TGI-4 Unconformity-related Uranium Deposits Synthesis: Tools to Aid Deep Exploration and Refine the Genetic Model

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Abstract

This report summarizes the key activities completed under the uranium ore systems project of the Targeted Geoscience Initiative Four (TGI-4) program operated by the Geological Survey of Canada. This collaborative project between government, academia and industry examined unconformity-related uranium systems in the Proterozoic Athabasca (Phoenix, Millennium and McArthur River deposits and Dufferin Lake zone), Thelon (Bong deposit) and Otish (Camie River deposit) basins in order to refine genetic models and exploration techniques for the deposits. Significant to the Canadian economy, high-grade unconformity-related uranium deposits remain prime exploration targets given their potential for large tonnage, high-grade ore. As the depths of discoveries increase in the established Athabasca Basin and geological settings hosting the ore diversify, a variety of new exploration methods are required to allow for efficient target identification and successful discovery of deeply buried ore deposits. The results of the project clearly illustrate that deeply buried ore, ore-forming fluids, structural-fluid controls and precipitation mechanisms produce diagnostic signatures that can be identified and modelled over the entire fluid pathway through fertile fault systems, including post-mineralization dispersal of elements into subsurface and surficial environments.

Introduction

The Targeted Geoscience Initiative (TGI-4) uranium ore systems project has been a five-year collaborative federal geoscience program focussed on providing industry with the next generation of geoscience knowledge and innovative techniques, to guide more effective targeting of deeply-buried uranium deposits. Building on the successful EXTECH IV program (Jefferson et al., 2007a), TGI-4 was tasked with addressing industry interest in refining uranium exploration tools and techniques in light of renewed uranium exploration at depth and technological advancements. Specifically, the hypothesis explored under the TGI-4 project is that the properties of the ore, ore-forming fluids, structural controls and precipitation mechanisms produce diagnostic signatures that can be identified and modelled over the entire fluid pathway through fertile fault systems, including dispersal of exotic radionuclides into subsurface and surficial environments. In order to refine methods of defining these signatures, TGI-4 activities focussed on geochemistry, fluid flow-structural modelling and genetic studies using several deposits in concert to develop a system-wide understanding of the basement-to-surface expressions of deep mineralization, and to refine critical factors favourable for the genesis of the unconformity-related uranium deposits.

Uranium in Canada

Uranium continues to rank amongst Canada's top 10 metal commodities. The nuclear energy industry is an integral part of the Canadian economy, with the mining, refining and electrical energy production components supporting more than 60, 000 direct and indirect full-time jobs (Calvert, 2013; Canadian Nuclear Assoc., 2013). All of Canada's current (2014) uranium production, which in 2013 accounted for about 16 % of the world production (World Nuclear Assoc., 2014), is from three high-grade deposits located in the eastern Athabasca Basin of Saskatchewan: Cigar Lake, Eagle Point and McArthur River. Despite containing the world's highest grade deposits and contributing significantly to the Canadian economy, Canadian resources currently account for only 8% of known recoverable resources of uranium globally (in the <130USD/kg U cost category; OECD, 2014). Nevertheless these high-grade unconformity-related uranium deposits remain prime exploration targets globally given the continued trend toward lower grades and higher production costs. A recent global synthesis of uranium resources noted significant decreases in identified and reasonably assured resources within the <80 USD /kg U cost category (36.4% and 39.9%, respectively). Furthermore, inferred resources were reduced by 6.1% in the <40USD /kg U cost category and 30% in the <80USD /kg U cost category. With their high-grade ore, existing infrastructure and modern mining methods, Athabasca Basin uranium resources comprise 47% of the global <40USD /kg U cost category (OECD, 2014).

One of several Proterozoic basins prospective for uranium in Canada (Fig. 1), the Athabasca Basin covers more than 85,000 km^2, but approximately 96% of its known uranium resources are located along a limited corridor near the shallow, eastern margin of the basin (Jefferson et al., 2007a). Situated along this trend, the McArthur River and Cigar Lake deposits represent the last of the 'first generation' of deposits mined in the basin. These deposits were discovered using the classic Rabbit Lake unconformity-related model of Hoeve and Sibbald (1978). However, exploration in recent years has discovered deposits in deeper areas of the basin and in different geological settings, such as the basement-hosted Patterson Lake South deposit located south of the basin (50–250 m below the surface; Armitage, 2013; Fisson Uranium Corp., 2015), Eagle Point mine (100–300 m below the surface in basement rocks; Lemaitre 2006; Cloutier et al., 2011), Millennium deposit (650–750 m below surface; Roy et al., 2005; Cloutier et al., 2009) and the non-graphitic con-

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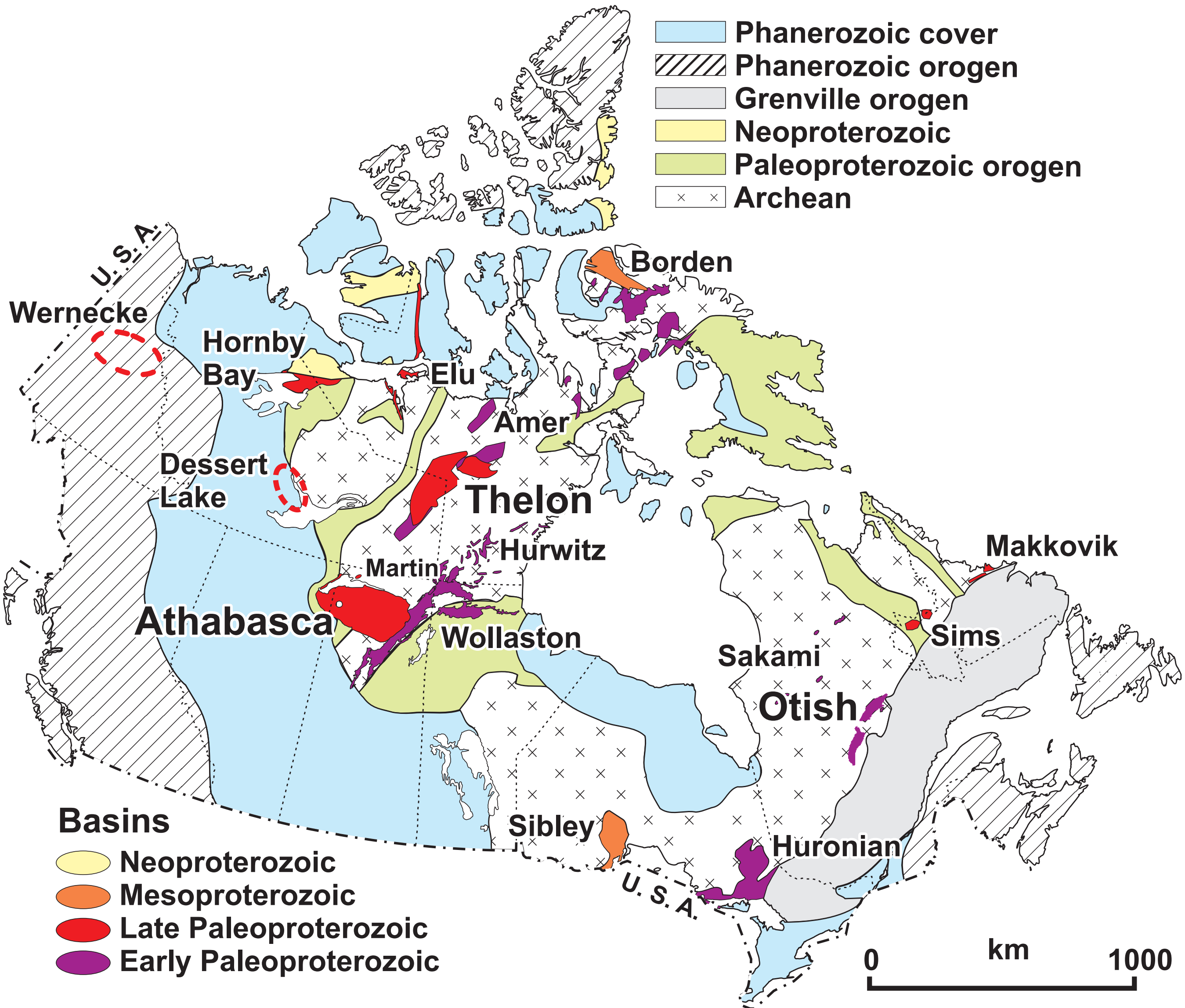

FIGURE 1. Known Proterozoic basins and sedimentary sequences in Canada, after Jefferson et al., (2007a).

ductor associated Centennial deposit (800–830 m below present-day surface; Jiricka, 2010; Alexandre et al., 2012; Reid et al., 2014). The basement-hosted systems can also extend up to 400 m below the unconformity along structures (Thomas et al., 1998). Additional Proterozoic basins in Canada with known uranium deposits include the: Thelon, Otish, Martin, Hornby Bay and Huronian. Prospective Proterozoic basins with potential to host uranium occurrences include: Sibley, Borden, Aston, Elu, and Dessert Lake. As the depths of discoveries increase and geological settings diversify, a variety of new exploration methods are required to allow for efficient target identification and successful discovery of deeply buried deposits. Furthermore, discovery of significant basement-hosted mineralization as an end-member of the unconformity-related systems has expanded the exploration potential beyond the present basin limits (e.g. Patterson Lake South). These basement-hosted deposits are challenging exploration targets because the diagnostic low temperature clay alteration is superimposed on metamorphic basement-rocks and is much smaller in size than that of the deposits hosted right at the unconformity or perched in the sandstone (Alexandre et al., 2005; Jefferson et al., 2007a). This volume summarizes research activities completed under the TGI-4 unconformity-related uranium systems project that focussed on deposits located in the Athabasca, Thelon and Otish Basins of northern Saskatchewan, Nunavut and Quebec, respectively, to develop a system-wide understanding of the basement to surface expressions of deep mineralization and refinement of critical factors leading to the genesis of the unconformity-related uranium deposits.

Unconformity-related uranium deposits: important characteristics

Unconformity-related uranium deposits contain high-grade uranium ore in pods, veins, breccia zones and semi-massive concentrations above, straddling or below the

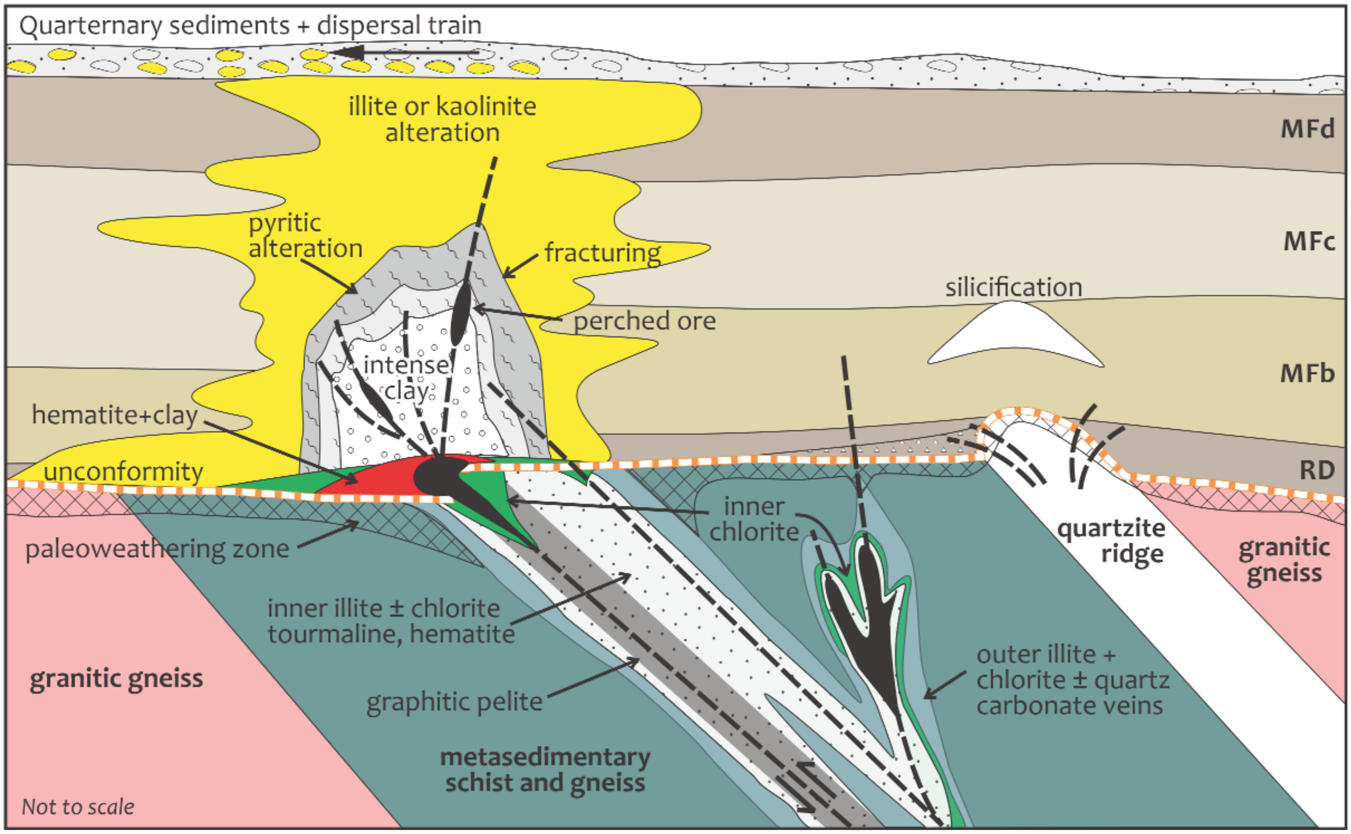

Figure 2. Simplified Athabasca Basin unconformity-related uranium deposit models, after Kyser and Cuney (2009) and Jefferson et al., (2007a). Abbreviations: RD = Read Formation, Members of the Manitou Fall Formation: MFb = Bird, MFc = Collins and MFd = Dunlop.

regional unconformity between Proterozoic conglomeratic sandstones and Archean to Paleoproterozoic metamorphosed basement rocks where intersected by reactivated fault systems (Jefferson et al., 2007b; Fig. 2). Alteration halos are characterized by the presence of illite, kaolinite, tourmaline, chlorite, euhedral quartz, and locally, by concentrations of Fe-Ni-Co-As-Cu sulphide minerals (Hoeve and Quirt, 1984; Wallis et al., 1985; Kotzer and Kyser, 1995; Jefferson et al., 2007b; Kyser and Cuney, 2009; Fig. 2). Exploration for these highly economic yet elusive deposits is dependent upon understanding the inter-relationships between: 1) ore fluids; 2) structure; 3) alteration and mineralization chemistry; and 4) the history of these deposits, encompassing pre-, syn-, and post-ore events. The products of these inter-relationships can be explored using a variety of tools (Fig. 3), with TGI-4 focusing on tracking fluid compositions and pathways in time and space through geochemical signatures, mineral assemblages and chemistry, and modelling the relationships between fluid flow and structural pathway development (tectonism and faults).

Fluids

Most conventional genetic models invoke circulation of oxidizing, basinal brines, heated to 160–250°C, reacting with reducing media in, or fluids in or permeating out of, reactivated basement shear zones (Pagel et al., 1980; Kyser et al., 2000; Derome et al., 2005), producing either egress- (dominantly sandstone-hosted) or ingress-type (basement-hosted) deposit end-members depending on the physical position of fluid interaction relative to the unconformity (Jefferson et al., 2007a and references therein). As uranium mobility is largely governed by oxidation state (Grandstaff, 1976; Romberger, 1984), uranium precipitation is inferred to occur in reactivated fault zones where the uranium-bearing, oxidized fluids were reduced. Critical to this model are the characteristics of the fluids, efficiency of metal precipitation and length of time in which the fluids were focussed along key structural intersections.

Fluid compositions

Although debate continues as to the source of the uranium in unconformity-related deposits (c.f. Kyser and Cuney, 2009), uranium transport is generally considered best achieved using warm (160–250°C), oxidized, acidic brine (Jefferson et al., 2007b). Variations on the chemistry of these fluids have been proposed, including multiple brines with differing compositions (NaCl-rich, $CaCl_2$-rich; Kotzer and Kyser, 1995; Kyser et al., 2000; Derome et al., 2005; Richard et al., 2010), halogen contents (Fayek and Kyser, 1997), gas contents (CO_2, CH_4, H_2S; Derome et al., 2003) and pH (weakly to highly acidic, i.e. pH = 5 or 2.5–4.5; Kotzer and Kyser, 1995; Richard et al. 2012; Sharpe, 2013).

From the Dufferin Lake zone, Pascal et al. (2015; Fig. 4) document the presence of CH_4- and N_2-rich fluids in fluid inclusions within quartz veins from graphitic pelitic schists, which support interaction of multiple fluids with the base-

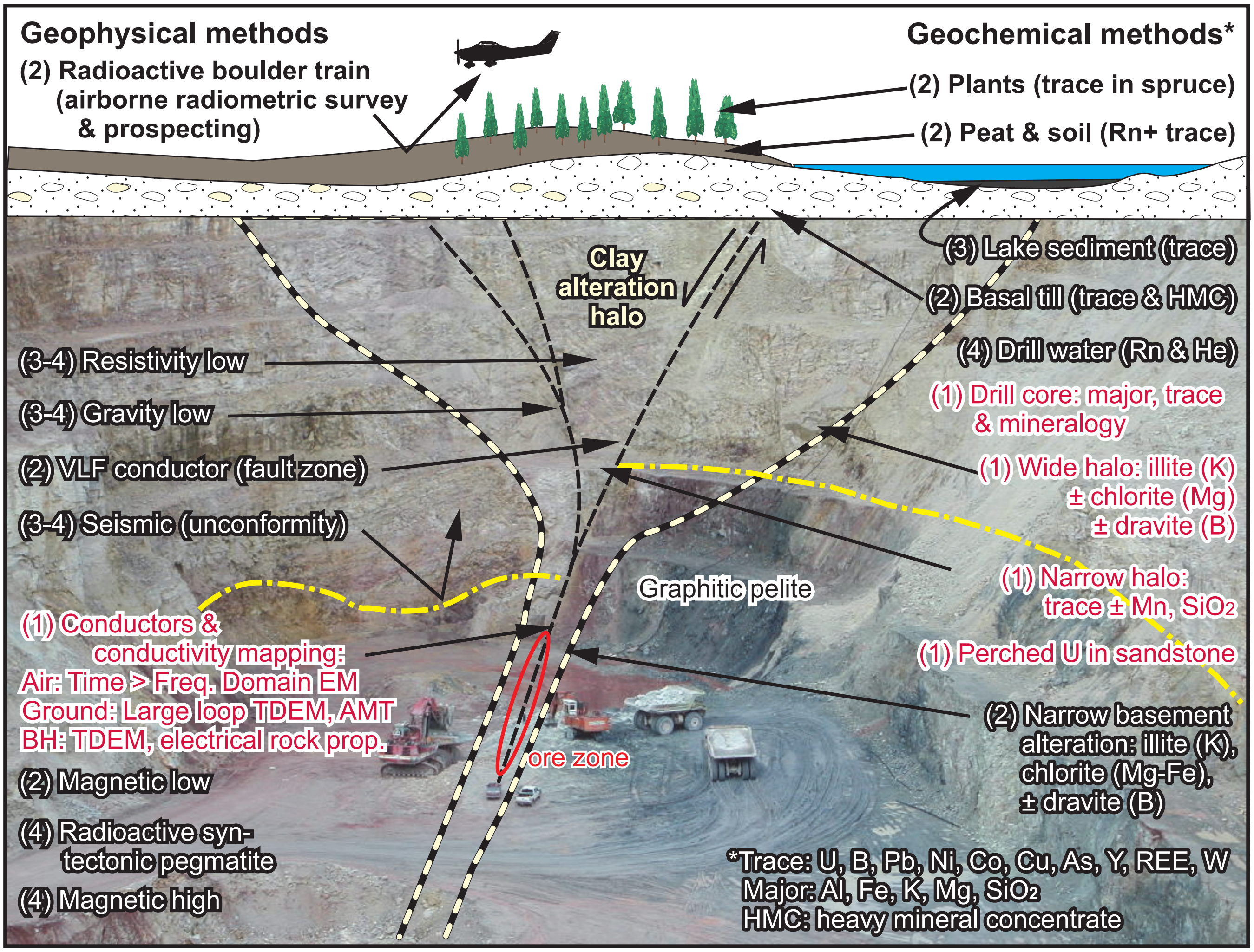

FIGURE 3. Synopsis of tools for exploration of unconformity-related deposits, divided by geochemical and geophysical techniques and ranked in order of importance (numbers in brackets). Modified from Jefferson et al. (2007b) and Tourigny et al. (2002, 2007). Photograph of Sue C Pit by C.W. Jefferson, 2002, courtesy of AREVA Resources Canada.

ment rocks underlying the mineralization. As proposed by the authors, retrograde metamorphism and diagenetic processes are the dominant processes that led to graphite depletion. During retrograde metamorphism, methane (CH_4) can be generated by the breakdown of graphite during hydration reactions and/or cooling of C-O-H fluids (Huizenga, 2010; Annesley and Wheatley, 2011; Card and Annesley, 2012), and N_2 by the breakdown of micas and feldspar (Duit et al., 1986; Bebout et al., 1999; Hurai et al., 2000; Sadofsky and Bebout, 2000). In the altered paleoregolith (Fig. 3) that is depleted in graphite at the Dufferin Lake zone, evidence of both NaCl- and $CaCl_2$-rich brines has been identified similar to the results from Derome et al. (2005) and Richard et al. (2010). By having circulated in the upper part of the basement, where graphite and sulphides are depleted, the $CaCl_2$-rich fluids may have reacted with graphite leading to the formation of methane. If the timing of these reactions was appropriate, the upward migration of gases (and associated fluids) could have reduced hexavalent uranium in oxidized basinal brines above the unconformity.

Fluid reduction mechanisms

In the original unconformity-related uranium model, Hoeve and Sibbald (1978) invoked reaction between graphite and oxidizing diagenetic brines to produce carbon dioxide and methane that reduced hexavalent uranium to the immobile tetravalent state. Alexandre et al. (2005) also proposed direct reduction of U^{6+} by radiolysis of graphite. Graphitic basement rocks, however are not spatially associated with ore at the Raven-Horseshoe, Cluff Lake, Maurice Bay and Centennial deposits in the Athabasca Basin nor at the Nabarlek deposit in the McArthur Basin of Australia (Cloutier et al., 2011; Rhys et al., 2008; Koning and Robbins, 2006; Alexandre et al., 2009; Reid et al., 2014) while at other deposits (e.g. Gartner-Key Lake and Shea Creek), uranium can be more strongly associated with other basement rocks (Yeo and Potter, 2010). This has led to the examination of alternative mechanisms such as: fluid hydrocarbons (Alexandre and Kyser, 2006); generation of H_2S from the breakdown of pyrite (Cheney, 1985; Ruzicka, 1993; Beyer et al., 2012); redox reactions involving Fe^{2+} liberated from pyrite oxidation, chloritization of biotite or illitization of hornblende (Wallis et al., 1985; Alexandre et al., 2005); or

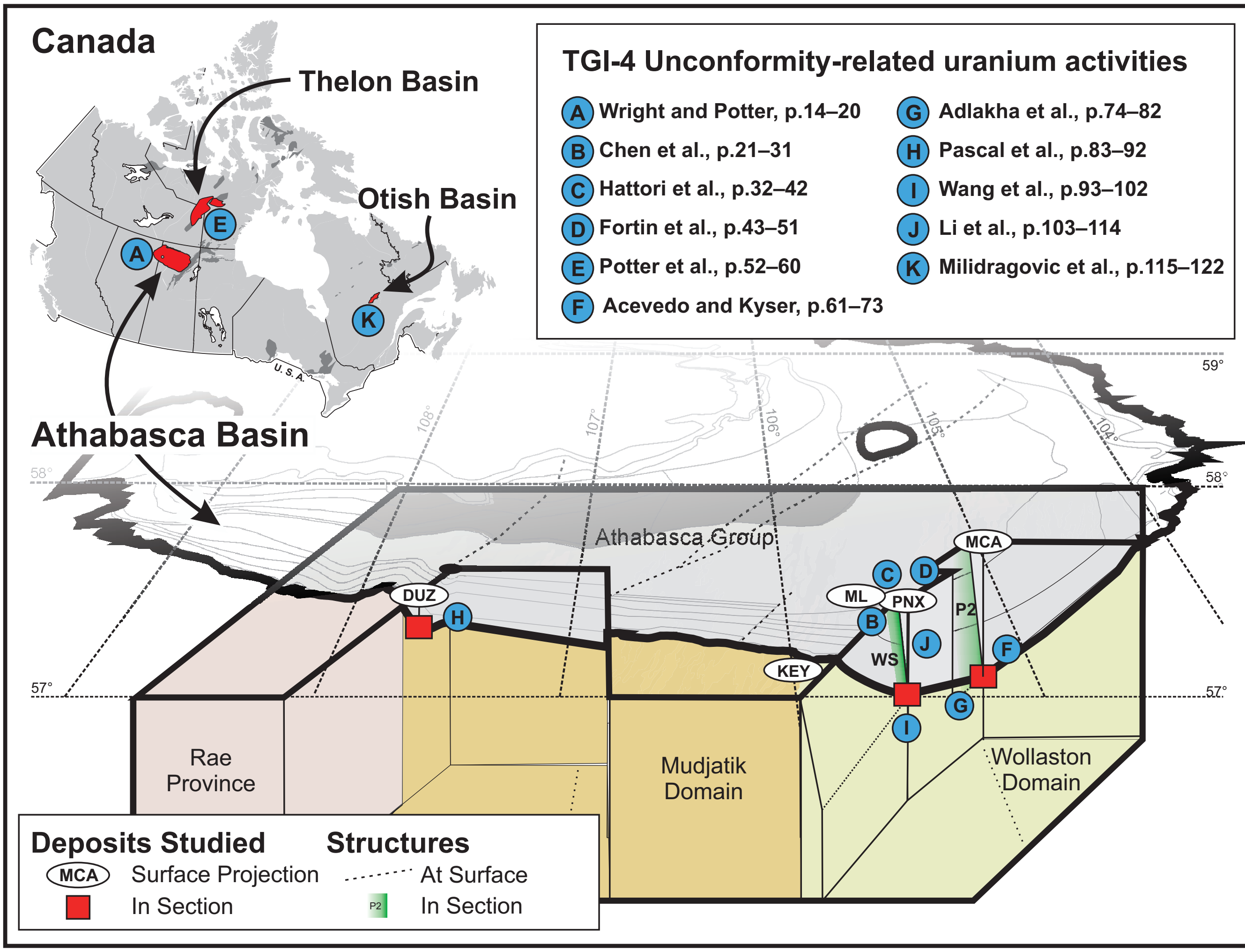

FIGURE 4. Location of TGI-4 uranium activities in three-dimensions. Abbreviations: DUZ = Dufferin Lake zone, ML = Millennium deposit, PNX = Phoenix deposits, KEY = Key Lake mine, MCA = McArthur River mine. P2 = P2 fault, WS = WS shear zone.

mixing of geochemically distinct NaCl-rich and $CaCl_2$-rich brines (Derome et al., 2005; Richard et al., 2010).

Research supported under TGI-4 by Pascal et al. (2015) and Wang et al. (2015) support graphite disaggregation as an indicator of hydrothermal fluid alteration. In addition to evaluating the role of graphite as a potential reductant, Pascal et al. (2015) also sought to investigate the petrogenetic disaggregation of graphite relative to P-T-t conditions within the Dufferin Lake Zone (Fig. 4). The authors propose that graphite and sulphide depletion proximal to mineralization reflects the final and most significant stage of graphite depletion associated with hydrothermal alteration of the basement, after deposition of the lower Athabasca Group sediments (e.g. associated with pre-/syn-ore alteration). Wang et al. (2015) also report a disordering of graphite with proximity to mineralization at the Phoenix deposit (Fig.4); investigation of this relationship continues. Wang et al., (2015) also present evidence supporting boiling in quartz veins during the waning stages of the systems while the stress regime transitioned from ductile to brittle deformation in the sandstones that would have facilitated precipitation of metals in solution.

The role of iron in unconformity-related systems, including as a potential reductant, is investigated by Potter et al. (2015) and Acevedo and Kyser (2015) by examining iron and magnesium isotope systematics in the alteration assemblages at the Bong and McArthur River deposits, respectively (Fig. 4). While Potter et al. (2015) note significant iron and magnesium isotope fractionations driven by leaching of iron during incursion of acidic, oxidized brines in the ore-forming alteration, Acevedo and Kyser (2015) were able to define a population of iron isotopic values ($\delta^{56}Fe_{IRMM-014}$ values >0.5‰) reflecting oxidation-reduction reactions related to uranium precipitation.

Fluid flow geometry

A primary classification of unconformity-related uranium deposits is based on their location relative to the unconformity and basement shear structures, with “egress”-type (sandstone-hosted) deposits primarily straddling or situated above the unconformity surface, and “ingress”-type deposits occurring underneath the unconformity, hosted entirely within Paleo-Proterozoic to Archean basement material. Li et al. (2015) specifically model regional fluid flow and structural relationships for the eastern Athabasca Basin (Fig. 4) to examine what physical and chemical conditions focussed the high flux of fluids required to form the large deposits at specific sites within the basin, especially along fault zones and within wider structural zones, and why some faults are more economically prospective than others. The regional-scale modelling results illustrate that widths of individual thermal convection cells are less than 2 km and are controlled by the location of faults. Deposit-scale studies within the regional fluid flow modelling study area complement these studies, providing a more detailed examination of the structural-fluid interactions and related fluid regimes (Wang et al., 2015). As mentioned above, it has been suggested that high fluid flux along key structural intersections is a potentially important component of the fluid dynamics of these systems, perhaps complemented by sharp decreases in fluid pressure under brittle deformation conditions, as recorded in drusy quartz veins in the sandstones (e.g. Wang et al., 2015).

Structures

Basement structures with displacement pre-, syn- and post-deposition of the Proterozoic sediments are considered integral parts of both genetic and applied exploration models of unconformity-related uranium deposits (Jefferson et al., 2007a, b). Specific structural orientation directions and intersections critical to unconformity-related uranium deposits have been defined from brittle overprints on basement shear zones (e.g. D_3 structures of Portella and Annesley, 2000; Annesley et al., 2005). Post-mineralization reactivation of pre-existing structures and magmatic intrusions (e.g. Mackenzie Dyke swarm in the Athabasca and Thelon Basins, Otish Gabbro sills and lamprohyric dykes in Otish Basin, Martin Group mafic sills and dikes in the Martin Basin and Nipissing Diabase in the Huronian (Morelli et al., 2009; Potter and Taylor, 2010; Reid et al., 2014; Milidragovic et al., 2015) offset earlier structures and may have also remobilized primary mineralization. A popular and effective method of identifying structural corridors for unconformity-related uranium deposits has been through the use of geophysical, and more specifically, electromagnetic (EM), techniques (Jefferson et al., 2007b). The EM techniques identify conductive material in the basement, typically inferred to represent pre-ore graphite. Ongoing application of EM geophysical techniques to unconformity-related uranium deposits has identified two important observations: 1) the targeting of prospective zones along conductive corridors is dependent on the disruption of the EM signature due to alteration (including disaggregation of graphite); and 2) not all structures or deposits are hosted by altered graphitic rocks or contain enough graphite contents to produce a conductive signature.

The TGI-4 uranium project did not undertake geophysical research to evaluate better methods of identifying structures, but several projects investigated graphite disaggregation as an exploration vector or identified alternate methods of prioritizing conductor trends and intersections through geochemistry. Graphite disaggregation was specifically examined by both Pascal et al. (2015) and Wang et al. (2015) as part of TGI-4 supported research. Both authors confirm graphite depletion and visible graphite disordering with proximity to mineralization at the Dufferin Lake zone (Pascal et al., 2015) and at the Phoenix deposits (Wang et al., 2015).

Wright and Potter (2015) highlight the distribution and ranking of key geochemical signatures using exploratory data analysis techniques (Tukey, 1977), including scatterplots, boxplot analysis, and multivariate correlation analyses to identify distinct element patterns associated with the ore-forming alteration. For instance, a combined signature of both elevated U^2/Th and Y^2/Th values display a spatial association with known deposits at depth and reflect structural trends and intersections in the uppermost sandstones of the Athabasca Basin, providing a method of prioritizing prospective structural intersections and emphasizing relative geochemical-structural relationships. The physical distribution of geochemical and radiometric signatures in soils also support the identification and ranking of prospective structural intersections (Hattori et al., 2015; Fortin et al., 2015; Wright, 2014)

Building on the recognition and classification of local to regional alteration systems along key structural corridors (Earle and Sopuck, 1989; Earle et al., 1999; Wasyliuk, 2002), Adlakha et al., (2015) examine subtle changes in mineral chemistry as vectors to ore in basement rocks along the 12 km long P2 fault that hosts the McArthur River deposit (Fig. 4). Within larger clay alteration systems, the presence of florencitic aluminum phosphate-sulphate (APS) minerals (building on earlier work by Gaboreau et al., 2005, 2007) and magnesio-foitite are proposed as additional mineralogical indicators of fertile structures.

Geochemical signatures

The geochemistry of unconformity-related uranium ores are categorized broadly into "simple" and "complex" suites corresponding respectively with basement-hosted and sandstone hosted end-members (Jefferson et al., 2007a, b). While individual deposits can exhibit combinations of both end-members, simple or ingress deposits tend to be basement-hosted and essentially monometallic. Complex or egress deposits occur at the unconformity or within sandstones and can contain significant concentrations of Co, Cu, Ni, As, S, Pb, Fe, Au, Ag and REE (Ruzicka, 1996; Fryer and Taylor, 1987; Jefferson et al., 2007a). Jefferson et al. (2007a, b) also identified REE relationships as a discriminating feature of ingress versus egress deposit types. The widespread adoption by industry of lower cost, more sensitive and precise multi-element analytical techniques (i.e. ICP-OES and ICP-MS) has rapidly expanded the geochemical dataset available to model unconformity-related chemical processes since publication of the EXTECH IV volume that was released in 2007 (e.g. Card et al., 2011). Much of this data has become available publicly due to mineral assessment filings, which were used to compile a large uranium exploration-specific geochemical dataset under TGI-4 to support further geochemical research in the basin (Athabasca Basin Uranium Geochemistry database (AUG); Wright et al., 2014, in press). The AUG database permitted TGI-4-supported research by Wright and Potter (2015) and Ramaekers et al. (in press) to undertake regional examination and integration of geochemical data with components of the uranium exploration model and basin geology.

Cuney (2010) emphasized the importance of modeling uranium content relative to thorium, which reflects the primary association of these elements under igneous conditions, and the preferred mobility of hexavalent uranium (U^{6+}) under hydrothermal, oxidizing conditions (Grandstaff, 1976; Romberger, 1984). In response to this relationship, chemical analyses for uranium have focussed on partial digestion techniques to favour more mobile uranium. TGI-4 supported research by Ramaekers et al. (in press) note that uranium released by the partial dissolution of the sample accounts for less than a third of the total uranium in the non-mineralized sandstones – stressing that uranium in resistate minerals is the dominant source of uranium in the surface outcrops and till. However, through application of Principal Component Analysis (PCA), the authors illustrate that the signal of hydrothermal uranium can be recognized.

As part of TGI-4, projects by Wright and Potter (2015) and Chen et al. (2015) demonstrate the relationship of uranium to other high field strength elements, including thorium, yttrium, and the rare earth elements within a sample suite of the Athabasca Group. Fryer and Taylor (1987), Quirt et al. (1991) and Fayek and Kyser (1997) were amongst the first to discuss the rare earth elements as important components of uranium mineralization in the Athabasca Basin, including the potential implications for required fluid composition (e.g. fluorine contents). Wright and Potter (2015) specifically identify and rank important uranium-thorium (U^2/Th) and yttrium-thorium (Y^2/Th) relationships that categorize types of uranium enrichments relative to an inferred genetic-temporal association between uranium mineralization and the Wolverine Point and Locker Lake Formations of the Athabasca Group. Spatially, a population of elevated U^2/Th and Y^2/Th values are significant as they consistently occur over known zones of mineralization in the uppermost sandstones. Wright and Potter (2015) also identify MgO-B-Li and Cu-Co relationships that display enhanced chemical relationships with tourmaline and base metal alteration relative to gross lithogeochemistry (e.g. McGill et al., 1993; Jefferson et al., 2007b). Distinct signatures within these groups also show important spatial relationships to known zones of mineralization, including within range of the present day surface.

At property-scales, access to industry geochemistry datasets and analysis of surficial media permitted documentation of the geochemical and mineralogical signatures from basement rocks into the surficial environment overlying the Phoenix uranium deposit and the uranium-poor, REE-rich Maw zone (Hattori et al., 2015, Chen et al., 2015). Principal Component Analysis (PCA) by Chen et al. (2015) highlights distinct elemental associations and geochemical variations in the sandstone units over the Phoenix uranium deposit, reflecting subtle changes in lithology and alteration related to ore-forming processes. When compared to the uranium-poor, REE-rich Maw zone, sandstones overlying the Phoenix deposit exhibit distinct element associations (e.g. U-HREE-Y, LREE-Pb) that can be used to recognize subtle geochemical expressions of ore-forming processes in exploration (Chen et al., 2015).

Based on the strong statistical and spatial geochemical inter-element relationships between uranium, thorium, yttrium, and the rare earth elements discussed by Wright and Potter, (2015), Chen et al. (2015), Hattori et al. (2015), and Adlakha et al. (2015), Chi et al. (2014) suggest an increased fluid flux to partially account for the strong element relationships and concentrations observed. This difference in flux may complement the fluorine-bearing brines proposed by Fayek and Kyser (1997) to explain elevated contents of typically immobile elements in the massive uranium ore.

Surficial techniques were also examined in several TGI-4 activities, linking metal, gas, and radiometric responses to better contrast potential mineralization and alteration signatures from background (Hattori et al., 2015; Fortin et al., 2015). Hattori et al. (2015) assess the expression of refined geochemical signatures within soils associated with deeply buried mineralization at the Phoenix and Millennium deposits and the presence of radon and helium dissolved in ground water as exploration vectoring tools. The authors highlight that both humus and B-horizon soil show elevated concentrations of U, Pb, ± Mo, Cu, Ag, Co, Ni, W and As directly above the deposits and/or structural zones. Elevated yet variable concentrations of radon and helium in groundwater over the deposits highlight the need for careful sampling and understanding of the local glacio-fluvial history, soil development and hydrological conditions. Fortin et al. (2015) discuss integration of quantitative analysis of the airborne data with surficial geological knowledge to differentiate between the complex patchwork of background signals and deposit-related surficial geochemical anomalies, based on focussed ground-truthing of airborne gamma-ray signatures along the McArthur River – Key Lake corridor (Fig. 4).

Alteration mineralogy

As with geophysical techniques, mineralogical evaluation of alteration relative to unconformity-related uranium deposits in the Athabasca Basin has seen widespread use (Jefferson et al., 2007a, b). Techniques applied have evolved from petrographic and X-ray diffraction methods (Hoeve and Quirt, 1984), through clay normative calculations (Earle and Sopuck, 1989), to the widespread use of short-wave infrared (SWIR or PIMA; e.g. Wasyliuk, 2002) clay identification techniques. Clay alteration phase proportions, primarily amongst illite, kaolinite, tourmaline (magnesio-foitite) and chlorite (sudoite), have been shown repeatedly to display spatial associations with known mineralized systems, although local variations in actual clay contents and clay species proportions illustrate complexities in the clay alteration systems.

In TGI-4 supported research, Adlakha et al. (2015) investigate the presence and distinct mineral chemistry amongst syn-ore minerals magnesio-foitite (MgF), APS (florencite) and sudoite along the P2 fault which hosts the McArthur River uranium deposits (Fig. 4). Building on previous work (e.g. Gaboreau et al., 2005, 2007), changes in APS mineral chemistry and relative changes in sudoite and MgF abundances in the alteration assemblage provide vectors to ore along fertile basement structures, with enrichment in REE and uranium in APS and increased sudoite and MgF proximal to ore (Adlkaha et al., 2015). These changes in APS and MgF chemistry also mimic the lithogeochemical patterns described by Wright and Potter (2015), Chen et al. (2015), and Hattori et al. (2015).

Potentially linked to precipitation mechanisms, recognition of graphite depletion and visible graphite disordering may also provide property-scale indications of fertile alteration along prospective structures (Pascal et al., 2015; Wang et al., 2015).

Iron, often as brick-red hematite, is commonly associated with uranium at most examples of unconformity-related mineralization within the Athabasca Basin (Jefferson et al., 2007a), and has been inferred to reflect a direct or sympathetic response to oxidation-reduction processes responsible for ore genesis (Wallis et al.,1985). The isotopes of iron and magnesium were investigated by Potter et al. (2015) and Acevedo and Kyser (2015) to assess actual iron and magnesium mobility in relation to uranium precipitation in the Thelon and Athabasca Basins (Fig. 4). Potter et al., (2015) propose that significant leaching of iron from the Bong deposit in the Thelon basin suggests that enrichment in whole-rock iron contents with low δ^{57}Fe values along faults may be a distal indicator of mineralization. In a similar manner, distinct δ^{56}Fe values indicative of reduction-oxidation reactions occur up to 300 m from the ore zone and above the projection of the P2 fault at McArthur River (Acevedo and Kyser, 2015), and thus provide an indication on the fertility of an alteration assemblage, particularly along ore-hosting faults. Acevedo and Kyser (2015) do emphasize a complex iron system at McArthur River, and assign the most distinct example of iron fractionation to a late, post-mineralization fluid event. Due to the sensitivity of iron to oxidation-reduction conditions, combined with evidence for multiple resetting events within the Athabasca Basin (and likely other prospective Proterozoic basins; Fig. 1), iron enrichment/depletion signatures can represent evidence for distal alteration associated with unconformity-related uranium deposits in the absence of detailed isotopic analysis.

Basin evolution and uranium deposits

The current physical expressions of any ore system, including unconformity-related uranium deposits, are products of multiple events spanning the pre- to post-history of each ore deposit. Multiple paragenetic stages and remobilization of ore elements during primary and secondary dispersal within unconformity-related uranium deposits of the Athabasca and Thelon Basins of Canada have been defined by authors such as Kyser et al. (2000), Cameron et al. (2004) and summarized in Jefferson et al. (2007a). Post-mineralization dispersion of ore and alteration elements have the potential to increase the physical expression of such deposits, but also produce diluted and complicated signatures. As a result, understanding the role of individual components and events affecting the deposit can be critical to their effective use in exploration.

The formation of primary unconformity-related uranium mineralization in the Proterozoic basins has been shown to be intimately linked to basin diagenesis (Kyser et al., 2000, and references therein). However, due to the chemically active nature of uraninite, its ability to recrystallize under low temperature conditions causes disruption of the U-Pb isotopic system through loss of radiogenic Pb (Finch and Murakami 1999; Fayek and Kyser 2000; Alexandre and Kyser 2005). Uraninite geochronology from the Athabasca, Otish and Thelon basins has revealed significant remobilization and precipitation of ore post-diagenesis, in relation to tectonic and intrusive events (Farkas, 1984; Alexandre et al., 2009 and references therein; Sharpe, 2013; Shabaga et al., in press; Milidragovic et al., 2015). While most unconformity-related deposits do not have syn-ore minerals amendable to age dating, molybdenite-bearing samples from Camie River in the Otish Basin presented a unique opportunity to apply Re-Os techniques and develop a better chronology of basin evolution and deposit formation (Milidragovic et al., 2015). This study produced an age date of 1724 ± 4.9 for the Camie River deposit, within error of uraninite U-Pb ages of 1723 ± 16 Ma and 1721 ± 20 Ma; from the Camie River (Höhndorf et al., 1987; Beyer et al., 2012) and 1717 ± 20 Ma from the Lorenz Gully occurrence (Höhndorf et al., 1987). These results, when coupled with an age of the basin defined by intrusion of the Otish Gabbros at 2165–2170 Ma (Hamilton and Bucham, 2007; submitted; Milidragovic et al., 2015), indicate that mineralization post-dated the deposition of the Otish Basin by ca. 450 Ma — clearly post-peak diagenesis.

The numerical modelling results of Chi et al., (2014) indicate that migration of hydrocarbons to the sites of uranium precipitation may be a factor in the formation and preservation of the high-grade ore characteristic of the Athabasca Basin (c.f. Jefferson et al., 2007a). For example, the authors were able to hydrodynamically model migration of oil and gas developed in the ca. 1541 Ma Douglas Formation to the base of the basin and the sites of the unconformity-related uranium deposits that formed at ca. 1600–1500 Ma and 1460–1350 Ma, with significant remobilization events at ca. 1176 Ma, 900 Ma, and 300 Ma (Hoeve and Quirt, 1984; Cumming and Krstic 1992; McGill et al., 1993; Fayek et al., 2002; Alexandre et al., 2003; Jefferson et al., 2007a; Creaser and Stasiuk, 2007). While Wilson et al. (2007) proposed that some of the hydrocarbons in the uranium deposits post-date the ore, biomarker results indicate they were derived from the Douglas Formation.

The importance of relative paragenesis is also emphasized by spatial-temporal relationships observed by other TGI-4 activities. Wright and Potter (2015) highlight that anomalous yttrium signatures associated with high-grade uranium mineralization and chemo-stratigraphically with the Wolverine Point and Locker Lake Formations suggest a temporal and possible genetic association. As Jefferson et al. (2007a) note, early diagenetic xenotime rimming zircon grains in the Wolverine Point Formation contain little to no uranium, but other generations of xenotime and diagenetic apatite contain locally abundant uranium (Rainbird et al., 2003). Age dates from the Wolverine Point Formation (ca. 1644 Ma; Rainbird et al., 2007) and fluorapatite cements in the Athabasca Group (1640–1620 Ma; Davis et al., 2008) overlap with those for pre-ore alteration (1730–1590 Ma, Alexandre et al., 2009). The association of elevated yttrium is also reflected in U-Y-REE-bearing florencite rims in APS minerals along the P2 fault (Adlakha et al., 2015), and early xenotime associated with zircon observed by Chen et al. (2015) at the Phoenix deposit.

Summary

Building on historical research, several primary exploration techniques and knowledge to guide application of these tools have been refined and/or identified by TGI-4 research activities including:

Exploration techniques

- *Geochemical signatures*
    - Geochemical expressions of deeply-buried mineralization and alteration in uppermost sandstones, soils and ground waters (Wright and Potter, 2015; Chen et al., 2015; Hattori et al., 2015; Ramaekers et al., in press)
    - Modelling of helium and radon dispersion from the ore zones (Hattori et al., 2015)
    - Deposit-related geochemical signatures spatially associated with lineaments produced from the intersection of brittle structures (Wright and Potter, 2015; Hattori et al., 2015)
    - Reconciliation of Quaternary geology with gamma-ray signatures to enhance application of regional airborne radiometric surveys to detected geochemical anomalies (Fortin et al., 2015)
    - Distinct iron and magnesium isotopic signatures in the alteration assemblages related to alteration and uranium precipitation mechanisms (Potter et al., 2015; Acevedo and Kyser., 2015)

- *Mineral assemblages and mineral chemistry:*
    - Relative proportions of APS, magnesio-foitite and sudoite and changes in APS and tourmaline chemistry related to alteration and ore-forming processes along fertile basement structures (Adlakha et al., 2015)
    - Graphite depletion and disordering proximal to ore along ore-hosting structures rooted in graphitic basement rocks (Pascal et al., 2015; Wang et al., 2015)

- *Fluid flow - structural relationships*
    - Intimate relationship between deposits, unconformity-surface offsets associated with NE-SW trending, fault-related quartzite ridges and later NW-SE trending cross structures (Li et al., 2015; Wang et al., 2015).
    - Fluid flow modelling relative to unconformity and structure intersections, highlighting possible structure distribution patterns required to produce ingress-egress fluid movement (Li et al., 2015).
    - Fault control on hydrothermal fluid convection which ultimately control the extent of geochemical signatures in the overlying sandstones (Li et al., 2015)
    - Numerical modelling supporting hydrocarbon migration from uppermost units to sites of uranium precipitation (Chi et al., 2014; Li et al., 2015).

Genetic Implications

Research supported by TGI-4 has influenced our understanding of the genesis of unconformity-related uranium deposits in several ways:

- *Brine-fluid compositions*
    - Re-emphasis on the need for the efficient transport and spatially restricted precipitation of uranium, thorium, yttrium, and the rare earth element-enriched source fluids (Adlakha et al., 2015; Chen et al., 2015; Wright and Potter, 2015)
    - Incursion of highly acidic brines into the basement rocks, neutralized or buffered through fluid-rock interactions (Potter et al., 2015)

- *Reduction mechanisms*
    - Potential for multiple reduction mechanisms in the high-grade deposits with:
        - Reduction-oxidation reactions recorded in iron isotopic values in clay alteration minerals linked to uranium precipitation at the McArthur River deposit (Acevedo and Kyser, 2015).
        - Reduction and neutralization of acidic fluids through fluid-rock interactions (Potter et al., 2015)
        - Graphite and sulphide depletion proximal to ore during pre- to syn-ore alteration (Pascal et al., 2015; Wang et al., 2015).

- *Fluid flow –structural relations*
    - Basement fluid flow was focussed along key structures over long distances (i.e. 12 km along the P2 fault; Adlakha et al., 2015).
    - Strong structural control on these uranium ore systems with the position and size of the hydrothermal convections cells controlled by the location of fault zones and estimated to be on the order of 2 km (Li et al., 2015).

Basin evolution

- Potential for primary ore precipitation post-peak diagenesis, related to regional tectono-magmatic events (Mildragovic et al., 2015).
- Hydrocarbon migration to the base of the basin syn- to post-ore formation (Li et al., 2015).

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