           | 16  | 40 |
|                                                                                  | CX48-1-684_E04   | 149934                                  | 0.01            | 1.2265                                 | 0.0089 | 0.1203                                  | 0.0013 | 0.499  | 0.0768                                  | 0.0005 | 734                                    | 57    | 823                                 | 1     | 1117           | 28  | 34 |
|                                                                                  | CX48-1-684_E06   | 100897                                  | 0.02            | 1.1891                                 | 0.0074 | 0.1165                                  | 0.0009 | 0.584  | 0.0767                                  | 0.0003 | 805                                    | 48    | 937                                 | 1     | 1224           | 18  | 34 |
|                                                                                  | CX48-1-689_12    | 410354                                  | 0.01            | 1.1582                                 | 0.0420 | 0.1288                                  | 0.0082 | 0.4334 | 0.0759                                  | 0.0033 | 780                                    | 265   | 780                                 | 8     | 1075           | 171 | 27 |
|                                                                                  | CX48-1-689_13    | 55613                                   | 0.01            | 1.0414                                 | 0.0601 | 0.1020                                  | 0.0081 | 0.284  | 0.0774                                  | 0.0067 | 470                                    | 376   | 562                                 | 8     | 644            | 343 | 27 |
|                                                                                  | CX48-1-689_14    | 21872                                   | 0.01            | 0.9902                                 | 0.0833 | 0.1045                                  | 0.0136 | 0.854  | 0.0747                                  | 0.0019 | 760                                    | 516   | 830                                 | 14    | 861            | 105 | 12 |
|                                                                                  | CX48-1-689_15    | 32337                                   | 0.04            | 1.0940                                 | 0.0469 | 0.1073                                  | 0.0064 | 0.591  | 0.0777                                  | 0.0029 | 842                                    | 296   | 974                                 | 7     | 1248           | 150 | 33 |
|                                                                                  | CX48-1-689_18    | 16326                                   | 0.01            | 1.2131                                 | 0.0336 | 0.1130                                  | 0.0033 | 0.185  | 0.0765                                  | 0.0032 | 804                                    | 213   | 935                                 | 3     | 1223           | 169 | 34 |
|                                                                                  | CX48-1-689_19    | 13000                                   | 0.11            | 1.1859                                 | 0.0652 | 0.1205                                  | 0.0065 | 0.746  | 0.0733                                  | 0.0024 | 732                                    | 407   | 812                                 | 7     | 1108           | 131 | 34 |
|                                                                                  | CX48-1-689_20    | 44322                                   | 0.01            | 1.0312                                 | 0.0560 | 0.1044                                  | 0.0084 | 0.713  | 0.0738                                  | 0.0030 | 569                                    | 52    | 649                                 | 8     | 762            | 166 | 25 |
|                                                                                  | CX48-1-689_21    | 68610                                   | 0.00            | 1.0929                                 | 0.0524 | 0.1018                                  | 0.0088 | 0.473  | 0.0797                                  | 0.0047 | 761                                    | 329   | 873                                 | 9     | 1126           | 233 | 32 |
|                                                                                  | CX48-1-689_22    | 44322                                   | 0.01            | 1.0312                                 | 0.0560 | 0.1044                                  | 0.0084 | 0.713  | 0.0738                                  | 0.0030 | 518                                    | 352   | 545                                 | 8     | 697            | 166 | 26 |
|                                                                                  | CX48-1-689_23    | 121601                                  | 0.02            | 1.1891                                 | 0.0460 | 0.1093                                  | 0.0051 | 0.661  | 0.0768                                  | 0.0023 | 742                                    | 290   | 856                                 | 5     | 1124           | 122 | 34 |
|                                                                                  | CX48-1-689_24    | 70487                                   | 0.00            | 1.0684                                 | 0.0408 | 0.1039                                  | 0.0089 | 0.740  | 0.0785                                  | 0.0024 | 827                                    | 258   | 862                                 | 9     | 1176           | 121 | 30 |
|                                                                                  | CX48-1-689_27    | 129519                                  | 0.03            | 1.0848                                 | 0.0582 | 0.1079                                  | 0.0050 | 0.451  | 0.0760                                  | 0.0045 | 829                                    | 365   | 917                                 | 5     | 1205           | 238 | 31 |
|                                                                                  | CX48-1-689_C1_01 | 351966                                  | 0.01            | 2.0693                                 | 0.0646 | 0.2076                                  | 0.0105 | 0.715  | 0.0585                                  | 0.0014 | 426                                    | 404   | 553                                 | 11    | 1072           | 103 | 60 |
|                                                                                  | CX48-1-689_C1_02 | 1546093                                 | 0.00            | 1.2391                                 | 0.0359 | 0.1237                                  | 0.0074 | 0.748  | 0.0600                                  | 0.0023 | 727                                    | 227   | 842                                 | 8     | 1114           | 165 | 35 |
|                                                                                  | CX48-1-689_C1_03 | 4922658                                 | 0.00            | 1.8271                                 | 0.0425 | 0.1754                                  | 0.0051 | 0.765  | 0.0601                                  | 0.0011 | 553                                    | 268   | 678                                 | 5     | 1152           | 82  | 52 |
|                                                                                  | CX48-1-689_C1_04 | 1088172                                 | 0.00            | 1.8396                                 | 0.0884 | 0.1782                                  | 0.0115 | 0.911  | 0.0611                                  | 0.0009 | 477                                    | 546   | 592                                 | 12    | 1026           | 67  | 54 |
|                                                                                  | CX48-1-689_C1_05 | 608863                                  | 0.00            | 1.7196                                 | 0.0583 | 0.1644                                  | 0.0077 | 0.729  | 0.0600                                  | 0.0015 | 479                                    | 366   | 580                                 | 8     | 962            | 109 | 50 |
|                                                                                  | CX48-1-689_C1_07 | <sup>206</sup> Pb <DL                   | 0.00            | 2.0157                                 | 0.0527 | 0.1996                                  | 0.0084 | 0.676  | 0.0599                                  | 0.0012 | 500                                    | 331   | 626                                 | 9     | 1091           | 89  | 54 |
| CX48-1-689_C1_08                                                                 | 1363763          | 0.00                                    | 2.0298          | 0.0692                                 | 0.1968 | 0.0116                                  | 0.627  | 0.0589 | 0.0014                                  | 430    | 431                                    | 554   | 12                                  | 1063  | 101            | 60  |    |
| CX48-1-689_C2_01                                                                 | 4183215          | 0.00                                    | 1.2720          | 0.0556                                 | 0.1276 | 0.0072                                  | 0.769  | 0.0599 | 0.0017                                  | 607    | 349                                    | 671   | 7                                   | 956   | 120            | 36  |    |
| CX48-1-689_C2_02                                                                 | 642495           | 0.00                                    | 1.5461          | 0.0548                                 | 0.1468 | 0.0074                                  | 0.797  | 0.0630 | 0.0010                                  | 569    | 344                                    | 673   | 7                                   | 1040  | 65             | 45  |    |
| CX48-1-689_C2_03                                                                 | 1636535          | 0.00                                    | 1.6575          | 0.0547                                 | 0.1619 | 0.0097                                  | 0.744  | 0.0622 | 0.0021                                  | 439    | 343                                    | 520   | 10                                  | 861   | 147            | 49  |    |
| CX48-1-689_C2_04                                                                 | 630040           | 0.00                                    | 1.6522          | 0.0580                                 | 0.1601 | 0.0093                                  | 0.730  | 0.0637 | 0.0022                                  | 575    | 363                                    | 707   | 9                                   | 1121  | 147            | 49  |    |
| CX48-1-689_C2_05                                                                 | 3090785          | 0.00                                    | 1.2690          | 0.0412                                 | 0.1192 | 0.0042                                  | 0.434  | 0.0626 | 0.0024                                  | 649    | 261                                    | 723   | 4                                   | 1010  | 160            | 36  |    |
| CX48-1-689_C2_06                                                                 | 220430           | 0.01                                    | 1.5068          | 0.0549                                 | 0.1476 | 0.0075                                  | 0.747  | 0.0609 | 0.0016                                  | 646    | 344                                    | 758   | 8                                   | 1131  | 113            | 43  |    |
| CX48-1-689_C2_07                                                                 | 409330           | 0.00                                    | 1.7347          | 0.0603                                 | 0.1635 | 0.0084                                  | 0.764  | 0.0627 | 0.0019                                  | 438    | 378                                    | 526   | 8                                   | 891   | 132            | 51  |    |
| CX48-1-689_C2_08                                                                 | 2535204          | 0.00                                    | 1.7329          | 0.0619                                 | 0.1679 | 0.0095                                  | 0.777  | 0.0607 | 0.0015                                  | 555    | 387                                    | 688   | 10                                  | 1116  | 108            | 50  |    |
| CX48-1-689_C2_09                                                                 | 282123           | 0.01                                    | 1.6198          | 0.0571                                 | 0.1588 | 0.0087                                  | 0.641  | 0.0620 | 0.0022                                  | 534    | 358                                    | 626   | 9                                   | 1017  | 152            | 47  |    |
| CX48-1-689_C4_01                                                                 | 7301             | 0.02                                    | 1.0266          | 0.0499                                 | 0.1032 | 0.0077                                  | 0.763  | 0.0778 | 0.0019                                  | 844    | 314                                    | 912   | 8                                   | 1123  | 99             | 25  |    |
| CX48-1-689_C4_02                                                                 | 93539            | 0.02                                    | 0.9449          | 0.0345                                 | 0.0924 | 0.0041                                  | 0.621  | 0.0743 | 0.0016                                  | 843    | 219                                    | 942   | 4                                   | 839   | 89             | 0   |    |
| CX48-1-689_C4_02a                                                                | 168767           | 0.01                                    | 1.0473          | 0.0685                                 | 0.1063 | 0.0088                                  | 0.719  | 0.0734 | 0.0028                                  | 733    | 427                                    | 791   | 9                                   | 1014  | 156            | 28  |    |
| CX48-1-689_C4_02a[1]                                                             | 5065248          | 0.01                                    | 1.5169          | 0.0856                                 | 0.1443 | 0.0113                                  | 0.784  | 0.0655 | 0.0022                                  | 631    | 529                                    | 713   | 11                                  | 1132  | 141            | 44  |    |
| CX48-1-689_C4_03                                                                 | 32071            | 0.05                                    | 0.9578          | 0.0501                                 | 0.0898 | 0.0061                                  | 0.688  | 0.0787 | 0.0023                                  | 806    | 315                                    | 932   | 6                                   | 817   | 114            | 1   |    |
| CX48-1-689_C4_04                                                                 | 23286            | 0.04                                    | 1.1159          | 0.0431                                 | 0.1056 | 0.0056                                  | 0.603  | 0.0777 | 0.0019                                  | 763    | 272                                    | 850   | 6                                   | 1144  | 98             | 33  |    |
| CX48-1-689_C4_06                                                                 | 14552            | 0.03                                    | 1.0117          | 0.0514                                 | 0.1030 | 0.0080                                  | 0.731  | 0.0755 | 0.0024                                  | 902    | 323                                    | 947   | 8                                   | 1093  | 129            | 18  |    |
| CX48-1-689_C4_08                                                                 | 516730           | 0.00                                    | 1.5384          | 0.0612                                 | 0.1400 | 0.0074                                  | 0.833  | 0.0675 | 0.0017                                  | 524    | 383                                    | 578   | 8                                   | 946   | 106            | 45  |    |

TABLE 5. (Cont.)

| Analytical method | Sample no.       | $\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ | com. Pb <sup>o</sup> (%) | $\frac{^{207}\text{Pb}}{^{235}\text{U}}$ | $\pm 1\sigma$ | $\frac{^{206}\text{Pb}}{^{238}\text{U}}$ | $\pm 1\sigma$ | R†     | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ | $\pm 1\sigma$ | Apparent ages ( $\pm 1\sigma$ , Ma) <sup>o</sup> |       |                                          |       | Disc.t† (%) |                                           |       |
|-------------------|------------------|-------------------------------------------|--------------------------|------------------------------------------|---------------|------------------------------------------|---------------|--------|-------------------------------------------|---------------|--------------------------------------------------|-------|------------------------------------------|-------|-------------|-------------------------------------------|-------|
|                   |                  |                                           |                          |                                          |               |                                          |               |        |                                           |               | $\frac{^{206}\text{Pb}}{^{238}\text{U}}$         | Error | $\frac{^{207}\text{Pb}}{^{235}\text{U}}$ | Error |             | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ | Error |
| HHR-ICP-MS        | CX48-1-689_C4_09 | 229206                                    | 0.01                     | 1.5946                                   | 0.0546        | 0.1487                                   | 0.0069        | 0.619  | 0.0668                                    | 0.0018        | 624                                              | 343   | 748                                      | 7     | 1168        | 111                                       | 47    |
|                   | CX48-1-689_C4_10 | 263783                                    | 0.01                     | 1.7593                                   | 0.0525        | 0.1671                                   | 0.0087        | 0.806  | 0.0680                                    | 0.0018        | 510                                              | 330   | 608                                      | 9     | 1039        | 113                                       | 51    |
|                   | CX48-1-689_C4_11 | 1015356                                   | 0.00                     | 1.5116                                   | 0.0550        | 0.1336                                   | 0.0079        | 0.789  | 0.0670                                    | 0.0021        | 626                                              | 345   | 723                                      | 8     | 1103        | 130                                       | 43    |
|                   | CX48-1-689_C4_12 | 952994                                    | 0.01                     | 1.6981                                   | 0.0423        | 0.1518                                   | 0.0044        | 0.240  | 0.0673                                    | 0.0026        | 519                                              | 267   | 636                                      | 4     | 1040        | 160                                       | 50    |
|                   | CX48-1-689_C4_13 | 351221                                    | 0.02                     | 1.5718                                   | 0.0573        | 0.1486                                   | 0.0088        | 0.805  | 0.0665                                    | 0.0021        | 574                                              | 359   | 692                                      | 9     | 1063        | 131                                       | 46    |
|                   | CX48-1-689_C4_14 | 567482                                    | 0.02                     | 1.2837                                   | 0.0485        | 0.1181                                   | 0.0070        | 0.641  | 0.0663                                    | 0.0022        | 757                                              | 305   | 891                                      | 7     | 1207        | 138                                       | 37    |
|                   | CX48-1-689_C4_15 | 130609                                    | 0.01                     | 1.2715                                   | 0.0470        | 0.1255                                   | 0.0066        | 0.743  | 0.0683                                    | 0.0018        | 710                                              | 296   | 795                                      | 7     | 1110        | 110                                       | 36    |
|                   | CX48-1-695_01    | 146577                                    | 0.01                     | 0.5142                                   | 0.0169        | 0.0647                                   | 0.0024        | 0.7135 | 0.0589                                    | 0.0012        | 404                                              | 108   | 420                                      | 2     | 556         | 86                                        | 27    |
|                   | CX48-1-695_03    | 30185                                     | 0.02                     | 0.4561                                   | 0.0156        | 0.0647                                   | 0.0030        | 0.1385 | 0.0598                                    | 0.0021        | 404                                              | 100   | 381                                      | 3     | 567         | 154                                       | 29    |
|                   | CX48-1-695_04    | 30496                                     | 0.02                     | 1.9615                                   | 0.0730        | 0.1961                                   | 0.0104        | 0.638  | 0.0811                                    | 0.0030        | 528                                              | 454   | 670                                      | 10    | 1147        | 143                                       | 54    |
|                   | CX48-1-695_206   | 131572                                    | 0.02                     | 1.3396                                   | 0.0190        | 0.1239                                   | 0.0020        | 0.597  | 0.0681                                    | 0.0008        | 659                                              | 121   | 740                                      | 2     | 1075        | 46                                        | 39    |
|                   | CX48-1-695_208   | 126709                                    | 0.02                     | 1.6564                                   | 0.0230        | 0.1384                                   | 0.0022        | 0.829  | 0.0757                                    | 0.0005        | 835                                              | 147   | 988                                      | 2     | 1081        | 27                                        | 23    |
|                   | CX48-1-695_210   | 13744                                     | 0.20                     | 0.2977                                   | 0.0091        | 0.0262                                   | 0.0010        | 0.727  | 0.0756                                    | 0.0013        | 166                                              | 59    | 263                                      | 1     | 1057        | 70                                        | 84    |
|                   | CX48-1-689_N01   | 768339                                    | 0.01                     | 1.4429                                   | 0.0058        | 0.1317                                   | 0.0005        | 0.956  | 0.0778                                    | 0.0000        | 631                                              | 38    | 708                                      | 1     | 1074        | 1                                         | 41    |
|                   | CX48-1-689_N01a  | 80613                                     | 0.01                     | 1.3238                                   | 0.0045        | 0.1220                                   | 0.0004        | 0.952  | 0.0771                                    | 0.0000        | 660                                              | 29    | 744                                      | 0     | 1075        | 1                                         | 39    |
|                   | CX48-1-689_N02   | 52102                                     | 0.02                     | 0.9809                                   | 0.0090        | 0.0963                                   | 0.0007        | 0.958  | 0.0724                                    | 0.0001        | 718                                              | 58    | 835                                      | 1     | 794         | 8                                         | 10    |
|                   | CX48-1-689_N03   | 32914                                     | 0.02                     | 1.4311                                   | 0.0051        | 0.1300                                   | 0.0004        | 0.945  | 0.0782                                    | 0.0000        | 657                                              | 33    | 778                                      | 0     | 1108        | 1                                         | 41    |
|                   | CX48-1-689_N04   | 410688                                    | 0.01                     | 1.2907                                   | 0.0030        | 0.1194                                   | 0.0002        | 0.941  | 0.0767                                    | 0.0000        | 639                                              | 19    | 716                                      | 0     | 1021        | 2                                         | 37    |
|                   | CX48-1-689_N05   | 94532                                     | 0.01                     | 1.2772                                   | 0.0066        | 0.1185                                   | 0.0005        | 0.956  | 0.0765                                    | 0.0001        | 690                                              | 42    | 806                                      | 1     | 1095        | 3                                         | 37    |
|                   | CX48-1-689_N06   | 159239                                    | 0.01                     | 1.3625                                   | 0.0081        | 0.1253                                   | 0.0007        | 0.959  | 0.0772                                    | 0.0001        | 668                                              | 52    | 793                                      | 1     | 1103        | 3                                         | 39    |
| HHR-MC-ICP-MS     | CX48-1-695_101   | 312661                                    | 0.02                     | 1.8589                                   | 0.0198        | 0.1585                                   | 0.0017        | 0.964  | 0.0835                                    | 0.0000        | 948                                              | 127   | 1066                                     | 2     | 1281        | 2                                         | 26    |
|                   | CX48-1-695_1C    | 39046                                     | 0.04                     | 0.5363                                   | 0.0121        | 0.0577                                   | 0.0012        | 0.9494 | 0.0663                                    | 0.0001        | 362                                              | 78    | 435                                      | 1     | 815         | 8                                         | 56    |
|                   | CX48-1-695_1D    | 19368                                     | 0.07                     | 0.5695                                   | 0.0102        | 0.0637                                   | 0.0010        | 0.7349 | 0.0642                                    | 0.0002        | 398                                              | 65    | 458                                      | 1     | 747         | 11                                        | 47    |
|                   | CX48-1-695_1K    | 42422                                     | 0.03                     | 0.9786                                   | 0.0105        | 0.0932                                   | 0.0010        | 0.948  | 0.0748                                    | 0.0001        | 487                                              | 67    | 558                                      | 1     | 510         | 8                                         | 5     |
|                   | CX48-1-695_1L    | 764765                                    | 0.03                     | 1.4069                                   | 0.0128        | 0.1247                                   | 0.0012        | 0.954  | 0.0804                                    | 0.0001        | 593                                              | 82    | 694                                      | 1     | 997         | 6                                         | 41    |
|                   | CX48-1-695_1M    | 62855                                     | 0.01                     | 1.5130                                   | 0.0117        | 0.1328                                   | 0.0011        | 0.960  | 0.0810                                    | 0.0001        | 673                                              | 75    | 757                                      | 1     | 1188        | 4                                         | 43    |
|                   | CX48-1-695_1N    | 172974                                    | 0.02                     | 2.0558                                   | 0.0233        | 0.1728                                   | 0.0020        | 0.965  | 0.0846                                    | 0.0000        | 1027                                             | 149   | 1133                                     | 2     | 1307        | 1                                         | 21    |
|                   | CX48-1-695_1P    | 92440                                     | 0.01                     | 1.6124                                   | 0.0212        | 0.1396                                   | 0.0018        | 0.966  | 0.0821                                    | 0.0000        | 531                                              | 135   | 600                                      | 2     | 995         | 2                                         | 47    |
|                   | CX48-1-695_1Q    | 108658                                    | 0.02                     | 1.5171                                   | 0.0106        | 0.1331                                   | 0.0009        | 0.960  | 0.0811                                    | 0.0001        | 507                                              | 68    | 595                                      | 1     | 912         | 3                                         | 44    |
|                   | CX48-1-695_1R    | 73853                                     | 0.02                     | 1.1533                                   | 0.0135        | 0.1073                                   | 0.0012        | 0.963  | 0.0765                                    | 0.0000        | 790                                              | 86    | 877                                      | 1     | 1187        | 2                                         | 33    |
|                   | CX48-1-695_1W    | 65207                                     | 0.02                     | 0.9702                                   | 0.0072        | 0.0899                                   | 0.0005        | 0.922  | 0.0768                                    | 0.0002        | 1151                                             | 46    | 1098                                     | 1     | 1201        | 9                                         | 4     |
|                   | CX48-1-695_1Z    | 43740                                     | 0.04                     | 1.0067                                   | 0.0094        | 0.0933                                   | 0.0008        | 0.952  | 0.0770                                    | 0.0001        | 752                                              | 61    | 860                                      | 1     | 854         | 4                                         | 12    |
|                   | CX56-3-711_103   | 834538                                    | 0.02                     | 0.9761                                   | 0.0403        | 0.0798                                   | 0.0033        | 0.908  | 0.0870                                    | 0.0001        | 495                                              | 254   | 689                                      | 3     | 1361        | 6                                         | 64    |
|                   | CX56-3-711_105   | 61132                                     | 0.01                     | 0.9762                                   | 0.0175        | 0.0773                                   | 0.0014        | 0.797  | 0.0898                                    | 0.0002        | 480                                              | 112   | 692                                      | 1     | 1421        | 7                                         | 66    |
|                   | CX56-3-711_109   | 67566                                     | 0.02                     | 1.2778                                   | 0.0281        | 0.1038                                   | 0.0021        | 0.927  | 0.0876                                    | 0.0001        | 637                                              | 179   | 835                                      | 2     | 1373        | 6                                         | 54    |
|                   | CX56-3-711_110   | 78053                                     | 0.01                     | 1.3116                                   | 0.0243        | 0.1070                                   | 0.0020        | 0.958  | 0.0871                                    | 0.0001        | 655                                              | 155   | 850                                      | 2     | 1363        | 2                                         | 52    |
|                   | CX56-3-711_111   | 53951                                     | 0.01                     | 1.2723                                   | 0.0376        | 0.1049                                   | 0.0031        | 0.944  | 0.0862                                    | 0.0001        | 642                                              | 238   | 831                                      | 3     | 1343        | 3                                         | 52    |

Symbols: <sup>o</sup> com. Pb (%) = % <sup>206</sup>Pb from common lead† Measured isotope ratios (except <sup>206</sup>Pb/<sup>204</sup>Pb) and calculated apparent dates are corrected for common lead, as estimated from monitored counts of <sup>204</sup>Pb

‡ R = error correlation coefficient

§ <sup>206</sup>Pb/<sup>238</sup>U, <sup>207</sup>Pb/<sup>235</sup>U, and <sup>207</sup>Pb/<sup>206</sup>Pb ages calculated using equations reported by Ludwig (2000)

†† Disc. = percent discordance

DL = detection limit

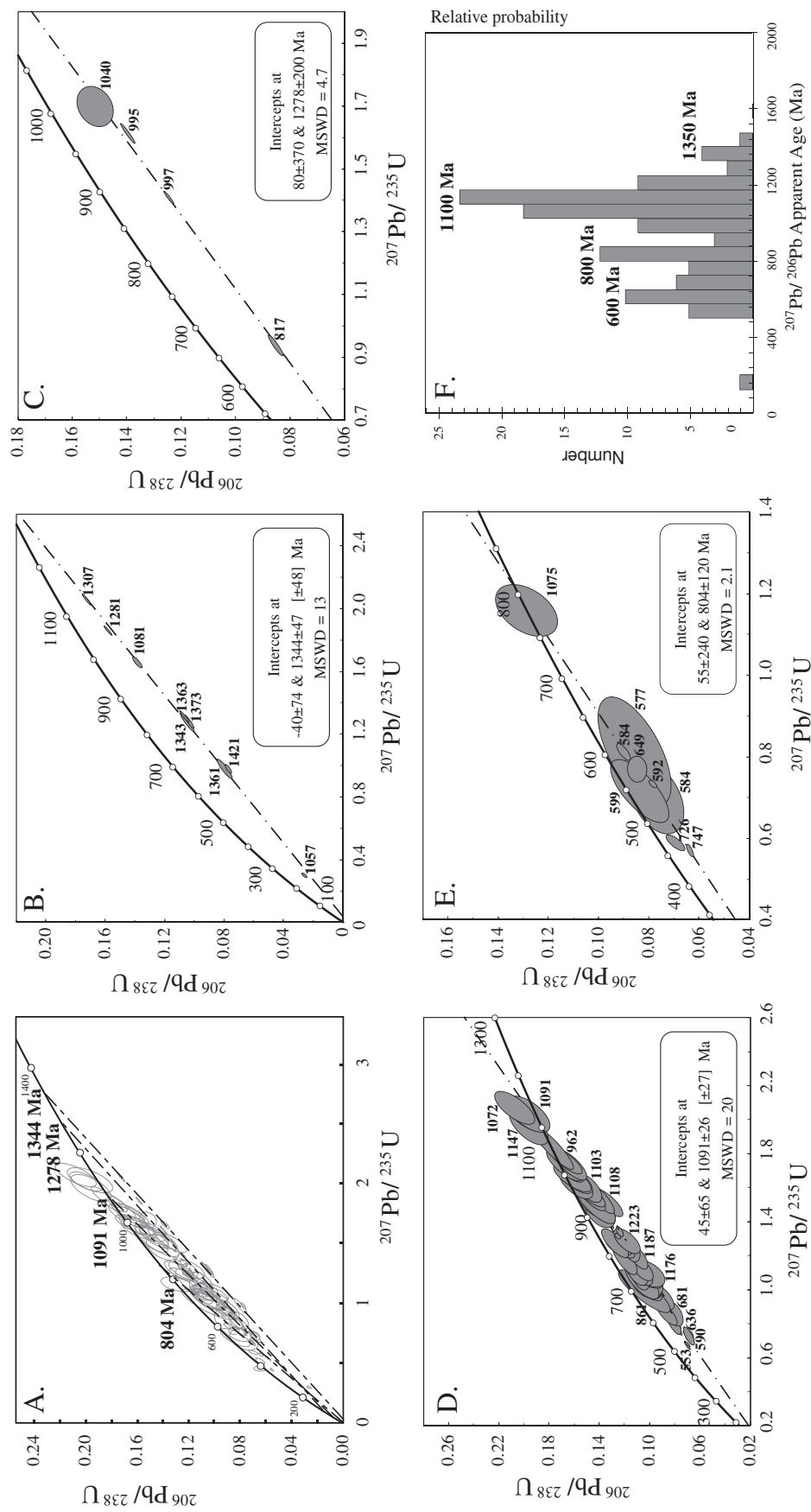


FIG. 12. Concordia diagram for Millennium uraninites showing (A) all the intercepts, (B) a resetting upper intercept at 1344 Ma, (C) a resetting upper intercept at 1278 Ma, (D) a resetting upper intercept at 1091 Ma, (E) a resetting upper intercept at 826 Ma and (F) a cumulative probability histogram of  $^{207}\text{Pb}/^{206}\text{Pb}$  apparent ages in Ma. Data from Table 5. Bold numbers beside analyses represent  $^{207}\text{Pb}/^{206}\text{Pb}$  ages.

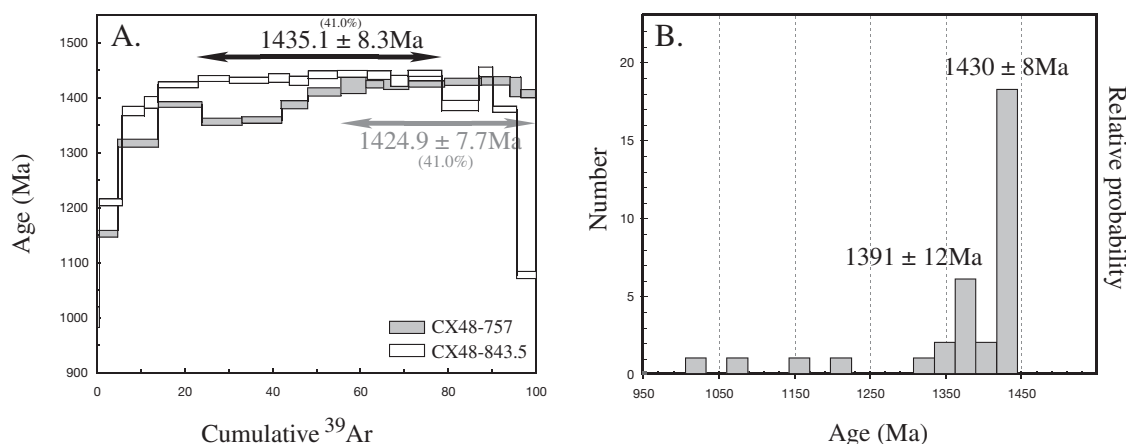


FIG. 13. (A)  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  spectra for preore muscovites at Millennium showing pseudoplateau  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $1425 \pm 8\text{ Ma}$  and  $1435 \pm 8\text{ Ma}$ ; (B) histogram of cumulative probability showing major perturbations of the  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics at 1430 and 1391 Ma.

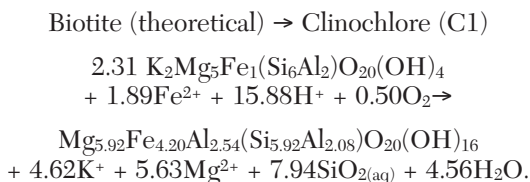
### Chemistry and Geochronology of the Leachable Phases

Holk et al. (2003) demonstrated that the isotopic composition of leachable Pb could be used to trace Pb loss events from uranium deposits. The isotopic compositions of Pb leach from around the Millennium deposit indicate the presence of radiogenic Pb ( $^{206}\text{Pb}/^{204}\text{Pb} > 30$ ) (Table 6) in the basement up to 75 m above and more than 100 m below the mineralized zone (Fig. 14A). The Pb leached from the basin gives a model  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron age of  $2875 \pm 360\text{ Ma}$ , whereas basement rocks give a model  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron age of  $1075 \pm 400\text{ Ma}$ , similar to the 1091 Ma major resetting event recorded by the uraninite.

### Discussion

#### Reactions during alteration and mineralization

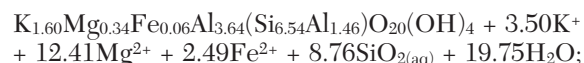
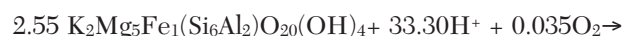
Petrographic relationships reveal four principal phases of alteration: a preore stage with minor C1 clinocllore alteration forming prior to pervasive M1 muscovite alteration, a preore stage with minor C2 chamoisite altering M1 muscovite, a synore stage with coeval precipitation of uraninite, M2 muscovite and H1 hematite and a postore stage where sudoite (C3 and C4) is the dominant alteration mineral. Based on petrographic observations, the starting mineral assemblage in the basement rocks is composed on average of 40 percent quartz, 25 percent plagioclase and 20 percent biotite, with minor amounts of potassium feldspar, cordierite, muscovite, graphite, hematite, rutile, pyrite, and amphibole. We estimate that the first chloritization event altered about 50 percent of the biotite to C1 clinocllore according to the reaction:



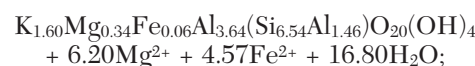
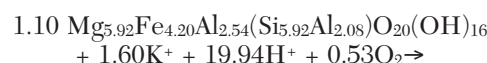
This reaction liberated K, Mg, and  $\text{SiO}_{2(\text{aq})}$  while consuming Fe,  $\text{H}^+$ , and  $\text{O}_2$ , creating about  $485\text{ \AA}$  (41%) of space per 2.31 biotite ( $497.79\text{ \AA}$  per formula unit) altered to clinocllore ( $699.59\text{ \AA}$

per formula unit), for a total space created in the rock of 4 percent during this phase of alteration. The C1 clinocllore alteration was followed by M1 muscovite alteration of remaining biotite, C1 clinocllore, and plagioclase according to the following reactions:

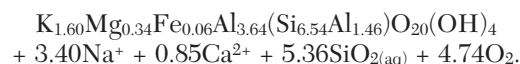
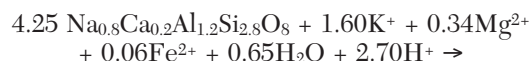
Biotite (theoretical)  $\rightarrow$  M1 Muscovite



C1 Clinocllore (as probed)  $\rightarrow$  M1 Muscovite (as probed)



Oligoclase (theoretical)  $\rightarrow$  M1 Muscovite (as probed)



Based on petrographic observations, we estimate that both biotite and clinocllore alteration to muscovite accounted for 22.5 percent each of the muscovite created whereas oligoclase alteration accounted for 55 percent. These reactions liberated Mg, Fe, Na, Ca,  $\text{SiO}_{2(\text{aq})}$ , and  $\text{O}_2$ , while consuming K and  $\text{H}^+$ . Up to 65 percent of the K consumed during these reactions can be derived from biotite, whereas the rest of the K had to be brought in with the fluids responsible for M1 muscovite alteration. This muscovite alteration ( $467.665\text{ \AA}$  per formula unit) created  $802\text{ \AA}$  (63%) of space per 2.55 formula unit of altered biotite,  $281\text{ \AA}$  (37%) of space per 1.10 formula unit of altered C1 clinocllore, and  $203\text{ \AA}$  (30%) of space per 4.25 formula units of altered oligoclase ( $158.26\text{ \AA}$  per formula unit). The total space created in the rock during this alteration is 21 percent, bringing the total space created in the

TABLE 6. Pb Isotope Compositions and Concentrations of Pb and U (ppb) in the Leachates from Two Cross Sections of the Manitou Falls Formation Sandstones and One Cross Section of the Basement Rocks

| Sample no.                                | $^{206}\text{Pb}/^{204}\text{Pb}$ | $^{207}\text{Pb}/^{204}\text{Pb}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ age | $^{207}\text{Pb}/^{235}\text{U}$ | $^{206}\text{Pb}/^{238}\text{U}$ | Pb (ppb) | U (ppb) |
|-------------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|---------------------------------------|----------------------------------|----------------------------------|----------|---------|
| <u>Manitou Falls Formation sandstones</u> |                                   |                                   |                                   |                                       |                                  |                                  |          |         |
| CX43-399                                  | 16.64                             | 14.87                             | 0.89                              | 5078                                  | 978.32                           | 9.20                             | 0.26     | 0.01    |
| CX43-522                                  | 17.98                             | 14.13                             | 0.79                              | 4896                                  | 595.77                           | 6.47                             | 0.11     | 0.00    |
| CX43-595                                  | 31.02                             | 16.10                             | 0.52                              | 4296                                  | 8.06                             | 0.11                             | 8.00     | 14.63   |
| CX44-392                                  | 20.20                             | 15.09                             | 0.75                              | 4825                                  | 64.13                            | 0.66                             | 0.13     | 0.05    |
| CX44-516                                  | 22.63                             | 15.43                             | 0.68                              | 4693                                  | 175.76                           | 1.73                             | 0.21     | 0.03    |
| CX44-577                                  | 25.88                             | 15.01                             | 0.58                              | 4458                                  | 20.34                            | 0.26                             | 0.13     | 0.12    |
| CX48-567.1                                | 29.39                             | 16.60                             | 0.56                              | 4420                                  | 84.45                            | 1.07                             | 1.32     | 0.28    |
| CX48-570.8                                | 30.26                             | 16.63                             | 0.55                              | 4380                                  | 31.36                            | 0.40                             | 1.43     | 0.19    |
| CX49-385                                  | 25.90                             | 15.78                             | 0.61                              | 4530                                  | 3189.86                          | 41.27                            | 2.38     | 0.02    |
| CX49-543                                  | 15.84                             | 13.72                             | 0.87                              | 5035                                  | 111.13                           | 1.11                             | 0.07     | 0.01    |
| CX49-628                                  | 25.95                             | 15.93                             | 0.61                              | 4541                                  | 37.93                            | 0.46                             | 1.15     | 0.56    |
| CX50-400                                  | 18.22                             | 15.10                             | 0.83                              | 4972                                  | 333.87                           | 2.96                             | 0.24     | 0.02    |
| CX50-542                                  | 22.34                             | 15.55                             | 0.70                              | 4722                                  | 95.73                            | 1.03                             | 0.19     | 0.04    |
| CX50-610                                  | 33.89                             | 16.44                             | 0.49                              | 4197                                  | 29.17                            | 0.48                             | 0.35     | 0.21    |
| CX51-381                                  | 17.32                             | 14.54                             | 0.84                              | 4990                                  | 409.78                           | 3.66                             | 0.15     | 0.01    |
| CX51-500                                  | 17.91                             | 14.36                             | 0.80                              | 4925                                  | 77.35                            | 0.70                             | 0.06     | 0.02    |
| CX51-663                                  | 18.75                             | 14.32                             | 0.76                              | 4856                                  | 6.98                             | 0.07                             | 0.08     | 0.25    |
| CX52-392                                  | 16.94                             | 15.15                             | 0.89                              | 5080                                  | 301.02                           | 2.92                             | 0.10     | 0.00    |
| CX52-519                                  | 17.59                             | 15.14                             | 0.86                              | 5026                                  | 584.35                           | 5.00                             | 1.03     | 0.05    |
| CX52-586                                  | 23.62                             | 15.62                             | 0.66                              | 4649                                  | 5.09                             | 0.06                             | 0.36     | 1.59    |
| CX53-1-617.5                              | 30.74                             | 17.55                             | 0.57                              | 4436                                  | 219.70                           | 2.64                             | 0.87     | 0.28    |
| CX53-1-622.5                              | 28.48                             | 16.45                             | 0.58                              | 4452                                  | 24.06                            | 0.30                             | 0.57     | 1.73    |
| CX54-350                                  | 16.94                             | 15.00                             | 0.89                              | 5066                                  | 968.05                           | 5.53                             | 0.21     | 0.01    |
| CX54-482                                  | 16.15                             | 13.83                             | 0.86                              | 5019                                  | 108.11                           | 1.22                             | 0.06     | 0.01    |
| CX54-548                                  | 30.92                             | 16.21                             | 0.52                              | 4311                                  | 3.14                             | 0.05                             | 0.07     | 0.54    |
| CX56-066                                  | 24.74                             | 16.33                             | 0.66                              | 4646                                  | 523.27                           | 5.51                             | 0.10     | 0.33    |
| CX56-186.5                                | 26.39                             | 18.12                             | 0.69                              | 4703                                  | 32.59                            | 0.34                             | 0.13     | 0.09    |
| CX56-265                                  | 22.72                             | 16.14                             | 0.71                              | 4752                                  | 419.18                           | 4.18                             | 0.16     | 0.08    |
| CX56-355                                  | 19.45                             | 16.01                             | 0.82                              | 4962                                  | 98.75                            | 0.83                             | 0.12     | 0.07    |
| CX56-425                                  | 19.31                             | 15.87                             | 0.82                              | 4960                                  | 149.43                           | 1.30                             | 0.13     | 0.06    |
| CX56-499.5                                | 21.50                             | 16.46                             | 0.77                              | 4859                                  | 88.94                            | 0.82                             | 0.85     | 0.25    |
| CX56-573                                  | 31.46                             | 16.74                             | 0.53                              | 4333                                  | 216.17                           | 2.86                             | 0.50     | 0.20    |
| CX58-371                                  | 17.39                             | 14.81                             | 0.85                              | 5011                                  | 219.38                           | 1.95                             | 0.11     | 0.01    |
| CX58-486                                  | 18.39                             | 14.91                             | 0.81                              | 4940                                  | 198.78                           | 1.76                             | 0.15     | 0.01    |
| CX58-545                                  | 21.18                             | 15.17                             | 0.72                              | 4764                                  | 11.72                            | 0.12                             | 0.07     | 0.14    |
| CX60-391                                  | 17.19                             | 14.04                             | 0.82                              | 4951                                  | 110.80                           | 1.13                             | 0.08     | 0.01    |
| CX60-525                                  | 18.94                             | 14.37                             | 0.76                              | 4846                                  | 25.07                            | 0.24                             | 0.05     | 0.04    |
| CX60-596                                  | 18.64                             | 15.05                             | 0.81                              | 4935                                  | 134.36                           | 1.39                             | 0.12     | 0.05    |
| CX61-358                                  | 16.90                             | 14.71                             | 0.87                              | 5042                                  | 233.43                           | 2.85                             | 0.12     | 0.01    |
| CX61-451                                  | 18.06                             | 14.91                             | 0.83                              | 4967                                  | 244.21                           | 1.92                             | 0.06     | 0.00    |
| CX61-498                                  | 17.24                             | 14.27                             | 0.83                              | 4970                                  | 105.23                           | 1.07                             | 0.09     | 0.02    |
| <u>Basement rocks</u>                     |                                   |                                   |                                   |                                       |                                  |                                  |          |         |
| CX48-593-0                                | 35.94                             | 17.41                             | 0.48                              | 4194                                  | 18.90                            | 0.27                             | 6.52     | 0.16    |
| CX48-625                                  | 159.57                            | 22.23                             | 0.14                              | 2219                                  | 0.77                             | 0.04                             | 3.35     | 0.16    |
| CX48-647                                  | 144.57                            | 26.85                             | 0.19                              | 2705                                  | 2.66                             | 0.11                             | 1.99     | 5.57    |
| CX48-678                                  | 171.05                            | 20.34                             | 0.12                              | 1940                                  | 5.16                             | 0.31                             | 2.90     | 0.19    |
| CX48-688                                  | 195.32                            | 23.95                             | 0.12                              | 1995                                  | 0.95                             | 0.05                             | 4.22     | 0.33    |
| CX48-713                                  | 516.03                            | 52.17                             | 0.10                              | 1644                                  | 0.26                             | 0.02                             | 3.07     | 0.13    |
| CX48-733                                  | 199.00                            | 33.45                             | 0.17                              | 2539                                  | 77.03                            | 3.34                             | 3.21     | 0.17    |
| CX48-852.5                                | 44.48                             | 17.71                             | 0.40                              | 3902                                  | 6.28                             | 0.11                             | 0.73     | 0.12    |
| CX48-856                                  | 74.99                             | 19.82                             | 0.26                              | 3272                                  | 33.70                            | 0.91                             | 6.42     | 0.27    |
| CX53-1-629                                | 27.55                             | 16.49                             | 0.60                              | 4505                                  | 80.18                            | 0.95                             | 1.62     | 0.09    |
| CX53-1-657                                | 33.38                             | 17.80                             | 0.53                              | 4336                                  | 4.73                             | 0.06                             | 1.52     | 0.13    |
| CX53-1-664                                | 33.93                             | 16.89                             | 0.50                              | 4235                                  | 8.96                             | 0.12                             | 0.40     | 0.40    |
| CX53-1-705.5                              | 76.46                             | 21.86                             | 0.29                              | 3396                                  | 15.36                            | 0.38                             | 4.00     | 0.19    |

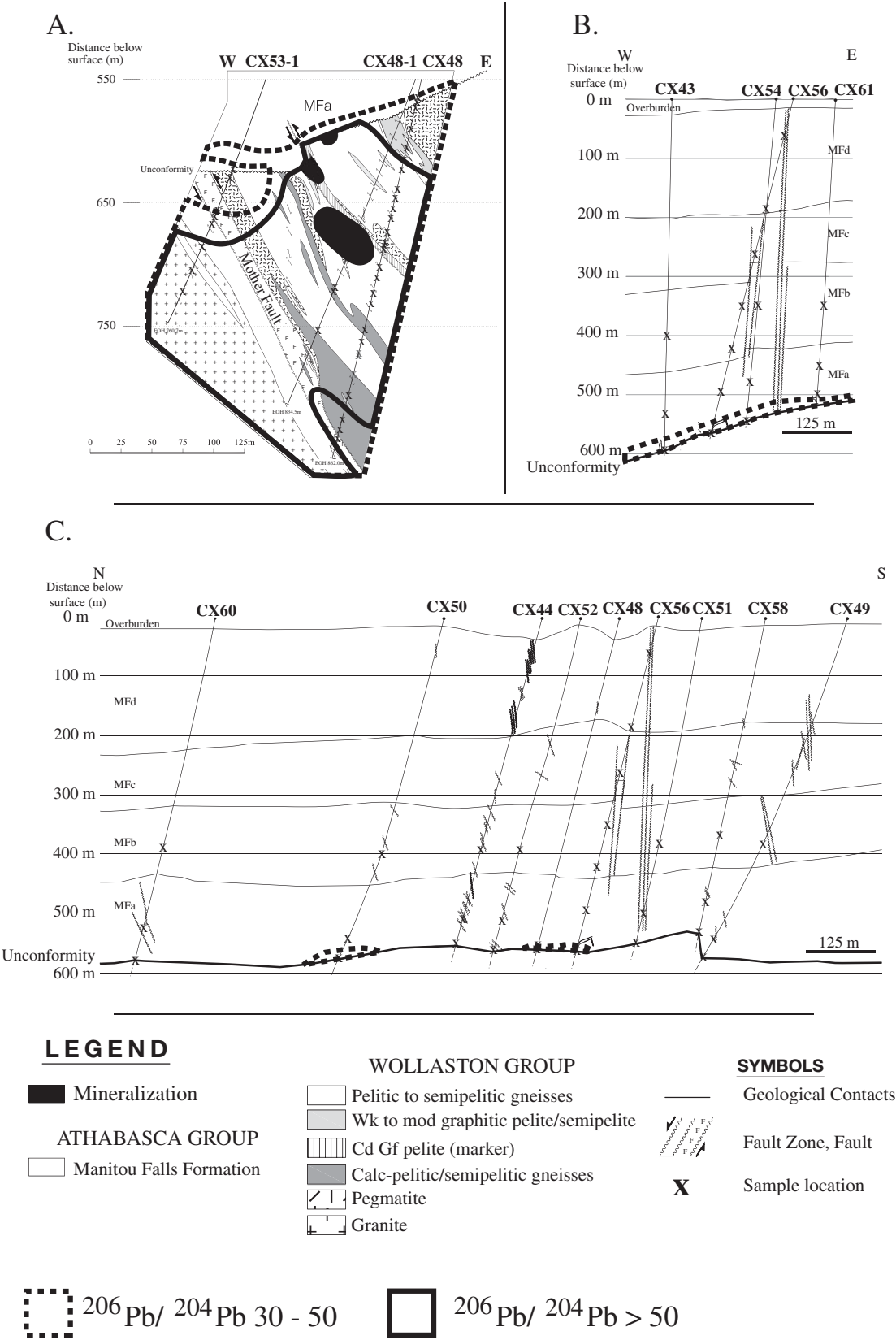
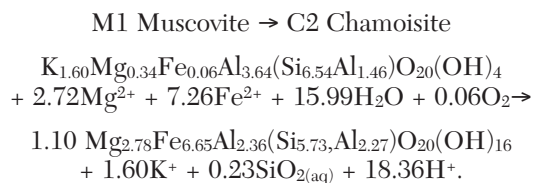


FIG. 14. Distribution of  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios for leachable Pb from the Millennium deposit and surroundings. (A) west-east cross section in the basement, (B) west-east cross section in the Athabasca sandstone across the deposit, and (C) north-south cross section in the Athabasca sandstone along the deposit.

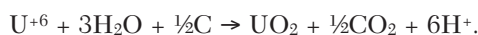
rock during both preore alteration events to ca. 25 percent if no muscovite was precipitated in the void created during the M1 muscovite basement alteration phase.

The M1 muscovite alteration was followed by minor C2 chamoisite alteration of M1 muscovite according to the following reaction:

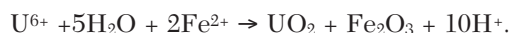


This reaction liberated K,  $\text{SiO}_{2(\text{aq})}$ , and  $\text{H}^+$  while consuming Mg, Fe, and  $\text{O}_2$ . The elements consumed during this reaction could have been derived from the alteration of basement rocks during preore M1 muscovite alteration. This C2 chamoisite alteration used 308 Å (66%) more space per 1.10 formula unit (704.40 Å per formula unit) than the muscovite, consuming voids created during the earlier alteration phases. The total space consumed during this phase was small, as chamoisite alteration is very localized. However, this alteration locally reduced the porosity of the system by partially filling some of the voids created during the earlier alteration phases.

The mineralizing event was characterized by the precipitation of uraninite, from the same fluid that precipitated M1 muscovite, and by formation of euhedral M2 muscovite and H1 hematite in the voids created during the preore stage. The uraninite precipitated by reduction of the basement where fluids encountered graphitic and Fe-rich chlorite lithologic units, following the reaction,



Hematite was also precipitated simultaneously with uraninite following the reaction,



Synore M2 muscovite precipitation required K, Fe, Al and  $\text{SiO}_{2(\text{aq})}$  while H1 hematite required Fe. The Al,  $\text{SiO}_2$  and up to 6% of the Fe consumed during these reactions can be derived from the previous alteration stages, whereas the rest of the Fe and the totality of the K had to be brought in with the fluid responsible for the synore alteration.

The postmineralization fluid would have been enriched in Ca, Mg, and Na. Derome et al. (2005) also observed a Ca-rich brine in their fluid inclusion study at McArthur River, which they suggested was derived from a Na-rich basinal brine that infiltrated and reacted with the basement rocks, resulting in a Ca-rich brine. The main postore alteration minerals consist of dravite, calcite, and sudoites (C3, C4), which precipitated in the space created during the preore alteration stage from the chemically modified fluids, considerably reducing the porosity and sealing the system to subsequent fluid infiltration in the basement rocks, except along fractures. Boron for the dravite might have been derived from the alteration of tourmaline in granitoids in the basement rocks or in detrital tourmaline in the Manitou Falls Formation sandstones, whereas the Ca needed for calcite was available in the chemically

modified postore residual fluid. The residual elements after dravite and calcite postore alteration phases would be Mg, Al, and Si, crystallizing late sudoite (C3 and C4).

Alexandre et al. (2005) also found similar results at the Dawn Lake, McArthur River, and Rabbit Lake deposits, where preore illite alteration of the basement rocks created space while liberating the Fe and Mg needed for preore chlorite and hematite. The chlorite alteration consumed space, reducing the porosity and closing the system. However, the Mg liberated by alteration of the basement rocks was principally used to produce preore clinocllore at those deposits, whereas postore sudoite consumed Mg at the Millennium deposit.

#### *Origin of the fluids responsible for alteration and mineralization of the Millennium deposit*

Preore alteration of the basement rocks at Millennium consists of minor amounts of C1 clinocllore on the outside edge of the alteration halo, followed by an extensive M1 muscovite alteration throughout the altered area. A formation temperature of 275°C for C1 chlorite that predates the preore M1 muscovite alteration suggests that C1 chlorite alteration of biotite may reflect retrograde metamorphism in the basement rocks following peak of the Trans-Hudson orogeny prior to deposition of the Athabasca basin. The temperature of formation and the isotopic compositions of the fluids in equilibrium with preore M1 muscovite are similar to those of SM muscovite in the sandstone above the Millennium deposit (Fig. 10), suggesting the same fluids were responsible for the alteration of both Manitou Falls Formation sandstones and underlying basement rocks. The Ca-Sr-rich and LREE-Th-poor nature of the APS mineral found in the Manitou Falls Formation sandstones is consistent with leaching of detrital apatite in the Manitou Falls Formation, suggesting a basin origin for the fluids responsible for the early hydrothermal alteration and preore stage. Preore M1 and early hydrothermal alteration SM muscovite alteration is therefore associated with a Na-K-Fe basin-derived fluid crystallizing the  $1\text{M}_c$  polytype at temperatures near 250°C. This muscovite alteration created the full extent of the alteration halo present at Millennium while creating voids used during later alteration phases, including that associated with the uranium mineralization.

Minor amounts of C2 chamoisite altered the M1 muscovite in the footwall of the fault associated with the cordierite-graphite metapelitic gneiss unit. The fluid that precipitated C2 chamoisite has stable isotopic compositions identical to those of the basinal brine that precipitated M1 muscovite, but the Mg needed to precipitate C2 chamoisite must originate from alteration of basement rocks by the basinal brine, as the basinal brine was Mg poor. The reaction from preore muscovite to preore chamoisite consumed  $\text{O}_2$ , also suggesting a precipitation from oxidized basinal fluids. Therefore, chemically modified basinal fluids were created from reaction between the basinal brine and basement rocks and resulted in Mg-Fe-rich fluids that were responsible for the small volume of C2 chamoisite in the footwall of the cordierite-graphite metapelitic gneiss unit.

Synore alteration consists mainly of M2 muscovite and minor APS minerals. Calculated  $\delta^{18}\text{O}_{\text{FLUID}}$  values for synore

muscovites are similar to those of preore muscovites, whereas the calculated  $\delta D_{\text{FLUID}}$  for synore muscovites are significantly lower than preore muscovites (Fig. 10). Low  $\delta D_{\text{FLUID}}$  values have been observed at Key Lake and McArthur River for alteration minerals both near and distal from the ore and reflect preferential hydrogen isotope exchange with later high latitude meteoric fluids that was facilitated by fractures and faults (Wilson and Kyser, 1987; Kotzer and Kyser, 1991; Kotzer and Kyser, 1995). Even given this later exchange, the stable isotopic compositions of the fluid in equilibrium with synore muscovites approach those of preore muscovites. Moreover, synore APS mineral compositions are similar to the early hydrothermal alteration substage APS minerals in the Manitou Falls Formation, suggesting similar formation fluids for those two phases, and reinforcing a basin origin for the fluid responsible for the mineralization. Synore alteration is therefore associated with precipitation of uraninite, muscovite, and iron oxide in the footwall of the fault related to the cordierite-graphite metapelitic gneiss from a basin-derived fluid crystallizing the 1Mc muscovite polytype at temperatures near 250°C.

Postore alteration is characterized by dravite and calcite veins and pervasive sudoite crystallization (C3, C4), filling the voids remaining from pre- and synore stage. Calculated  $\delta D_{\text{FLUID}}$  and  $\delta^{18}\text{O}_{\text{FLUID}}$  values for postore C3 chlorite are similar to the basinal fluids that precipitated M1 muscovite (Fig. 10; Table 4). Chemically, as for C2 chamoisite, the basinal fluids required Mg to precipitate C3 and C4 sudoites, which was acquired from the alteration of basement rocks. The isotopic composition and lower formation temperature of SC sudoite in the Manitou Falls Formation sandstones are similar to those of postore C3 and C4 chlorite in the basement. The similarity in chemical and isotopic composition between the sandstone and basement sudoites suggests that postore C3 and C4 sudoite is likely coeval with late hydrothermal alteration sudoite (SC). Postore alteration is therefore associated with Ca-Mg chemically modified basinal fluids that precipitated sudoite at temperatures near 185°C, indicating a decrease in temperature of ca. 65°C since the synore alteration stage. Precipitation of sudoite in the basement used the remaining voids created during the preore stage by infiltration of basinal fluid, reducing the porosity of the system.

#### *Timing of mineralization and alteration*

The oldest date obtained at Millennium is 1590 Ma extrapolated from the chemical age of unaltered uraninite. This possible mineralization age is identical to the age reported by Alexandre et al. (2009) for sandstone- and basement-hosted deposits throughout the Athabasca basin and is consistent with the hypothesis that the major, primary mineralizing event in all the Athabasca basin deposits occurred at about 1590 Ma.

Wilson et al. (1987) demonstrated that the interlayer region of fine-grained muscovite can interact with residual basinal brines and late meteoric waters at low temperatures, lowering the K-Ar ages. The ca. 1430 Ma  $^{40}\text{Ar}/^{39}\text{Ar}$  date for the preore muscovite is older than the major resetting ages obtained from U-Pb on uraninite, but younger than the age of primary mineralization at 1590 Ma. This suggests that the muscovite was altered during subsequent fluid circulation events or that

there was residual fluid in the basement reacting with the muscovite until 160 m.y. after the primary mineralization event.

A maximum age of postore C3 sudoite can be estimated from the leachable Pb data if we assume that all the radiogenic Pb present in postore C3 sudoite samples resulted from decay of the uranium mineralization and was leached from the mineralization during the C3 sudoite alteration phase. If the C3 sudoite alteration occurred shortly after the mineralizing event, only a small amount of radiogenic Pb would have had the time to form in the deposit. The typical  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio in basement rocks affected by C3 sudoite is 50, which can be used to constrain how much time passed after the uranium ore formed to produce enough  $^{206}\text{Pb}$  to elevate the  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio in the basement to 50. Based on a volume of  $5 \times 10^6 \text{ m}^3$  of basement rocks affected by the fluid that precipitated the postore C3 sudoite, and assuming that all the radiogenic  $^{206}\text{Pb}$  available within the mineralization was leached from the deposit at the time of C3 sudoite crystallization, the minimum amount of time required for the uranium to decay to enough  $^{206}\text{Pb}$  would be 100 m.y. after the ore-forming event. This would give an estimated age of ca. 1490 Ma for the C3 sudoite event, similar to the 1430 Ma date obtained from  $^{40}\text{Ar}/^{39}\text{Ar}$  on preore alteration M1 muscovite. Given that the date from the M1 muscovite is the time when fluids were last in the basement interacting with muscovite, a maximum age for the last alteration event recorded by both the  $^{40}\text{Ar}/^{39}\text{Ar}$  systematic of the M1 muscovite and the C3 sudoite is 1430 Ma, 160 m.y. after the mineralization event.

Several episodes of resetting of the U-Pb and  $^{40}\text{Ar}/^{39}\text{Ar}$  isotope systematics are recorded in uraninite grains at ca. 1390, 1350, 1275, 1090, and 804 Ma (Fig. 12A-F), reflecting episodic Pb loss from the deposit. These resetting events correspond to fluid circulation in fractures in the Athabasca basin induced by far-field tectonic events. The 1390 Ma is similar to the ca. 1400 Ma resetting age obtained by Alexandre et al. (2009) on preore and synore illites and chlorites at Dawn Lake, McArthur River, and Rabbit Lake basement-hosted deposits and the Virgin River prospect, which they interpreted as fluid movement in the Athabasca basin induced by the distal Bertoud orogeny (Nyman et al., 1994; Sims and Stein, 2001), disturbing the  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics in muscovites from the basement. The ca. 1350 Ma partial resetting event corresponds to the 1360 to 1370 Ma regional rifting and deformation associated with the East Kootenay orogeny southwest of the Athabasca basin (McMechan and Price, 1982; Doughty and Chamberlain, 1996; Beaudoin, 1997). The ca. 1275 Ma date is interpreted to correspond to a well-known fluid circulation event in the Athabasca basin induced by the emplacement at ca. 1270 Ma of the MacKenzie dike swarms (LeCheminant and Heaman, 1989). The ca. 1090 Ma date is not commonly recorded elsewhere in deposits of the Athabasca basin as a dominant age and does correspond to the timing of the Grenville orogeny (Hoffman, 1990; Mosher, 1996). Millennium is located in the Wollaston-Mudjatik transition zone whereas other deposits are hosted within the Wollaston Domain, so that the former setting may have facilitated resetting of Millennium ores during the Grenville orogeny because there was fluid movement in the transition zone. The

804 ± 120 Ma date to fluid circulation due to the break up of Rodinia (Mayers et al., 1996; Condie, 2001).

#### *Comparison of the alteration zone with other basement deposits*

The alteration zone present at Millennium consists of a weak distal retrograde metamorphism C1 clinochlore alteration (>75 m from the ore zone), a pervasive proximal preore M1 muscovite alteration (0–100 m from the ore zone) and a minor zone of preore C2 chamoisite in the footwall of the fault associated with the cordierite-graphite metapelitic gneiss unit. Uranium mineralization is closely associated with synore M2 muscovite and H1 hematite. During the postore stage, pre- and synore minerals were overprinted by dravite and sudoite. In contrast, alteration zones in basement-hosted deposits at Dawn Lake, McArthur River, and Rabbit Lake consist of a weaker distal preore muscovite alteration zone (30–100 m from the ore zone) and a stronger proximal preore clinochlore alteration zone (0–30 m from the ore zone). Mineralization in all basement-hosted deposits is closely associated with synore euhedral muscovite and hematite while postore alteration consists of sperulitic dravite in voids, calcite, and clinochlore veinlets (Alexandre et al., 2005).

Isotopic compositions of preore muscovite from Millennium, Dawn Lake, McArthur River, and Rabbit Lake deposits (Alexandre et al., 2005) all reflect a consistent 230° to 250°C basinal brine for their origin. Preore C2 chamoisite at Millennium is related to the presence of a chemically modified basinal fluids produced by interaction of the basinal fluid with basement rocks, as it is the case at Dawn Lake, McArthur River, and Rabbit Lake (Alexandre et al., 2005). The observed temperatures of these basement-related fluids range from 180° to 300°C, and the higher temperature observed at Millennium and McArthur River may reflect the depth of the chemically modified basinal fluids at Millennium and McArthur compared to the fluid at the Dawn Lake and Rabbit Lake deposits.

The mineralizing event at the Millennium, Dawn Lake, McArthur River, and Rabbit Lake deposits is associated with synore muscovite and hematite at a temperature around 250°C. The isotopic compositions of synore muscovites are similar among Millennium, Dawn Lake, McArthur River, and Rabbit Lake deposits, and are consistent with a basin origin for the fluids that precipitated uranium in all the basement-hosted deposits in the Athabasca basin. The same minerals forming during the synore stage combined with similar fluid isotopic compositions, chemical compositions, and formation ages for Millennium and all other basement deposits support the model proposed by Alexandre et al. (2009) wherein unconformity-related uranium deposits in the Athabasca basin formed from basinal brines at around the same time in response to a far-field tectonic event.

The isotopic composition and chemistry of postore sudoite (C3 and C4) suggests chemically modified basinal fluids derived from the alteration of basement rocks by a basinal brine at Millennium, as it is the case at McArthur River (Alexandre et al., 2005). The formation temperature at the Millennium and Rabbit Lake deposits also differs, with 185°C for C3 and C4 sudoite at Millennium compared to 135°C for postore clinochlore at Rabbit Lake. The formation temperature of

postore sudoite at Millennium is similar to preore chlorite found at Dawn Lake.

#### *Implications for exploration of Millennium-type deposits*

Leachable radiogenic Pb is found at the Millennium deposit in the basement up to 75 m above and more than 100 m below the mineralized zone (Fig. 14A). The Pb leached from basement rocks gives a model Pb-Pb age of 1075 ± 400 Ma, similar to the 1091 Ma major resetting event recorded by the uraninite. This indicates that major Pb loss from the ores occurred during the Grenville orogeny, concordant with what was recorded in the U-Pb isotope systematics in the uraninites. Radiogenic Pb is also locally observed near the unconformity (Fig. 14A, B, C), which is expected as the basal Manitou Falls Formation has been a conduit for fluids throughout the history of the basin (Holk et al., 2003). In contrast to what is observed above sandstone-hosted deposits (Holk et al., 2003; Kister et al., 2004), radiogenic Pb is absent in the Manitou Falls Formation sandstones above Millennium (Fig. 14B, C). Leachable Pb from Manitou Falls Formation sandstones above Millennium gives a model Pb-Pb age of 2875 Ma, which is older than the Athabasca basin. Therefore, radiogenic Pb in the sandstone above Millennium does not host radiogenic Pb derived from the Millennium deposit, and has to be derived from an older source, such as the detrital components in the basin fill. The data from Millennium show that the Pb mobilized from the deposit by different resetting events did not infiltrate the sandstone, except along fractures, and affected the basement up to 100 m from the ore zone. Hence, to apply this technique to find basement deposits, basement units, and fractures in the Manitou Falls Formation should be sampled during drill program.

The atypical halo present at the Millennium deposit is reflected by the absence of predominant preore clinochlore alteration paragenetically later than preore muscovite, a greater amount of postore dravite and the presence of postore sudoite. In terms of fluids, the atypical alteration zone at Millennium can be attributed to the scarcity of chemically modified basinal fluids during the preore alteration phase. The presence of chemically modified basinal fluids crystallizing clinochlore at Dawn Lake, McArthur River, and Rabbit Lake, or chamoisite at Millennium in the early phases in the evolution of the deposits seems to be critical for basement-hosted deposits. The amount of chemically modified basinal fluids produced by the system during the early alteration phases may produce a more pronounced and effective redox front if the preore clays are ferrous, resulting in a larger and richer deposit, as it is the case at the McArthur River deposit.

#### **Conclusions**

The atypical alteration halo at Millennium is the result of pervasive muscovite alteration of the basement rocks by Na-K-Fe basinal brines during the preore stage at ca. 250°C and the lack of predominant preore clinochlore alteration. As alteration of the basement rocks progressed, the basinal brines acquired Ca, Fe, and Mg and precipitated chamoisite at ca. 300°C at a similar stratigraphic level as the mineralization. This chamoisite alteration might have been one of the reductants for the precipitation of uraninite during the synore stage. Preore muscovite and chamoisite alteration were

important for the formation of the deposit as basement rocks altered to muscovite by basin-derived fluids created up to 20 percent voids in the basement rocks while chemically modified basinal fluids emplaced an Fe-rich chamoisite that demarcates a redox front during the synore stage where uranium ore was precipitated. Uranium mineralization occurred at ca. 1590 Ma, primarily from basin-derived fluids. Postore dravite and sudoite precipitated from the residual Ca-Na-Mg fluids filling the voids created during the preore stage and sealing the system. Timing of postore sudoite alteration was no more than 160 m.y. after the mineralizing event. Pb mobilized from the deposit by different resetting events did not infiltrate the sandstone, except along fractures, and affected the basement up to 100 m from the ore zone.

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