The paragenesis and chemistry of alteration associated with the P2 fault in metamorphic rocks underlying the Athabasca Basin

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Introduction

The P2 Fault (Figure 1), a subtle net-reverse structure offsetting the basal unconformity of the Athabasca Basin, Saskatchewan, hosts McArthur River, the world's largest high-grade uranium deposit. This deposit is classified as unconformity-type because it is located at the unconformity (~500 m depth) between the Athabasca sandstone and the underlying metamorphic (basement) rocks. The P2 Fault is constrained to graphite-bearing paragneiss of the basement but is splayed and refracted into the overlying sandstone. Paleoproterozoic basement rocks of the Wollaston Supergroup vary in composition and record a long history before deposition of the Athabasca Group: deposition on a trailing margin then foreland molasse, fold and thrust tectonics, upper-amphibolite metamorphism, retrograde metamorphism and paleo-weathering. During and after deposition of the Athabasca Group, multiple diagenetic and low-temperature hydrothermal fluids extensively altered both the Group and tectonically brecciated basement, particularly along intersecting faults that preferentially host ore pods: ~050° P2 and Vertical Quartzite (VQ), and ~140° cross faults.

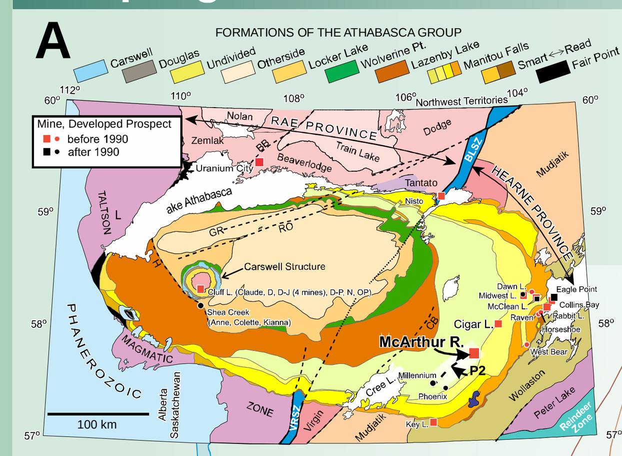
Objectives

I) To identify the mineralogy of the basement rocks during each geologic event.

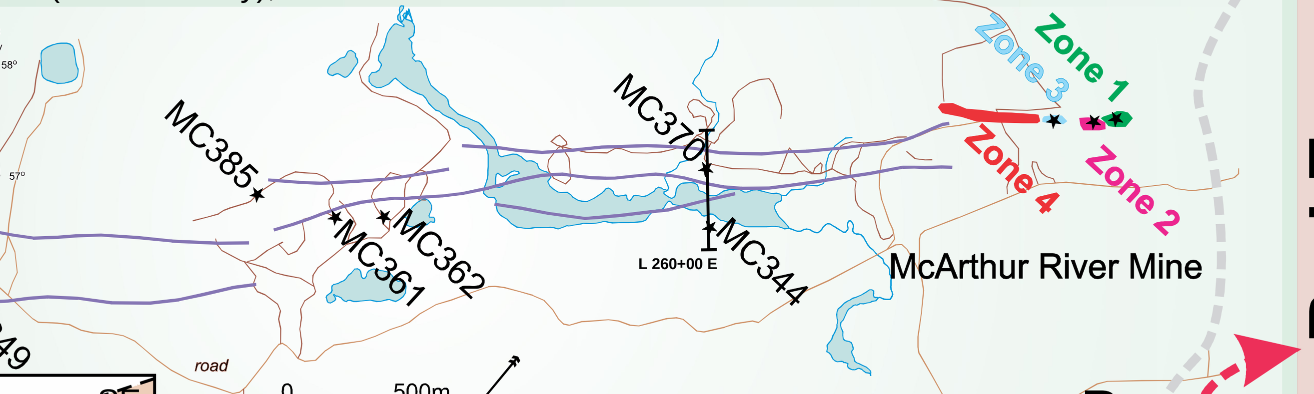
II) To establish the paragenetic sequence of alteration minerals associated with the P2 and VQ faults.

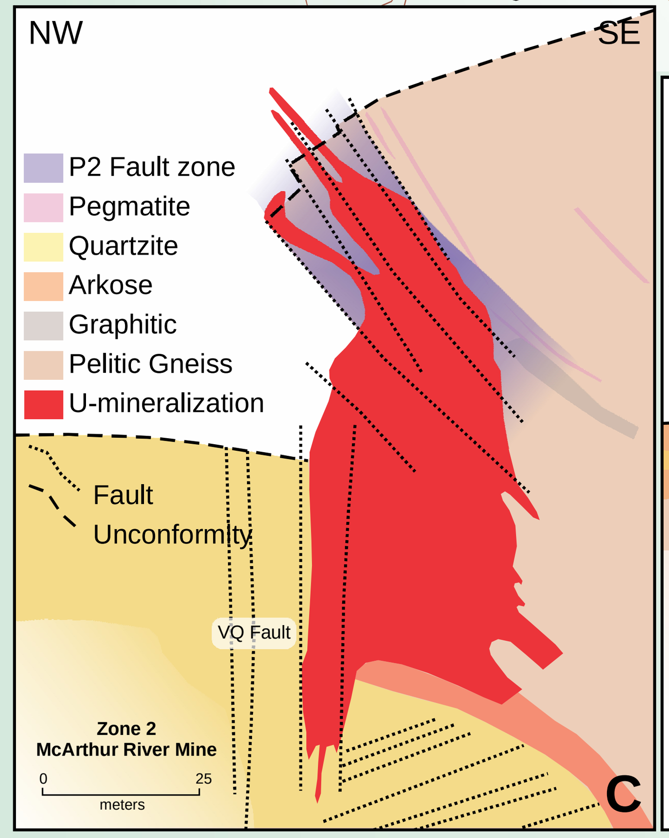
III) To characterize alteration mineral chemistry within the basement expression of the P2 Fault proximal to: i) pods of ore-grade pitchblende at the McArthur River deposit, ii) uranium minerals perched within the overlying sandstone (P2 Main deposit), iii) sub-economic grade disseminated pitchblende, iv) non-mineralized rock and v) the VQ fault.

Sampling



This project was initiated with field work in August, 2012, including the examination of rock samples from the McArthur River underground mine and drill-cores. We sampled two barren drill-holes that did not intersect the P2 Fault (MC-344 and -385), two barren holes that did intersect the P2 Fault (MC-361 and -362), and two weakly mineralized holes that intersect the P2 Fault outside of the mine area (MC-370 and -349). Twelve drill-holes from the McArthur River mine were also sampled: two from Zone 1, nine from Zone 2 (main ore body), and one from Zone 3.





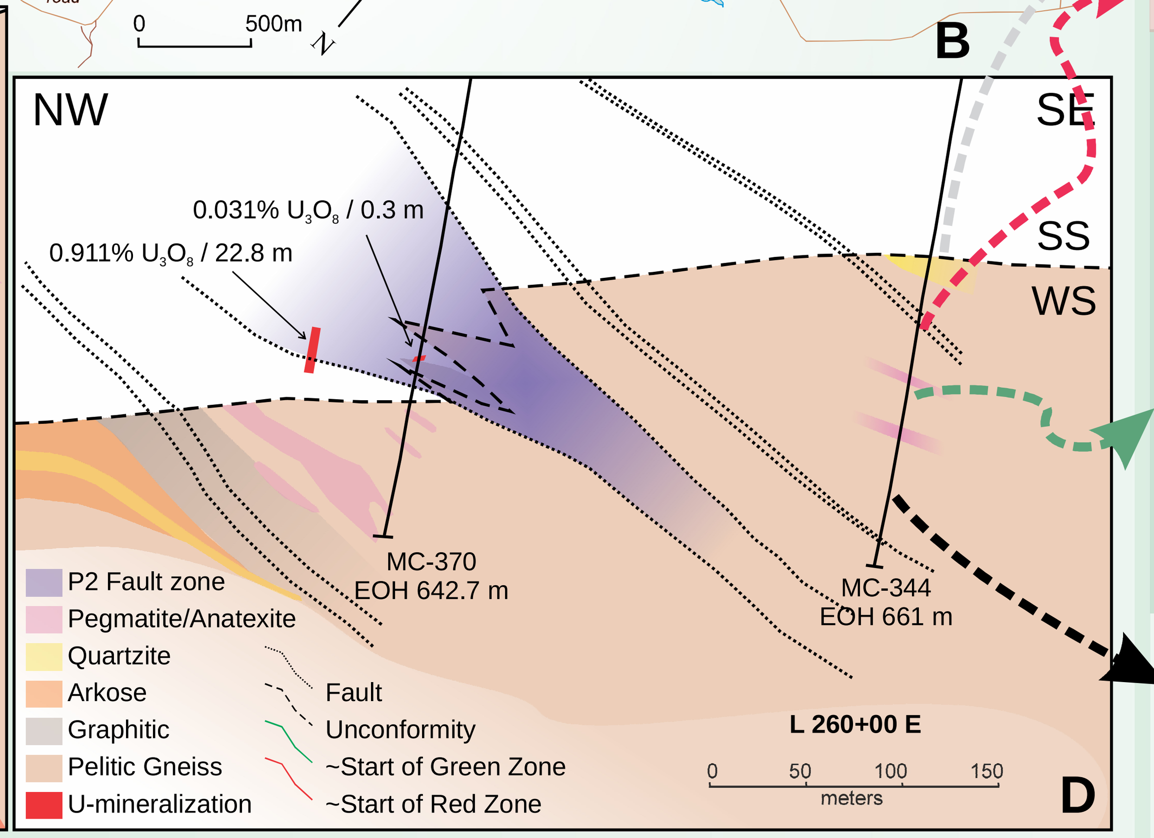


Figure 1: A) Map of the Athabasca Basin showing the locations of high-grade uranium deposits and major structural features, including the reverse P2 Fault (highlighted in white) (adapted from Jefferson et al., 2007). **B)** Plan-view map showing the surface expression of the P2 Fault in purple, access roads in brown, collars of diamond drill holes sampled for this study, and the McArthur River mine site. **C)** Typical cross section of Zone 2 from McArthur River Mine. **D)** Cross section of exploration line 260+00 E shows sampled drill holes MC-370 and MC-344 in geological context. Cross-sections are adapted from the Cameco McArthur River Operation Technical Report (2012)

Methodology

Thin section petrography

-This poster presents results for non-mineralized background holes MC370 and MC385 (do not cross-cut P2), sub-economic mineralized drill-hole MC370, MC349 (cuts P2 zone), and mineralized drill-holes H729 (Zone 1) & H201 (Zone 2). (Sections were examined in plane-polarized (PPL), cross-polarized (XPL) and reflected light (RL))

Terraspec short-wave infrared spectroscopy (SWIR)

Scanning electron microscopy

-Quantitative electron dispersive spectra (EDS) and back scatter electron imaging (BSE) to help identify metamorphic and alteration minerals in thin section.

Electron Microprobe Analyser

-Quantitative wavelength spectrometry to determine mineral chemistry of important alteration phases

Alteration preceding mineralization

Below the unconformity (200-300 m), the laterally extensive vertical alteration profile comprises a lower Green Zone (GZ) through a Red Zone (RZ) to a Bleached Zone (BZ) that overprints the Red Zone and straddles the unconformity. The rocks below the Green Zone are the Least Altered (LA).

Bleached Zone

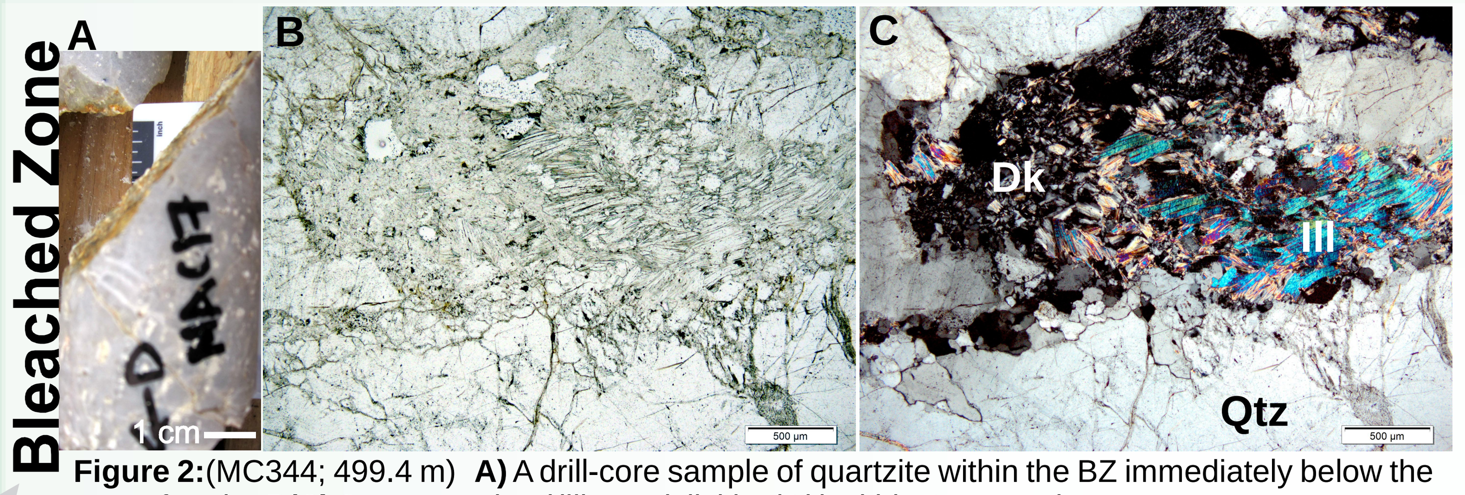
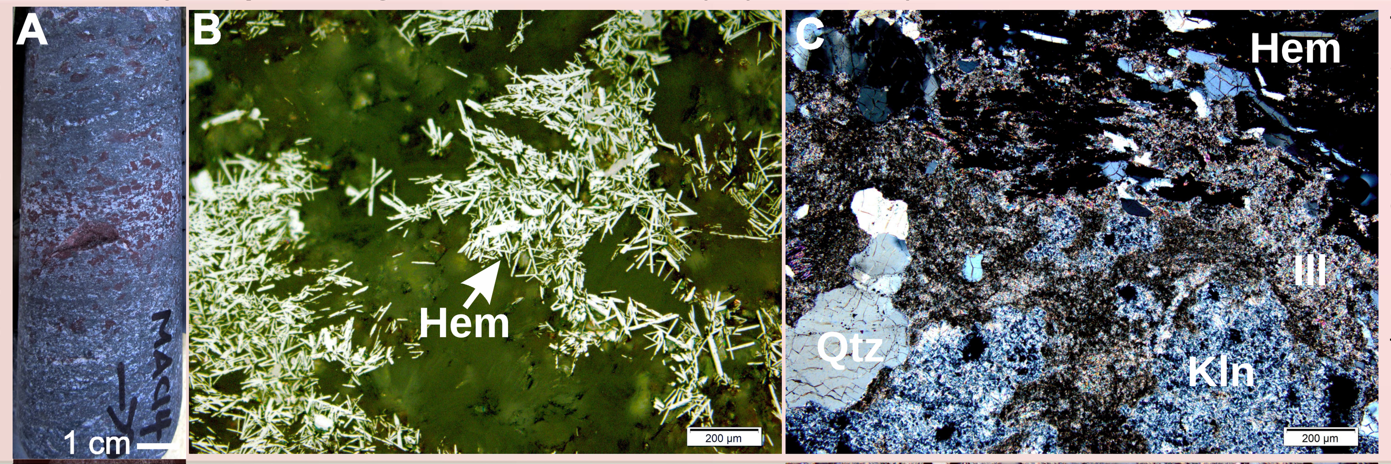


Figure 2:(MC344; 499.4 m) **A)** A drill-core sample of quartzite within the BZ immediately below the unconformity. **B/C)** Coarse-grained illite and dickite (Dk) within BZ quartzite.

The Bleached Zone consists of fine grained white-yellow clay alteration that overprints the Red Zone along the unconformity and extends up into the basal Athabasca Group. The BZ alteration is dominated by fine-grained kaolinite-group minerals and two generations of illite: early, fine-grained illite and late, coarse-grained illite $[(K_{0.9})(Al_{1.8}Mg_{0.1}Fe_{0.1})(Si_{3.2}Al_{0.8}O_{10})(F_{0.02}[OH]_{1.98})]$. SWIR spectral analyses of BZ samples (and some RZ samples) suggests the pseudomorphic replacement of kaolinite by dickite. Coarse-grained illite also occurs in high concentration within the P2 fault and sporadically within the RZ. BSE-imaging shows that illite locally forms mixed layers with kaolin. The BZ was developed after deposition of the lower Athabasca Group by interaction with a K-bearing diagenetic fluid that permeated the basement rocks and propagated along the P2.

Red Zone



The Red Zone developed during the paleo-weathering of the basement and is distinguished from the Green Zone by the presence of hematitized Fe-bearing minerals and of kaolinite (identified by SWIR analysis). The removal of K during paleo-weathering may have also resulted in the illite alteration (K addition) observed within chlorite altered garnet + cordierite of the GZ and least altered rocks.

Figure 3: A) A drill-core sample of metapelite (MC344; 520.4 m) from the RZ illustrates hematite that overprinted the GZ. **B)** Photomicrograph (RL) of hematite needles in the RZ; sample is of basement pegmatite from MC385 at 678.8 m. **C)** Photomicrograph (XPL) shows fine-grained illite replaced by hematite and kaolinite within basement pegmatite (MC385; 678.8 m).

Green Zone

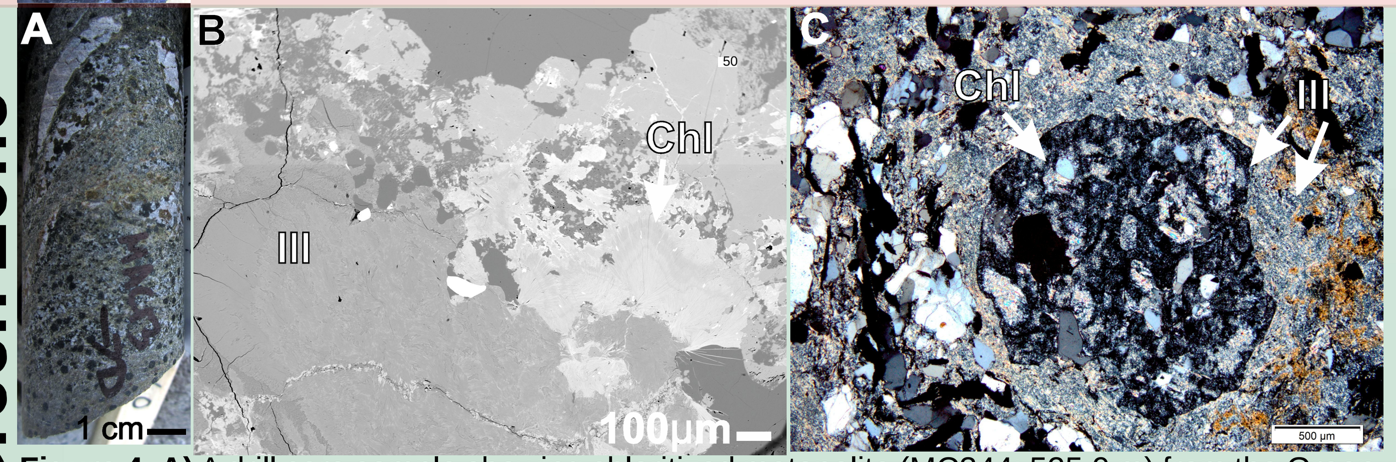


Figure 4: A) A drill core sample showing chloritized metapelite (MC344; 525.9 m) from the Green Zone. **B)** A BSE-image showing radial chlorite and fine grain illite (MC344; 628.2). **C)** A photomicrograph (XPL) showing chloritized garnet and fine grain illite (Ill). Notably, the chloritized garnet is also being replaced by illite.

The GZ was produced by weathering and distal hydrothermal alteration. It consists of coarse-grained radial chlorite aggregates (>100 µm), some of which completely replaced garnet + biotite. Feldspar is replaced by fine-grained illite $[(K_{0.74}Na_{0.02}[H_3O]_{0.24})(Mg_{0.19}Fe_{0.11}Al_{1.23})(Al_{1.09}Si_{2.91}O_{10})(F_{0.02}[OH]_{1.98}[H_2O])]$.

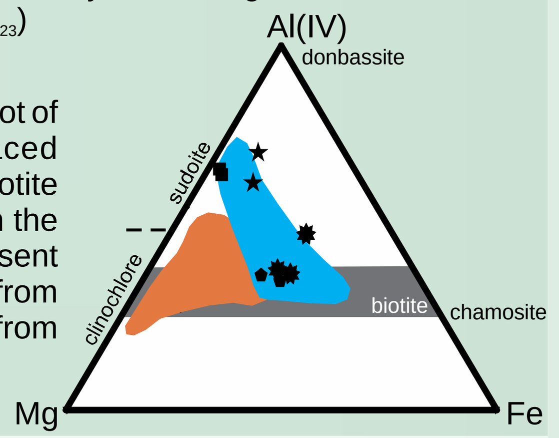
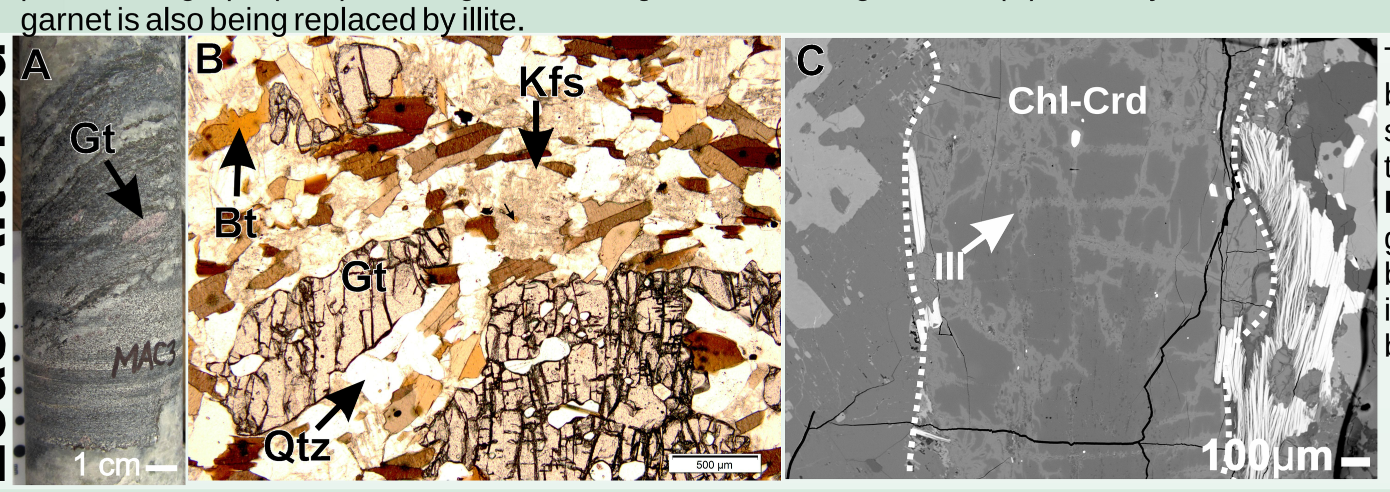


Figure 5>: Ternary Al-Fe-Mg plot of chlorite species that replaced garnet (■), cordierite (★) and biotite (⬟) with radial chlorite (✹) from the GZ (this study). The fields represent chlorite in basement rocks from McArthur River & Millennium from Alexandre et. al (2012).

Least Altered



The LA basement rocks are well below the unconformity, characterized by pink garnet, fresh to slightly chloritized biotite, chloritized cordierite, slightly illitized K-feldspar, and quartz. The LA rocks gradationally transition into the overlying GZ.

Figure 6: (MC-344; 651.5 m) **A)** Drill-core sample of relatively unaltered gneiss. **B)** Photomicrograph (PPL) of gneiss composed of garnet (Gt), biotite (Bt), slightly illitized K-feldspar (Kfs) and quartz (Qtz). **C)** BSE-image of chloritized cordierite (Chl-Crd). Illite located at grain boundaries and fractures is interpreted as evidence of K addition.

Alteration mineralogy along the P2 Fault

The P2 Fault zone underwent intense hydrothermal alteration, particularly below the Zone 2 ore body at McArthur River Mine. Two generations of tourmaline are consistent along the P2 Fault: early, euhedral to subhedral, coarse-grained (up to 0.5 mm), zoned, dravite (Mg-tourmaline) in 1-2 cm wide veins, and later, fine-grained (<0.2 mm) magnesiofoitite $[(\square_{0.75}K_{0.08}Na_{0.17})(\square_{0.23}Ca_{0.02}Fe_{0.04}Mg_{2.10}Al_{0.61})Al_6(Al_{0.22}Si_{5.78}O_{18})(BO_3)_3(F_{0.02}OH_{3.98})]$ as radial aggregates in thin veinlets (< 2 mm), as overgrowths on earlier tourmaline, and disseminated within fine-grained illite. Therefore a B-bearing fluid was introduced during hydrothermal activity along the P2 Fault. Discrete alteration minerals (hematite, chlorite, illite) occupy fractures and post-date tourmaline within the P2 Fault .

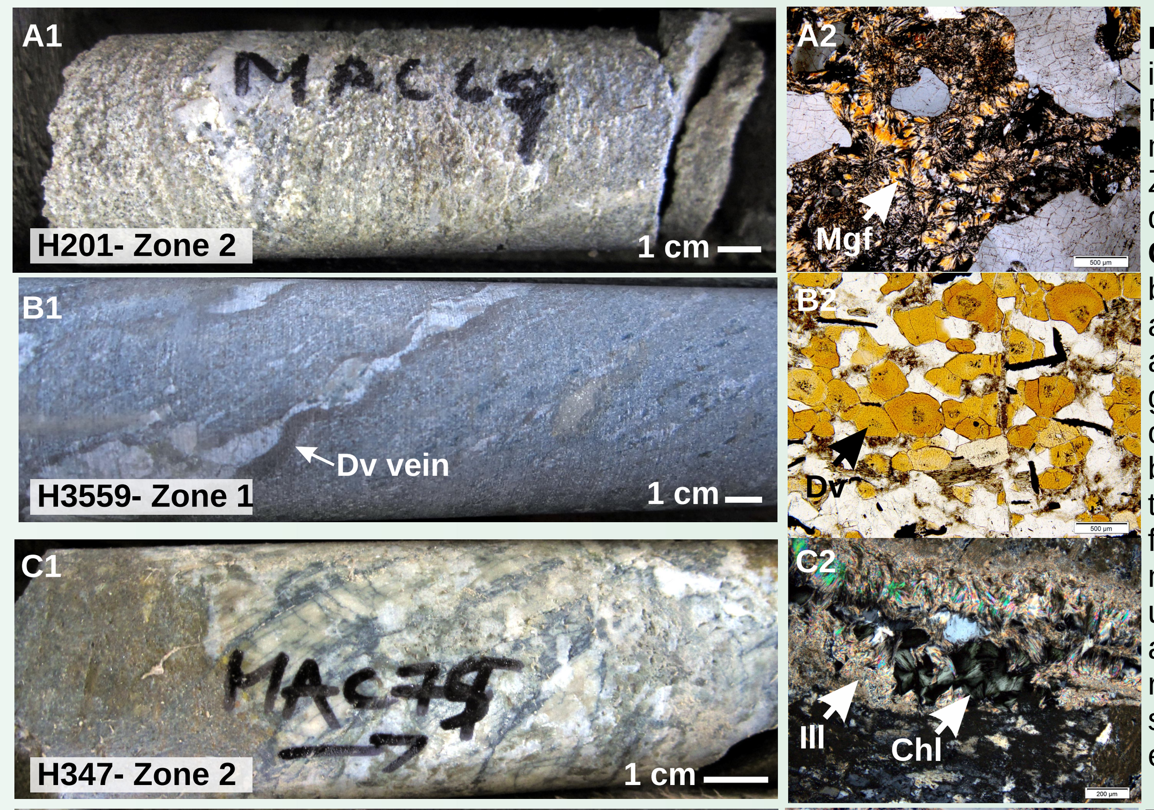
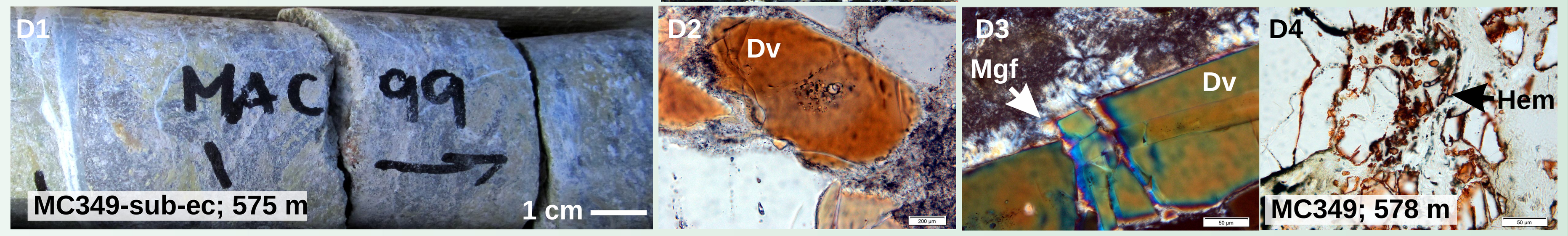


Figure 7: Drill core and photomicrographs illustrating mineralogy and textures within the P2 Fault zone: **A1&2.** Pervasive, radial, magnesiofoitite (Mgf) alteration adjacent to the Zone 2 ore body. **B1&2.** Veins of early, euhedral dravite (Dv) in graphitic metapelite from Zone 1. **C1&2.** Pegmatite adjacent to the Zone 2 ore body brecciated by vein assemblages of radial chlorite and illite that cross-cut early magnesiofoitite alteration.**D1/2/3)** metapelite proximal to low-grade uraninite mineralization (e.g 4.48 $\%U_3O_8$ over 0.5 m and 0.448% U_3O_8 over 45 m) that is brecciated by two generations of tourmaline. Early tourmaline is zoned and hosts an array of primary fluid inclusions within its core (D2), whereas later magnesiofoitite is fine grained and nucleated upon the earlier generation (D3). **D4)** hematite-altered metapelite. **Not shown:** Hematite and rutile also overprint early tourmaline within the same sample, and chlorite has partly replaced early tourmaline within the same drill core.



Paragenesis summary & on-going work

Metamorphism

Least-altered
- Prograde, upper amphibolite facies
- Gneiss (garnet-biotite, cordierite), pegmatite & quartzite
- Chloritization of cordierite
- llitization of feldspar

Uplift & erosion

Paleo-weathering

"Green Zone"
- Chloritization of mafic minerals (biotite, cordierite & garnet)
- Illitization of feldspar
- Introduction of K

"Red Zone"
- Formation of regolith through weathering
- Hematization & kaolinization

Deposition of the Athabasca Grou

Diagenesis

"Bleached Zone"
- White clay overprints Red Zone along unconformity
- Illite & dickite formation by K-bearing diagenetic fluids.

Alteration specific to P2

1. Early tourmaline
2. Magnesiofoitite
3. Latest pre-ore events:
   - Pervasive hematite
   - Chlorite and illite veinlets

? Uranium mineralization

On-going work:

Mineral chemistry and crystal structures of individual alteration phases

XRD of mixed clay samples

Trace element analyses (LA-ICPMS) of tourmaline and illite.

B-Isotopes of tourmaline (SIMS)

Chracterization of Fe-oxides

Quantification of ferric Fe in chlorite and illite

Acknowledgments & references

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