Host-Rock Protoliths, Pre-Ore Metasomatic Mineral Assemblages and Textures, and Exotic Rocks in the Western Athabasca Basin: Ore-System Controls and Implications for the Unconformity-Related Uranium Model

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Abstract

Framework geological investigations of drillcore from several uranium exploration projects in Saskatchewan's western Athabasca Basin region were undertaken in order to better characterize the geological controls on uranium ore systems in crystalline rocks of the Rae Province that lie below the Athabasca Supergroup. Two major basement rock types were identified in the region. The first comprises variably to intensely altered orthogneisses derived from quartz monzodioritic or quartz dioritic protoliths, with the original composition of the original plutonic rocks difficult to discern due to later alteration. The second is a suite of mafic to ultramafic plutons that intruded the orthogneisses. Variable composition (gabbro to clinopyroxenite) and grain size (fine and coarse grained) suggest that the mafic to ultramafic suite was originally a layered intrusive complex.

The rock units have been observed in core derived from drilling that targeted fault zones with long fluid-flow histories. As a result, metasomatic mineral assemblages that predate uranium mineralization are common, and probably include early albitization. In the mafic to ultramafic suite, an early assemblage of chlorite and white mica prevails. These events preceded at least two pervasive silicification events. In the mafic to ultramafic suite, these events led to disaggregation and further sericitization of the rocks. At least two later phases of vein quartz crosscut the silicified mafic to ultramafic rocks. Pervasive silicification of the orthogneisses produced 'pseudopelites', containing plagioclase, quartz, biotite, garnet and sillimanite; however, no two minerals were stable at the same time. Biotite is the oldest mineral and was variably consumed first by albite and then by quartz, which partially consumed both minerals. Protracted and episodic silicification led to further destruction of biotite and plagioclase, with both minerals partially replaced by sillimanite. Both sillimanite and biotite were later partly replaced by garnet. As silicification proceeded, garnet was eventually replaced by quartz. Therefore, crosscutting relationships suggest that this mineral assemblage was generated by metasomatic processes rather than representing the original composition of the altered rocks.

*Hydrothermal graphite and iron-sulphides postdate the pervasive silicification. The graphite and iron-sulphides were emplaced in brittle–ductile structural zones that developed along competency contrasts between hard (*e.g.*, silicified) and soft (*e.g.*, chloritized or sericitized) rocks. In quartz-rich rocks, graphite and iron-sulphide occur in anastomosing fracture networks, whereas the softer rocks were replaced by these minerals. Uraniferous fluids later used the same fault systems and the resultant mineralization overprinted the graphite and iron-sulphide–bearing structures.*

The metasomatic mineral assemblages documented in crystalline fault zones of the western Athabasca region are very similar to those of the eastern Athabasca Basin, regardless of original rock protolith. Therefore, it is reasonable to assume that similar pre-ore geological processes were active in deep-seated structures across the Athabasca region. A calcite carbonatite identified in the Patterson Lake corridor, Saskatchewan's only known magmatic carbonatite, further demonstrates the deep-seated nature of prospective structural corridors in the western Athabasca Basin.

Keywords: *western Athabasca region, orthogneiss, mafic to ultramafic intrusive suite, silicification, pseudopelite, hydrothermal graphite, hydrothermal iron-sulphides, brittle–ductile structures, uranium mineralization, carbonatite*

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1. Introduction

This report details framework geological investigations of basement rocks below the southwestern Athabasca Basin, comprising rocks of the Rae Province (Figure 1). Since the publication of a remote predictive map for this region (Card, 2006), mapping and analytical follow-up of exposed bedrock in the southern Taltson Domain (Figure 1) has improved the understanding of the geology in this part of the Rae Province. In addition, successful uranium exploration projects have provided access to drillcore from parts of the region that were previously poorly understood. This work aims to integrate the rocks being explored for uranium deposits into the broader framework of the southwestern Rae Province. Site visits were conducted at five core repositories: AREVA Resources Canada's (AREVA) cache at Cluff Lake; Big Bear Camp at Grygar Lake; Fission Uranium Corp.'s (Fission) Patterson Lake cache; NexGen Energy Ltd.'s (NexGen) cache at Patterson Lake; and Purepoint Uranium Group's (Purepoint) cache at Patterson Lake. Cores from two mineralized areas, Patterson Lake and Shea Creek (Figure 1, Table 1), were the primary focus of this field investigation. In addition, cores from the Patterson Lake north and Border Block properties (Figure 1, Table 1), controlled by Fission 3.0 Corp. and NexGen, respectively, were also investigated.

Uranium mineralization identified to date in the western Athabasca Basin is predominantly hosted beneath its basal unconformity. This contrasts with the scenario in the eastern Athabasca Basin, where the largest deposits are hosted in, or in close proximity to, the basal unconformity (*e.g.*, Key Lake, McArthur River and Cigar Lake). In addition, the Patterson Lake corridor contains minimal (<200 m) Athabasca Supergroup and Phanerozoic cover rocks and, as a result, basement sections with greater than 200 m of core are common. The principle goal of this project was characterization of the geological features in the basement rocks that might have influenced the mineralizing system.

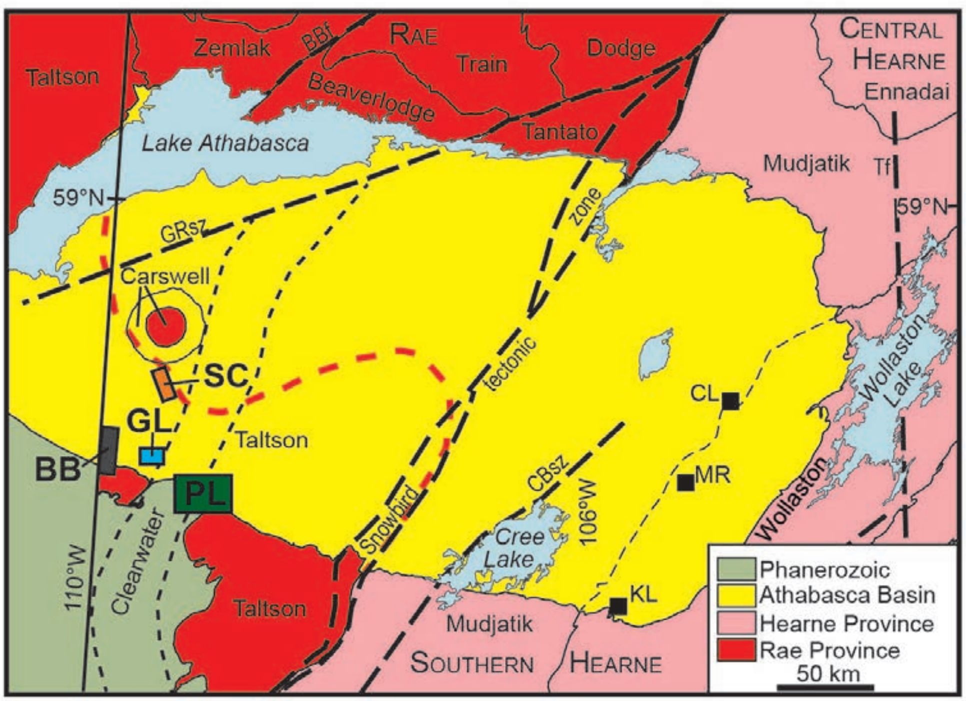

Figure 1 *– Geological framework of the Athabasca Basin region including lithostructural domains. Rocks detailed in this report are from the Taltson Domain, which extends beneath the Athabasca Basin (dashed red line). The geophysical expression of the Clearwater Domain granites, not exposed within the extents of this map, lies between short-dashed black lines. Four uranium exploration areas[3] from which drillcores were investigated during this project are shown: Border Block (BB); Grygar Lake area (GL); Patterson Lake area (PL); and Shea Creek (SC). Some of the major fault and shear zones of the Canadian Shield, demonstrating a variety of common orientations, are displayed: BBf – Black Bay fault; CBsz – Cable Bay shear zone; GRsz – Grease River shear zone; Tf – Tabbernor fault zone. Other Abbreviations: CL – Cigar Lake; KL – Key Lake; MR – McArthur River.*

[3] Polygon outlines are general in nature and do not correspond directly to the actual land tenure of specific exploration companies.

Table 1 – List of drillcores mentioned in this report and their corresponding exploration area. The length of each basement core is indicated. The proportion of mafic to ultramafic rocks, silicified rocks and graphite- and iron-sulphide (Gr – Fe-S)–bearing rocks is indicated. Graphite- and iron-sulphide (Gr – Fe-S) were deposited from fluids after the major silicification event and, therefore, there is overlap between these rocks and silicified rocks.

Drillcore Name	Exploration Area	Operator	Core Length (m)	Mafic to Ultramafic (m)	Silicified (m)	Gr – Fe-S (m)
AR-15-42A	Patterson Lake	NexGen	651.9	651.9	139.8	16.2
AR-16-79	Patterson Lake	NexGen	869	869	716	98.4
HK-13-07	Patterson Lake	Purepoint	not logged in detail			
HK-15-23	Patterson Lake	Purepoint	251.1	235.4	147.8	7.7
HK-15-29	Patterson Lake	Purepoint	163.75	110.95	48.4	0
MB-10-01	Border Block	NexGen	137.5	51.3	61.1	0
PLN14-14	Grygar Lake	Fission 3.0	163.4	92.5	92.5	0
PLS14-245	Patterson Lake	Fission	209.9	82.3	37	27.8
PLS14-295	Patterson Lake	Fission	329	329	106.9	88.6
PLS15-349	Patterson Lake	Fission	195.4	185.1	106	23
PLS15-401	Patterson Lake	Fission	386.85	386.85	264.7	62.1
SHE-117	Shea Creek	AREVA	74.4	4.8	22.4	0
SHE-144	Shea Creek	AREVA	141.3	87.6	71	3.9
SHE-145	Shea Creek	AREVA	119.8	0	110.8	2

2. Regional Geology

Rocks of the southwestern Rae Province south of the Athabasca Basin (Figure 1) are in the recently defined Taltson Domain (previously referred to as Western Granulite or Lloyd domains; Card, 2012a). The Taltson Domain was originally mapped in the 1970s (Wallis, 1970; Sibbald, 1974; Scott, 1977); however, the domain has been revisited in order to provide modern geological descriptions and analytical controls. The details of those investigations are contained in a variety of publications (Card, 2002; Stern *et al.*, 2003; Card and Bosman, 2007; Card *et al.*, 2007, 2008, 2014; Card, 2009). A summary of that work follows.

The Taltson Domain is underlain by orthogneisses derived predominantly from diorite, quartz diorite and quartz monzodiorite, with subordinate tonalite, granodiorite and granite. The crystallization age of these orthogneiss protoliths remains relatively poorly understood. A single sample of tonalite, most common along the Snowbird tectonic zone (Figure 1), has been dated at *ca.* 3.13 Ga (Card, 2016) and is the oldest known rock in the Taltson Domain of Saskatchewan. A gneissic granite from the Clearwater Domain (Figure 1) was likely emplaced between 2.53 and 2.50 Ga (Stern *et al.*, 2003). Together, these are the only two Archean rocks identified in the region. All of the dated dioritic rocks, the most common composition in the Taltson Domain, have returned Paleoproterozoic ages that fall into two broad ranges. The oldest diorite, from 40 kilometres south of the Patterson Lake area (Figure 1), returned a crystallization age of *ca.* 2.46 Ga, whereas other samples have returned ages of *ca.* 1.99 and 1.98 Ga (Stern *et al.*, 2003), and *ca.* 1.94 Ga (Card, 2016). The current state of knowledge therefore indicates that the majority of the rocks that constitute the regionally extensive orthogneisses are of Paleoproterozoic derivation. Southeast of the Patterson Lake area, the *ca.* 2.11 Ga Clearwater anorthosite complex (Card *et al.*, 2014) contains dominantly anorthosite and gabbroic anorthosite (Card, 2009). Metasedimentary rocks of the Careen Lake group were intruded by the *ca.* 1.99 to 1.98 Ga diorites. They are dominated by metatexitic to diatexitic pelites and make up less than 5% of the exposed rocks in the region. All of these rocks were metamorphosed during granulite-facies conditions, presumably during the Taltson orogeny at *ca.* 1.94 Ga (Card *et al.*, 2014). A second, *ca.* 1.90 Ga, amphibolite-facies, metamorphic phase is best developed near shear zones and is characterized by hydration of the older metamorphic assemblage (Stern *et al.*, 2003; Card *et al.*, 2014).

Post-metamorphic granites are common in regional faults such as the Snowbird tectonic zone (Figure 1). Two samples of post-metamorphic monzogranite from the Snowbird tectonic zone south of the Athabasca Basin have returned ages of *ca.* 1.83 (Stern *et al.*, 2003) and 1.82 Ga (Bickford *et al.*, 1994). In addition, a granite from the Clearwater Domain (Figure 1) returned an age of *ca.* 1.84 Ga (Stern *et al.*, 2003).

Sometime after 1.80 Ga, deposition of the effectively flat-lying, unmetamorphosed conglomeratic siliciclastic sedimentary rocks of the Fair Point Group of the Athabasca Supergroup began on exhumed crystalline basement of the Rae craton in the Jackfish Basin (Bosman and Ramaekers, 2015). This was followed by deposition of dominantly quartz arenites in the Cree Basin. The uppermost strata of the Cree Basin, the Wolverine Point Group, have a depositional age of *ca.* 1.64 Ga (Rainbird *et al.*, 2007). Later, a third basin, the Mirror, began receiving siliciclastic detritus of the McFarlane Group (Bosman and Ramaekers, 2015). Together, rocks of these three basins now reside in the Athabasca Basin, with rocks of the Cree Basin the most extensive.

North of Shea Creek (Figure 1), a plug of basement rocks termed the Carswell structure protrudes through the sedimentary rocks of the Athabasca Supergroup. The Carswell structure is thought to have formed due to a large bolide impact in the Ordivician Period (Bleeker *et al.*, 2015). The impact site has a down-dropped ring of Athabasca Supergroup surrounding the central basement uplift. This is the only place in the Athabasca Basin where rocks of the Douglas (dominantly mudstones) and Carswell (dolostones) formations of the McFarlane Group are preserved (Ramaekers *et al.*, 2007).

3. General Geology

a) Major Rock Types in Drillcore

Gneissic Quartz Monzodiorite/Quartz Diorite

Orthogneisses constituting mainly quartz monzodioritic, quartz dioritic and dioritic protoliths are the most common rock type in the region (Figure 2A; Card *et al.*, 2014). These rocks are common at Shea Creek, the Border Block, Patterson Lake North, west and east of Patterson Lake, and at Forrest Lake (Figures 1 and 2A). The rocks are medium grained, pink to white (Figures 3A and B) and have a colour index of 10 to 25 (Figures 3A, 3B and 3C). Mafic minerals are dominated by biotite and define the regional foliation. Biotite has likely replaced pyroxene, which was originally dominant in the granulite-facies rocks (Card *et al.*, 2014). The rocks tend to be quartz bearing (both blue and white); however, the original quartz content of these rocks is difficult to determine as subsequent flooding by both blue and white quartz is common (*e.g.*, Figures 3B, 3D and 3E). Rusty red colouration is common in these rocks (Figures 3C and 3E). The colour overprint makes distinguishing whether or not K-feldspar is present difficult. Both quartz monzodiorite and quartz diorite are common regionally (*e.g.*, Card *et al.*, 2008) and as a result this ambiguous unit name has been adopted. Garnet that crosscuts the regional foliation is also common in the rusty red rocks and in silicified examples (Figure 3E). Later brittle–ductile deformation events appear to have been focused in the ferromagnesian minerals (Figure 3D).

Mafic to Ultramafic Intrusive Suite

The quartz monzodioritic to quartz dioritic rocks were intruded by mafic to ultramafic sheets (Figure 3F). The sheets are locally common but are not present in every drillcore. Intersections range from a few centimetres of core length (Figure 3F) up to several metres (Table 1). Grain sizes are variable, ranging from medium to coarse, and the sheets generally contain greater than 70% ferromagnesian minerals. At Patterson Lake, a suite of mafic to ultramafic rocks dominates (Figure 2A) and, in part, hosts the uranium deposits being delineated there. Grain size in the unit is variable but typically is greater than 3 mm. The content of original ferromagnesian minerals varies from 40 to over 90%, in some cases over the span of a few centimetres of core length. Although the original compositions of the members in this unit are difficult to ascertain due to the effects of pervasive alteration, the suite appears to contain a number of different compositional units. Among them are medium- to coarse-grained gabbro (Figure 4A), which contains rare, randomly oriented, altered plagioclase phenocrysts (Figure 4B). Melagabbros are also common and vary to ultramafic compositions over short lengths of core (Figure 4C). These rocks appear to have been mainly clinopyroxene bearing on the basis of a few fresh samples and a single augite-dominated thin section. In some cases, the original ferromagnesian minerals were apparently round, suggesting the rocks might have originally been olivine-bearing cumulates (Figure 4C). Finer-grained, relatively massive melagabbro to ultramafic rock (Figure 4D) is also common. Changes in grain size, the shape of grains and the apparent composition of the rocks, including potential relict cumulate textures, suggests that the mafic to ultramafic suite was originally layered (Figure 4E).

The mafic to ultramafic rocks vary from massive to strongly foliated. The foliated rocks were then strongly metasomatized in advance of uranium mineralization. Chlorite, serpentine, biotite and white mica replaced ferromagnesian minerals. White mica also replaced plagioclase. Alteration in the ferromagnesian minerals is commonly zoned, with cores of chlorite and white mica surrounded by zones of white mica. The zoning leads to rocks with distinctive dark patches surrounded by light green, white-mica aggregates (Figures 4E and 4F). It is apparent that alteration in these rocks commenced due to fluid infiltration along crystal boundaries and then replacement proceeded toward the cores of the original ferromagnesian minerals (Figure 4F). Therefore, relict patches of dark chlorite might represent pseudomorphed crystal cores. The chlorite patches are a potential, albeit inexact, proxy for the original grain size of the protolith. The altered mafic to ultramafic rocks are an important unit as they clearly host uranium mineralization along the Patterson Lake corridor.

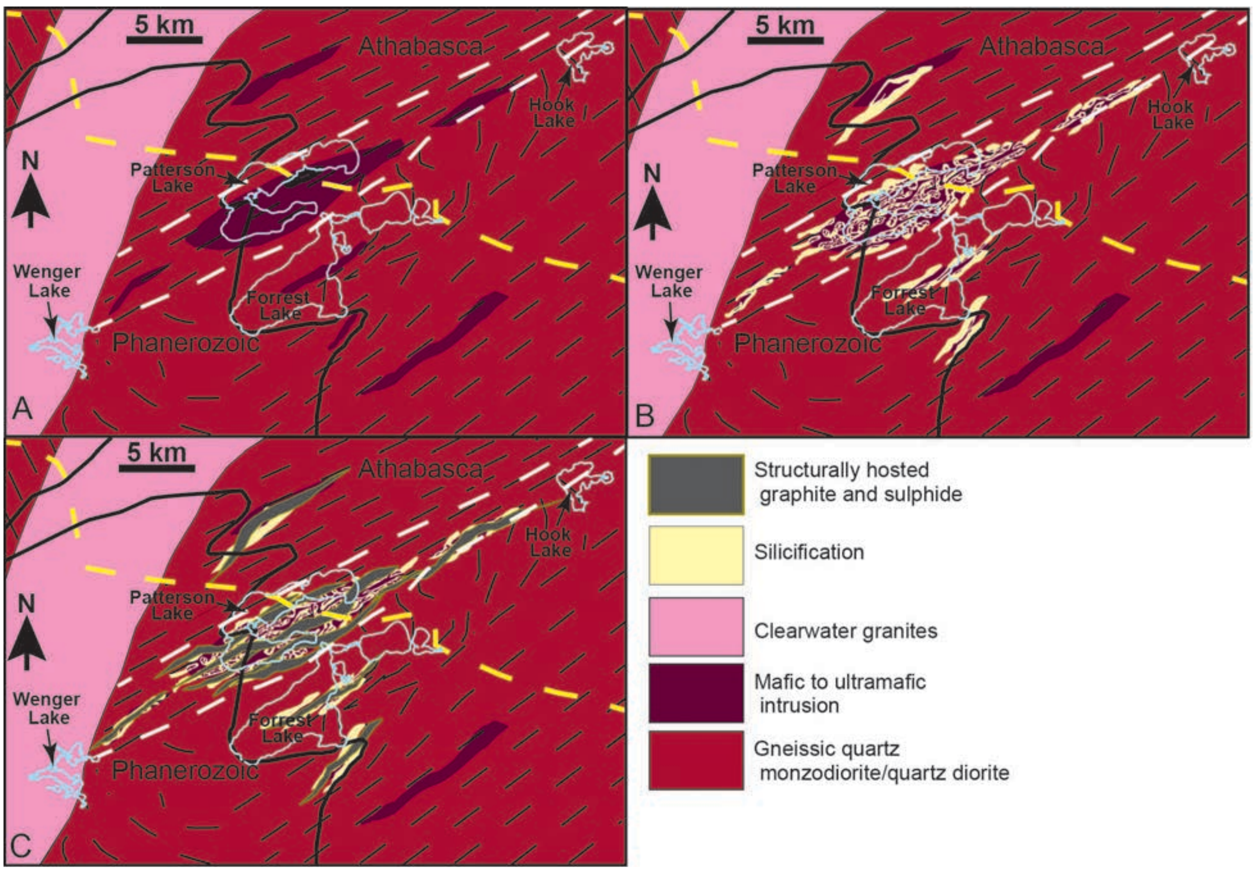

Figure 2 – Cartoon geological maps based on known age relationships in the Patterson Lake area at three different points in time. Information used to draft the maps was taken from bedrock mapping south of the Athabasca Basin and relationships in drillcore. In these cartoons, long-dashed black lines represent the trend of the regional foliation. The Patterson Lake exploration corridor, which was superimposed on a regional high-strain zone, is shown between white dashed lines. A) The general distribution of geological units in the Patterson Lake area after the cessation of major metamorphic activity at about 1.90 Ga. The Athabasca Supergroup overlies the Rae Province basement north of the yellow dashed line. Phanerozoic rocks are preserved west and south of the solid black line. B) Rocks of the Patterson Lake area after pervasive quartz flooding (see text for discussion). C) Rocks of the Patterson Lake area after emplacement of graphite and sulphides in anastomosing, brittle–ductile structural zones (see text for discussion).

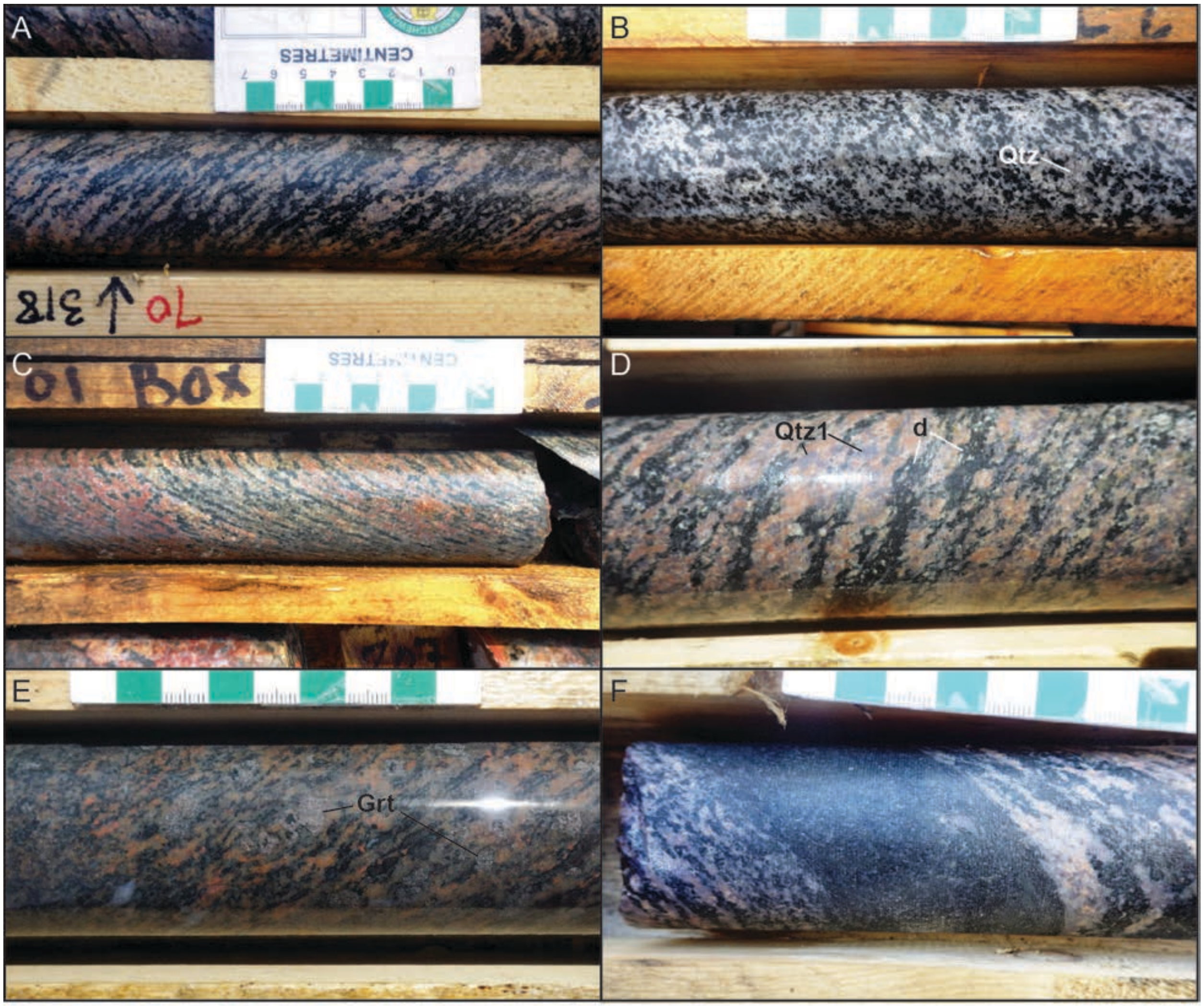

Figure 3 – A) Pink, foliated quartz monzodiorite/quartz diorite (PLS14-245, 317.9 m[4]). B) White to grey, foliated quartz monzodiorite/quartz diorite. Patches of quartz (Qtz[5]) apparently crosscut white plagioclase, likely indicating silicification (PLN14-14, 221.5 m). C) Foliated quartz monzodiorite/quartz diorite with rusty red colouration locally (see also Figures 3A and 3B). Rock colour cannot be used to ascertain the composition of the igneous rock protoliths for this unit due to influence of alteration(s) (MB-10-01, 205.5 m; UTM 205770E, 6417920N[6]). D) Foliated quartz monzodiorite/quartz diorite with a later deformation event (d) focused in the mafic minerals (in this case biotite). The rock also contains blue quartz (Qtz1) (core diameter is 4.76 cm[7]; PLS14-245, 158.4 m). E) Garnet porphyroblasts (Grt) overgrowing the foliation in a rusty red altered quartz monzodiorite/quartz diorite (HK-15-23, 332.7 m). F) A subcordant mafic to ultramafic sheet that intruded quartz monzodiorite/quartz diorite. Strong local transposition is interpreted to be the cause of the nearly coplanar attitude of the contacts of the mafic to ultramafic sheet and the foliation in the country rock (PLS14-245, 324.4 m).

[4] Depth measurements represent core lengths from the drill collar regardless of the orientation of the drillhole and are not elevations.
[5] All mineral abbreviations are from Siivola and Schmid (2007).
[6] All Universal Transverse Mercator (UTM) coordinates in this report are given in the appropriate figure captions for the first reference to a drillcore. Coordinates are omitted for drillcores that were confidential at the time of publication. UTM coordinates are in North American Datum (NAD) 83, extended zone 13.
[7] Core diameter is used as a scale reference where no scale card is present in the image.

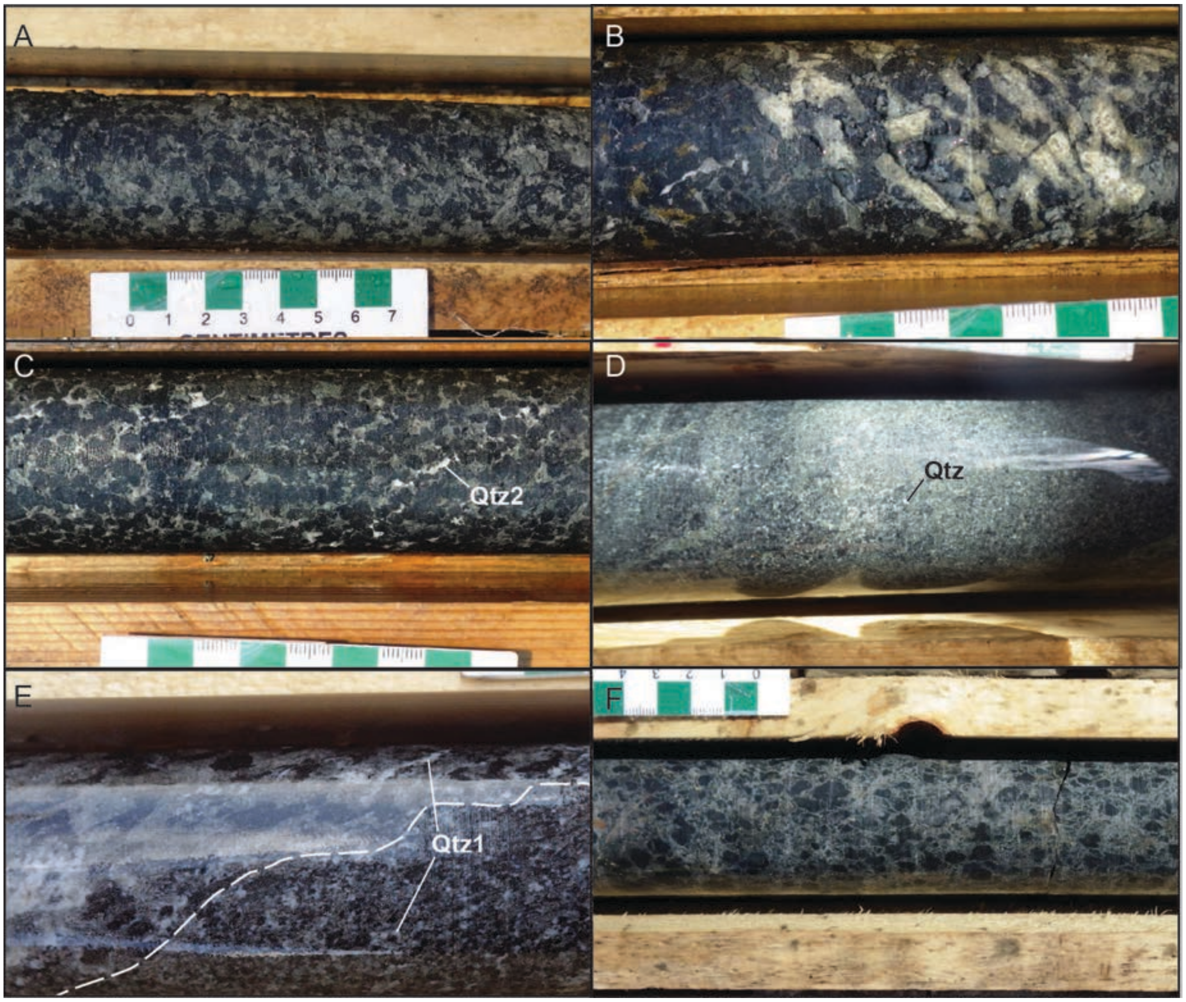

Figure 4 – A) Coarse-grained gabbro near mineralization (AR-15-42A, 659.2 m). B) Gabbro with coarse, randomly oriented, altered plagioclase laths (AR-15-42A, 663.7 m). C) Incipiently silicified (Qtz2) ultramafic rock, with pseudomorphed round grains with light green matrix material. This rock may have originally been olivine bearing (AR-15-42A, 664 m). D) Fine- to medium-grained ultramafic intrusive rock with incipient silicification (Qtz) (core diameter is 4.67 cm; PLS15-349, 228.3 m). E) Apparent layering in silicified (Qtz1) mafic rocks with coarse gabbro and a finer-grained, more pervasively silicified gabbro. The differences in the silicification textures and the apparent similarity in original composition suggest an original grain-size difference (core diameter is 4.67 cm; white dashed line indicates the approximate boundary between the two phases; PLS15-401, 417.5 m). F) Coarse-grained, altered mafic to ultramafic rock (HK-13-07, 305.7 m). Rocks with this appearance are common along the Patterson Lake exploration trend.

b) Altered/Metasomatized Rocks

All of the cores investigated during this study were drilled in fault zones, which are well-known to be associated with uranium deposits (*e.g.*, Hoeve and Sibbald, 1978). To that end, altered varieties of both the major rock types in the region have been discussed above. Rocks that are so strongly altered and/or metasomatized that the rock protolith is difficult to determine or that are dominated exclusively by metasomatic minerals are described below. Metasomatic rocks are described on the basis of the relative age, with the oldest mineral assemblages described first.

Albitization of Gneissic Quartz Monzodiorite/Quartz Diorite?

Patchy to pervasive rusty-red colouration is common in the gneissic quartz monzodiorite/quartz diorite (Figures 3C and 3E) and this type of colouration is commonly associated with hematization that accompanies albitization events (Ashton *et al.*, 2013). The relationships between plagioclase and other minerals in thin sections from the Shea Creek property are curious. Two types of plagioclase are commonly present: one with exsolution lamellae of another feldspar (microcline?) and no twinning; and a well-twinned variety (no exsolution lamellae). Although typically too altered to perform accurate Michel-Levy tests on the extinction angles, the limited successful attempts to use the method suggest that the well-twinned plagioclase species is albite. Both varieties apparently grew at the expense of biotite[8] (Figures 5A and 5B) as indicated by embayed inclusions and inclusion trails in plagioclase (Figure 5C). These relationships suggest that albitization might be an early alteration facies in the Shea Creek region, although further petrographic work will be required to fully understand the plagioclase systematics in these rocks. The plagioclase was replaced by quartz, indicating that it predated widespread silicification in the Shea Creek area (Figure 5).

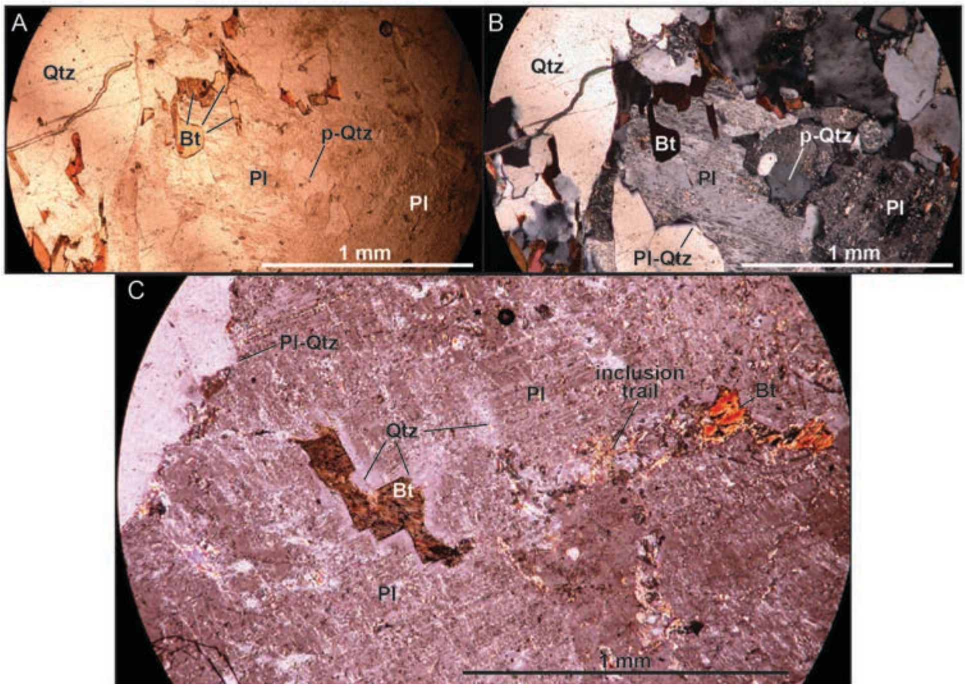

*Figure 5 – A) Photomicrograph of 'pseudopelite' in plane-polarized light showing sericitized, twinned plagioclase (Pl) embaying biotite (Bt). Quartz (Qtz) also embayed biotite. Patches of quartz (p-Qtz) replaced the plagioclase (SHE-145, 773.6.3 m). **B)** The same view as in Figure 5A in cross-polarized light showing sericitized, twinned plagioclase (Pl) embaying biotite (Bt). The grains of biotite indicated in Figure 5A are all in extinction. This optical continuity indicates that they were once a single grain. Quartz embays the plagioclase (Pl-Qtz). C) Photomicrograph of 'pseudopelite' in cross-polarized light showing sericitized, twinned plagioclase (Pl) with inclusions of biotite (Bt) indicating biotite is the older mineral phase. Inclusion trails of biotite suggest that plagioclase grew at the expense of biotite. The rock was later silicified as indicated by embayed plagioclase (Pl-Qtz) and preferential silicification (Qtz) along the boundaries of the biotite inclusions. The perpendicular nature of some of the boundaries of the biotite inclusion on the left implies that the silicifying fluid migrated along the nearly orthogonal cleavage planes in the plagioclase and further replaced the biotite (SHE-145, 854.3 m).*

Silicification of Mafic to Ultramafic Rocks

Quartz flooding is ubiquitous at all the sites visited during this program. There are apparently two phases of early quartz flooding. The first is characterized by blue quartz (quartz 1) and the second by white quartz (quartz 2). Both of these phases of quartz pervasively replaced the host rocks.

In the Patterson Lake area, silicified rocks of the mafic to ultramafic suite abound (Figure 2B). Figure 6A shows a strongly altered mafic to ultramafic rock in which patches of chlorite and white mica from the originally altered rock now rest in a matrix of blue quartz (image was taken 0.5 m from Figure 4F). The relationship suggests that the original rocks were partly replaced by chlorite and white mica in advance of the blue-quartz–flooding event. This silicification further advanced the alteration process, introducing zoning along the contacts between blue quartz and

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[8] Indicates addition of Na and loss of Fe, Mg, K and H_2O.

the country rocks. The contact zones contain hydrothermal quartz and a new phase of white mica (Figure 6B), which give way to a zone dominated by randomly oriented biotite, and finally a zone of older chlorite and white mica in the least-silicified part of the rock (Figure 6B). In strongly silicified units, fragments of the original mafic to ultramafic units appear to be 'floating' in the blue quartz (Figure 6C). The smallest fragments are commonly replaced by garnet that was, in turn, replaced by chlorite along fractures (Figure 6C). A phase of white quartz (Figure 6D) also flooded the mafic to ultramafic rocks with sporadically preserved remnants of blue quartz indicating the age relationship. The event led to further replacement of the host rocks with white mica (Figure 6D).

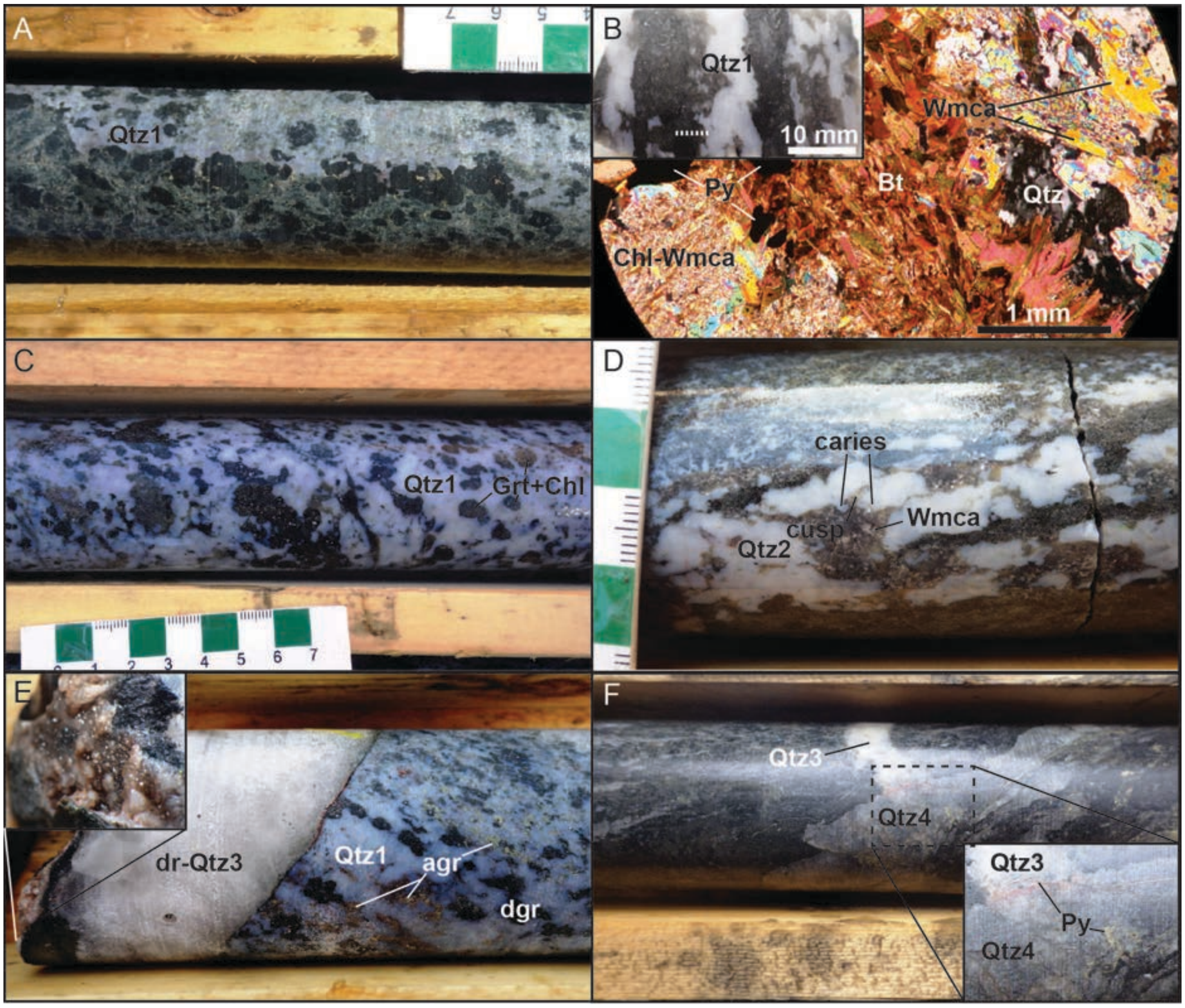

Figure 6 – A) Altered mafic to ultramafic rock (lower part of core) crosscut by blue quartz (Qtz1). Partly digested clasts of chlorite and white mica were disaggregated from the mafic to ultramafic rock (HK-13-07, 306.2 m). B) Inset: thin section cut-off showing the silicified (Qtz1) mafic to ultramafic rock. Dotted line indicates the transect in the associated photomicrograph. Photomicrograph (cross-polarized light) showing zoning in a silicified (quartz 1) mafic rock. Chlorite and white mica (Chl-Wmca) represent the previously altered part of the rock. The silicified part of the rock contains quartz (Qtz) and white mica (Wmca; likely muscovite) and the intervening zone is dominated by biotite (Bt). Embayed contacts indicate that pyrite (Py) overgrew all the other minerals (AR-16-79, 476 m). C) Variably sized relicts of mafic to ultramafic rock 'floating' in blue quartz (Qtz1). Some of the smaller relicts of chlorite and white mica have been replaced by garnet and then a younger chlorite (Grt+Chl) (AR-16-79, 830.8 m). D) Mafic to ultramafic rock flooded with white quartz (Qtz2). Reflective flecks of white mica (Wmca) have replaced the original ferromagnesian minerals in this rock. Quartz embayed the host rock resulting in well-developed cusp and caries texture[9] (PLS14-245, 243.3 m). E) A mafic to ultramafic rock flooded by blue quartz (Qtz1) with chloritized clasts (dgr – dark green) and sericitized clasts (agr – apple green). A druzy white quartz vein (dr-Qtz3) crosscuts the foliated clasts and the blue quartz. Euhedral quartz crystals are present on the white to pink broken surface (inset) (core diameter is 4.67 cm; AR-16-79, 390.5 m). F) Grey quartz (Qtz4) crosscutting a white quartz (Qtz3) vein. The grey quartz is pyrite bearing (Py; see inset) and both phases of quartz are crosscut by wispy pyrite veins (core diameter is 4.67 cm; PLS14-295, 193.8 m).

Both blue and white quartz replaced rocks that were foliated (Figures 6D and 6E); however, the silicification textures were not deformed during the same event, which is indicated by cusp and caries textures[9] that have not been reoriented. This indicates that the silicifying fluids likely migrated along the regional foliation. Later, ductile and brittle–ductile deformation events overprinted these early quartz phases.

Two phases of vein quartz have also been identified. White quartz (Qtz3) that is locally druzy (Figure 6E) crosscuts the quartz-flooded mafic to ultramafic units. Those veins are, in turn, crosscut by grey quartz veins (Qtz4; Figure 6F) that commonly have associated iron-sulphides and graphite. It is unclear if the iron-sulphides and graphite are directly associated with the grey quartz veins, as veins of iron-sulphide crosscut them (Figure 6F, inset).

Silicification of Gneissic Quartz Monzodiorite/Quartz Diorite: 'Pseudopelite'

The gneissic quartz monzodiorite/quartz diorite was also strongly silicified, particularly at Shea Creek and the Border Block. Although locally blue-quartz–bearing (Qtz1; Figure 3D), the younger white quartz (Qtz2) is typically dominant (Figure 7). Incipiently silicified rocks are reddish and are consistently garnet bearing (Figures 3E and 7A). Silicification intensifies across gradational boundaries, with the pink gneissic rocks becoming white (Figures 7A and 7B are separated by 3 m in SHE-117). The result is rocks that are dominated by quartz, with intervening layers and lenses of garnet and biotite (Figures 7B, 7C and 7D). Sillimanite and plagioclase are also common (Figures 7D and 8) in the intervening layers and lenses. This assemblage is reminiscent of high-grade pelites; however, unlike metamorphosed pelites, where two or more of the phases tend to be in equilibrium (*i.e.*, stable at the same pressure and temperature), no two minerals in this assemblage were stable at the same time. In fact, the preserved assemblage appears to have been a result of the silicification process and, thus, the moniker 'pseudopelite' is proposed for these rocks.

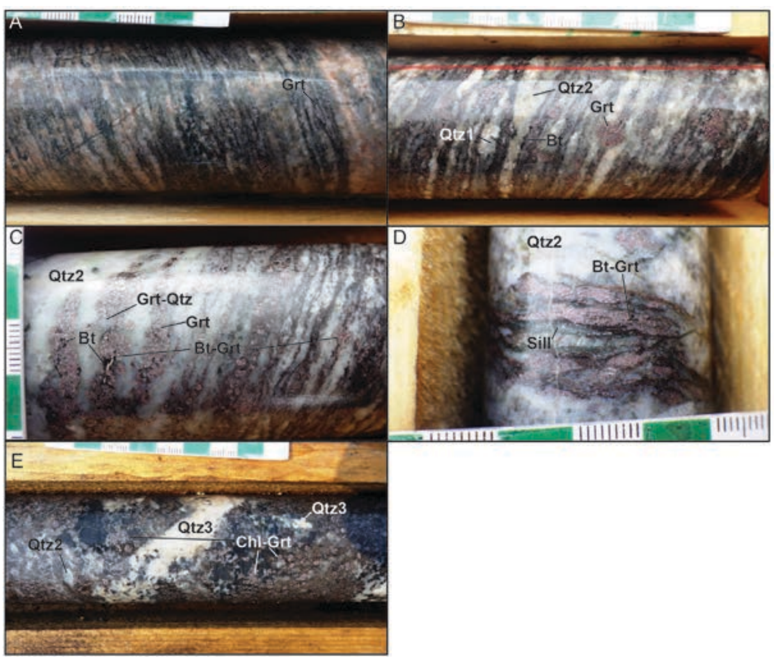

Figure 7 – A) Garnet-bearing silicified rock. This rock has a texture and composition reminiscent of the less-silicified quartz monzodiorite/quartz diorite (Figures 3A, 3C, 3D and 3E); the two rock types are typically separated by gradational boundaries. The garnet porphyroblasts (Grt) appear to be flattened parallel to the foliation in the rock but are actually pseudomorphing foliated minerals (SHE-117, 789.9 m; UTM 232762E, 6465130N). B) More pervasively silicified rock from 3 m below the rock in Figure 7A. Quartz introduced to the rock is mimicking the foliation, suggesting the silicifying fluids used the foliation as a transport path. On the basis of colour, more than one phase of quartz (blue-grey Qtz1, white Qtz2) is likely present. Garnet (Grt) overgrows the quartz and the biotite (Bt) that helps to define the foliation (SHE-117, 792.9 m). C) Pervasively silicified rock dominated by white quartz (Qtz2). Biotite was replaced by garnet (Bt-Grt) on the basis of inclusion trails in garnet porphyroblasts and garnet that crosscuts the biotite-defined foliation. In addition, garnet was apparently embayed by quartz (Grt-Qtz) (SHE-117, 773.5 m). D) Lenticular garnet in silicified (Qtz2) rock. Garnet porphyroblasts took their habit by replacing biotite (Bt-Grt) parallel to the rock's relict foliation. This is indicated by inclusion trails of biotite in the porphyroblasts. Blue-grey mineral within lenticular areas of biotite and garnet is sillimanite (Sill; SHE-144, 813.7 m). E) Silicified mafic to ultramafic rock demonstrating two phases of quartz (white Qtz2 and white Qtz3). Garnet overgrew the chloritized mafic minerals (Chl-Grt) in the rock (MB-10-01, 235.3 m).

[9] A texture in which the younger minerals form scallop-shaped incursions into the host mineral that resemble filled dental cavities (Glossary of Geology 5th Ed., 2005, p.100).

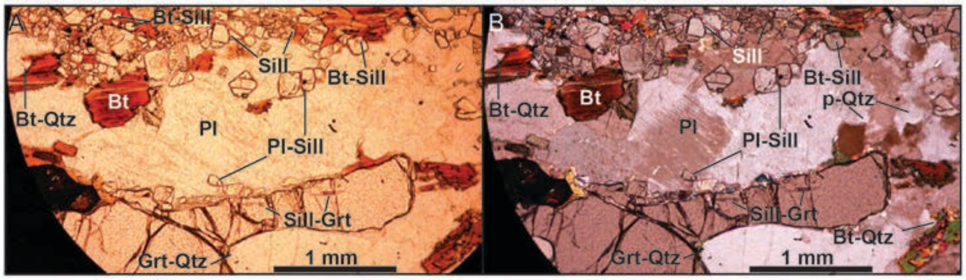

Figure 8 – A) Photomicrograph (plane-polarized light) of a pseudopelite. Quartz (Qtz) is the youngest mineral, occupying embayments in biotite (Bt-Qtz) and garnet (Grt-Qtz). In addition to overgrowing biotite (Bt; see Figures 7C and 7D), garnet also overgrew sillimanite (Sill-Grt). Sillimanite overgrew both plagioclase (Pl-Sill) and biotite (Bt-Sill) (SHE-145, 854.3 m). ***B)*** *The same view as Figure 8A, in cross-polarized light. In addition to the relationships described in Figure 8A, quartz replaced plagioclase (Pl) in patches (p-Qtz).*

The oldest mineral in the silicified rocks is biotite and it is parallel to the original gneissic regional foliation (Figures 7B, 7C and 7D). As noted above, however, the mineral that typified the peak metamorphic assemblage in gneissic quartz monzodiorite/quartz diorite is pyroxene. Therefore, biotite is a mineral phase that indicates replacement of the peak metamorphic pyroxenes (and addition of potassium). Biotite was apparently overgrown by albitic plagioclase (Figure 5), proposed above to have been the product of sodic alteration. Identifying zones of potential albitization is confounded by the later silicification events, which disguised the context of older mineral phases. Silicification was apparently accompanied by sericitization of the plagioclase. Plagioclase was replaced and embayed by quartz. In some silicified plagioclase grains, relict twinning is still recognizable. Quartz also embayed and replaced biotite (Figure 8). Silicification was also focused along biotite inclusions in the plagioclase (Figure 5).

Silicification was apparently a long-term, albeit episodic, process and, as it proceeded, the older mineral phases were progressively replaced by quartz, with the relict aluminum ending up in other mineral phases. Randomly oriented sillimanite overgrew the contacts between the silicified remnants of biotite and plagioclase (Figure 8), suggesting a causal relationship between the sillimanite and the silicification process. Inclusion trails of biotite (Figure 7D) and sillimanite (Figure 8) in garnet indicate that the latter was a slightly younger phase. Garnet also replaced the twinned plagioclase. Interpreting the age of garnet is challenging as it had a tendency to grow as elongate porphyroblasts, implying that it was deformed during a foliation-forming event (Figure 7D). However, in all instances and regardless of morphology, garnet overgrows the biotite-defined foliation and the associated secondary quartz is only weakly deformed along grain boundaries[10] (Figures 7B, 7C and 7D). Although garnet clearly grew as a consequence of silicification (Figures 3E and 7A), it was eventually replaced by later quartz as the inundation by siliceous fluids eventually led to complete replacement of the host rocks (Figures 7C and 7E).

The mafic and ultramafic rocks have also been converted to pseudopelite locally. Figure 7E shows an example where the original texture of the silicified ultramafic(?) rock is still recognizable. On the right of the image, however, the rock is dominated by biotite, garnet and quartz, and long core lengths with this texture would be difficult to differentiate from pseudopelite derived from the gneissic quartz monzodiorite/quartz diorite.

Graphitic and Sulphidic Rocks

Graphite, graphitic carbon[11] and iron-sulphide (both pyrite and pyrrhotite[12]) are common at all of the sites (Figure 2C). In all cases the minerals were deposited from carbon-oxygen-hydrogen+sulphur (C-O-H+S fluids[13]) hydrothermal fluids (Figures 2C and 9). The minerals were deposited in several styles, including as replacements of

[10] The nature of quartz grain boundaries, *i.e.*, sutured grain boundaries with bulges and patches of recrystallization, indicates deformation temperatures of 400°C or less (Stipp *et al.*, 2002).
[11] The difference between graphite and graphitic carbon lies in the degree of the carbon's crystallinity (Beyssac and Rumble, 2014), which cannot be accurately determined in field studies. For simplicity, all forms will be referred to as graphite.
[12] These mineral species are difficult to differentiate without using a magnetic susceptibility meter and are grouped together using the term Fe-sulphide. There is no abbreviation for Fe-sulphide in Siivola and Schmid (2007) so the abbreviation for pyrite (Py) is used in figures.
[13] C-O-H fluids carry C in solution and are responsible for hydrothermal deposits (Huizenga, 2010). Because sulphides are associated with the graphite, it is inferred that the C-O-H fluid also carried S.

the host rocks (Figures 9A, 9B and 9C); along fractures in faulted rocks (Figures 2C, 9D and 9E); and as veins (Figure 9F). It is unclear if all the styles were deposited contemporaneously or represent cyclic events. Replacement-style iron-sulphides and graphite occur in weakly deformed to massive rocks. They are common in both weakly (Figure 9A) and strongly altered (Figure 9B) massive clinopyroxenites (Figure 9A) of the mafic to ultramafic suite. The fluids responsible for deposition clearly migrated along clinopyroxene crystal boundaries, partly replacing the rims of the grains mainly with iron-sulphide and some graphite (Figure 9A, inset). The process left partly rounded clinopyroxene grains with the interstices filled with iron-sulphide, graphite, quartz and carbonate minerals. The more intensely altered rocks were serpentinized and more comprehensively replaced by graphite and iron-sulphide (Figure 9B). Both sulphides and graphite appear to have a spatial association with quartz, in particular the grey quartz veins (Qtz4). Figure 9C shows a grey quartz vein with an irregular contact that displays well-developed cusp and caries texture. The cusps were replaced by iron-sulphide.

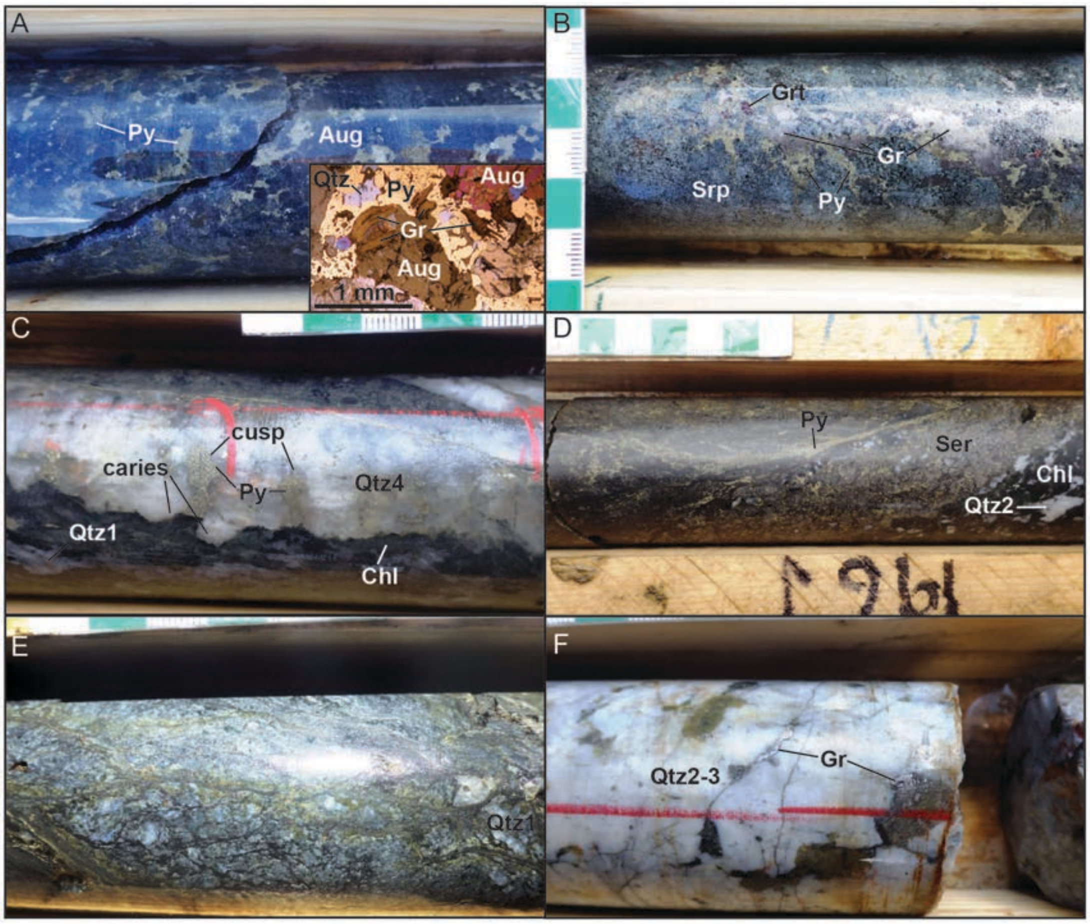

*Figure 9 – A) Clinopyroxenite composed of augite (Aug) with interstitial pyrite (Py). **Inset:** Augite (Aug) with interstitial iron-sulphide (Py) and quartz (Qtz). Graphite (Gr) occurs both in the pyrite and as replacements of the clinopyroxene (AR-15-42A, 710.7 m; inset: AR-16-79, 563.5 m). B) Serpentinized clinopyroxenite (Srp) with iron-sulphide (Py) and graphite (Gr) replacing the altered rock. Garnet (Grt) apparently predates the iron-sulphide (AR-16-79, 562 m). C) Grey quartz (Qtz4) vein cutting a previously silicified (Qtz1) and chloritized (Chl) mafic to ultramafic rock. Cusp and caries texture, where cusps of the chloritized rock embayed by quartz have been replaced by iron-sulphide (Py), imply the introduction of sulphur during vein formation (PLS14-295, 190.8 m). D) Iron-sulphide (Py) introduced along a brittle–ductile shear zone in silicified (Qtz2) mafic to ultramafic rock. Iron-sulphide extends from the shear zone into the sericitized (Ser) wall rock and then into less altered wall rock dominated by chlorite (Chl) (PLS14-295, 196 m). E) Networks of graphitic carbon and iron-sulphide healing brecciated blue quartz (Qtz1). The fractures are mainly parallel to the core axis and seem to originate from a wider vein at the left of the image (PLS15-349, 177.8 m). F) White quartz (Qtz2-3) that was cracked and then sealed by quartz (generation unknown). Graphite (Gr) occupies some of the sealed cracks and also replaces fragments of country rock (PLS15-401, 208.8 m).*

Fault-zone–hosted iron-sulphide and graphite is the most common mode of sulphidization. Anastomosing shear zones and fracture networks coated with the minerals are common. Ductile structures are most common in softer rocks, such as the altered mafic to ultramafic rocks (Figure 9D), and fractures zones healed by iron-sulphide and graphite are common in quartz (Figure 9E). Although the iron-sulphides and graphite are typically confined to structures, replacement-style textures developed in permeable wall rocks (Figure 9D), perhaps providing some insight into the source of this texture elsewhere.

Vein-type iron-sulphide and graphite occur both in relatively undeformed rocks and in structural zones. In the former, well-developed reaction rims are present along the interface between the altered wall rock and the irregularly shaped veins. It is likely in these cases that these veins represent a continuum with replacement-style deposition (Figure 9B). Vein graphite and iron-sulphide were also emplaced along fractures in the various hydrothermal quartz phases (Figures 6F and 9F). Figure 9F shows an example where white quartz was cracked and then healed by grey quartz (Qtz4). Graphite also occupies the healed fracture and may have been deposited at the same time as the grey quartz. Note that a fragment of more permeable country rock in the quartz was replaced by graphite.

c) Structural Geology

No comprehensive structural analysis was completed during this work; however, some broad observations on the structural characteristics of these rocks are warranted. Although there are rocks that are relatively weakly deformed in all the exploration areas, there are clearly parts of each rock type in which the oldest foliation was steep and well developed. These more highly strained zones apparently acted as conduits for early hydrothermal alteration processes such as silicification and, possibly, albitization. Later ductile high-strain zones, which have not experienced high-temperature crystal recovery, overprinted the silicified rocks. The graphite and iron-sulphides appear to have been emplaced at or near the brittle–ductile transition. This is indicated by obvious differences in competency between the altered mafic to ultramafic rocks (sheared; Figure 9D) and the quartz that invaded them (brecciated; Figure 9E). These well-developed competency contrasts were later reused during the uranium mineralization, which postdated emplacement of the iron-sulphides and graphite. Fracture-hosted uranium was precipitated in more competent rocks and replacement uranium in the more permeable, chloritized mafic to ultramafic rocks.

d) Exotic Rock: Carbonatite

A well-preserved, undeformed calcite carbonatite dyke has been identified in a core from northeast of Patterson Lake, where it is the dominant rock type in over forty-seven metres of core. The rock has been interpreted as a magmatic carbonatite (as opposed to hydrothermal; Mitchell, 2005) on the basis of the following relationships. 1) There are straightforward crosscutting relationships along the contacts of the intrusion. Where not silicified, the wall rocks have been extensively fenitized[14] (Figure 10B). Where the wall rocks are quartz rich (Figure 10A), they are less fenitized. 2) There are copious rounded to subrounded, partially digested xenoliths of country rock in the calcite matrix, some of which contain a relict foliation (Figure 10C). The carbonatite is dominated by calcite (Figure 10D) and effervesces vigourously when weak hydrochloric acid is applied. Other prominent minerals are partly resorbed phenocrysts of clinopyroxene (likely aegirine-augite based on extinction angles; Figure 10D). An as of yet unidentified brown mineral (under plane-polarized light) is also prominent in thin section. Partly resorbed xenoliths also contain aegirine-augite. On the basis of relationships in thin section, sporadic, anhedral quartz in the carbonatite was likely derived from digestion of the xenoliths that carried it.

Although a carbonatite occurrence is noted in Saskatchewan at Nissikatch Lake (Woolley and Kjarsgaard, 2008), this occurrence is based on the inference that the rare earth element–bearing phases in the mineral deposits there (Saskatchewan Mineral Deposits Index numbers 1610, 1611 and 1612) were derived from a carbonatitic source (Pandur *et al.*, 2016); no actual carbonatite has been identified. Therefore, this rock represents the only known carbonatite occurrence in Saskatchewan.

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[14] Fenitization is an alkalic alteration process commonly associated with the emplacement of alkaline igneous rocks, such as carbonatites (Zharikov et al., 2007). Fenites are composed mainly of K-Na-feldspars, albite, nepheline, alkaline pyroxenes and alkaline amphiboles.

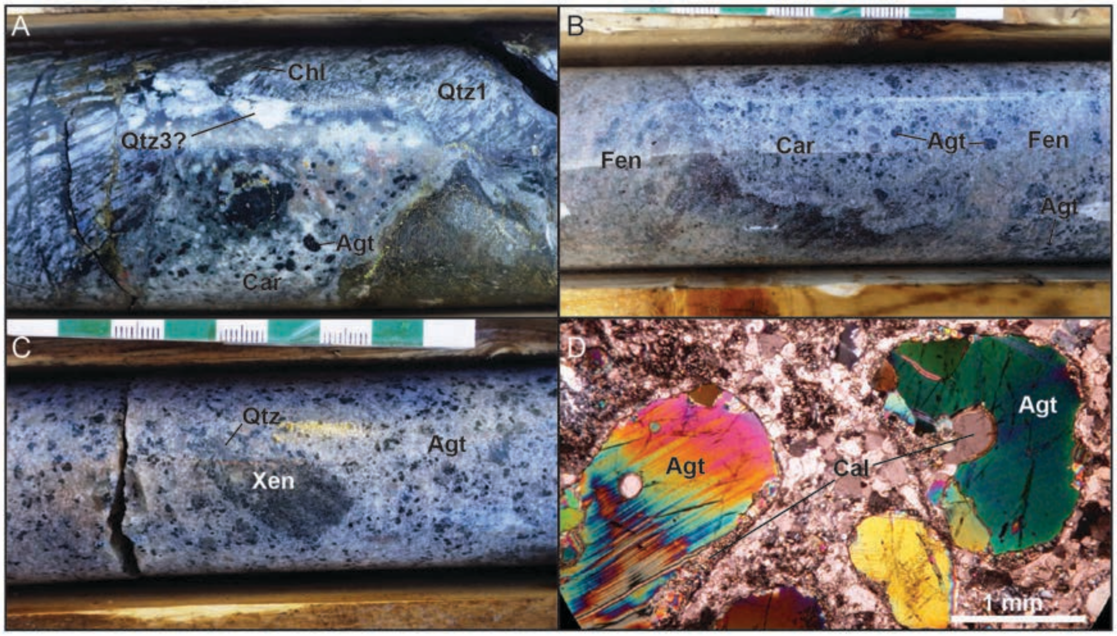

*Figure 10 – A) Silicified and chloritized (Chl) mafic to ultramafic rock. High strain in the rock postdates blue-quartz silicification (Qtz1). The highly strained rocks were crosscut by white quartz (Qtz3) before being intruded by carbonatite (Car) with aegirine-augite phenocrysts (Agt) (core diameter is 4.67 cm; HK-15-29, 297.6 m). B) Aegirine-augite–phyric (Agt) carbonatite (Car) intruding a country rock with a poorly preserved foliation. The country rock has been strongly fenitized (Fen) (HK-15-29, 354.4 m). C) Xenolith (Xen) of weakly foliated country rock in aegirine-augite–phyric (Agt) carbonatite. Quartz (Qtz) in this rock is likely a remnant of digested xenoliths of country rock (*i.e.*, xenocrysts) (HK-15-29, 363.4 m). D) Photomicrograph of carbonatite dominated by calcite (Cal) with extreme interference colours. Both of the large aegirine-augite phenocrysts (Agt) in this image were partly rounded in the carbonate magma and partly replaced. The phenocryst on the right is clearly embayed by calcite. Dark patches likely represent fenitized xenoliths (cross-polarized light; HK-15-29, 397.7 m).*

4. Discussion

Observations from uranium-associated host rocks underlying the western Athabasca Basin contradict the notion that metasedimentary rocks in the basement are a primary control on uranium mineralization sites in unconformity-related uranium deposits (*e.g.*, Hoeve and Sibbald, 1978; Jefferson *et al.*, 2007). In this respect, the pervasively metasomatized mafic to ultramafic rocks and quartz monzodioritic/quartz dioritic orthogneisses that host uranium mineralization in the region suggest that postmetamorphic metasomatic events along reactivated shear zones might be more important. In this region, early albitization of the quartz monzodioritic/quartz dioritic orthogneisses (Figures 5 and 11) is suspected, as is an early chlorite-sericite event that appears to have affected all rock types (Figures 4F, 6A and 11). Those events were followed by at least two pervasive quartz-flooding events (Figures 2B, 7, 11 and 12A). The progressive silicification process led to the formation of biotite-, garnet- and sillimanite-bearing pseudopelites due to pervasive metasomatism and replacement by quartz in both major host rock types. The silicification events provided competency contrasts between the chloritized host rocks and secondary quartz that were utilized during later deformation events. Deposition of graphite and iron-sulphides from C-O-H+S fluids followed during brittle–ductile deformation in the silicified host rocks (Figures 2C, 9, 11 and 12A). Uraniferous fluids later reused these brittle–ductile structural zones during the mineralizing process (Figure 12B). It is apparent from the plethora of alteration phases present that long-term ground preparation due to hydrothermal alteration in reactivated shear zones is a far more fundamental factor in the uranium ore system than the original composition of the basement host rocks.

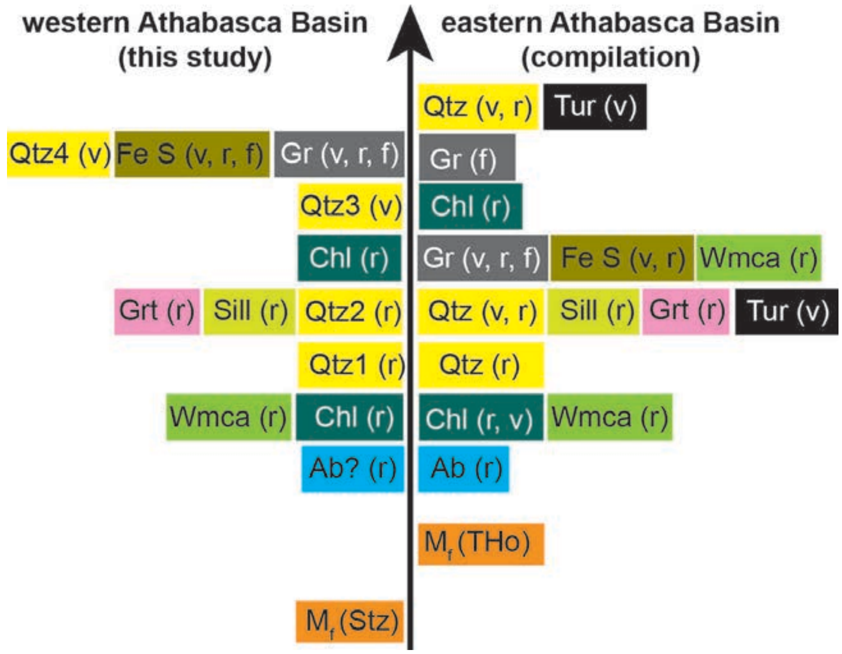

Figure 11 – Comparison of the alteration facies in the western (this study) and eastern Athabasca Basin (Card, 2012b, 2013, 2015; Fetter, 2011) documented during field and petrographic studies by this and other authors. The mineral phases and their relative ages are similar. The long arrow separating the western and eastern assemblages represents the Snowbird tectonic zone (Stz) and mineral phases decrease in relative age in the direction of the arrow. Mineral abbreviations: Ab = albite; Chl = chlorite; Fe S = iron sulphides; Gr = graphite; Grt = garnet; Qtz = quartz; Sill = sillimanite; Tur = tourmaline; Wmca = white mica. Other abbreviations: THo = Trans-Hudson Orogen; f = fracture hosted; M_f = final major metamorphic episode; r = replacement; v = vein.

It is reasonable to make a comparison between the geological controls in this area of the Athabasca Basin and those in the east, where the model for unconformity-related uranium was born (Hoeve and Sibbald, 1978). The host rocks are clearly different, residing on different sides of the Snowbird tectonic zone (Figure 1) across which there is a fundamental geological change (*e.g.*, Card, 2016). In the east, the southern Hearne Province comprises two principal rock units: Archean, felsic orthogneisses; and an overlying Paleoproterozoic metasedimentary succession, the Wollaston Supergroup. Past models (*e.g.*, Hoeve and Sibbald, 1978) have advocated that graphitic rocks in fault zones were derived from reworking the high-grade graphitic pelites of the Wollaston Supergroup. In recent years, however, the accuracy of the interpretation of a metasedimentary origin for the host rocks to uranium mineralization in the eastern Athabasca Basin has been called into question (Card, 2012b, 2013, 2015). Rather, it has been proposed that many of the rocks interpreted as metasedimentary rocks were dominated by metasomatic mineral assemblages. Rocks in reactivated shear zones are strongly chloritized (Card, 2015) and the rocks have been subjected to widespread and pervasive early silicification (Card, 2013). In addition, albitites are well known to be present in the east, including those associated with the Rabbit Lake deposit (Hoeve and Sibbald, 1978; Fetter, 2011). The dominant mineral assemblages in these altered basement host rocks of the eastern Athabasca Basin (*e.g.*, Card, 2015) are entirely comparable to those in the pseudopelites described above and, most importantly, no two minerals are in equilibrium in either locality. The identification of pseudopelites is complicated in the east, however, by the presence of actual metamorphosed pelites of the Wollaston Supergroup, which contain similar mineral assemblages. Hydrothermal graphite postdates these alteration facies (Card, 2012b, 2013). The similarity between the metasomatic facies that grew during ground preparation in reactivated shear zones in the eastern and western Athabasca Basin is remarkable and, perhaps, not coincidental (Figure 11). Therefore, it is reasonable to suspect that similar pre-ore geological processes (*i.e.*, ground preparation) were active across the Athabasca region.

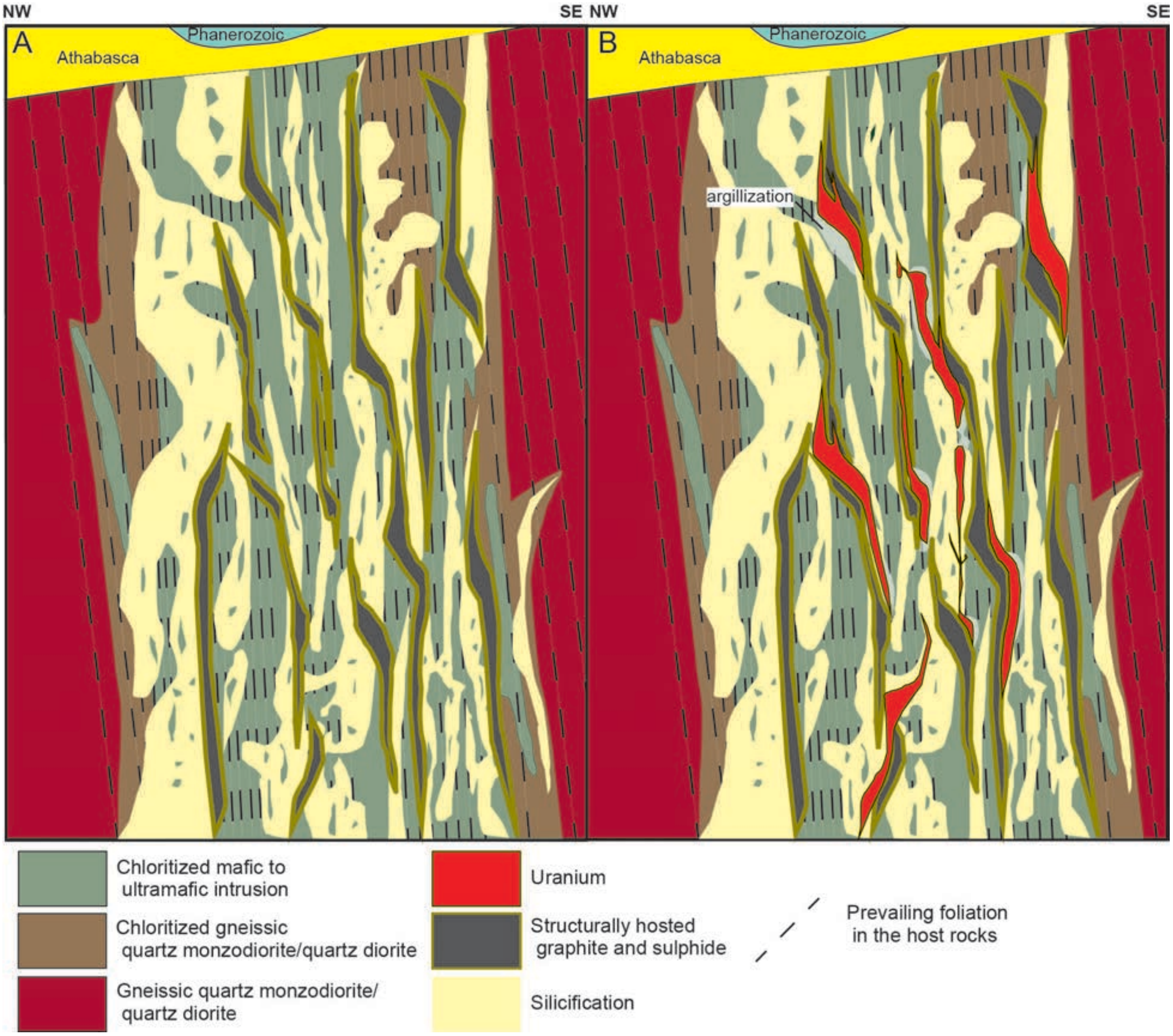

Figure 12 – Cartoon cross-sections across the mineralized trend in the Patterson Lake south area (see Figure 2) looking northeast. A) The pre-ore alteration status of the host mafic to ultramafic rocks after chloritization, silicification and emplacement of hydrothermal graphite and iron-sulphide. B) The host rocks after uranium mineralization. Argillization overprinted the chloritized host rocks. The uraniferous fluids likely used the same structural discontinuities as the C-O-H+S fluids that deposited graphite and iron-sulphides.

The discovery of a magmatic carbonatite in this region is both exciting and interesting given that the western Athabasca Basin is now being actively explored for kimberlites (Mahmoodi, 2016). Carbonatites are known to be associated with kimberlites (Mitchell, 2005). More importantly, the carbonatite dyke demonstrates deep structural control in the Patterson Lake area. Considering that the uranium deposits there are hosted by an apparently layered, premetamorphic mafic to ultramafic intrusive complex, deep crustal conduits must have been present before the *ca.* 1.99 to 1.93 Ga Taltson orogeny. These conduits have been used periodically since the emplacement of the mafic to ultramafic complex, facilitating major metasomatic events, uranium mineralization and emplacement of the carbonatite dyke.

5. Conclusions

The following major conclusions can be drawn from this work:

- Unconformity-related uranium deposits in the Patterson Lake area of the western Athabasca Basin are hosted by altered mafic to ultramafic intrusive rocks and orthogneisses with quartz monzodioritic to quartz dioritic protoliths, demonstrating that metasedimentary rocks are not essential to the uranium ore system. However, this does not preclude metasedimentary rocks, or other rock types, from being potential host rocks.
- Rocks in the uranium exploration corridors were strongly altered after regional peak metamorphism. An early phase of albitization is suspected and early chloritization and sericitization is prominent. At least two subsequent phases of pervasive quartz flooding were followed by two more phases of vein quartz.
- The competency contrast between chloritized (and albitized?) rock and silicification zones focused younger brittle–ductile structures, and hydrothermal graphite and iron-sulphide was precipitated in these structures. Uranium mineralizing fluids likely reused these pathways.
- The pre-uranium alteration facies in the western Athabasca Basin are similar in both composition and relative age to those in the eastern Athabasca Basin.
- A calcite carbonatite was identified in the Patterson Lake structural corridor. The massive, postmetamorphic dyke helps to demonstrate the propensity for deep-seated events along the Patterson Lake corridor.

6. Acknowledgments

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