Rachel Anne Boulanger, candidate for the degree of Master of Science in Geology, has presented a thesis titled, *Geological, Petrographic and Geochemical Characterization of the Roughrider West Zone Unconformity-type Uranium Deposit, Athabasca Basin, Saskatchewan*, in an oral examination held on May 16, 2012. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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Abstract

The Roughrider unconformity-type uranium deposit is located in northeastern Athabasca Basin, Saskatchewan, and currently comprises 3 mineralized zones: the West Zone, East Zone, and Far East Zone. This study, focused on the West Zone (RWZ), comprises petrographic, paragenetic, and geochemical studies, and aims to document both the mineralization and alteration, and to construct a model for the genesis of the deposit, which may assist in future exploration in the Athabasca Basin.

The RWZ is dominantly hosted in the deformed basement rocks (Wollaston Group paragneisses and Archean orthogneisses) underneath the Paleoproterozoic Athabasca Group siliciclastics. Despite being predominantly basement-hosted, it exhibits some signatures, such as extensive clay alteration and the presence of base metals that are akin to sandstone-hosted unconformity-type uranium deposits. Spatial analysis of the clay alteration pattern indicates an illite-dominant pervasive alteration halo that extends vertically to surface, laterally for up to 50 metres surrounding the deposit, and reaches 200 metres into the basement below the unconformity. Conversely, strong chlorite alteration occurs only proximal to mineralization.

Detailed petrographic analysis of approximately 100 polished thin sections in reflected and transmitted light, and selective electron microscopy and electron microprobe studies were used to document host rock, ore, and alteration mineralogy, and unravel the paragenetic history. Results indicate that RWZ comprises at least six phases of uranium mineralization (U1 to U6) with local
enrichment of base metals including Cu, Ni, Co and Zn. Two episodes of
uraninite mineralization (U1 & U2) are interpreted to represent the primary
mineralization event, whereas the other four uraninite phases (U3 – U6)
represent remobilization of the primary ore. U1 predates most base metal-
bearing sulphides, although some copper sulphides may predate primary
uranium mineralization. Fluid-rock interactions between oxidizing basinal fluids
and basement rocks (especially graphite and ferrous iron-bearing minerals)
before and throughout uranium mineralization were mainly responsible for
precipitation and remobilization of uraninite.

U/Pb isotopic geochronology yields an upper intercept age of 1,188±52
Ma for U1 uraninite, and 262±24 Ma for U4 and U5 uraninite, whereas the
chemical ages of U1 to U5 range from ca. 1,482 to ca. 35 Ma. The young ages
reflect lead loss and the ability of the system to mobilize and re-precipitate
uraninite after the primary mineralization over a period of 900 Ma.

The conceptual fluid flow model suggests that basinal fluids infiltrated the
basement to the west of RWZ, flowed eastward and upward in the basement,
channelled along networks of fractures, and expelled back into the basin. This
overall upward fluid flow model explains the extensive development of alteration
in the sandstones above the sites of mineralization, and it does not exclude the
possibility that downward flow took place after the main phase of mineralization,
causing uranium remobilization.
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1. INTRODUCTION

Increased awareness and concern regarding carbon emissions and pollution, coupled with uncertainty respecting limited petroleum supplies and their safe transportation has enforced an interest in greener energy sources, such as nuclear fuels. Uranium has been established as a useful resource for creating clean energy with a carbon footprint that is comparable to wind or solar power (Canadian Nuclear Association, 2011). Unconformity-type uranium deposits in the Proterozoic Athabasca Basin are unrivalled as the highest grade uranium deposits found to date in the world (Kyser & Cuney, 2008), constituting approximately 22% of total current global production in 2008 (Saskatchewan Mining Association, 2011). As such, the Athabasca Basin has been an excellent uranium exploration target for over 50 years. The Roughrider uranium deposit, located in the northeastern margin of the Athabasca Basin, represents one of the newest discoveries in the basin. Its geological and geochemical characteristics have never been systematically documented, which constitute the main subject of this thesis.

1.1 Previous Work on Uranium Deposits in the Athabasca Basin

Northern Saskatchewan is host to numerous high grade uranium deposits. The first uranium showing, in the form of pitchblende, was discovered in 1935 at Nicholson Bay, north of the Athabasca Basin, on the northern shore of Lake Athabasca in the Beaverlodge Domain (Trueman, 2006). The federal government of Canada incorporated Eldorado Mining and Refining Ltd. in 1943, which staked...
mineral claims and advanced exploration in the Beaverlodge area in 1944. In 1946, Einar Larum and Philip St. Louis found the first uranium deposit, the Ace deposit, north of Beaverlodge Lake (Trueman, 2006), and production began in 1953 at the Beaverlodge Mine and Mill (Mahon & Remy, 2001). The discovery of the first unconformity-type uranium deposit – Rabbit Lake – by Gulf Minerals Ltd. in 1968 (Sibbald, 1985) shifted the focus of exploration to the eastern side of the Athabasca Basin. Whereas the uranium deposits in the Beaverlodge area are hosted in Archean to Paleoproterozoic rocks exposed at the surface, those in the western and eastern Athabasca Basin occur near the unconformity between the Paleoproterozoic to Archean basement rocks and the Athabasca Basin, and thus were named unconformity-type (Sibbald, 1977). Since that time, numerous other unconformity-type uranium deposits have been discovered, including, but not limited to, Collins Bay (1971), Key Lake (1975), Midwest (1978), Eagle Point (1980), McLean Lake (1980), Cigar Lake (1981), McArthur River (1988), Millennium (2002; Jefferson et al., 2007), and the Roughrider deposit in 2008 by Hathor Exploration Limited (Hathor).

Since the discovery of the Rabbit Lake deposit, the nature and metallogenesis of this deposit type has been studied at length (e.g. Pagel, 1975; Hoeve & Sibbald 1978; Hoeve et al., 1980; Sibbald, 1985; Fayek & Kyser 1993; Kotzer & Kyser, 1995; Quirt, 1999; Portella & Annesley, 2000; Fayek et al., 2002; Lorilleux et al., 2003; Jefferson & Delaney, 2007, and references therein; Alexandre et al., 2009; Mercardier et al., 2010; Bosman et al., 2011; Cloutier et al., 2011). Additionally, extensive research over the last 50 years has been
devoted to the regional geology, stratigraphy, and structural history of the Athabasca Basin and underlying basement rocks. Extensive mapping around the Athabasca Basin was initially undertaken in the early 1900’s by the Canadian Geological Survey. Since the 1960’s, various branches of the Government of Saskatchewan have conducted several multi-disciplinary geoscientific studies to refine these early works, the most recent of which was the EXTECH IV study, a joint product of the Federal and Provincial Geological Surveys in conjunction with various industry and investment partners (Jefferson & Delaney, 2007, and references therein).

Updated aeromagnetic geophysical surveys of the eastern and southern Athabasca Basin and Cree Lake area were initiated in 2007 in a partnership between the Geological Survey of Canada (GSC) and the Saskatchewan Ministry of Energy and Resources (SMER) (Buckle et al., 2008). These data, compiled with regridded historic gravity data, were subsequently enhanced using a variety of analytical techniques to better delineate structural trends and magnetic and gravity anomalies (Card et al., 2010). In addition, a basin-wide analysis of background geochemical signatures and anomalies was completed in 2011 by SMER (Card et al., 2011). This data is in the process of being integrated in SMER’s Athabasca Basin Ore-systems Project, initiated in 2011, that is designed to study and better understand ore systems in Saskatchewan by presenting the compiled data in three dimensions (Bosman et al., 2011).

Biogeochemical analyses of black spruce trees, lake sediments, and soil, conducted from 1960 – 1975 (Hornbrook, 1974, Dunn, 1975), proved ineffective
for use in uranium exploration as the permeable Athabasca Group sandstones allow for relatively unrestricted basin-wide fluid flow. An updated geophysical and geochemical analysis of the Athabasca Basin and their associations to the uranium deposits is currently underway, as part of a Memorandum of Understanding between the Province of Saskatchewan and the State of South Australia (Card et al., 2010).

At the deposit scale, petrographic work has been conducted to define the alteration minerals associated with mineralization, and determine their paragenetic relationships in many of the unconformity-type uranium deposits. These deposit-scale studies have suggested multiple phases of uranium mineralization, preceded by quartz dissolution or precipitation, and/or argillization of the basement and/or overlying sandstone. Mineralization is accompanied by illite alteration, sometimes with hematite, and is usually followed by local chlorite alteration (Pagel & Rhulmann, 1985; Kotzer & Kyser, 1990, 1995; Fayek & Kyser, 1993, 1997; Derome et al., 2005; Alexandre et al., 2005; Kyser & Cuney, 2008). Some detailed petrographic and geochemical work has been done on the mineralization-associated clay alteration minerals to obtain information on clay paragenesis, temperature of formation, and to explore the potential use of clay minerals as tracers for exploration. These studies have established illite and chlorite as having a close association to uranium mineralization (Quirt, 1986), while dickite/kaolinite appear to be associated with basin diagenesis, and late alteration in the basement. Chlorite has also been established as an early, pre-ore alteration mineral that may have decreased or filled porosity in the basement,
reducing the circulation of mineralizing fluids (Zhang et al., 2001; Cloutier et al., 2009). Limited clay crystallinity and geothermometry studies indicate syn-ore clay crystallization temperatures of 140°C - 230°C (Kotzer & Kyser, 1995; Quirt, 1999; Alexandre et al., 2009). Stable isotope studies were used to characterize the fluids associated with mineralization and determine their sources (Kotzer & Kyser, 1995; Fayek & Kyser, 1993, 1997; Quirt, 1999; Hiatt et al., 2007; Alexandre et al., 2009, Cloutier et al., 2009). These studies have resulted in several hypotheses regarding the number of fluid sources involved in the mineralization process, including those derived from the basement, the basin, or from both. Fluid inclusion studies have been carried out on several of the Athabasca Basin uranium deposits to characterize the ore-forming fluids, and estimate the original thickness of the Athabasca Group sandstone. These studies have led to the recognition that unconformity-type uranium deposits appear to be associated with up to three different fluid signatures: 1) a NaCl-rich brine; 2) a CaCl₂-rich brine; and 3) a low-salinity NaCl-dominant fluid (Pagel et al., 1975, 1977, 1980; Kotzer & Kyser 1995; Derome et al., 2003, 2005; and Mercadier et al., 2010). Fluid inclusion analysis also supports the formation temperature found in clay mineral studies, and has proposed a minimal basin thickness of 5 Km at the time of mineralization (Derome et al., 2003, 2005). A copious amount of research has attempted to date these deposits using U/Pb isotopes, chemical age dating, or, less commonly, ⁴⁰Ar/³⁹Ar and ⁸⁷Rb/⁸⁶Sr. These works indicate that mineralization occurred between 1,075 and 1,640 Ma, depending on the method used, with numerous remobilization events between 2 and 900 Ma (Hoeve &
Sibbald, 1978; Fayek & Kyser, 1993, 1997; Fayek et al., 2002a; Fayek et al., 2002b; Alexandre & Kyser, 2005; Alexandre et al., 2007, 2012; Cloutier et al., 2009). The efforts made by researchers have provided a framework for outlining the key requirements for the formation of unconformity-type uranium deposits and the minerals associated with them, as well as generating and modifying a few theories regarding their genesis. However, unconformity-type uranium deposits remain largely enigmatic in terms of the factors controlling their genesis and the source of uranium and associated base metals (Jefferson et al., 2007).

1.2 Study area

The Midwest NorthEast property is located in the eastern Athabasca Basin of northern Saskatchewan (Figure 1.1). It is situated eight kilometers north of Points North Landing, a service centre at the terminus of provincial Highway 905, approximately 400 km north of La Ronge and approximately 700 km north of Saskatoon. It is within the Northern Mining District, on 1:50,000 NTS sheet 74-I-08 and 64-L-05. The property comprises three mineral leases (ML-5544, ML-5546, and ML-5545) with a maximum north-south dimension of 2.5 kilometres, and a maximum east-west dimension of 3.0 kilometres (Figure 1.2). The project adjoins the northeastern boundary of AREVA’s mining lease ML 5264 and as such is 4.7 km northeast of AREVA/Denison Mines Corp. planned open pit Midwest uranium mine and 1.8 km northeast of the ‘Midwest A’ deposit (formerly called “Mae Zone”). Immediately west of the Midwest NorthEast mineral lease boundaries is Fission Energy’s sandstone-hosted J-zone uranium mineralization.
Figure 1.1: Regional aeromagnetic map of the Athabasca Basin, northern Saskatchewan, showing regional faults (dashed black lines) and delineating major unconformity-type uranium deposits (Modified from the Geological Survey of Canada, 1987). The insert in the top right corner indicates the location of the Athabasca Basin in Saskatchewan. (original in colour)
Figure 1.2: Plan map of Hathor’s mineral leases (bold black lines), and location of the Roughrider deposit, Midwest deposit, Points North Landing service centre, and the nearest highway (after Elash & M’Cready, 2011; original in colour)
Access to the property is by a winter road or helicopter from Points North Landing. The area consists of 60% jack pine and black spruce forest and 40% lakes, rivers, and swamps, produced by northeast to southwest glacial flow during the Laurentide Glaciation. As currently defined, the Roughrider deposit comprises three mineralized zones: the West, East, and Far East Zones (Figure 1.3). The first of these to be discovered, the Roughrider West Zone (RWZ), is located at approximately 215 m depth under MᶜMahon Lake. The East and Far East Zones are located east along strike of RWZ, under the eastern edge of MᶜMahon Lake and flanking a glacial drumlin, respectively.

1.2.1 The Roughrider property exploration history

1.2.1.1 Previous Companies
The Roughrider property was initially explored from 1969 – 1974 by Numac Oil and Gas (Numac), which held the mineral lease permit that encompassed the Dawn Lake and Midwest area (Figure 1.2; Forgeron, 1969; Beckett, 1972). As such, the early history of the Midwest NorthEast property corresponds to that of the Dawn Lake Project’s “Esso North Grid”. The Asamara Oil Corporation initiated the successful Dawn Lake Project in 1976, discovering the Dawn Lake 11, 11A, 11B, and 14 zones by 1978. The Midwest NorthEast property is located approximately six kilometres northwest of these uranium deposits (Keller et al., 2011). Cameco Corporation’s (Cameco) predecessor company, Saskatchewan Mining and Development Corporation (SMDC) obtained operating control of the Dawn Lake Joint Venture Project in 1983 (Keller et al., 2011).
Figure 1.3: Aerial view of three mineralized zones that comprise the Roughrider deposit projected to surface (after Elash & M’Cready, 2011) (Original in colour)
Asamara conducted airborne geophysical surveys to delineate conductive trends proximal to the Midwest NorthEast property in the early 1980’s, and followed up with 21 drill holes west of Hathor’s current claim boundary. These holes were only drilled 25 metres below the unconformity, with some intersecting local structure, alteration, and elevated radioactivity in the sandstone, but no uranium mineralization (Keller et al., 2011). These unfavourable results halted exploration until the mid-1990’s, when Cameco resurveyed the area with TEM, and drilled along a strong east to west conductor and a weak northeast conductor; three of the holes drilled are located within the Midwest NorthEast claim boundary (Keller et al., 2011). Favourable structure, illite alteration, and elevated uranium and lead values were noted in drill core from the sandstone, but follow up work was not conducted (Keller et al., 2011).

1.2.1.2 Hathor Exploration

In 2004, Roughrider Uranium Corp. acquired a 90% interest in a joint venture with Bullion Fund Inc. in one mineral claim (S-107243) and two fractional mineral claims (S-110759 and S-110760) that encompass the current Roughrider deposit area. In 2005, property-wide aeromagnetic geophysical surveys were conducted to determine the sub-Athabasca Basin structural geology and outline graphitic conductive units, which were not detected on the Midwest NorthEast property (Keller et al., 2011). Roughrider Uranium Corp. became a wholly owned subsidiary of Hathor Exploration Ltd. in August, 2006, and in the fall of 2006, Hathor re-logged historic drill core and took clay and lithogeochemical samples. Property scale aeromagnetic EM surveys and three diamond drill holes were
drilled in the winter of 2007. Between 2007 and 2008, Hathor conducted a property-scale gravity survey which identified ten gravities lows, interpreted as sandstone alteration, and enlisted Kinetix Incorporated to conduct a three dimensional seismic reflection survey to identify favourable structures for mineralization (Keller et al., 2011). Property-wide resistivity surveys were undertaken from 2007 – 2009, which were subsequently inverted into three dimensional models to outline sandstone alteration (Keller et al., 2011). These geophysical surveys highlighted resistivity and gravity anomalies that were followed up in the summer 2008 drill program, resulting in the discovery of the West Zone of the Roughrider deposit (Keller et al., 2011). Subsequent drilling delineated the West Zone, as well as discovered and delineated the East Zone in 2009 and the Far East Zone in early 2010. Late 2010 saw completion of a resource estimate for the Roughrider deposit, and initiation of a resource estimate for the East Zone. In 2011, Hathor purchased Terra Ventures Inc., converted their minerals claims into three mineral leases (ML-5544, ML-5546, and ML-5545), and completed a preliminary economic assessment report on the Roughrider property. In late 2011, Hathor was purchased by Rio Tinto at an all-cash share price of $4.70, valuing the company at approximately $635 million.

1.3 A review of unconformity–type uranium deposits

Unconformity-type uranium deposits derive their name from their typical spatial association with a nonconformity between Paleoproterozoic to Mesoproterozoic sedimentary rocks in intracratonic basins such as the Athabasca Basin in Canada or the McArthur Basin in Australia, and Archean to
Paleoproterozoic metasedimentary, meta-igneous, and pegmatitic basement rocks (Kyser & Cuney, 2008). These deposits are hosted either in the basement rocks, in the overlying sedimentary basins, or at the unconformable contact between them. Most of these deposits consist of massive to semi-massive replacement, veins, lenses, and/or breccias that have been constrained to have formed between 1,600 and 1,350 Ma (Jefferson et al., 2007). Despite the vast amount of research that has been conducted on this deposit type, the genesis, source of uranium, associated metals, and fluids, as well as their driving forces remain poorly understood.

1.3.1 Factors controlling the formation of unconformity-type uranium deposits

It is generally agreed upon by researchers and industry geologists alike that unconformity-type uranium deposits are structurally controlled and are associated with basinal brines and/or formation waters that interact with a reduction front (Kyser & Cuney, 2008). The unconformity-type uranium deposits in the eastern Athabasca Basin are located along a geophysical feature defined by a structural trend marking the transition zone between the Wollaston and Mudjatik structural domains (Jefferson et al., 2007). Most of the studied deposits coincide with brittly reactivated ductile to brittle-ductile graphitic faults (Harvey & Bethune, 2007; Alexandre et al., 2007; Cloutier et al., 2011). These reactivated NNE/SSW structures focus the downward percolation of basinal brines into and/or their upward flow from the basement, precipitating uranium ore near the unconformity, which appears to coincide with the oxidation-reduction front.
A key component to the formation of unconformity-type uranium deposits is the ability of an oxidized U\textsubscript{(VI)}-bearing fluid to be reduced and precipitate relatively insoluble U\textsubscript{(IV)}. A number of theories have attempted to explain this phenomenon. Some researchers suggest that U\textsubscript{(VI)} is sourced from altered detrital monazites and/or zircons in the basin sandstones, and carried in the oxidized basinal brine down to or just below the unconformity, where the U\textsubscript{(VI)}-bearing fluid is reduced via reaction with either basement rocks or a reduced fluid in the basement, precipitating U\textsubscript{(IV)} out of solution (Hoeve et al., 1980; Kotzer & Kyser, 1995; Fayek & Kyser, 1997). Other researchers suggest that uranium is leached from monazites and zircons in the basement rocks by downward percolating basinal brines, precipitating concentrated U\textsubscript{(IV)} upon interaction with either reducing basement rocks or a reduced fluid at or near the unconformity (Dahlkamp, 1978; Hecht & Cuney, 2000; Annesley et al., 2000; Cuney, 2009). Graphite dissolution (Hoeve & Sibbald, 1978; Alexandre et al., 2005; Jefferson et al., 2007) or ferrous iron liberated from mafic minerals in the basement (Quirt, 1989; Hetch & Cuney, 2000; Derome et al., 2003) are predominantly postulated to be responsible for reduction of the uranium-bearing fluid.

Unconformity-type uranium deposits are known to be hosted at the unconformity, in the sandstone above it, in the underlying basement rocks, or sometimes, in all three. This suggests movement of the mineralizing fluid downward into the basement, and upward out of the basement (bi-directional flow). Stratigraphic studies have identified local horizons of increased silicification in the form of diagenetic quartz overgrowth cement that may focus or inhibit fluid
flow in the basin (Hiatt et al., 2007). Britty-reactivated steep or shallow hematitic and/or graphitic basement faults that intersect the sandstone are postulated to provide a pathway for fluid flow into and/or out of the basement, and create void space for the precipitation of concentrated uranium minerals (Jefferson et al., 2007). Numerical fluid flow modelling has suggested that free convection of basinal brines into and back out of the basement rocks was sustainable considering the generally agreed upon conditions present at the time of deposit formation (Raffensperger & Garven, 1995).

1.3.2 Genetic models for unconformity-type uranium deposits

The consensus among researchers is that at least one brittly-reactivated fault, one or more uraniferous basinal brine(s), and a source of reduction of uranium are simultaneously required for the precipitation of an unconformity-type uranium deposit. This has resulted in few genetic models that have been repeatedly modified. These deposits have been divided into two broad categories on the basis of the immediate host rock: 1) Sandstone-hosted mineralization and, 2) Basement-hosted/fracture-controlled mineralization (Jefferson et al., 2007), each with different alteration patterns and mineralization signatures (Figure 1.4).

The basement-hosted/fracture-controlled deposit model is characterized by monometallic (simple) uranium deposits that are hosted in faulted or strongly fractured basement rocks, below the unconformity. This deposit model is typified by a narrow alteration halo, referred to as ingress-style alteration, which occurs only proximal to the ore deposit (Figure 1.5; Jefferson et al., 2007).
Figure 1.4: Diagram of basement-hosted/fracture-controlled and sandstone-hosted end members of unconformity-type uranium deposits, outlining key differences in alteration patterns and mineralization style (modified from Jefferson et al., 2007) (original in colour)
It is generally agreed upon that oxidized basinal brines travel into the basement rocks along graphitic faults and leach uranium from monazites and zircons either in the sandstones or in the basement. An oxidation-reduction reaction with either the basement rocks or a reduced fluid in the basement results in the precipitation of uranium minerals (Jefferson et al., 2007). This interaction between the mineralizing fluid and the basement rocks is limited to the fault/fracture zone, thus the ingress-style alteration halo is spatially confined to the immediate deposit area (Figure 1.5). Host rock alteration is characterized by chloritization (clinochlore) of mafic minerals, pervasive illitization of feldspars, cordierite, and sillimanite, and later chloritization (sundoite) of some illite (Figure 1.5). These
deposits are generally considered to be blind exploration targets given their narrow alteration halo and constrained geochemical signature.

The sandstone-hosted deposit model is characterized by polymetallic (complex) uranium deposits that are hosted either within the Athabasca Group sandstones, or at the unconformity (Figure 1.4). These deposits commonly contain anomalous concentrations of Ni, Co, Pb, Zn, Mo, and Cu sulphides and arsenides, and sometimes Au and PGE's, in addition to U (Figure 1.4; Jefferson et al., 2007). As the sedimentary rocks in the basin are significantly more permeable and porous than the basement rocks, relatively unrestricted flow of mineralizing fluid(s) results in a widespread clay alteration halo; this is referred to as egress-style alteration (Figure 1.5; Jefferson et al., 2007). These deposits are postulated to form when a uranium-saturated, oxidized basinal fluid reacts with a reduction front at the unconformity, or an upward-migrating reduced fluid (Kotzer & Kyser, 1995, Jefferson et al., 2007). Sandstone-hosted deposits, therefore, also have a close spatial association with strongly fractured or (usually reactivated) faulted zones that crosscut the basement and the overlying sandstones, providing a locus for the movement of fluid(s) into and out of the basement. The resulting redox front occurs at or above the unconformity, where uranium and base metal sulphide/arsenide minerals precipitate out of solution to form a deposit. The associated widespread egress-style alteration halo consists of pervasive illite replacement of diagenetic dickite, quartz dissolution and/or precipitation, local chlorite proximal to the unconformity, and a hematite, illite and/or chlorite clay cap immediately surrounding the deposit (Figure 1.5).
1.4 Purpose and objectives of study

The West Zone of the Roughrider deposit (RWZ) was selected for this study for two main reasons. Firstly, only limited amounts of geoscientific research have been carried out to date (McCready & Elash, 2009; McCready & Elash, 2010), and its microscopic petrographic and geochemical characteristics have yet to be documented. Secondly, although the deposit is hosted within the basement, approximately 10 – 50 m below the unconformity, and, thus, is classified as basement-hosted, it is characterized by several attributes common of sandstone-hosted deposits. These features include the development of a widespread illite alteration “chimney” in the sandstones above the deposit, the pervasive and extensive size of alteration within the basement rocks, and locally anomalous concentrations of copper, nickel, cobalt, zinc, and molybdenum. As such, the RWZ does not conform to the generalized end-member deposit models discussed above, and an investigation of its petrographic and geochemical characteristics could provide new insights into the mineralization mechanisms of unconformity-type uranium deposits. The purpose of this study is, therefore, to provide a complete description of the geological, petrographic and geochemical characteristics of the RWZ and to decipher its metallogenesis, with an aim to enrich the theories of unconformity-type uranium mineralization and to help future uranium exploration in the Athabasca Basin, especially in the areas surrounding the Roughrider deposit.

The objectives of this study are to: 1) describe the geological setting and characteristics of the Roughrider West Zone; 2) characterize the mineral
composition of the ore body and associated alteration in time (paragenetic sequence) and space (zonation); 3) characterize the element assemblages associated with mineralization and alteration, their correlations and spatial distribution; 4) determine the ages of mineralization and subsequent remobilization events; and 5) evaluate the mineralization processes and their controlling factors. The methods used to achieve these objectives are described in Chapter 3.
2. GEOLOGICAL SETTING

The Roughrider deposit is located on the east-northeastern edge of the Paleoproterozoic to Mesoproterozoic Athabasca Basin in northern Saskatchewan. The Athabasca Basin unconformably overlies basement rocks of the Taltson magmatic zone in the west and, dominantly, the Western Churchill structural Province, which is divided into the Rae and Hearne sub-provinces (Figure 2.1). Recent studies have determined that the basement rocks to the southwest of the Athabasca Basin, which used to be assigned to the Rae sub-Province, belong to the 2.0 – 1.9 Ga Taltson magmatic zone (Card et al., 2008). The Churchill Province is flanked to the north-northwest by the 2.02 – 1.91 Ga Taltson-Thelon Orogeny (Hoffman, 1988), and to the southeast by the 1.9 – 1.8 Ga Trans-Hudson Orogeny (Card et al., 2007).

2.1 Geology of the Archean and Proterozoic basement

2.1.1 Taltson magmatic zone

The western edge of the Athabasca Basin in northeastern Alberta unconformably overlies the southern extension of the 2.0 – 1.9 Ga Taltson magmatic zone (Figure 2.1; Card et al., 2007), the northern-most reach of which is terminated by the MacDonald Fault along the eastern shore of Great Slave Lake in the Northwest Territories (Hoffman, 1988; Ashton et al., 2009).
Figure 2.1: Geological map depicting the Athabasca Basin in northern Saskatchewan and Alberta, unconformably underlying three lithotectonic zones (Modified from Card et al., 2008). (Original in colour)

The Taltson magmatic zone is interpreted as a continental magmatic arc attributed to the 2.0 – 1.9 Ga Thelon Orogeny, which arose from the collision of the western Slave and the eastern Churchill cratons (McNicoll et al., 2000). The north-south trending Taltson magmatic zone comprises Archean to
Paleoproterozoic basement granitic gneisses and amphibolites, pelitic gneisses, and Paleoproterozoic plutonic rocks (Card et al., 2007; McNicoll et al., 2000). Intrusions include 1.99 – 1.955 Ga I-type granitoids and 1.95 – 1.92 Ga S-type granites (Card et al., 2007). Metamorphism prior to the Taltson-Thelon orogeny is poorly recorded in the Taltson magmatic zone; the only noted occurrences are a Neoarchean to Paleoproterozoic event (M1), suggested from a 2.47 Ga Rb/Sr isochron age in the basement gneisses that is otherwise unpreserved, and a well constrained 2.09 Ga granulite facies regional metamorphic event (M2) (Card et al., 2007). Peak metamorphism was attained by ca. 1.93 Ga, coincident with displacement along many shear zones in this region (Card et al., 2007).

2.1.2 Rae sub-Province

The Churchill Province comprises the Rae sub-province in the west-northwest and the Hearne sub-province in the east (Figure 2.1; Card et al., 2007; Hoffman, 1988). The Rae sub-province in northern Saskatchewan, exposed around the Carswell Structure in western Athabasca Basin and north of Lake Athabasca, is composed of Archean and Proterozoic rocks that have been subdivided into seven lithotectonic domains: (1) Nolan; (2) Zemlak; (3) Ena; (4) Train Lake; (5) Beaverlodge; (6) Dodge; and (7) Tantato (Ashton et al., 2009). The Nolan Domain consists of a 2.64 – 2.58 Ga batholith that was weakly metamorphosed around 2.37 Ga (Ashton et al., 2009). The Zemlak and Ena Domains comprise 2.71 – 2.34 Ga igneous gneisses that have been strongly deformed and metamorphosed to amphibolite facies, metasedimentary gneisses that make up the Murmac Bay Group pelitic rocks, and 1.97 – 1.93 Ga
leucogranites associated with the Taltson magmatic zone that also extend into
the Beaverlodge Domain. The Zemlak Domain is separated from the
Beaverlodge Domain by the multiply-reactivated ductile to brittle Black Bay Fault
(Ashton et al., 2000). The Train Lake Domain consists of felsic igneous gneisses
with remnants of a granitic-greenstone belt that was metamorphosed to upper
amphibolite facies (Ashton et al., 1999). It is also characterized by late granitic
stocks that follow the Oldman-Bulyea Shear Zone, which divides the Train Lake
Domain from the Beaverlodge Domain (Ashton et al., 2009). The Beaverlodge
Domain is composed of 3.0 Ga and 2.33 – 2.29 Ga granitoid rocks that have
reached upper amphibolite facies metamorphism, a Paleoproterozoic succession
of upper amphibolite to lower granulite facies basalt-pelite-quartzite rocks
comprising the Murmac Bay Group, and granulite facies 2.6 Ga and 2.34 Ga
granitoids, igneous gneisses, and garnet-bearing migmatites (Ashton et al.,
2007). The Dodge Domain is dominantly composed of metasedimentary
amphibolites and granitoid gneisses intruded by late granites (Knox & Ashton,
2009). These rocks were subsequently metamorphosed to granulite facies which
was later overprinted by an upper amphibolite facies metamorphic event (Knox &
Ashton, 2009). The Tantato Domain is characterized by 2.63 – 2.58 Ga
granitoids, garnet-bearing migmatites, and metabasites in the west, and the 3.4
Ga Chipman Batholith in the east, all of which have also been subjected to
granulite facies metamorphism around 2.55 – 2.52 Ga (Mahan et al., 2003;
Ashton et al., 2009). This early metamorphic event was overprinted by a 1.91 –
1.90 Ga granulite facies metamorphic event (Ashton et al., 2009), attributed to
the Thelon Orogeny (Card et al., 2007). Of these lithotectonic domains, the Beaverlodge is the only one known to host vein-type uranium deposits, such as the Nicholson Bay and Gunner deposits north of Lake Athabasca, and unconformity-type uranium deposits in the Carswell Structure, for example, Cluff Lake and Shea Creek (Jefferson et al., 2007; Ashton, et al., 2007).

2.1.3 Hearne sub-Province

The Rae sub-Province is separated from the Hearne sub-Province by the 1.92 – 1.85 Ga Snowbird Tectonic Zone (Hoffman, 1988), which is interpreted as a suture between the two cratons (Berman et al., 2007). The Hearne sub-Province in northeastern Saskatchewan has been subdivided into four northeast trending lithotectonic domains, from west to east: (1) Virgin River, (2) Mudjatik, (3) Wollaston, and (4) Peter Lake (Figures 2.2, 2.3; Annesley et al., 2005).

The Virgin River and Mudjatik domains, disconnected by the Cable Bay Shear Zone, are both characterized by Archean granitoid gneisses intruded by a 2.68 – 2.6 Ga magnetite-bearing monzogranite (Orrell et al., 1999). The Archean granitoids are overlain by locally gneissic quartzite and psammites – pelites, and amphibolite facies rocks with uncommon oxide facies banded iron formation, which were subsequently intruded by late granitoids (Card et al., 2008). The Virgin River Domain is defined by a linear hybrid type 2 and 3 fold interference pattern, and lacks the type 1 dome and basin fold interference pattern (D2) that characterizes the Mudjatik Domain (Card et al., 2008).
Figure 2.2: Summary of regional sub-Athabasca basement geology, outlining the various domains of the Hearne Province in northern Saskatchewan, and location of some unconformity-type uranium deposits, including the Roughrider deposit (Midwest NorthEast Project). MD = Mudjatik Domain; WMTZ = Wollaston-Mudjatik Transition Zone; WWD = Western Wollaston Domain; EW = Eastern Wollaston Domain; PLD = Peter Lake Domain; WB = Wathaman Batholith; RZ = Reindeer Zone (Modified from Annesley et al., 2005). (Original in colour)
Figure 2.3: Cross-section of the architecture and structure of the Mudjatik, Wollaston, and Peter Lake domains that comprise the eastern portion of the Hearne Province in northern Saskatchewan (Jefferson et al., 2007). (Original in colour)
The Mudjatik Domain also displays a subordinate type 3 fold interference pattern produced by D3 that is only observed in aeromagnetic maps (Card et al., 2008). The rocks in the Virgin River and Mudjatik domains have been affected by upper amphibolite facies metamorphism, with the south and west regions locally indicating granulite facies conditions (Card et al., 2008).

The Wollaston Domain, juxtaposed to the Mudjatik Domain along the Wollaston-Mudjatik Transition Zone (WMTZ), is a fold-thrust belt characterized by rocks similar to the Mudjatik and Virgin River Domains – 2.65 – 2.50 Ga charnockite and granitoid gneisses, amphibolite gneisses, and, near the margin, a heterogeneous assemblage of metasedimentary and intrusive rocks (Yeo & Delaney, 2007). These rocks were unconformably overlain by locally gneissic psammitic – pelitic, quartzite, metavolanic, and subordinate calc-silicate metasedimentary rocks comprising the Wollaston Supergroup (Annesley et al., 1991). Proximal to this unconformable contact, the granitoid basement displays evidence of paleoweathering in the form of a bleached and kaolinite-altered zone (Yeo & Delaney, 2007). Pre-Wollaston Supergroup Archean deformation is suggested based on foliation preserved in Wollaston Supergroup clasts, but has been thoroughly overprinted by later deformational events, and syn-depositional faulting is inferred from examination of Wollaston Supergroup stratigraphy (Yeo & Delaney, 2007). Four post-deposition deformational events have been identified in the Wollaston Domain, the first (D1) and third (D3) of which define the dominant structural style (Yeo & Delaney, 2007). Doming of the basement rocks is inferred to have caused the foliation associated with D1, characterized by
poorly preserved isoclinal folds (Lewry & Sibbald, 1980). The type 1 fold interference pattern created by D2 in the Mudjatik Domain is poorly developed in the Wollaston Domain whereas isoclinal to tight folding and late dextral shearing associated with D3 created the features that define its structural style (Yeo & Delaney, 2007). Northwest-trending open folds and associated dextral shearing caused by D4 are best observed in the western Wollaston Domain along the WMTZ and are interpreted to be associated with initial basin subsidence (Portella & Annesley, 2000). Post-orogenic brittle sinistral faults that extend into the Athabasca Group are also observed (Yeo & Delaney, 2007), and are a vital component to the formation of the unconformity-type uranium deposits hosted in these rocks. The rocks of the western Wollaston Domain have attained upper amphibolite facies to locally lower granulite facies metamorphism, with two distinct metamorphic phases evidenced by local discontinuous anatctic melts and multiple generations of metamorphic minerals that coincide with D1/2, and the dominant D3 event (Yeo & Delaney, 2007). In contrast, the eastern Wollaston Domain preserves upper greenschist to lower amphibolite facies rocks, which is attributed to early tectonic uplift associated with the Trans-Hudson Orogeny (Yeo & Delaney, 2007).

The Peter Lake Domain is an irregularly shaped, enigmatic package that is unconformably overlain by the Wollaston Supergroup in the northwest and is truncated in the southwest by the Needle Falls shear zone, and in the south by the Parker Lake shear zone and Wathaman Batholith (Rayner et al., 2005). The Peter Lake Domain is characterized by Neoarchean to Paleoproterozoic
metamorphosed granitoid rocks of the Granodiorite Complex, with minor locally PGE-bearing meta-diorites to gabbros of the Swan River Complex, and trace local migmatitic metasedimentary rocks (Maxeiner & Rayner, 2011). These rocks were subsequently intruded in the southwest by a post-peak metamorphism monzogranite to quartz monzodiorite suite (Maxeiner & Rayner, 2011). There are at least two metamorphic events and three ductile deformational events that have affected the Peter Lake Domain rocks; an upper amphibolite metamorphic event is proposed, correlative to the Archean metamorphism in the rest of the Hearne Province, and lower amphibolite facies was attained during the Trans-Hudson orogeny (Maxeiner & Rayner, 2011). The Trans-Hudson orogen also marks the earliest preserved ductile deformational event in the Peter Lake Domain; later deformation is recorded by the dextral Needle Falls and Parker Lake shear zones (Maxeiner & Rayner, 2011).

The WMTZ is a corridor defined by the gradual transition from the D2 dome and basin structural style of the Mudjatik Domain in the western Hearne sub-Provience to the linear isoclinal D3 structural style of the Wollaston Domain in the east-central Hearne sub-Provience. It is defined in aeromagnetic geophysical maps by a northeast-southwest trending magnetic low (Figure 1.1) that crosses the eastern Athabasca Basin obliquely. This linear structural transition zone hosts the majority of all world-class unconformity-type uranium deposits in: (1) the lower Athabasca Group sandstones; (2) the Wollaston Supergroup supracrustal sequence and subordinately, the interleaved Archean to Paleoproterozoic basement granitoids of the Wollaston Domain; and/or (3) in both the sandstone
and the basement rocks, along the unconformable contact between them (Jefferson et al., 2007). As previously mentioned, unconformity-type uranium deposits are spatially associated with late (post-D4), commonly reactivated, brittle faults that extend into the Athabasca Basin sedimentary rocks (Yeo & Delaney, 2007), particularly where these faults have intersected a larger pre-existing brittle-ductile shear zone in the WMTZ.

2.2 Geology of the Proterozoic Athabasca Basin

The Athabasca Basin is a ca. 100,000 km$^2$ Paleo- to Mesoproterozoic tectonically-controlled intracontinental basin that unconformably overlies the western Churchill Province (Ramaekers, 1980; Jefferson et al., 2007; Kyser & Cuney, 2008). It was named from early outcrop studies around mining camps near Lake Athabasca by McCann (1893), who referred to the rocks as the Athabasca sandstone (Ramaekers, 1990). The name was subsequently formalized and revised by several authors until 1961, when Fahrig named and defined the stratigraphic boundaries of these sandstones, which included weakly metamorphosed sedimentary rocks of the Thluicho Lake Group that underlie the Athabasca Basin around Lake Athabasca (Ramaekers, 1990). Fahrig’s work was edited by Ramaekers in 1975 when the Saskatchewan Geological Survey initiated the Athabasca Program, a project designed to thoroughly map the Athabasca Group sandstones in order to better understand the newly discovered unconformity-type uranium deposits (Ramaekers, 1990). Ramaekers’ extensive mapping, core logging, and integration of previous works with geophysical surveys led to the division of the east – west elliptical Athabasca Basin observed
at surface today into three structurally-controlled elliptical sub-basins: (1) Jackfish in the west, (2) Mirror in west – central, and (3) Cree in the east (Ramaekers, 1980). Subsidence of these sub-basins is postulated to result from movement along large basement faults and their associated highs. The Jackfish sub-basin, associated with the Black Bay Fault, is alienated from the Mirror sub-basin by the Patterson High, whereas the Mirror and Cree sub-basins formed due to differential subsidence along the Snowbird Tectonic Zone, and are divided from each other by the Dufferin High (Ramaekers, 1980). The Cree sub-basin may also have been affected by the Cable Bay Shear Zone (Ramaekers, 1980).

The current stratigraphic names of the Athabasca Basin sedimentary rocks were formalized in 1978 (Ramaekers, 1978), with minor revisions since (Ramaekers et al., 2007). The Athabasca Group consists predominantly of fluvial to marine or lacustrine quartz arenite that has been divided into eleven lithostratigraphic formations with twenty recognized formal members and a total current preserved thickness of ca. 1,500 m (Figure 2.4; Ramaekers et al., 2007). The formations of the Athabasca Group, from lower to upper are: (1) Fair Point, constrained to the Jackfish sub-basin; (2) Reilly, located east of the Athabasca Basin in the Reilly Basin; (3) Read, confined to the Cree sub-basin (formerly the MFa); (4) Smart, restricted to Mirror sub-basin; (5) Manitou Falls, marking the start of Athabasca Basin-wide infill; (6) Lazenby Lake, where mudstone intervals begin to become more prevalent; (7) Wolverine Point; (8) Locker Lake; (9) Otherside; (10) Douglas, dominated by mudstones and; (11) Carswell, the only preserved carbonate interval (Figure 2.4; Ramaekers et al., 2007).
Figure 2.4: Cross section of Athabasca Basin showing eleven formations that make up the Athabasca Group. D = Douglas Formation, C = Carswell Formation, RY = Reilly Lake Formation, VRMH = Virgin River Magnetic High, STZ = Snowbird Tectonic Zone (Modified from Jefferson et al., 2007). (Original in colour)

Fluid inclusion studies of core drilled near Rumple Lake have suggested an original thickness of 5,000 m for the Athabasca Group (Pagel, 1975). The sedimentary rocks comprise dominantly flat lying, unmetamorphosed and relatively undeformed fluvial to shoreface quartz arenites with local discontinuous siltstone lenses, and minor late marine or lacustrine carbonates, mudstones, and evaporites, best preserved in and proximal to the Carswell Structure (Ramaekers, 1990).

The age of formation of the Athabasca Basin is < 1,750 Ma, constrained by the Ar/Ar age of retrograde metamorphic muscovite in the basement (Alexandre et al., 2007), whereas the end of sedimentation occurred after 1,540 Ma, based on Re-Os dating of the uppermost shale of the Douglas Formation (Creaser & Stasiuk, 2007). Tectonic activity in the sub-Athabasca basement is interpreted to have ended near the end of the deposition of the Manitou Falls Formation (MF), after which the Athabasca Basin began behaving as the singular large sedimentary basin observed today (Ramaekers, 1990). Paleofluid flow and
sedimentation are inferred to have been dominantly from east to west, with a minor south to north component, associated with eastern uplift related to the Trans-Hudson Orogeny (Ramaekers, 1990).

The Athabasca Basin was subsequently affected by two contentiously inferred meteorite impacts, identified by their macroscopic morphology, lamellae in quartz and feldspar, radial fractures, and the presence of extremely high pressure shock metamorphism (Currie, 1967): the ca. 478 Ma Carswell structure on the western side of the basin (Collier, 2007), and the Pasfield Lake basement high on the eastern side of the basin (Bosman et al., 2011). The basin was further subjected to multiple continental-scale glaciation events – most recently, the Quaternary Laurentide Ice Sheet – which have covered the Athabasca Group in glacial sediments (Campbell, 2007). The southwest advance and northeast retreat of the Laurentide Ice Sheet controlled the topography of the present day Athabasca Basin and has resulted in the use of uranium-mineralized boulder train tracking to locate a few unconformity-type uranium deposits, with limited success (Campbell, 2007).
3. STUDY METHODS

3.1 Introduction

This study will define the mineralogy and geochemistry of uranium mineralization at RWZ as well as that of the alteration and host rocks, and determine their spatial and temporal relationships. This was achieved through the employment of a variety of techniques, including: (1) core logging of fifteen variably mineralized diamond drill holes (DDH); (2) hand sample descriptions and microscopic petrography; (3) Scanning Electron Microscopy – Energy Dispersive Spectroscopy (SEM-EDS) analysis; (4) Electron probe microanalysis (EPMA); (5) geochronology using EPMA and Secondary Ion Mass Spectrometry (SIMS); (6) mass balance/isocon studies; (7) three dimensional (3D) spatial modelling of zinc – uranium concentrations at RWZ and spatial modelling of clay types; and (8) element correlation analysis.

3.2 Sample selection

A total of 160 representative samples of all lithologies, variations in alteration, and styles of mineralization were selected from 26 drill holes. Hathor’s database of whole rock geochemical analysis and drill core photographs were used to help with the sample selection. The selected samples include:

(1) Five samples representative of anomalous nickel, zinc, copper, cobalt, and molybdenum concentrations at RWZ;
(2) Eighty nine samples that outline the systematic progression of alteration from very weak through to very strong, encompassing all of the basement lithotectonic zones and the overlying sandstone;

(3) Thirteen relatively unaltered reference samples distal to RWZ mineralization, comprising all encountered lithologies in the area; and

(4) Fifty three samples encompassing all of the different styles, types, and intensities of uranium mineralization encountered at RWZ.

3.3 Microscopic Petrography

All of the 160 core samples were sent to Saskatchewan Research Council (SRC) in Saskatoon, Saskatchewan to be prepared as polished thin sections (~30 μm). Due to the extremely sectile or friable nature of many of the altered samples, only 105 of the polished thin sections were suitable for detailed petrographic examination, which are included as Appendix A. Thin sections were examined in both transmitted light and reflected light on an Olympus BX51 microscope to determine the mineralogy, textures, microstructures, and paragenetic sequence of the rocks and RWZ ores. Photomicrographs were taken with an Olympus Q-Color 3 camera attached to the microscope. Upon establishing the mineralogy of the RWZ and their cross-cutting relationships, the paragenetic sequence of the minerals relative to each other and relative to mineralization were deciphered.
3.4 Scanning Electron Microscopy (SEM) – Energy Dispersive Spectroscopy (EDS) analysis

Twelve thin sections were selected for detailed study using a JEOL JSM-6360 SEM, fitted with a Thermo Scientific Noran System 7 EDS system in the Department of Geology at the University of Regina. Each polished thin section was cleaned, after which areas of interest were outlined in black permanent marker and photographed. The marked thin sections were subsequently scanned to create a ‘thin section map’, carbon coated, and when necessary, wrapped on one side with a thin strip of copper tape to create a sufficiently conductive surface. Each sample was mounted, placed under a vacuum, and set 10 mm below the electron column. Secondary electron images (SEI) and backscattered secondary electron (BSE) photomicrographs were taken of the samples using an electron beam set to 10 kV. When necessary, semi-qualitative EDS analysis was used to confirm the composition of minerals, and to create semi-quantitative elemental maps of images to characterize any zonation within minerals. As the EDS system was not calibrated with natural or synthetic standards, quantitative data was not possible.

3.5 Electron Probe Microanalysis (EPMA)

The chemical composition of uranium and base metal minerals in five samples, and clay minerals from four samples were determined using a CAMECA XS-100 electron microprobe equipped with four wavelength dispersive x-ray spectrometers (WDX) at Saskatchewan Research Council (SRC) in Saskatoon. Base metal and uranium mineral analyses were conducted using a
20 kV beam with a 20 nA beam current. Counting times were 30 seconds per element for all elements except thorium, uranium, and lead, which had 60 second count times. Clay mineral analyses were conducted using a 15 kV beam with a 20 nA beam current. Counting times were 30 seconds per element, except magnesium, sodium, and fluorine, which had counting times of 20 seconds. The raw data collected was corrected for dead time, peak interference, and background. Uraninite and base metal mineral raw data were converted to oxide weight percent values, whereas oxygen content of clay mineral raw data was calculated stoichiometrically based on ideal chemical compositions. The list of elements analyzed, their analytical precision, correction method, and the calibration standard used for each element is included as Appendix B.

3.6 Secondary Ion Mass Spectrometry (SIMS)

Uranium and lead isotope concentrations of two uraninite samples, one relatively unaltered and one altered, were measured via secondary ion mass spectrometry (SIMS), using a CAMECA IMS 7F ion microprobe at the University of Manitoba. The ion microprobe was calibrated by running eight analyses on standard TKK for the unaltered uraninite sample, and five analyses on standard LAMNH for the altered uraninite sample. A primary O− beam diameter was set to 10 μm for the unaltered uraninite sample and 5 μm for the altered uraninite sample. The beam was accelerated at 12.5 Kv, with a secondary accelerating voltage of +8 Kv. A mass resolving power of 1400 was used with a voltage offset of −50 V to correct for hydride isobaric interferences. Analyses ran for 10 minutes to collect 30 cycles. The concentrations of the following isotopes were analyzed:
\(^{204}\text{Pb}, {^{206}\text{Pb}, {^{207}\text{Pb}, {^{235}\text{U, and} {^{238}\text{U. Common lead (}^{204}\text{Pb) concentrations were negligible, and it was analyzed in part for quality assurance by verifying the ratio of}^{206}\text{Pb to}^{204}\text{Pb.}

### 3.7 Geochronology

The ages of uraninite were calculated using two different methods, the chemical age dating and the U-Pb isotopic age dating, as described below.

#### 3.7.1 Chemical age dating

The ages of uraninites in five samples were estimated from concentrations of uranium, thorium, and lead as obtained from EPMA analysis described above. The ages thus obtained are called chemical ages, and the equation for age calculation is as follows (Montel et al., 1996):

\[
Pb = \frac{Th}{232} \left(\lambda_{232t}\right)^{-1} \times 208 + \frac{U}{238.4} \left(0.9928\right) \left(\lambda_{238t}\right)^{-1} \times 206 + \frac{U}{238.4} \left(0.0072\right) \left(\lambda_{235t}\right)^{-1} \times 207
\]  

[1]

where \(Th\), \(U\), and \(Pb\) are the concentrations (ppm) of these elements in the sample, \(\lambda_{232}\), \(\lambda_{235}\), and \(\lambda_{238}\) are the decay constants of \(^{232}\text{Th}, {^{235}\text{U, and} {^{238}\text{U, respectively, and} t is time (Montel et al., 1996). This technique requires the assumption that all Pb in the analyzed sample is of radiogenic origin and that Pb was neither lost nor gained in the mineral since its initial crystallization (Fayek & Kyser, 1997). For the uraninite samples analyzed in this study, Th content is below detection limits, and therefore Pb decay from Th is negligible.

#### 3.7.2 U/Pb isotopic age dating

Upon obtaining isotopic concentrations with the SIMS method as described above, ratios of \(^{206}\text{Pb}/^{204}\text{Pb,}^{207}\text{Pb}/^{206}\text{Pb,}^{235}\text{U}/^{238}\text{U,}^{207}\text{Pb}/^{235}\text{U, and}^{238}\text{U.}
$^{206}\text{Pb}/^{238}\text{U}$ were determined and corrected using the above mentioned standards. These data were subsequently plotted on a U/Pb concordia with an analysis error of 2.5% and a correlation coefficient of 0.9, using Isoplot 3.0 (Ludwig, 1993).

### 3.8 Geochemical analysis of major and trace elements

Geochemical whole rock (bulk) assay data was collected by Hathor over seven field seasons and was analyzed by SRC on a per-field season basis. This database comprises approximately 246 DDH’s, encompassing over 20,000 mineralized and unmineralized samples from the sandstone and the basement. Sandstone composite samples comprise ~2 cm rock chips taken at the end of every core box across 10 m sample intervals until drill hole depth is within 10 m of the unconformity, at which point the sample intervals are shortened to 5 m, 3 m, and two 1 m intervals are taken before and up to the unconformity. Basement point samples comprise a 5 cm long section of core sampled every 5 m, regardless of lithology, until relatively unaltered basement is intersected. Where scintolometer readings exceeded 500 counts per second (cps), sampled core comprised 0.5 – 1.0 m long half-core samples, including a 1 – 3 m shoulder of core on either side of the elevated zone, without regard to lithological uniformity. This extensive database was used to create a series of bivariate plots in Microsoft Excel 2007 for the purpose of exploring various major and trace element relationships within the sandstone and the basement rocks at Roughrider.

Five of the samples collected in this study, which show different degrees of alteration in different parts within the sample, were selected for additional
chemical analysis in order to estimate element gain and loss during the alteration processes, using the isocon method (Grant, 2004). These samples were powdered using a drill press at the University of Regina, by carefully pressing the drill bit into the area of interest until 1.0 g of powder was collected. The drill bit was then either changed or cleaned using a solution of ammonia, rinsed with water and air dried to prevent sample contamination. This procedure was repeated for the collection of powders from three areas of varying alteration in sample RB26108, and two differentially altered areas from each of the samples labelled RB26102, RB26096, RB26079, and RB26057. The powders were sent to SRC in Saskatoon for Inductively Coupled Plasma –Mass Spectrometry (ICP-MS) total digestion (TD) and partial digestion (PD) analysis. For TD analysis, a 0.125 g pulp was created from the sample, which was heated in a mixture of ultrapure HF/HNO₃/HClO₄ until it dried. The subsequent residue was then dissolved in diluted ultrapure HNO₃. For PD analysis, a 0.500 g pulp was created from the sample and digested with 2.25 mL of an ultrapure solution consisting of eight parts HNO₃ to one part HCl for one hour at 95°C. The resulting data was used to create bivariate plots of the relatively unaltered sample against the relatively more altered sample in Microsoft Excel 2007 for major and trace elements, using Al₂O₃ as the relatively immobile element in the system, which is further discussed in Section 7.5.

3.9 Three – dimensional (3D) spatial zinc modelling

A 3D model outlining the spatial relationship between anomalous zinc (Zn) (> 0.1%) and uranium (U) mineralization in the basement at RWZ was also
constructed using the MapInfo and Discover programs, in order to evaluate their complex geochemical relationship. As above, Hathor’s whole rock assay database was used. Zinc concentrations (ppm) were exported into MapInfo, and displayed in the cross-sections that were created for the above clay model. Anomalous concentrations of Zn were outlined in each section and subsequently imported into the Discover 3D program and converted to wireframes. The 2010 National Instrument 43-101 compliant resource estimate wireframes for RWZ were added to the imported zinc wireframes to display the spatial relationship between these two elements. Wireframes of the basement geology around RWZ, created by Dr. A.J. Mccready, were also included.

3.10 Clay alteration

A spatial model of mineralization-associated clay alteration in the sandstone and basement surrounding RWZ was constructed in an attempt to delineate its extent and to constrain the flow path of mineralizing fluids. This was accomplished using Hathor’s database of portable short wave infrared mineral analyzer (PIMA) and normalized whole rock assay data from 233 DDH’s, collected between 2007 and 2010. PIMA analysis is run on every DDH, according to Hathor’s protocol of selecting a 2 – 5 cm thick core sample every 5 m, except where the scintillometer reading exceeded 500 counts per second (cps), until relatively unaltered Archean granitoid gneisses become the prevalent rock type. The sample depth is written on the sample in grease pencil then all of the collected samples from each individual DDH are put into labelled plastic bags, keeping the sandstone samples separate from the basement samples. The
Bagged samples are shipped to Ken Wasyliuk at JNR Resources, for PIMA analysis. The PIMA is placed within 5 mm of the sample, covers a spot size of approximately 10 mm in diameter, penetrates roughly 2 – 3 mm into the sample, and requires roughly less than one minute for analysis (Bowitz & Ehling, 2008). The PIMA irradiates the sample with a non-destructive beam of near infrared (NIR) radiation in the wavelength region of 1,300 – 2,500 nm that is partially absorbed by the mineral(s) (Bowitz & Ehling, 2008). Radiation that is not absorbed is reflected back to the PIMA, which is split by a monochromator, creating a characteristic absorption spectrum from which various clay minerals can be identified (Bowitz & Ehling, 2008).

Normative (norm) calculations of clays using Hathor's whole rock assay database was used in conjunction with the PIMA data to construct the cross sections across the RWZ. The weight percent concentrations of Al₂O₃, K₂O, B, Fe₂O₃ (total), and MgO are organized in a Microsoft Excel spreadsheet, converted to molar proportions, and used to calculate the normalized mineral clay assemblage present, using the ideal chemical structures for analyzed minerals in the Athabasca Basin (Quirt, 1995). The listed oxide and elemental data is entered into the FORTRAN 77 program CLAYNORM.FOR (version 3) in Microsoft Excel, which calculates the percentage of dravite, illite, chlorite, and kaolinite in each sample, in that order (Quirt, 1995).

The resultant PIMA and norm data are imported into the MapInfo program, along with the topographic, DDH collar, UTM, and uranium mineralization data for RWZ. A total of 52 north – south, east-facing cross sections set 10 m apart and
84 west–east, north-facing cross-sections set 5 m apart were constructed across the RWZ deposit. The MapInfo program allows for the display of all of the DDH’s relative to each other, with their respective clay norm and PIMA data, in each of the cross-sections. This information was used to trace out and group zones of dominant (>80%) illite, dickite, kaolinite, and chlorite. Drill core logs and photographs were employed to delineate paleoweathered zones and depth where basement rock became relatively unaltered. As the clay norms are constructed from data acquired from whole rock (bulk) sampling whereas PIMA analysis is done on a smaller scale, sometimes discrepancies were encountered between the two datasets in the cross-sections. This issue was resolved by surmising that the simple sandstone mineralogy allows the clay norm data to provide an accurate representation of clay mineral proportions present above the unconformity, and was, therefore, weighted preferentially in cases of conflicting data. However, the extensive and complex basement mineralogy reduced the reliability of the clay norm data; as such, PIMA data was weighted preferentially in conflicting cases below the unconformity.
4. GEOLOGY OF STUDY AREA

The Roughrider deposit is located along the regional northeast – southwest trending WMTZ along with most of the other world-class unconformity-type uranium deposits, such as McArthur River, Cigar Lake, and McLean Lake. The RWZ deposit is located below the east – northeastern extent of McMahon Lake (Figure 1.2), which is approximately 477 m above mean sea level.

Overlying the deposit is a Quaternary cover sequence of variable thickness consisting of lake sediments and glacial till. Below this is ca. 195 – 215 m of relatively flat lying Athabasca Group quartz arenite with local discontinuous siltstone lenses, corresponding to the MF Formation. The upper 75 – 100 m of the MF sandstone comprises the fine to medium grained, homogeneous quartz arenites of the Collins Member (MFc). This unit is purple to tan, fine grained, moderately sorted, and homogeneous. The arenite is predominantly composed of purple and white subround spherical quartz clasts with a maximum grain size of 6 mm. The MFc is sometimes locally interrupted by 1 – 2 cm pebbly conglomeratic lenses. Hematite liesegang bands of variable thickness impart a purple stain on 90% of the quartz arenite. Pale grey 2 – 5 cm siltstone beds are uncommon. Approximately 1 – 5% interstitial white diagenetic dickite-dominant clay cement is also present. Sub-horizontal planar bedding is intersected at 80° – 90° to core axis (TCA) and subordinate parallel cross-laminations at 50° – 60° TCA are also common throughout the MFc. Fractures in the core are rare, oriented between 10° and 40° TCA and are either lined with white or pale yellow soft clay, or are unlined. The MFc is locally weakly bleached, overall preserving
its diagenetic purple colour, and shows no evidence of significant desilicification. Trace yellow to orange limonite alteration is noted as mm-sized laminations that conform to cross-bedding, and occurs as a lining in some fractures, often with white clay.

The lower 95 – 140 m consists of heterogeneous fine to medium grained, locally pebbly quartz arenites and subordinate quartz conglomerates of the Bird Member (MFb). This MFb includes two informally subdivided, regionally correlatable units: the “Marker Conglomerate”, and the “Basal Conglomerate”. The MFb is a pale purple to tan moderately sorted quartz arenite to pebbly quartz arenite that contains 10% framework grains and 85 – 89% quartz-dominant matrix. The framework grains dominantly consist of purple and white subround quartz clasts with a maximum grain size of 15 mm that float in fine to medium grained quartz matrix (Figure 4.1). Other framework grains include trace round, spherical, heavy mineral laminations that are subparallel to bedding. The MFb arenite is often interrupted by 2 – 5 cm conglomerate beds of the same mineralogy, and less commonly, by 2 – 5 cm buff to pale grey siltstone beds.

Diagenetic dark to pale purple hematite liesegang bands are particularly concentrated in the conglomerate beds, staining 20% – 30% of the MFb. Planar bedding is observed at 75° – 90° TCA, with parallel cross-laminations at 50° – 60° TCA. The number and intensity of fractures and diagenetic alteration are distinctly different in the MFb below the Marker Conglomerate, referred to hereafter as the lower MFb, relative to the MFb above it, termed the upper MFb.
Figure 4.1: Photograph of MFb quartz arenite from DDH 09-501 (179.1 – 188.2 m). Dark purple to pink hematite leisengang and yellowish limonite laminations highlight planar bedding and parallel cross laminations respectively, with rare intervals of moderately bleached tan to buff sandstone. Blue box shows location of a core sample for polished thin section analysis. (Original in colour)

Fractures are uncommon in the upper MFb, oriented at 10° – 40° TCA, and are lined with yellow to orange limonite, yellow-stained clay, or are unlined. Fractures in the lower MFb occur at the same orientations, exhibit local minor desilicification, and are often unlined, or lined with white to pale pink clay. Bleaching is weak to moderate with increasing depth as the core preserves much of its pale purple to locally pink hematite stain, and the arenite shows no significant desilicification. Yellow-orange limonite occurs as a partial fracture lining with clay, laminations conformant to cross-laminations, and sometimes as an irregular mottled stain on 10% – 15% of the core. Hematite staining and limonite laminae become less common with proximity to the unconformity.

The regionally correlatable, variably sized, locally absent, monomictic, matrix-supported quartz conglomerate informally referred to as the Marker Conglomerate is usually intersected at ca. 150 m, dividing the relatively unaltered upper MFb from the weakly altered and fractured lower MFb (Figure 4.2). It consists of a dark to medium purple, moderately sorted monomictic matrix-supported quartz conglomerate that ranges in thickness from < 1 m – 10 m.
White and purple up to 35 mm quartz pebbles, comprising 30 – 40% of the conglomerate, are subround to subangular, spherical, and rarely have mm-sized dissolution vugs that are sometimes filled with white or yellow clay. The pebbles are either segregated in 10 – 25 cm beds, separated by 10 – 30 cm intervals of quartz arenite, or float in the quartz arenite. Purple to pale pink hematite leisengang stains 80 – 90% of the unit. Planar bedding, only visible when quartz pebbles are organized in beds, is oriented 70° – 80° TCA; cross-laminations are absent. Rarely intersected fractures are oriented 65° – 75° TCA, and are typically unlined. Argillization is trace, as interstitial white dickite-dominant cement and infill of dissolution pits in quartz. Local trace desilicification in some quartz pebbles are observed, and the conglomerate is weakly bleached, preserving the purple to pale pink hematite stain, and trace laminations and patches of yellow limonite stains <5% of the unit.

The variably thick, locally absent monomictic clast-supported buff to tan quartz conglomerate that marks the unconformable contact between the Athabasca Group and the basement rocks is unofficially named the Basal...
Conglomerate (Figure 4.3). Well rounded up to 60 mm white and grey quartz pebbles comprise 25 – 35% of the rock, are spherical, and often contain mm-sized round dissolution vugs that are sometimes filled by yellow to buff clay.

The pebbles are surrounded by moderately consolidated MFb quartz arenite with 20 – 30 cm zones of rubbly sand. Bedding is absent, and fracture orientations are difficult to measure due to the large size of the pebbles. Argillization is more prevalent than in the overlying sandstone when present, as trace dickite and illite cement fill dissolution vugs in the quartz pebbles. The Basal Conglomerate is moderately bleached buff, with small patchy irregular pink to red hematite staining up to 20% of the core. Rare limonite alteration presents only as a pale yellow stain of the clays.

The unconformity between the overlying MFb and the basement typically occurs at ca. 200 m at the Midwest NorthEast property area, except where affected by reactivated brittle reverse faults which locally displaced the unconformity to ca. 215 m, and overturns the lower MFb. Away from the RWZ, basement alteration is constrained to the rocks proximal to the unconformity. It is characterized by saprolitic red to green paleoweathering profile immediately below the unconformity that is variable in its development but typically extends to a depth of 10 – 35 m. It comprises three alteration zones: (1) a less than one metre zone of bleached rock that is typically illitic to kaolinitic in composition (Figure 4.4); (2) An immediately underlying zone of variably developed hematite alteration (red zone; Figure 4.4);
Figure 4.3: Photograph of MFb and the Basal Conglomerate from DDH 09-500 (213.0 – 222.2 m). Pale purple and pink to red hematite leisengang and rare yellow limonite laminations highlight planar bedding and parallel cross-laminations in the arenite. Orange box outlines the Basal Conglomerate, with zones of poorly consolidated quartz pebbles and sand. (Original in colour)

Figure 4.4: Photograph of faulted lower MFb quartz arenite, Basal Conglomerate, and paleoweathered granite from DDH 09-509 (189.8 – 201.0 m). Orange box outlines the bleached zone; blue box outlines the hematized red zone. Fractures in the red zone are lined with orange – pink iron oxide and have 1 cm bleached halos. (Original in colour)

and (3) the lowermost chlorite-altered green zone, separated from the red zone by a transitional red-green zone, which is a combination of hematite and chlorite alteration (Figure 4.5; McCreary & Elash, 2010). The green zone is often poorly defined or absent, in which case the red zone transitions into either the red-green zone, or into relatively unaltered granitoids.
The basement rocks on the Midwest NorthEast property have been divided into four lithotectonic packages based on drill hole and property scale aeromagnetic data: (1) Wollaston Supergroup (WSPG), (2) Hanging Wall Wedge (HWW); (3) Footwall Wedge (FWW) and, (4) Midwest Dome (MWD; Figures 4.6, 4.7). At Roughrider, the Wollaston Supergroup rocks comprise garnet-cordierite-pyrite±sillimanite pelitic gneisses and weakly graphitic pelitic gneisses, as well as subordinate psammopelitic to psammitic gneisses, and local to rare garnet-bearing ironstone (Figure 4.8). The strong foliation is inconsistently oriented 30° – 60° TCA, and preserves evidence of mesoscopic folds. Fractures and/or faults are somewhat common, and tend to follow or cross foliation at 30° – 70° TCA. Most fractures in the pelitic and psammopelitic gneisses are lined with dark green chlorite, graphite, pyrite, or dark grey soft carbonaceous clay.
Figure 4.6: Plan map of interpreted property-scale basement geology of the Roughrider uranium deposit area; updated based on 2011 drilling (Elash & McCready 2011). Black dashed line through the West Zone marks location of cross-section in Figure 4.7. (Original in colour)
Figure 4.7: Two dimensional cross-section of deposit-scale geology, from line in Figure 4.6. Black lines mark drill holes, open circles mark where drill holes exit the cross-section, circles with a plus sign mark where drill hole enters the cross-section. MFC = Manitou Falls Formation Collins Member; MFB = Manitou Falls Formation Bird Member; HWW = Hanging wall wedge. (Original in colour)
Figure 4.8: Photograph of relatively unaltered transition zone between granitoid and pelitic gneisses (blue box; DDH 09-506; 279.8 – 288.8 m). The transitional contact between these units is initiated by a quartzofeldspathic pegmatite (orange box) which transitions into a migmatitic mix of granitic and pelitic gneisses. Pelitic gneiss below the migmatitic transitional zone includes 90 cm of garnetiferous ironstone (yellow box). (Original in colour)

Evidence for ductile or brittle-ductile shear zones includes increased dark green chlorite alteration, clay gouge, local boudinage of quartz leucosome, local brecciation of feldspars, garnet, and quartz, and sometimes, by an interval of attenuated and/or micro-folded or brecciated leucosome set in deep green chlorite, dark grey silicified clay, or calc-silicate minerals. The occurrence and distribution of graphitic pelitic gneisses is more prevalent than initially believed. In many cases, proximal to mineralization, the alteration/mineralization has consumed the graphite, whereas distal to mineralization, the graphite appears to be disconnected. These two features may help explain the absence of basement-hosted graphitic conductors in the RWZ or elsewhere on the property (McCready & Elash, 2010).

The HWW to the west – northwest and the FWW, located in the western side of the WSPG rocks (Figures 4.6, 4.7), comprises Archean and Paleoproterozoic metamorphosed, locally leucocratic granitic to granodioritic rocks that are uncommonly intruded by leucogranitic pegmatites (Figure 4.9). These rocks
rarely exhibit regular foliation; instead they are characterized by an equigranular sugary texture which is inconsistently interrupted by 5 – 25 cm quartzofeldspathic anatectite. Fractures and/or faults are atypical and tend to follow foliation at 30° – 70° TCA. Fractures are commonly lined with soft, white or dark red hematite-stained clay, or orange limonite that is rimmed by a 1 – 2 cm bleached white, or hematite stained halo (Figure 4.9).

The MWD to the east – southeast (Figures 4.6, 4.7) consists of granitic to tonalitic gneisses and rare quartz diorite gneisses with local anatectites that are commonly intruded by leucogranitic pegmatites, and have uncommonly been affected by post-peak metamorphism local calc-silicate hydrothermal alteration (Figure 4.10; Mccready & Elash, 2010). Well defined gneissosity in the MWD is generally intersected at 50° – 70° TCA, and sometimes also evidences folding (Figure 4.10). Relatively uncommon fractures and/or faults in the MWD tend to cut foliation at 30° – 70° TCA, and are often unlined, or lined with white to pistachio green indurated clay, clear or white quartz, or pink carbonate (Figure 4.10). Decreased grain size, local boudinage of quartz leucosome, and/or micro-brecciation of quartz and feldspars preserve evidence of ductile or brittle-ductile shear zones.

The basement rocks are locally cut by pegmatites, which are presumed to be equivalent to the Hudsonian pegmatites (Figures 4.8, 4.9, 4.10; Annesley et al., 2005).
These leucocratic granitic intrusions are often noted to preferentially cut along the contact between the Archean granitoids and the metasedimentary gneisses, creating a transitional zone up to several metres thick where differentiating the ortho- and para-gneisses can be challenging.

The RWZ is dominantly located approximately 20 – 30 m below the unconformity, in the steeply-dipping isoclinally-folded WSPG, in an area where these supracrustal rocks are present at the unconformity, sandwiched between the HWW to the west and the MWD to the east (Figures 4.6, 4.7). The current structural synthesis suggests that Roughrider is located at the crest of an east –
west-trending, west-plunging, overturned, isoclinal antiform (Mccready & Elash, 2010). The limbs of this fold were subsequently sheared and reactivated during a phase of brittle reverse faulting, which thrust the WSPG rocks southward onto the MWD. These late brittle faults locally extend into and offset the overlying MFb sandstone, and are directly associated with mineralization. Uranium mineralization is especially concentrated where these cross-cutting brittle-reactivated shear zones and/or brittle faults have created the largest dilational jog(s), proximal to the crest of the MWD (Mccready & Elash, 2010).

Mineralization-associated alteration at RWZ is fundamentally associated with increased fracturing proximal to mineralization. Moderate to strong alteration associated with RWZ mineralization is pervasive and widespread, extending up to 55 m into the overlying MFb, and approximately 100 m below the unconformity into the surrounding basement lithologies (Figure 4.8). Alteration of Athabasca Group siliciclastic rocks include intense bleaching (i.e., removal of primary/diagenetic hematite), limonitization, hematization (Figure 4.11), minor silicification, quartz dissolution (Figure 4.11), local solution collapse breccia development, and argillization (Figure 4.11). Away from the RWZ, the dominant clay species within the Athabasca sandstone is dickite; within the RWZ, it is illite. Within the basement, clay alteration is spatially-extensive, extending up to ca. 100 m in thickness and up to 80 m in distance away from known mineralization. Within the RWZ, the paleoweathered regolith is overprinted and obliterated by hydrothermal alteration. In some cases, however, a ghost clay signature of the kaolinitic zone is still evident.
Alteration varies in strength, ranging from weak to intense where massive clay has totally replaced the now, indeterminable protolith (Figures 4.11, 4.12). The clay alteration is predominantly white to pale green in colour and illitic in nature, and locally extends downward into the Archean rocks (McCready & Elash, 2009).
5. PETROGRAPHIC STUDIES

The mineral compositions, textures and structures of various rocks encountered in the Roughrider deposit and surrounding areas are described in this chapter, based mainly on microscopic studies of polished thin sections, and core logging to a lesser extent. The rocks are grouped into host rocks distal from uranium mineralization, alterations related to mineralization, and uranium ores, and are described in separate sections below, followed by a summary of the relative timing of the various minerals, or paragenetic sequence.

5.1 Host rocks distal from uranium mineralization

Five samples from three DDH’s distal from the RWZ that lack mineralization-associated alteration were selected to represent unaltered host-rocks for detailed petrographic analysis. These include MFb quartz arenite and basement rocks.

Microscopic analysis of a polished thin section from the lower MFb indicates that the framework grains of these, locally pebbly, quartz arenite and quartz conglomerate units are moderately to poorly sorted. Quartz clasts have tangential, long or, less commonly, concavo-convex grain contacts, suggesting weak to moderate compaction (Figures 5.1, 5.2). The heavy mineral laminations observed in core are composed primarily of hematite-replaced ilmenite, and trace zircon (Figure 5.2). Trace quantities of round, spherical zircon and monazite “float” around quartz grains in the dickite-dominant cement; these accessory minerals also occur as inclusions within quartz (Figure 5.2).
Figure 5.1: Transmitted light photomicrograph with polars crossed of lower MFb pebbly quartz arenite (RB26101; 185.6 m, DDH 09-501). Quartz clasts (Qtz) have tangential, long, and concavo-convex grain contacts. Locally a minor dickite and illite (Dck & Ill) interstitial cement is present. (Original in colour)

Figure 5.2: Reflected plane polarized light photomicrograph of lower MFb pebbly quartz arenite (RB26101; 185.6 m, DDH 09-501). Quartz clasts (Qtz) occur with hematite-replaced ilmenite (Hm) leisengang, and zircon (Zr) in a minor dickite and illite (Dck & Ill) interstitial cement. (Original in colour)
Approximately 1 - 3% unoriented < 1 mm sericite laths were also locally observed, often sandwiched between quartz clasts, or floating in the clay cement. Approximately 5 – 7% cement is present, consisting of trace quartz overgrowth (Figure 5.3A), and 6% interstitial clays comprising approximately 65% dickite and 35% illite (Figure 5.3B).

The basement rocks distal from the RWZ comprise three broad lithologies: (1) Granitoids and orthogneisses, comprising locally leucocratic granitic to tonalitic rocks and gneisses, with less common quartz diorite gneiss; (2) paragneiss including locally calcareous pelitic and subordinate psammitic to psammo-pelitic gneisses; and (3) leucogranitic pegmatites (Annesley et al., 2005; McCready & Elash, 2009). The inconsistently foliated granites are composed of 45 - 50% clear quartz, 25 – 35% white plagioclase which is locally 60 - 75% altered to sericite, 15 – 35% pink potassium feldspar, which is 40 – 65% altered to sericite, 5 – 15% biotite, and accessory zircon, monazite, rutile, pyrite, and rarely, garnet (Figure 5.4). Biotite regularly preserves two or three growth orientations, generally defining two microscopic foliations that intersect at 30° – 40°. Some of the granitic gneisses also contain up to 5% orthoamphibole.

Granodioritic gneisses have similar composition; 30% quartz, 40% plagioclase which has been variably sericitized (5 – 75%), up to 10% potassium feldspar which has been 80 – 95% altered to sericite, 10 - 15% calcic orthoamphibole, 2 – 10% biotite, and accessory pyrite, chalcopyrite, rutile, zircon, and monazite (Figure 5.5).
Figure 5.3: Transmitted light photomicrographs in crossed polarized light of cements in lower MFb quartz arenite (RB26101; 185.6 m, DDH 09-501): (A) Quartz (Qtz) clasts with dust trail indicates quartz overgrowth cement (o/g), in dickite and illite cement (Dck & Ill); (B) Quartz (Qtz) grains with interstitial dickite (Dck) and illite (Ill) cement. (Original in colour)

Figure 5.4: Transmitted light photomicrograph in crossed polarized light from leucogranitic gneiss (RB26100; 249.65 m, DDH 10-642) depicting typical mineralogy and two phases of biotite growth (Bio 1 and Bio 2). Potassium feldspar (Kfs) is differentiated from quartz (Qtz) by sericite alteration. Plagioclase (Plag) also shows sericite alteration (DDH 10-642, 249.65 m). (Original in colour)
Leucotonalitic to tonalitic gneisses are characterized by 35% quartz, 55% plagioclase that has been approximately 5 – 20% sericitized, 5 – 10% biotite, 1 – 2% muscovite, up to 2% pyrite, and accessory zircon, monazite, calcite, and variably chloritized garnet (Figure 5.6).

The interleaved locally calcareous pelitic gneisses of the Wollaston Supergroup are composed of 20 – 35% plagioclase, 15 – 20% quartz, and variable amounts (15 – 20% each) of clinopyroxene (augite), orthoamphibole (cummingtonite – grunerite), and biotite, up to 5% muscovite, 5 – 15% garnet when present, 2 – 5% potassium feldspar, 5 – 10% graphite, sillimanite, cordierite, and pyrite, when present, and accessory carbonate, titanite, chalcopryite, rutile, and zircon (Figures 5.7, 5.8).
Figure 5.6: Transmitted light photomicrograph with polars crossed of leucotonalitic gneiss (RB26104; 305.0 m, DDH 09-501), with quartz (Qtz), plagioclase (Plag), and two phases of biotite. (Original in colour)

Figure 5.7: Transmitted light photomicrograph in crossed polarized light of pelitic gneiss (RB26107; 361.3 m, DDH 08-003), depicting typical mineralogy of foliation – defining clinopyroxene (Cpx), calcic orthoamphibole (C-amph), and biotite (Bio), as well as plagioclase (Plag), garnet (Grt), and quartz (Qtz). (Original in colour)
Subordinate psammopelitic gneisses are composed of ca. 20% quartz, 20% plagioclase (up 95% altered to sericite), 10% potassium feldspar, which is often also up to 90% sericitized, 15% biotite which is up to 40% chloritized, 5 – 10% muscovite, up to 15% garnet, when present, and accessory hematite, graphite, chalcopyrite, and pyrite (Figure 5.9). Rare up to one metre quartzite intervals composed of 90 – 95% quartz, up to 5% chloritized garnet locally, and accessory pyrite and chalcopyrite have also been intersected.

The Hudsonian pegmatites that cross-cut these lithologies maintain a locally potassic leucogranitic to locally potassic leucomonzonitic simple mineralogy of variable amounts of quartz and potassium feldspar (30 – 80%), 10 – 30% plagioclase, 2 – 5% biotite, and accessory pyrite, chalcopyrite, garnet, dravite, zircon and rare flecks of graphite.
5.2 Alteration spatially associated with uranium mineralization

Mineralization-associated alteration at RWZ can be subdivided into nine categories: (1) argillization, (2) silicification, (3) desilicification, (4) bleaching, (5) hematization (6) limonitization (goethite) (7) chloritization, (8) de-graphitization, and (9) carbonatization. The first six alteration sub-categories are not significantly affected by the pre-alteration lithologies, whereas the last three have strong lithological controls that will be outlined.

Argillization comprises the weak to pervasive alteration and replacement of pre-existing minerals in all lithologies to white to pale green fine-grained illite with less common fine-grained off-white to pale green chlorite (sudoite), as identified by PIMA. Illite also replaces diagenetic dickite in the quartz arenites, and fills dissolution pits in the quartz clasts (Figure 5.10).
Figure 5.10: Photographs of moderate to strongly argillized lower MFb quartz arenite in a (A) core hand sample (RB26052; 207.7 m, DDH 09-116), showing dissolution of quartz matrix and pervasive replacement by hematite – stained illite ± sudoite; (B) Transmitted light photomicrograph in crossed polarized light of moderately argillized lower MFb quartz arenite (RB26053; 208.9 m, DDH 09-116), showing quartz (Qtz) dissolution pits filled by illite (Ill), with rims of dark red hematite (Hm) alteration. (Original in colour)

The scale of intense argillization is dependent on the proximity of the affected rock to mineralization, the extent of uranium mineralization (high grade vs. low grade), and to a lesser degree, the lithology (orthogneiss vs. paragneiss). Within roughly 5 to 7 m of high grade (>3% U₃O₈) uranium mineralization at RWZ, argillization is defined by 100% pervasive alteration and replacement, beyond which the scale of argillization decreases (Figure 5.11). The pelitic gneiss host rocks (Figure 5.11A, B) within 8 m of uranium mineralization are strongly altered to white illite with lesser sudoite. Their original fabric and mineralogy, with the exception of graphite, are not preserved. Within 11 m of high grade mineralization, a granitic gneiss from the FWW is weakly altered to white illite and sudoite, with locally bleached black chlorite replacing biotite and amphibole (Figure 5.11C).
Figure 5.1: Photographs of core samples proximal to high grade uranium mineralization, showing rapid transition from strong to weak argillization with increasing distance (DDH 09-131): (A) Graphitic pelitic gneiss (RB26085, 274.4 m) is 7.9 m from high grade mineralization, and has strong illite±sudolite alteration: no grain boundaries are visible, except mm-sized graphite, and foliation is not preserved; (B) Graphitic pelitic gneiss (RB26086; 281.6 m) is 8.8 m from high grade uranium mineralization and shows strong illite±sudolite alteration, with some minor preserved quartz and graphite, and minor dark chlorite alteration, fabric is not preserved; (C) Granodioritic gneiss (RB26087; 283.2 m) from the FWW 11.3 m away from high grade mineralization shows weak illite±sudolite alteration of some feldspars, and moderate chloritization of mafic minerals while preserving quartz, some potassium feldspar, and the dominant fabric. (Original in colour)

It has well-preserved grain boundaries, relatively unaltered potassium feldspars, and well-preserved foliation, which preserves evidence of both the relative competency contrast between the granitoids and the pelitic gneisses and the spatial constraints of penetrative massive clay alteration associated with uranium mineralization. Conversely, around low grade uranium mineralization (0.05 – 3% $\text{U}_3\text{O}_8$) total illite-dominant clay alteration is more localized and develops a moderate to weak signature more quickly. Strong argillization is also observed within and proximal to faults and fractures; however weak to moderate clay alteration is present within 200 m around the RWZ.
In the basement rocks, moderate argillization is identified as buff, pale green, or bluish grey rock with commonly preserved quartz leucosome or sugary quartz crystals +/- chloritized biotite floating in a matrix of illite±sudooite and minor sericite that sometimes preserves original fabric (Figure 5.12). Strong argillization in the basement is characterized by massive alteration and replacement of pre-existing host-rock mineralogy by illite±sudooite and minor sericite (Figure 5.13). Strong argillization renders confident identification of basement lithologies difficult, if not impossible. Furthermore, illitization is closely associated with uranium mineralization as the two are sometimes intergrown, which will be described in the section on uranium mineralization below.

Silicification is defined by the precipitation of quartz that fills pore space and locally coats the quartz arenite and some of the paragneisses, or precipitates drusy quartz as cement along fractures in the MFb and in the basement rocks, which commonly also contain variable amounts of carbonate, euhedral pyrite, and/or anhedral chalcopyrite (Figure 5.14). Uranium mineralization-associated silicification is a paragenetically late alteration phase that is associated with alteration of uraninite to a secondary uranyl silicate mineral, uranophane [Ca(UO$_2$)$_2$(SiO$_3$OH)$_2$*5(H$_2$O)], and occurs in the sandstone and basement rocks relatively distal to RWZ mineralization.

Desilicification comprises the partial to complete dissolution of quartz and silicate minerals in both the basement rocks and overlying quartz arenites, along the same scope and reach as that outlined for argillization above.
Figure 5.12: Photographs of moderately argillized granite: (A) core sample (RB26020; 218.8 m, DDH 10-197A), shows pervasive illite±sudioite alteration of all minerals except quartz; (B) Transmitted light photomicrograph with polars crossed of moderately argillized granite (RB26027; 243.4 m, DDH 10-197A), with quartz (Qtz) dissolution and total alteration of feldspars and amphibole by fine-grained illite (Ill), sericite (Ser), and minor hematite (Hm). Clay minerals are dark due to the thickness of the polished thin section. (Original in colour)

Figure 5.13: Photographs of strongly argillized pelitic gneiss in (A) core sample (RB26010; 240.4 m, DDH 09-091), showing complete desilicification and pervasive replacement of pre-existing mineralogy by massive illite ± sudoite, bleached chlorite, and minor sericite; (B) Transmitted light composite photomicrograph in crossed (top) and plane (bottom) polarized light of strongly argillized pelitic gneiss (RB26053; 208.9 m, DDH 09-116), showing pervasive replacement of pre-existing mineralogy by bleached chlorite, a fine-grained mix of illite and minor sudoite (Ill & Sud) and sericite (Ser) with rare preservation of ghost chloritized biotite (Chl), with rutile (Rt) along cleavage planes. (Originals in colour)
Dissolution of quartz and alteration of silicate minerals is intimately associated with argillization, as desilicification creates pore space for fluid flow that is subsequently filled by illite±sudinite, chlorite, hematite, or goethite. Desilicification is weak to moderate outside of a zone of ca. 15 m from the RWZ, and is characterized by dissolution pits in quartz pebbles and up to 75% dissolution of the quartz clasts in the sandstone (Figures 4.12, 5.10). In the basement rocks, silicate minerals appear corroded, and drill core competency decreases. Strong desilicification consists of 75 – 100% dissolution of quartz and all other silicates, leaving massive illite±sudinite with or without chlorite, hematite, limonite, and various sulphide minerals (Figures 4.12, 5.11, 5.12, 5.13).

Bleaching is an empirical term used to refer to the removal of colour (and usually hematite) from the rocks during fluid alteration/migration. Mineralization-associated bleaching results predominantly from the complete removal of hematite or limonite from host rocks that have been affected by reduced ore fluids. Bleaching causes the affected rocks to become buff to white or pale grey,
effectively masking their mineralogy. Bleaching is variable, but is generally spatially associated with uranium mineralization in the RWZ, and is best defined in the mineralization-proximal lower MFb. Moderate to strong bleaching removes the primary purple hematite leisengang, leaving buff to white pebbly quartz arenite. Strong bleaching manifests as pale grey sandstone, which is also associated with the presence of micron-sized “sooty” pyrite (Figure 5.15). Bleaching of the basement rocks is difficult to establish, given their alteration to buff or pale grey clay, or pervasive hematite alteration. Identification of local bleached haloes around fractures in the basement granitoids from drill core distal to RWZ suggests that bleaching may not be exclusively associated to uranium mineralization (Figure 4.4).

Hematization comprises the bright red to deep maroon precipitation of remobilized hematite and/or its partial to pervasive staining of clays in strongly argillized host rocks. Hematite alteration is closely tied to uranium mineralization at the RWZ, especially within ca. 10 – 15 m above the deposit, and is rarely observed below RWZ mineralization. Deep red coloured soft hematite alteration typically occurs with illite as a fracture lining and as a partial to pervasive stain of the illitized rocks proximal to mineralization. Massive deep red indurated hematite also locally replaces the host rock and stains uranium mineralization. Moderate hematite alteration presents as fracture lining, pink to bright red partial to total stain of argillized rocks, and as an overprinting stain with an irregular, mottled appearance (Figure 4.12).
Figure 5.15: Photographs of moderately argillized MFb quartz arenite: (A) core sample RB26006 (205.5 m, DDH 09-094), showing strong pervasive bleaching, and pale grey sooty pyrite alteration (bottom of sample), and (B) Reflected light photomicrograph in plane polarized light of moderately argillized quartz arenite sample RB26053 (208.9 m, DDH 09-116), showing partial dissolution of quartz (Qtz) clasts and matrix, and precipitation of fine grained illite (Ill) and pyrite (Py), with minor hematite (Hm) stain. (Original in colour)

Strong pervasive replacement of the host rocks by indurated hematite sometimes preserves their original fabrics, or will overprint them with mm-sized sub-vertical TCA laminations. Strong, localized hematite alteration also occurs with uraninite in fractures, along the transition from oxidation to reduction, or hosts mm- to cm-sized uraninite nodules rimmed by illite and limonite (Figures 5.16, 5.17, 5.18). Immediately below the deposit, approximately 50 m below the unconformity, hematite alteration generally disappears and is rarely observed again, except as rare partial stain of potassium feldspar crystals, or fracture lining.

Limonite alteration is the partial replacement or remobilization of yellow or beige goethite, or its alteration from hematite in both the MFb and in the basement rocks.
Figure 5.16: Photograph of strongly argillized pelitic gneiss (greyish core) from DDH 09-091, with fracture-hosted uranium mineralization and associated yellow goethite and red hematite alteration (red boxes). White tags mark geochemical half core assay sample intervals, wood blocks and green numbers indicate drill hole depth from surface, red writing indicates radioactivity, in cps. (Original in colour)

Figure 5.17: Zoomed in photograph of fracture-hosted uranium mineralization highlighted in the red boxes from Figure 5.15 above. A strongly argillized grey pelitic gneiss contains several fractures at 65° TCA that have been infilled by black uraninite (red arrow). Alteration associated with the fracture transitions from uraninite replacement into red hematite then yellow goethite (orange arrow) and back into red hematite (yellow arrow). Another uraninite – lined fracture (dark red arrow) is present at the same orientation, also surrounded by red hematite (blue arrow) and beige goethite (green arrow). A third uraninite – lined fracture (pink arrow) is intersected in strongly argillized pelitic gneiss, without any associated iron oxide alteration. (Original in colour)

Goethite in the RWZ is more prominent in the sandstone directly overlying uranium mineralization, and surrounding uraninite with hematite alteration in the basement rocks. It is not significantly observed otherwise.
Figure 5.18: Drill core photographs of disseminated low grade uranium mineralization in a strongly hematized and argillized pelitic gneiss (DDH 09-156): (A) Pelitic gneiss sample RB31011 represents strongest degree of hematite (red) and illite (red stained and white) alteration, with lesser goethite (beige) alteration. Finely disseminated uraninite is intergrown with and rimmed by illite, which is also outlined by beige goethite and mm-sized rutile. Alteration is locally strong enough to destroy grain boundaries and foliation was not preserved (240.9 m); (B) A similar sample 0.5 m away from (A) shows the same strong degree of hematite and illite alteration, weakly defined goethite, also evidencing pervasive replacement that destroys grain boundaries and does not preserve foliation (241.4 m). (Original in colour)

Goethite alteration is rarely strong, occurring in the sandstone as a stain of 10 – 25% of the argillized core (Figure 4.11), partial fracture lining with hematite and/or illite, or sometimes, as up to one metre pervasive beige alteration of strongly fractured sandstone with hematite and/or illite overlying mineralization. In the basement rocks, goethite is observed with uraninite and/or hematite in fractures (Figures 5.16, 5.17) or forms mm-sized haloes with illite around small uraninite blebs hosted in massive hematite (Figures 5.18, 5.19).
Chlorite alteration associated with mineralization at the RWZ occurs in two forms: (1) as pale green to bleached, very fine grained sudoite intergrown with illite (included as argillization); and (2) as medium to dark green chlorite that replaces biotite, garnet, amphibole, pyroxene, and cordierite. The former is the more common mineralization-associated chloritic alteration at RWZ (Figures 5.11, 5.12, 5.13, 5.20A, B, C) and is only identified from polished thin section study, PIMA, and EPMA, as its pale colour and fine-grained habit renders it impossible to identify in hand sample. It is poorly developed above the unconformity, occurring only immediately proximal to mineralization. Sudoite alteration is more common in the basement rocks, especially in strongly argillized pelitic gneisses immediately proximal to uranium mineralization. Characteristic dark green chlorite alteration, also best developed in the pelitic gneisses proximal to uranium mineralization, is absent above the unconformity (Figures 5.20B, D).
Figure 5.20: Backscattered secondary electron images (BSEI) of strongly altered pelitic gneisses: (A) illustrating the fine-grained and intergrown nature of illite and sudoite (Ill & Sud) in the samples at RWZ (RB26080; 248.3 m, DDH 09-131); (B) intergrown illite (Ill) and sudoite (Sud) altering pre-existing mineralogy. Defining foliation across the centre of the image is dark green chlorite (Chl), which has replaced biotite (RB26089; 350.0 m, DDH 09-131); (C) weakly mineralized pelitic gneiss has fine-grained and intergrown illite and sudoite with hematite (Hm, Ill & Sud), and fine grained kaolinite (Kao) rimming uraninite (Ur; RB31050; 241.6 m, DDH 09-131); (D) replacement of biotite by relatively coarse-grained chamosite (Chl), intergrown with rutile (Rt) and corroded cobaltite (Co; RB26089; 350.0 m, DDH 09-131).

It alters metamorphic mafic silicates and lines fractures in the pelitic gneisses (Figures 5.20B, D, 5.21). In the granitoid rocks, dark green chlorite replaces amphibole, pyroxene, and biotite, but as these minerals make up a relatively small proportion of the rocks, dark green chlorite alteration is less prevalent.
De-graphitization has also been observed as a mineralization-associated alteration. It is characterized by the dissolution of graphite and precipitation of rutile in the host pelitic gneisses. Graphite is generally only present in significant proportions in the pelitic gneisses and has previously been considered a pathfinder mineral for unconformity-type uranium deposits. At the RWZ however, it has been repeatedly observed in core and in doubly polished thin sections that uranium mineralization is associated with the absence of graphite, such that within 1 – 5 m of high grade uranium mineralization, graphite disappears (Figure 5.22). Uraninite and graphite are only rarely observed in the same thin section, each present as trace disseminations, and are not observed together in core at RWZ throughout the scope of this project.
Within the alteration zone around the RWZ deposit, however, there are many fractures in the pelitic gneisses that are lined with graphite with slickenstriae, suggesting the possibility that it behaved as a lubricant to facilitate the creation or remobilization of brittle structures, thus indirectly facilitating uranium mineralization.

Carbonatization encompasses minor local post-ore alteration or replacement of argillized pelitic gneisses by coarse, euhedral ankerite and/or dolomite veins and veinlets often also containing associated sulphides, sulpharsenides, and quartz. It also comprises fine-grained euhedral or anhedral late ankerite, calcite, and siderite alteration intergrown with illite and chlorite in strongly altered pelitic gneisses. Carbonate alteration appears to be spatially
restricted to the pelitic gneisses within and around uranium mineralization, however, the extent of this alteration relative to the RWZ has not been delineated. At the RWZ, carbonatization has been identified as paragenetically late, occurring predominantly as veins and veinlets that cross-cut uraninite, and locally alter it to a secondary uranium carbonate mineral rutherfordine \([\text{UO}_2\text{CO}_3]\). These veins may also contain variable amounts of galena, pyrite, sphalerite, marcasite, and/or gersdorffite, as well as minor drusy quartz (Figure 5.23), as it is paragenetically associated with minor post-ore silicification and uranophane alteration described above. Fine-grained carbonate alteration is observed as anhedral to euhedral ankerite, calcite, and siderite filling void space or replacing illite, sudoite, and chlorite in some of the strongly altered pelitic gneisses with rutherfordine and/or uranophane (Figure 5.24). Coarse-grained ankerite is also observed in one sample to fill pore space in a pervasively argillized and strongly hematized pelitic gneiss, with specular hematite, fine-grained euhedral pyrite, and trace micron-sized euhedral siderite and tourmaline (Figure 5.25).
Figure 5.23: Thin section photomicrographs of strongly argillized and carbonatized weakly graphitic pelitic gneiss (RB26040; 278.9 m, DDH 09-101). (A) Timing relationship between earlier galena (Gn) and later sphalerite (Sl), with last formed marcasite (Mr) along cracks in sphalerite grain, all within ankerite (Ank) and minor quartz (Qtz) vein; (B) fine- and coarse-grained euhedral ankerite around colloform sphalerite, with minor quartz at the edge of sphalerite. (Originals in colour)

Figure 5.24: Transmitted light thin section photomicrographs of late carbonatization in strongly altered, mineralized pelitic gneiss (RB31016; 240.6 m, DDH 10-200). (A) Plane polarized light photomicrograph of late anhedral bleby uraninite (Ur) that cross-cuts a uranophane (Urph) veinlet, set in a carbonate, illite (Carb & Ill), and uranophane matrix, with minor hematite (Hm) stain; (B) Photomicrograph with polars crossed of uraninite (Ur) and hematite-stained (Hm) rutherfordine (Ruth) laths in carbonate, illite (Carb & Ill), and uranophane (Urph) matrix, which also has minor hematite stain. (Originals in colour)
Figure 5.25: SEM BSEI of a strongly argillized, hematized, and carbonate-altered pelitic gneiss (RB26055; 219.7 m, DDH 09-116). Void space created by dissolution and clay alteration (Ill & Sud) and chlorite (Chl) is infilled by specular hematite (Hm) and euhedral ankerite (Ank) rhombs with hematite-stained growth zones, and micron-sized pyrite (Py) inclusions.

5.3 Uranium mineralization

Four different styles of uranium mineralization have been documented at RWZ (Figure 5.26), based on detailed petrographic analysis of core and polished thin sections: (1) Massive, (2) “Wormrock”, (3) Fracture – hosted, and (4) Disseminated, each of which is locally monometallic (Figure 5.26A), or polymetallic (Figure 5.26E). Each mineralization style is defined by unique textures, mineral associations, and paragenetic relationships. Massive mineralization occurs as void space infilling or pervasive replacement of an interval of faulted pelitic gneiss or (Figure 5.26A), less commonly, granite. It is bound on either side by fractures at 5° – 30° TCA or 65° – 80° TCA that are lined with illite, uraninite, goethite, hematite, or some combination of those minerals.
Figure 5.26: Drill core photographs of four styles of uranium mineralization at RWZ, including monometallic and polymetallic examples: (A) Massive monometallic botryoidal void-space filing mineralization (RB31039; 248.5 m, DDH 09-116); (B) Disseminated monometallic black micron-sized blebs of uraninite in pervasively argillized pelitic gneiss (RB31044; 242.9 m, DDH 10-179); (C) Wormrock monometallic mineralization: black uraninite is surrounded by a halo of illite, rimmed by yellow goethite, hosted in a completely hematized pelitic gneiss (RB31041; 237.6 m, DDH 10-179); (D) Monometallic, fracture-hosted, black uraninite also partially replaces the surrounding strongly argillized pelitic gneiss, with beige goethite alteration. Uraninite is altered to yellow uranophane (bottom) (RB31048; 239.2 m, DDH 09-131); (E) Massive polymetallic replacement mineralization contains anomalous nickel, uranium, cobalt, and copper (RB31001; 234.8 m, DDH 08-018. (Originals in colour)

Massive uranium mineralization is defined by euhedral to subhedral mm- to cm-sized, homogeneous uraninite botryoids and subordinate cubic grains that may have resulted from the pseudomorphous replacement of pyrite (Figure 5.27).
EPMA analysis revealed that uraninite botryoids are composed of micron-sized acicular radiating crystals of uraninite (Figure 5.28). Fine-grained euhedral cubes and veinlets of galena cross-cut botryoidal uraninite and massive anhedral galena cements cubic uraninite, as well as rare euhedral twinned cubic pyrite. Also locally identified, often in trace amounts, are disseminated copper minerals, as rare mm-sized inclusions of chalcopyrite in uraninite botryoids (Figure 5.29), and as trace chalcocite and subordinate covellite partial replacement of uraninite cubes and botryoids along their edges proximal to galena (Figures 5.27B; 5.29B).

Wormrock is an informal name bestowed on uranium mineralization when small blebs of uraninite precipitate in a pervasively argillized and hematized host rock, usually pelitic gneiss (Figures 5.19, 5.26B). The round, equant to elongate blebs of uraninite can range from mm- to cm-scale, and lend a wormy appearance to the core. Microscopic analysis shows micron-sized wispy blebs of uraninite are intergrown with or pseudomorph illite and sudoite.
Figure 5.28: BSEI of a uraninite botryoid composed of fine-grained radiating fibrous uraninite (Ur). Darker grey alteration around the edges and near core is coffinite (Cof) alteration (RB31039; 248.5 m, DDH 09-116).

Figure 5.29: Reflected light photomicrographs in plane polarized light of uraninite (Ur) botryoids from massive, void space filling uraninite: (A) Uraninite botryoid with inclusions of yellow chalcopyrite (Cpy) and pale grey galena (Gn) at the core (RB31039; 248.5 m, DDH 09-116) (B) Example of altered polymetallic mineralization; a uraninite botryoid (Ur) has been almost entirely pseudomorphed by covellite (deep blue) and chalcocite (grey to pale blue; CC & Cov) and is rimmed by fine-grained white galena (Gn), all of which is surrounded by fine-grained anhedral uraninite (Ur) with inclusions of galena (RB31004; 311.1 m, DDH 08-037). (Originals in colour)

Uraninite is surrounded by mm-sized halo of white kaolinite, rimmed by intergrown illite and orange to beige goethite (Figures 5.20C, 5.30). The rest of
the host rock consists of intergrown illite, sudoite, and hematite, with disseminated rutile (Figures 5.20C, 5.30).

Fracture-hosted mineralization is characterized in hand sample by fractures oriented either 10° – 30° TCA, or 65° – 75° TCA that are lined with uraninite and sometimes, hematite and goethite (Figure 5.26C). Uraninite often also replaces a portion of the surrounding rocks (usually pelitic gneisses), then grades outward into goethite alteration followed by deep red hematite and clay alteration, when present, and then into massive pale grey to buff illite±sudoite (Figures 5.16, 5.17).

The main uraninite phase has been identified as fine-grained, heterogeneous, locally laminated uraninite with trace coffinite that fills numerous micro-fractures (Figure 5.31). These veinlets cross-cut fibrous intergrown uraninite and illite±sudoite, or illite±sudoite intergrown with hematite and are often associated with brecciated mm- to micron-sized fragments of pyrite, galena, chalcopyrite, skutterudite [(Co, Ni, Fe)As₃], and gersdorffite [NiAsS]. The fracture-hosted and disseminated styles of mineralization are the only ones identified to depict a close spatial association with yellow uranophane alteration (Figure 5.32).
Figure 5.30: Composite transmitted and reflected light photomicrograph in plane polarized light of fibrous uraninite (Ur) intergrown with illite (Ill) (centre), with a halo of white illite, rimmed on the right edge by beige goethite (Goe), all of which is hosted in fine-grained intergrown illite and hematite (Hm & Ill). Subhedral rutile (Rt) crystals overprinting illite and hematite (bottom) are also visible (RB31011; 240.9 m, DDH 09-156). (Original in colour)

Figure 5.31: Photomicrographs of uraninite veinlets (RB31048; 239.2 m, DDH 09-131). (A) Reflected light image in plane polarized light of a uraninite (Ur) veinlet with euhedral chalcopyrite (Cpy) that cuts intergrown hematite (Hm) and illite (Ill), which is subsequently cut by a heterogeneous uraninite veinlet. Numerous micro-veinlets of uraninite are also visible, as well as minor galena. (B) BSEI of finely laminated uraninite (Ur) and coffinite (Cof) filling void space in a fracture. Image also shows heterogeneous nature of associated uraninite replacement of host rock, and evidence of re-fracturing of a pre-existing uraninite veinlet. (Originals in colour)
Disseminated uranium mineralization is characterized by fine-grained equant anhedral blebs of uraninite, or uranium alteration minerals such as uranophane or rutherfordine, intergrown with, and usually hosted in, massive illite, chlorite, and/or hematite (Figure 5.26D). Uranium mineralization is often not visible in hand sample and is identified on the basis of elevated scintillometer readings. When visible in hand sample, uraninite is restricted to equant, mm-sized black blebs in massive illite±sudoite, which may also be pervasively hematized. Doubly polished thin section analysis shows anhedral wispy blebs of uraninite, locally intergrown with illite±sudoite (Figure 5.33A), often with micron-sized inclusions of galena.
Disseminated uraninite can also display complex intergrowth or replacement textures with partially corroded base metal sulphides, such as pyrite, chalcopyrite, nickeline [NiAs], and skutterudite (Figures 5.33B, C, D). Some doubly polished thin sections of uranium mineralization that contained no visible uraninite were found to be composed of 5 – 25% uranium carbonate alteration minerals uranophane and/or rutherfordine, in massive intergrown illite and/or
chlorite with disseminated fine- to coarse-grained carbonate minerals (Figures 5.24, 5.33). Uranophane commonly pseudomorphs anhedral uraninite grains or euhedral uraninite botryoids, and occurs as veinlets, often with carbonate, and sometimes with hematite staining, that cross-cut uraninite botryoids and veins. Micaceous euhedral rutherfordine usually overprint or take advantage of void space in massive illite, sudoite, and chlorite, often with minor intergrown carbonate, and are sometimes stained by hematite (Figure 5.34).

As previously mentioned uranium mineralization at RWZ is locally polymetallic (Figures 5.26E, 5.33B, 5.33D), characterized by elevated Ni, Cu, Co, As, Zn, and Mo. Most of these base metals form as a variety of Ni, Cu, Co, and Zn sulphides, arsenides, and sulpharsenides that illustrate complex paragenetic and spatial relationships to uraninite.

Elevated concentrations of molybdenum were also locally identified as deep cerulean blue oxidation in core, however no Mo-bearing mineral phases were identified in these samples. As such, it was not possible to determine the spatial and paragenetic relationships between molybdenum and uranium minerals.

The Ni sulphide, arsenide, and sulpharsenide minerals identified in this study are nickeline, skutterudite, gersdorffite, and, uncommonly, vaesite. These fine-grained silver to pinkish metallic minerals are difficult to identify in hand sample, as they usually appear to be intergrown with dull black uraninite.
Figure 5.34: Transmitted light thin section photomicrograph in plane polarized light of a strongly chloritized pelitic gneiss with weak to moderate illite, dark green chlorite, and carbonate alteration (RB31014; 259.4 m, DDH 10-200). Euhedral laths of micaceous rutherfordine (Ruth; high relief) overprints chlorite and illite (Chl & Ill) with small anhedral disseminated galena (Gn). (Original in colour)

In doubly polished thin section, nickeline, skutterudite, and minor vaesite are usually intergrown, forming euhedral micro-colloform cubes and anhedral grains (Figure 5.35). These minerals often have anhedral inclusions of uraninite, are rimmed by fine-grained uraninite, or rarely are partially pseudomorphed by uraninite (Figures 5.33B, D). Nickel-bearing minerals were not observed proximal to euhedral botryoidal uraninite, but skutterudite and rare nickeline fragments were identified near or within uraninite-lined fractures.

Copper mineralization can be locally significant in whole rock assay data, but is uncommonly observed in core as it dominantly occurs as mm- to micron-sized inclusions in or alteration around uraninite in all the different mineralization styles (Figures 5.29, 5.31A).
Chalcopryite is also commonly disseminated throughout the host basement rocks. Copper-rich uranium mineralization is represented by anhedral chalcopryite in the cores of uraninite botryoids in massive mineralization (Figure 5.29), as well as local covellite and chalcocite alteration of remnant pyrite cubes pseudomorphed by uraninite (Figure 5.27B). Wormrock and disseminated mineralization usually contains trace micron-sized chalcopryite fragments randomly disseminated in the argillized host rock around fine-grained uraninite. Euhedral micron-sized chalcopryite is also observed in some of the fracture-hosted uraninite veinlets (Figure 5.31A), and as fragments disseminated with, or partial replacement of other sulphides/sulpharsenides in the intergrown hematite or uraninite and illite±sudoite-altered host rocks (Figure 5.36).

Cobalt and zinc are less common at RWZ (maximum assays of 2.8% and 5%, respectively).
Figure 5.36: Reflected light plane polarized thin section photomicrograph of a strongly altered, mineralized pelitic gneiss (RB31037; 267.4 m, DDH 09-129). Fracture cross-cutting intergrown fine-grained uraninite and illite (Ur & Ill), and contains anhedral chalcopyrite (Cpy) with cores of skutterudite (Skut), evidencing pseudomorphic replacement of skutterudite by chalcopyrite. (Original in colour)

Cobalt, in skutterudite and as cobaltite [CoAsS], is only observed with nickel minerals, as cobaltite, nickeline, and skutterudite have a close spatial and temporal relationship. Skutterudite is often being altered to nickeline or cobaltite around fractures and grain boundaries, along with minor disseminated uraninite (Figure 5.37). Conversely, sphalerite is exclusively associated with galena and marcasite in quartz-ankerite veins in altered pelitic gneisses (Figure 5.23A). It is never observed with uraninite or even with uranyl-carbonate alteration minerals. Sphalerite overprints cm-sized anhedral galena, and is rimmed by euhedral to subhedral marcasite (Figure 5.23A). Galena is rimmed by euhedral gersdorffite encrusted with marcasite. Trace micron-sized subhedral skutterudite with cores of cobaltite are also disseminated in the vein.
Figure 5.37: Reflected light thin section photomicrograph in plane polarized light of polymetallic wormrock (RB31002; 308.8 m, DDH 08-037). White anhedral to colloform skutterudite (Skut) is being altered to pink nickeline (Nk) and greyish violet cobaltite (Cob) along grain edges and fractures. Skutterudite also contains inclusions of corroded uraninite (Ur) cubes. Fine-grained uraninite has also precipitated along some microfractures. (Original in colour)

5.4 Paragenesis

The relative timing of minerals, or paragenetic sequence, is established based on cross-cutting relationships observed in thin sections as well as in cores. The sequence is divided into the following stages or mineral assemblages: 1) metamorphic and magmatic minerals in basement rocks, 2) pre-Athabasca basin alteration of basement rocks, 3) detrital minerals of the Athabasca Group, 4) diagenesis of the Athabasca Group, 5) uranium mineralization and associated alteration, and 6) uranium remobilization and associated alteration, as summarized in Figure 5.38 and described below.
Figure 5.38: Paragenetic sequence for alteration and uranium mineralization of the RWZ of the Roughrider unconformity-type uranium deposit, Athabasca Basin, SK. (Original in colour)
Metamorphic and magmatic minerals in the basement rocks are listed without determining their relative timing (Fig. 5.38), as they resulted from a long and complex geologic history that is unrelated to uranium mineralization and not examined in detail in this study. Pre-Athabasca Basin, post-deformation and regional metamorphism alteration of the basement rocks is represented by the saprolitic paleoweathering profile that occurs at and 20 to 30 metres below the unconformity, preserving evidence of subareal exposure. The paleoweathering profile is defined by illite and kaolinite alteration at the expense of plagioclase, potassium feldspar, cordierite, garnet, and muscovite that was subsequently bleached, followed by hematite staining and alteration, marking the oxidized red zone which transitions gradually into the green chlorite alteration at the expense of garnet, biotite, amphibole, and clinopyroxene that defines the reduced green zone.

Diagenesis in the Athabasca Basin rocks comprises minor compaction, evidenced by the presence of long and concavo-convex contacts between the quartz clasts as well as the presence of moderate porosity, which also caused a minor (< 5%) amount of quartz overgrowth cement. Continued diagenesis resulted in the precipitation of illite. Minor dissolution is evidenced as small dissolution vugs in the quartz clasts. Replacement or alteration is contentiously suggested to have occurred in the form of argillization, initially as sericite and illite after any feldspars that may have originally been present in the sandstone.

The mineralization and alteration phase of the paragenetic sequence (Figure 5.38) can be further subdivided into pre-primary ore alteration, primary
mineralization, and post-primary pre-remobilization alteration. Pre-primary ore alteration comprises substantial quartz dissolution in both the sandstone and the basement rocks. It is also defined by illite, sericite, and sudoite, which alter and replace diagenetic dickite and fill pore space in the lower MFb, and alter plagioclase, potassium feldspar, and cordierite in the basement rocks. Pre-ore dark green chlorite replaces biotite, garnet, amphibole, and clinopyroxene in the basement rocks, and is not observed above the unconformity (Figure 5.38). The presence of pre-existing chalcopyrite is also inferred from its presence in the core of some uraninite botryoids (Figure 5.29). Dissolution of graphite is inferred to have taken place prior to and during uranium mineralization, as suggested by the absence of graphite in the mineralized zone. Graphite dissolution may have provided reductants (e.g., CH₄) which were readily used for uranium ore precipitation in the primary mineralization stage.

Primary mineralization is defined by the precipitation of two distinct primary phases of uraninite (U1 and U2), along with sericite, chlorite, illite, pyrite, rutile, hematite, goethite, galena, chalcopyrite, nickeline, skutterudite, cobaltite, gersdorffite, chalcocite, covellite, and vaesite. The earliest uraninite mineralization (U1) is defined by euhedral botryoids and cubes of uraninite with minor coffinite alteration that coincide with the massive void-space filling style of mineralization (Figures 5.26A, 5.27, 5.28, 5.29). The second uranium mineralization (U2) is identified as a primary uranium mineralization event on the basis of its homogeneity, and is defined by fine-grained anhedral to sub-botryoidal uraninite that commonly characterizes some of the wormrock
mineralization style, and to a lesser extent, the disseminated mineralization style as well (Figures 5.11, 5.18, 5.19, 5.30, 5.33A).

The first syn-primary mineralization base metal mineral is post-U1 and pre-U2 galena that rims some U1 botryoids, cuts them as micro-veinlets, and cements U1 cubes (Figure 5.29). Galena from this point forward is inferred to have precipitated discontinuously throughout uranium mineralization and alteration, as the daughter product phase of the decay of uraninite. Illite and sudoite are intergrown with U2, suggesting post-U1 co-precipitation for these clay minerals (Figures 5.30, 5.33A). Sericite is sometimes noted proximal to U2 with illite-sudoite in wormrock, and is inferred as syn-illite-sudoite, and syn-U2. Gersdorffite and skutterudite appear to locally rim and replace U1 cubes, suggesting they are post-U1. Inclusions of U2 intergrown with illite and sudoite suggest the sulpharsenides and arsenides are syn-U2 (Figures 5.36, 5.38). Nickeline and cobaltite form as alteration around the edges of and in fractures in skutterudite, and are sometimes intergrown with illite, sudoite, and U2, suggesting these minerals are late syn- to post-skutterudite and syn- to post-U2 (Figure 5.37). Vaesite also appears to alter nickeline and gersdorffite, and as such is inferred as an early post-U2 (Figure 5.33B). Some subhedral to euhedral chalcopyrite has inclusions of skutterudite which implies post-U2 copper remobilization but it is also observed as inclusions and fragments in remobilized ore, and therefore has been interpreted as pre-U3 (Figure 5.31A). The paragenesis of covellite and chalcocite is difficult to determine with certainty, as they are only noted as alteration around U1 cubes and corroded botryoids,
therefore rendering them post-U1 (Figures 5.27B, 5.29B). Confident constraint on their timing beyond this is not possible, as the only other mineral that can restrict their timing is galena, which has precipitated discontinuously since U1. As such, the chemical composition of covellite and chalcocite necessitate an influx of copper into the system, leading to the suggestion that these minerals formed from alteration of pre-ore chalcopyrite during the syn- to early post-U2 copper enrichment phase defined by chalcopyrite. Trace amounts of goethite rim U2 in the illite-sudoite assemblage, resultant from the oxidation of remnant pre-ore hematite that was not leached away by the mineralizing fluids. Disseminated subhedral to euhedral late syn-U2 rutile is not overprinted by syn-U2 illite and sudoite, but is frequently observed in illite and goethite proximal to U2, overprinting bleached zones where pre-ore hematite was remobilized.

Post-ore remobilization and alteration comprises at least four phases of uranium remobilization, uranophane and rutherfordine alteration of uraninite, and a host of associated alteration minerals, including quartz, sericite, dravite, carbonate (ankerite), sphalerite, kaolinite, illite, pyrite, rutile, hematite, marcasite, and siderite (Figure 5.38). Remobilized uraninite was identified based on cross-cutting relationships with other minerals, crystal habit, and its heterogeneity in EPMA analyses. Uraninite remobilization is associated with fracture-hosted and disseminated mineralization styles, as U3 – U5 coincide with another phase of brittle reactivation of earlier structures, or the creation of new fractures and faults. The first remobilization phase, U3, is characterized by anhedral massive uraninite with fine-grained galena inclusions that post-dates the altered U1 botryoids
(Figure 5.29B), and as partial pseudomorphs of brecciated and mobilized sulphides and arsenides (Figures 5.33B, C, D). Heterogeneous vein-type fracture fill uraninite and minor coffinite have been identified as U4 and U5, which cross-cut U1, U2, U3, syn-U2 hematite and illite-sudoite, as well as each other (Figure 5.31). Micron-sized inclusions of galena are relatively common in both U4 and U5. The last uraninite remobilization event (U6) is a minor, anhedral phase that is difficult to recognize. Identification of U6 was on the basis of its cross-cutting relationship to uranophane veinlets that cross-cut U4 and U5 (Figure 5.24B).

Brittle reactivation of structures resulted in the mobilization of brecciated skutterudite, pyrite, chalcopyrite, and nickeline, and also precipitated pre-U3 euhedral galena. Syn-U3 illite-sudoite and hematite are locally intergrown with or in close proximity to U3, and hematite and euhedral to subhedral rutile are present in or around the edges of some of the fractures with the brecciated sulphides and sulpharsenides. This syn-U3 rutile phase also occurs immediately proximal to U3, suggesting they precipitated from the same fluid. Micron-sized euhedral chalcopyrite inclusions in U4 veinlets (Figure 5.31A) confirm a syn-U4 copper mineralization event.

Carbonate alteration is observed as: (1) local to pervasive replacement of illite-sudoite and dark green chlorite alteration by carbonate minerals or void space filling around these clays, co-incident with rutherfordine (Figure 5.24B); (2) coarse-grained void space-filling ankerite with specular hematite and micron-sized pyrite (Figure 5.25); and (3) as large veins with galena, pyrite, gersdorffite, sphalerite, marcasite, and minor drusy quartz (Figures 5.23, 5.24A). Local to
pervasive carbonate alteration is cross-cut by carbonate veinlets that cross U4 – U5, but are cut by anhedral bleby U6, thus constraining carbonate alteration to post-U4 – U5 and pre-U6. This carbonate alteration and replacement of clay minerals is associated with the alteration of uraninite to rutherfordine, both of which are locally variably stained with hematite (Figure 5.24A). Uranophane alteration, associated with late silicification, is also spatially and temporally related to extensive carbonate alteration, as these two minerals have replaced some of the early illite-sudoite alteration in a strongly argillized and fractured pelitic gneiss (Figure 5.24A). As such, uranophane, silicification, and fine-grained carbonate replacement of clays have also been inferred as post-U4 – U5 and pre-U6. Euhedral ankerite fills dissolution vugs in argillized and dolomitized pelitic gneiss, along with specular hematite and micron-sized pyrite (Figure 5.25), further preserving evidence of post-U4 – U5, pre-U6 hematite and pyrite precipitation. Illite-sericite and kaolinite micro-veinlets cross-cut carbonate alteration which restricts their precipitation to post-U5 however, they are not constrained by any later mineral phase. Large veins of post-U4 – U5 ankerite with radiogenic galena, sphalerite, and marcasite, with minor drusy quartz (Figure 5.23A) formed during carbonatization, however the presence of drusy quartz has led to the suggestion that these sulphides precipitated toward the end of carbonatization, and the start of silicification (Figure 5.38). Tourmaline, micron-sized euhedral siderite, and some rutile do not intersect, nor are they cross-cut by other late alteration minerals that could be used to constrain their paragenesis. Siderite is presumed to have precipitated with the post-U5 pre-U6
carbonate and hematite alteration. The presence of gersdorffite encrusting the edges of pyrite in quartz veins and the edges of galena in carbonate veins, combined with the presence of drusy quartz in the post-U5 pre-U6 ankerite vein, further suggest that silicification took place syn- to early post-carbonatization, thereby making the drusy quartz-pyrite±chalcopyrite veins a pre-U6 alteration phase. Euhedral, pristine tourmaline and rutile crystals are present in the carbonate and clay matrix, suggesting they precipitated either with, or after carbonate alteration which, combined with a lack of evidence for any later phase of mineral growth or alteration, resulted in their identification as a post-carbonate, post-U6 last alteration phase (Figure 5.38).
6. SPATIAL MODEL OF CLAY ALTERATION

Complimentary to the detailed microscopic descriptions of mineralization-associated alteration in Chapter 4, a spatial model of clay alteration encompassing the RWZ was constructed to provide a property scale delineation of the extent of mineralization-associated illite and chlorite alteration. The clay alteration model comprises 49 north–south, east-facing cross-sections set 10 m apart and 86 west–east, north-facing cross-sections set 5 m apart that transect the RWZ segment. To avoid redundancy, only three representative cross-sections that transition along strike across uranium mineralization will be included here. Their locations relative to uranium mineralization are delineated in Figure 6.1.

Mineralization-associated illitization outlined in these cross-sections defines a broad chimney shape in the sandstone that is traceable to the current surface and is particularly concentrated directly above uranium mineralization. The chimney is most prominent proximal to the unconformity and has increased lateral reach along the Marker Conglomerate as well. Even outside of the RWZ, illite-dominant argillization is traceable in all of the cross-sections to the present day erosional surface despite the fact that mineralization-associated argillization is poorly represented in core above the Marker Conglomerate, as outlined in Section 5.2.

In the basement, argillization outside of the RWZ forms a poorly defined sag that does not extend to depth below the unconformity.
Illite-dominant clay alteration within and around uranium mineralization defines an inverted cone shape that extends downward 210 m below the unconformity, but is most expansive near it and around mineralization. Chlorite alteration associated with uranium mineralization at RWZ, only observed below the unconformity, occurs within the inverted cone shape defined by argillization but does not follow this pattern. Alternatively chloritization shows its affinity to uranium mineralization at RWZ by occurring predominantly in the WSPG and defining isolated north – south elongate alteration pods that are either
subhorizontal, or sometimes appear to dip north or south, perhaps outlining the structures associated with uranium mineralization.

6.1 Clay alteration outside of the RWZ mineralization

Immediately outside of the RWZ, diagenetic dickite in the narrow alteration chimney is locally replaced by mineralization-associated illite in the sandstones, especially where they directly overlie the faulted WSPG (Figures 6.2, 6.3). Illite-dominant mineralization-associated argillization in core is moderate in the lower MFb, as fracture linings, sometimes with hematite or goethite, replacement of dickite, and local void space-filling of quartz dissolution vugs (Section 5.2). Conversely, the upper MFb and MFc quartz arenites contain only trace argillization as interstitial replacement of dickite.

Basement argillization to the west of the RWZ is constrained to the upper portion of the WSPG and does not extend beyond ca. 75 m below the unconformity (Figure 6.2). It is generally only expressed as the weak to moderate replacement of feldspars, cordierite, and micas, and as a fracture lining, but can be locally extensive, associated with quartz dissolution and moderate deep red hematite alteration in and around fractures (Section 5.2).

Mineralization-associated chlorite alteration in the basement west of RWZ is absent, as it is typically only represented in the immediate vicinity of mineralization. Kaolinite alteration, associated with the uppermost portion of the paleoweathering profile, is narrow, defined only along the unconformity, except where overprinted by mineralization-associated argillization. As such, kaolinite alteration is referred to as the “kaolinite paleo-unconformity” (KPU).
Figure 6.2: North – south, east-facing cross-section S-250W illustrating geology and distribution of clay alteration at Roughrider West, constructed from PIMA and normative clay calculations derived from core samples. S-240W is perpendicular to strike of the RWZ, located approximately 5 m away from the western edge of mineralization. PW Profile = Paleoweathered profile. Red shades on drill holes indicate >80% illite (<20% dickite), yellow and peach indicate 50 – 80% illite (20 – 50% dickite), blue and green shades indicate 0 – 50% illite (>50% dickite). See text for detailed descriptions. (Original in colour)

For the sake of clarity and cohesiveness among the cross-sections, the paleoweathering profile was not subdivided into the red, red-green, or green zones. As noted in Figure 6.2, the paleoweathering profile and KPU are only
locally overprinted by illitic argillization in a narrow zone where the WSPG occurs at the sandstone unconformity.

To the east of the RWZ, the basement alteration profile is considerably more extensive (Figure 6.3). Mineralization-associated illite alteration in the basement reaches up to 175 m below the unconformity, especially to the north, which reflects both the intersection of cross-section S-0 with the eastern tip of the RWZ and perhaps the presence of a linked structure between RWZ and the east zone mineralized segment (RRE), creating a clay alteration overprint. As further evidence of this, the paleoweathering profile and KPU to the north are thoroughly overprinted by the stronger and more pervasive mineralization-associated illitization. Conversely, illite-dominant argillization is less extensive to the south, locally preserving the KPU, and only affecting rocks up to 45 m below the unconformity.

Chlorite-dominant alteration in the basement east of RWZ remains dominantly confined to the WSPG, but is also weakly represented in the FWW. Furthermore, chloritic alteration is more prevalent in the central area of the cross-section, associated with proximity to the edge of RWZ mineralization. Preservation of the KPU above uranium mineralization and around the associated illite and chlorite alteration is a reflection of the intersection of this cross-section with the low grade shell at the edge of the RWZ, and thus the associated relatively weak to moderate degree of clay alteration.
6.2 Clay alteration within the RWZ mineralization

A cross-section through the centre of the RWZ highlights the ability of mineralizing fluids to use the weaker WSPG as a fluid conduit, as the vertically...
extensive illite alteration chimney in the sandstone is predominantly constrained to the region overlying the WSPG, and these rocks are the most pervasively altered (Figure 6.4). Illite-dominant alteration in the sandstone highlights the ease with which mineralizing fluids can travel along the conglomerate beds, and their ability to reach the present surface. Argillization directly overlying mineralization is also broader and more laterally extensive than that outlined in Figures 6.2 and 6.3 (Figure 6.4). Illitization of the lower MFb is moderate to strong, associated with quartz dissolution, as white to yellow or pink replacement of part or all of the grains, infill of dissolution vugs in pebbles, and as fault gouge and fracture lining. This scale of argillization is frequently associated with moderate to strong red hematite alteration, moderate beige goethite alteration, and/or local strong pervasive bleaching of the core, as described in Section 5.2 (Figures 4.12, 5.10). Pervasive illitization near RWZ mineralization has significant reach into the basement, extending roughly 210 m below the unconformity, as mineralizing fluids take advantage of increased porosity caused by faulting (Figure 6.4). Significant faulting is particularly evidenced by the approximate 20 m offset of the unconformity, marked by the Basal Conglomerate, as well as from the ridges of unaltered basement between valleys of argillized basement, which could be indicative of the brittle re-activation of structures.
Illite-dominant alteration in this cross-section, although best represented in the WSPG, is no longer relatively restricted to the paragneisses, but also strongly alters the surrounding granitoids. Complete illitization has also thoroughly
overprinted the paleoweathering profile and the KPU, as these are no longer expressed in the core.

Chloritization is substantially more extensive near the RWZ, especially within 10 m of high grade uranium mineralization (>3% $\text{U}_3\text{O}_8$). The perceived affinity of chlorite alteration to uranium mineralization at RWZ could be an artefact of the host rocks, as the bulk of mineralization-associated chlorite alteration is constrained to the WSPG, which also hosts the vast majority of uranium mineralization at Roughrider. This is supported at the microscopic scale, wherein most of the mineralization-proximal strongly argillized metasedimentary gneisses analyzed in this study were composed dominantly of a fine-grained mix of illite and sudoite, along with a lesser and variable amount of bleached iron-rich chlorite alteration of mafic metamorphic minerals, as discussed in Section 5.2 (Figures 5.12, 5.18, and 5.20).
7. GEOCHEMICAL STUDIES

This chapter aims to: (1) analyze the relationships between uranium and other elements; (2) delineate the ages of primary mineralization and remobilization; (3) determine the composition of clay minerals associated with mineralization; and (4) evaluate the mobility of various elements during the alteration and mineralization processes. Over the course of this project, numerous bivariate diagrams were constructed using Hathor’s geochemical whole rock assay data to investigate potential relationships between uranium and other elements and gain insight on the geochemical controls on uranium mineralization. The assay data used for construction of the bivariate graphs are divided into sandstone and undifferentiated basement rocks in order to evaluate the influences of proto-lithologies on geochemical signatures. The complex geochemical relationship identified between uranium and zinc was further explored by outlining their 3D spatial relationships. The mobility of elements is analyzed with isocons constructed from paired altered and less altered samples, and the ages of mineralization were estimated from chemical and U-Pb isotopic dating of uraninite.

7.1 Relationships between uranium and major elements

Uranium (U₃O₈ %wt) is plotted against the major elements (%wt) Na₂O, CaO, K₂O, Fe₂O₃, Al₂O₃, MgO, TiO₂, and P₂O₅. A strong, near mutually exclusive correlation is observed in the basement data between U₃O₈ and Na₂O or MgO (Figure 7.1).
Figure 7.1: Bivariate diagrams of (A) U$_3$O$_8$ wt% vs. Na$_2$O wt%, and (B) U$_3$O$_8$ wt% vs. MgO wt%, showing a mutually exclusive relationship. (Originals in colour)

This preclusive relationship is less defined in the sandstone, which may be due to the smaller sample size, or perhaps to the low overall concentration of these elements in the sandstone. These trends may be explained by three mechanisms: 1) uranium mineralization is associated with a strong depletion of Na and Mg in the host rocks; 2) mineralization is only associated with lithologies that were depleted of Mg and Na before mineralization; and 3) uranium mineralization only occurs in veins that do not contain Na- and Mg-bearing minerals. The third mechanism may explain some of the high grade data (e.g., massive and fracture-hosted ore) however, it cannot be applied to the low grade data (e.g., wormrock and disseminated ore). It is difficult to distinguish the first and second mechanism, and both may have contributed to the observed trend: the host rocks may have been depleted in Mg and Na through pre-ore alteration,
especially argillization, as a ground preparation, and then further depleted in these elements through syn- and post-ore argillization.

A similar relationship occurs in the bivariate plots of $\text{U}_3\text{O}_8$ vs. $\text{CaO}$ and $\text{U}_3\text{O}_8$ vs. $\text{P}_2\text{O}_5$ (Figure 7.2), but the mutual exclusion is not as strong as that observed in Figure 7.1. Low concentrations of Ca associated with moderate to high concentrations of U may be associated with pre-ore argillization. Moderate to high concentrations of Ca and P are found both for low and high uranium concentrations, indicating that Ca and P may have been co-enriched with U, or indicative of Ca enrichment during post-ore carbonate alteration. The lack of a positive correlation between U and these two elements may be contributed to the “dilution effect” for the high-grade ore, i.e., the proportion of Ca and P is lowered due to an increase in the proportion of U.

The bivariate plots of $\text{U}_3\text{O}_8$ vs. $\text{K}_2\text{O}$ and $\text{U}_3\text{O}_8$ vs. $\text{Al}_2\text{O}_3$ show negative associations (Figure 7.3), contrary to the expected positive relationships considering the close affiliation of uraninite to illite alteration. This tendency is poorly defined in the sandstone, which may reflect the comparative lack of uranium ore above the unconformity. The trend between U and $\text{K}_2\text{O}$ in the basement rocks may in part reflect the differential abundance of potassium in potassium feldspar (avg. 17%), which makes up a portion of the basement host rocks, relative to that of illite (avg. 7%) that alters feldspar during pre- and syn-ore alteration.
Figure 7.2: Bivariate diagrams of (A) U wt.% vs. Ca wt.% and (B) U wt.% vs. P wt.%, showing nearly mutually exclusive relationships. (Originals in colour)

Figure 7.3: Bivariate diagrams of (A) U wt.% vs. K wt.% and (B) U wt.% vs. Al wt.%, illustrating negative correlations between U and these elements. (Originals in colour)
However, considering the “dilution effect” as mentioned above, it is possible that K$_2$O and Al$_2$O$_3$ were gained or immobile during uranium mineralization despite the negative correlation between these two elements and U, as will be further discussed in section 7.5.

### 7.2 Relationships between uranium and trace elements

Given the locally polymetallic nature of RWZ, the affiliation of Zn, Co, Cu, Ni, and As to U is examined, as well as the unique trends observed between U and Th, and Zr vs. Hf. The bivariate plot of U vs. Cu illustrates a nearly mutually exclusive relationship, similar to that between U and CaO (Figure 7.4A). This trend may indicate co-enrichment of Cu and U during mineralization. The concentration of data points along the x-axis of these graphs may also be representative of the locally monometallic nature of uranium mineralization at RWZ, and thus the absence of Cu in the ore. These interpretations are supported by the petrographic observations that some uraninite contains chalcopyrite, covellite, and chalcocite (Figures 5.29, 5.31A), whereas some ore contains only uraninite and clay minerals (Figures 5.30, 5.31B). The high concentrations of Cu in barren and low-grade ore, however, may indicate a separate Cu mineralization event unrelated to U mineralization.

Zn and Co also show a nearly mutually exclusive relationship with U (Figure 7.4B, C). This is consistent with the observation (Chapter 4) that sphalerite never occurs in proximity to uraninite or uranium alteration minerals, and displays a paragenetically late relationship to radiogenic galena (Figure 5.23).
Figure 7.4: Bivariate plots of (A) U vs. Cu, (B) U vs. Zn, and (C) U vs. Co showing near mutually exclusive trends in both the sandstone and basement. (Originals in colour)

Cobalt is observed with Fe-Ni sulpharsenide minerals that were identified to have co-precipitated with, or shortly after, U2 (Figure 5.38). Furthermore, the outliers in the bivariate plot of U vs. Co are in agreement with some of the data points in the plots of U vs. As and U vs. Ni (Figure 7.5), suggesting that they represent the established association of cobalt with Fe-Ni sulpharsenide minerals (Section 5.3).
The geochemical relationships of these elements to uranium suggest that more than one fluid flow event is associated with the RWZ segment, which is supported by the petrographic and paragenetic analyses in Chapter 5.

The bivariate plots of U vs. As or Ni display weak positive correlations (Figure 7.5). The similarity of the relationships of these elements to uranium is not surprising as most Ni-bearing minerals also contain As. These relationships agree with the paragenetic observations outlined in Chapter 4 (Figure 5.38), and suggest that some nickel, uranium, and arsenic could have been transported in the same fluid. As outlined above, the data points that populate the x-axis in each graph may highlight the locally monometallic nature of the RWZ.

Despite relatively low concentrations of thorium in the mineralized basement rocks, five positive linear trendlines can be identified in the bivariate
plot of U vs. Th (Figure 7.6). These relationships are not well understood, as they are not controlled by the style of uranium mineralization, its chemical age, or the location of samples within the RWZ segment. The trendlines do include twelve DDH’s that were sampled for this study, which are located throughout the RWZ segment. This unique trend may be indicative of the number of fluid resetting or remobilization events that have affected RWZ mineralization.

The correlation between Zr and Hf at RWZ is perplexing. These high field strength elements (HFSE) are geochemically similar, and therefore should behave similarly in nature. The bivariate plot of Zr vs. Hf in the RWZ illustrates two positive linear trendlines: one which represents the standard ratio between these elements in nature (~30:1) whereas the other displays an anomalous relative depletion of Zr and/or enrichment of Hf (Figure 7.7). The standard correlation between Zr and Hf is associated with background concentrations of U and low grade ore (<0.15% – 1.0% U₃O₈), whereas high grade mineralization favours the exclusion of Zr in favour of Hf. This abnormal behaviour in the presence of high grade U may be caused by the increased solubility of HFSE’s in low temperature hydrothermal systems (Bau, 1996) like that present at Roughrider, however, this relationship is poorly understood. Perhaps the fluid associated with uranium mineralization favours mass-dependant fractionation of Zr and Hf, mobilizing lighter Zr (40 amu), and leaving an anomalous concentration of heavier Hf (72 amu) (Niu, 2012). Mobilization of otherwise incompatible Hf and Zr (to a lesser extent) is possible in potassium fluoric complexes (K₂[Zr,Hf]F₆) (Niu, 2012).
Figure 7.6: Bivariate plot of basement assay data from the RWZ of U (ppm) vs. Th (ppm). Despite low total values of Th at RWZ, five positive trendlines between these elements are clearly discernible, and do not appear to be related to the style of mineralization, be affected by sample location within the RWZ, nor by the chemical age of mineralization. (Original in colour)

Figure 7.7: Bivariate plot of zirconium (Zr ppm) vs. hafnium (Hf ppm) relative to background to high grade uranium (U₃O₈ %wt) concentrations. Low and background uranium is associated with a characteristic Zr/Hf ratio, whereas relatively high grade uranium mineralization is associated with an abnormal ratio. (Original in colour)
While there is potassium available in the fluid during pre-ore alteration of potassic feldspar and micas, F-bearing minerals at RWZ are uncommon, and observed only distal to uranium mineralization. Perhaps these elements were carried in fluid as phosphate complexes, as the mineralizing fluid may have contained PO$_4$$^-$ as it broke down monazite, and/or any aluminum-phosphate-sulphate (APS) minerals. Alternatively, perhaps Zr or Hf was mobilized as a chloride complex, as the mineralizing fluid has been suggested to be saline (i.e.: NaCl- and/or CaCl$_2$-bearing) by several studies (e.g.: Pagel et al., 1975; Kotzer & Kyser, 1995; Derome et al., 2003, 2005).

### 7.3 Three Dimensional spatial zinc – uranium diagram

Pursuant to the nearly mutually exclusive relationship identified between uranium and zinc, a three dimensional (3D) spatial diagram of anomalous zinc (> 0.1% Zn) was constructed and then compared to the location of the delineated 2011 NI-43-101 compliant 3D wireframes of the RWZ segment in order to better understand the geochemical signature observed in Figure 7.4B (Figure 7.8; Elash & McCready, 2011). This diagram reveals that anomalous zinc is predominantly hosted below and rarely contacts uranium mineralization, supporting the paragenetic observations outlined in Section 5.3. Furthermore, a cross-section taken through the centre of the 3D diagram, with the addition of property scale 3D geology at RWZ (Figure 7.9), highlights other noteworthy observations. Zinc is exclusively hosted in the WSPG, whereas the RWZ segment is dominantly hosted in the WSPG, but is also present in the granitoids and locally, at the unconformity.
Figure 7.8: Spatial diagram, in 3D, of elevated zinc (> 0.1%) wireframes (green) relative to the RWZ segment. The RWZ is made up of the 2011 NI 43-101 compliant wireframes of high grade (red; > 5% U₃O₈) uranium mineralization and the low grade shell (pink; < 5% U₃O₈). Uranium clearly overlies the zone of anomalous zinc, and the two pods are rarely in contact with each other. White line indicates the location of the cross-section in Figure 7.9 below (modified from Elash & M'Cready, 2011). (Original in colour)

Figure 7.9: Cross-section from Figure 7.8 above, with property-scale geology. Red bands denote high grade mineralization; pink represents the low grade shell. Purple, blue, and violet represent basement rocks; orange marks the trace of the Basal Conglomerate. Again, U clearly overlies the zone of anomalous zinc. Furthermore, Zn is hosted exclusively in the WSPG, conformant to structure, whereas uranium mineralization at RWZ does not conform to structure and is locally observed in the granitoids, and at the unconformity. (Original in colour)
The shape of the outline of anomalous zinc also shows that it is conformant to local structure, whereas uranium mineralization is not. Given the paragenetic timing relationships identified between uranium mineralization and sphalerite, this supports the petrographic observation that zinc was concentrated post-ore, during a period of brittle fault reactivation in the WSPG, which is associated with brecciation and late remobilization and alteration of the primary ores (Section 5.4).

### 7.4 Composition of clay minerals

Clay minerals constitute a significant portion of the mineralization-associated alteration at RWZ, and have been identified to exhibit a close spatial and temporal relationship to uraninite. As such, EPMA analysis was employed to attempt to determine their compositions. Four strongly altered samples were selected for this work, from which 86 data points were collected, including: (1) An unmineralized, strongly argillized, and weakly chloritized granitic sample 1.0 m away from disseminated uranium mineralization; (2) an unmineralized, strongly argillized and chloritized pelitic gneiss 0.2 m from disseminated mineralization; (3) wormrock mineralization hosted in a strongly argillized and chloritized pelitic gneiss; and (4) disseminated mineralization in a strongly chloritized and argillized pelitic gneiss. This work proved challenging because of the closely intergrown and extremely fine-grained (micron-sized) nature of the clay minerals, which rendered their compositional analyses impossible to obtain without a large degree of interference from the surrounding clay minerals (Appendix C).
It became evident during EPMA that there are at least two clay minerals, presumed to be illite and sudoite based on the EPMA data, that are intergrown on the micron scale in these samples (Figure 5.20). Within and immediately surrounding fine-grained uraninite in disseminated and wormrock mineralization, there are often three clay minerals present, as illite and sudoite are usually intergrown with hematite proximal to fine-grained uraninite, however SEM-EDS analysis revealed that kaolinite surrounds uraninite in wormrock mineralization, and therefore may also be the clay mineral intergrown with U2 (Figure 5.20C). The only other clay mineral that was coarse-grained enough to provide reliable data that was not subject to interference from nearby minerals was chamosite, an iron-rich chlorite that has altered and pseudomorphed the mafic minerals (Figures 5.20B, D). All of the other sample analyses yield unreliable data that have been affected by nearby or intergrown clay minerals.

7.5 Mass balance

Four core samples comprising two granites, a pelitic gneiss, and a quartz arenite were selected for mass balance analysis using the isocon method (Grant, 2004). These samples are composed of two portions, one that is relatively unaltered, and one that is more altered than the first. The paired samples were powdered and sent to SRC laboratory for laser ablation induced coupled plasma mass spectrometry (LA-ICP-MS) analysis, the results of which are presented in Table 1.

The isocons are constructed by plotting the elemental/isotopic LA-ICP-MS data obtained for the altered portion relative to the unaltered portion. The
fundamental necessity for the construction of element mobility diagrams (isocons) is the assumption that at least one element remained immobile throughout the alteration event. It appears that no one element has remained truly immobile at RWZ in both the basement and the sandstone. Titanium may not have been an immobile element as petrographic observations indicate that rutile (TiO$_2$) has been multiply reprecipitated during pre- and post-uranium mineralization alteration, which is further supported by its graphical relationship with U and other elements (Section 5.3; Figures 5.20, 5.22, 5.30, 5.33A, C). Titanium has been observed to become at least locally mobile under reducing conditions in a wide range of pH, controlled by its association with a silica-rich fluid, or carbonate-rich fluid (Morad & Aldahan, 1986).

The REEs and HFSEs are also unreliable as immobile elements, as evidence has been found in this study for the partial dissolution and mobilization of zircon, monazite, and apatite in all of the host rocks; their non-linear graphical relationships to uranium and other elements further suggest their mobility (Figures 7.6, 7.7). Analysis of the REE-enriched Maw Zone, located along the WMTZ in the eastern Athabasca Basin, sandwiched between the Key Lake and McArthur River deposits (Figure 1.1), suggest that REEs were mobilized during hydrothermal alteration of garnet, apatite, and other REE-bearing minerals prior to and during uranium mineralization (Quirt et al., 1991), and evidence was found in Greenland for the ability of REE to become mobilized in Ca- and carbonate-bearing metasomatic fluids (Coulson & Chambers, 1996), perhaps similar to those associated with post-ore carbonatization.
Table 1: Data from LA-ICP-MS analysis of nine whole rock powdered samples for
isocon analysis

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Furthermore, HFSEs have been shown to be mobilized in hydrothermal or metamorphic fluids across a range of T and P conditions, especially in basic (high pH) environments (Jiang et al., 2005), such as those required for desilicification.

Given the low solubility of Al$_2$O$_3$ in low temperature (<300°C) hydrothermal systems (Lorilleux et al., 2003), such as that present at Roughrider, it is possible that aluminum may have remained immobile within the small sample area. As such, Al$_2$O$_3$ has been selected as the best relatively immobile element, with the consideration of a margin of error around the isocon.

Sample RB26057 is granite 0.4 m away from low grade uranium mineralization that has been strongly hematized and weakly argillized, and contains a mm-sized beige fracture (Figure 7.10). The less altered portion of the sample was taken from the red hematized area, and the more altered portion was taken from the beige vein cross-cutting it. The isocon constructed from this data indicates that U, La, Eu, Sm, Nd, Gd, and V, have been gained, whereas Fe$_2$O$_3$ was lost (Figure 7.11).

As uranium mineralization is proximal to this sample and has been shown to have a close spatial relationship to goethite (the yellow vein) it is expected that mineralizing fluid travelling along this fracture would result in relative enrichment of uranium. The relative depletion of Fe$_2$O$_3$ is logical, as hematite is usually remobilized around fractures, resulting in a cm-sized bleached halo. The relative enrichment or depletion of the other plotted elements in this sample is uncertain, due to their proximity the isocon line.
Figure 7.10: Drill core photograph of granitic sample RB26057 (230.4 m; DDH 09-116) 0.4 m away from low grade uranium mineralization at RWZ. Location of less altered powder (blue arrow) and more altered powder (red arrow) that were sent for LA-ICP-MS, and converted to the isocon diagram below are indicated. (Original in colour)

![Figure 7.10: Drill core photograph of granitic sample RB26057 (230.4 m; DDH 09-116) 0.4 m away from low grade uranium mineralization at RWZ. Location of less altered powder (blue arrow) and more altered powder (red arrow) that were sent for LA-ICP-MS, and converted to the isocon diagram below are indicated. (Original in colour)](image1)

Figure 7.11: Isocon constructed from sample RB26057 (230.4 m; DDH 09-116) granite 0.4 m away from low grade uranium mineralization at RWZ. Black line marks isocon, crossing aluminum. Some elements were multiplied or divided by a constant to separate values in the graph as follows: Al$_2$O$_3$*3, CaO*1000, Ce*3, Fe$_2$O$_3$*25, K$_2$O*100, La*14, MgO*70, MnO*3500, Na$_2$O*5000, P$_2$O$_5$*3000, TiO$_2$*200, Be*60, Bi*1000, Cd*1050, Co*10, Cs*500, Cu*13, Dy*225, Er*650, Eu*575, Ga*4, Gd*200, Hf*17, Ho*445, Nb*25, Nd*18, $^{204}$Pb*1000, $^{207}$Pb*35, $^{208}$Pb*100, Pr*20, Sc*150, Sm*130, Sn*120, Ta*140, Tb*190, Th*3, W*5, Y*100, Yb*900, and Zn*39 (Original in colour)

Pelitic gneiss sample RB26079 (233.6 m; DDH 09-131) is also approximately 0.5 m from low grade uranium ore. This sample exemplifies strong
argillization and hematization that has been locally bleached by mineralizing fluids. The red area of the sample represents the less altered portion, whereas the bleached area represents the more altered portion (Figure 7.12).

The isocon produced indicates that despite their proximity to uranium mineralization, $\text{Fe}_2\text{O}_3$, $^{207}\text{Pb}$, Dy, Ho, Y, Nb, Er, Ag, Cd, Bi, Tb, TiO$_2$, Zr, Hf, and W have been lost, whereas Cu, La, Ce, Pr, Eu, Nd, Sr, Ba, and P$_2$O$_5$, have been gained (Figure 7.13). As hematite is lost during the alteration process in this sample, depletion of $\text{Fe}_2\text{O}_3$ is expected. Depletion of some radiogenic Pb indicates that continued alteration of this sample may be associated with post-ore remobilization and/or lead resetting. Decreases in Zr, Hf, and TiO$_2$ may be associated with the breakdown zircons and mobilization of rutile, as observed in Chapter 4. The increase in Cu suggests that this stage of alteration is associated with one of the three copper enrichment phases outlined in Figure 5.38, two of which are post-ore. This lends support the interpretation that this represents post-ore alteration.

Sandstone sample RB26096 (209.1 m; DDH 10-642), distal from the RWZ, is weakly argillized and hematized, with a small fracture that has a bleached halo and mm-sized lining of goethite (Figure 7.14). The pink hematite-stained portion of the core was selected as the less altered sample, and the more altered sample was taken from the bleached and fractured area.
Figure 7.1: Drill core photograph of pelitic gneiss (RB26079; 233.6 m; DDH 09-131) 0.5 m away from low grade uranium mineralization. Location of less altered powder (blue arrow) and more altered powder (red arrow) that were sent for LA-ICP-MS, and converted to the isocon diagram below are indicated. (Original in colour)

Figure 7.13: Isocon constructed from sample RB26079 (233.6 m; DDH 09-131) pelitic gneiss 0.5 m away from low grade uranium mineralization at RWZ. Black line marks isocon, crossing aluminum. Some elements were multiplied or divided by a constant to separate values in the graph as follows: Al₂O₃*10, CaO*1000, Fe₂O₃*30, K₂O*20, MgO*100, MnO*5000, Na₂O*2500, P₂O₅*1000, Sr*2, TiO₂*100, Ag*300, Be*20, Bi*1500, Cd*1000, Co*50, Cs*75, Cu*25, Dy*100, Er*100, Eu*40, Gd*25, Hf*32, Ho*375, Mo*100, Nb*7, Ni*15, ²⁰⁴Pb*650, ²⁰⁶Pb*8, ²⁰⁷Pb*300, ²⁰⁸Pb*25, Pr*10, Sm*5, Sn*65, Ta*18, Tb*200, U*9, V*10, Th*3, W*175, Y*12, and Yb*25 (Original in colour)
Figure 7.14: Drill core photograph of sandstone sample RB26096 (209.1 m; DDH 10-642) is distal to mineralization at RWZ and was sampled for isocon analysis. The location of the less altered powder (blue arrow) and more altered powder (red arrow) that were sent for LA-ICP-MS are indicated, and the resultant data was converted into the isocon diagram below. (Original in colour)

The isocon formed from this data indicates that element mobility is relatively small in this sample. Despite being distal from mineralization, alteration shows only Bi was gained, whereas Er, Sn, Mo, MnO, Fe$_2$O$_3$, and Na$_2$O were lost during bleaching, argillization, and minor desilicification (Figure 7.15). Depletion of Fe$_2$O$_3$ is due to mobilization of hematite and bleaching along the fracture. The chemical disagreement between U and Mo, similar to that identified between U and Zn, indicates that its loss relative to a potential increase of U is not unforeseen. Depletion of Na$_2$O and MnO may be the result of mineralization-associated alteration, or reduction due to fluid-rock interaction.

Granitic sample RB26108 (210.2 m; DDH 10-227A) was selected for isocon analysis on the basis of its alteration texture. The strongly argillized granite has mm-size blebs of white to yellowish clay alteration within the deep red hematite alteration, similar to the wormrock style of uranium mineralization, despite its lack of mineralization (Figure 7.16).
Figure 7.15: Isocon constructed from sample RB26096 (209.1 m; DDH 10-642) weakly argillized and hematized quartz arenite. Black line marks Isocon, crossing aluminum. Some elements were multiplied or divided by a constant to separate values in the graph as follows: CaO*100, Ce÷3, Fe₂O₃*100, K₂O*15, MgO*100, MnO*10000, Na₂O*1000, P₂O₅*300, Sr÷3, TiO₂*300, Zr÷7, Ag*250, Be*21, Bi*100, Co*60, Dy*17, Er*45, Eu*60, Ho*90, Mo*90, Nb*7, ²⁰⁴Pb*150, ²⁰⁶Pb*10, ²⁰⁸Pb*3, Pr*5, Sc*15, Sm*7, Sn*35, Ta*70, Tb*75, U*5, W*90, Y*5, and Yb*17 (Original in colour)

Figure 7.16: Drill core photograph of granitic sample RB26108 (210.2 m; DDH 10-227A), 2.0 m away from low grade uranium mineralization. Location of less altered powder (blue arrow) and more altered powder (red arrow) that were sent for LA-ICP-MS and converted to the isocon diagram below are indicated. (Original in colour)

The deep red area was selected as the less altered sample; the most altered sample was taken from the white to yellowish clay alteration.
The subsequent isocon illustrates an increase of U, Zr, Th, $^{207}$Pb, $^{208}$Pb, Ta, Be, Tb, Sr, Ce, Ho, Hf, Ba, MnO, P$_2$O$_5$, Dy, Gd, Cs, and TiO$_2$. Depleted elements include: Mo, W, V, Cr, and Sn (Figure 7.17). The increase of TiO$_2$ could represent the precipitation of remobilized rutile around uraninite, as identified in Chapter 4 (Figures 5.30, 5.38). A relative enrichment of U, radiogeneic Pb, and Th during this alteration could indicate that it is associated with uraninite alteration or remobilization, and lead resetting, supporting the geochemical relationship in Figure 7.6. Furthermore, the increase of uranium is interesting, as this sample is strongly altered in a pattern that is consistent with wormrock mineralization, but is unmineralized. This sample perhaps had the potential to become mineralized, but lacked a sufficient reducing agent to precipitate uranium from solution as the mineralizing fluid permeated it. As Mo has a near mutually exclusive relationship with U, its depletion is in accordance with a relative increase in U.
Figure 7.17: Isocon constructed from sample RB26108 (210.2 m; DDH 10-227A) with micro-wormrock texture. Black line marks isocon, crossing aluminum. Some elements were multiplied or divided by a constant to separate values in the graph as follows: CaO*250, Cr÷3, Fe₂O₃*4, K₂O*3, La*4, Li÷3, MgO*10, MnO*1000, Na₂O*1500, P₂O₅*1000, Sr÷2, TiO₂*100, Zr÷3, Ag*300, Be*20, Bi*300, Cd*400, Co*3, Cs*300, Dy*40, Er*100, Eu*90, Gd*10, Hf*9, Ho*100, Ni÷3, ²⁰⁴Pb*100, ²⁰⁷Pb*25, ²⁰⁸Pb*9, Pr*20, Sm*25, Sn*100, Ta*100, Tb*200, U*3, V÷3, Th*20, and Yb*40 (Original in colour)

7.6 Geochronology

7.6.1 U/Pb isotopic age dating

Two samples comprising one example of primary and one example of remobilized uraninite at RWZ were selected for U/Pb isotopic age dating using SIMS. Analyses were conducted on fifteen points from massive euhedral botryoidal and cubic U1 (RB31039: 248.5 m; DDH 09-116; Figures 5.27, 5.28), and fourteen points from remobilized vein-type U4 and U5 (RB31048: 239.2 m; DDH 09-131; Figure 5.31). The data (Table 2) was plotted using Isoplot 3 on a
concordia as a discordant line, the upper intercept of which corresponds to the age of mineralization, as outlined in Chapter 3. The results indicate that euhedral U1 at RWZ has an upper intercept age of 1,188±53 Ma, with a mean standard weighted deviation (MSWD) of 2.2 (Figure 7.18). Challenges in these analyses included the minor amounts of coffinite alteration around the rims of primary U1 botryoids, inclusions and veinlets of chalcopyrite and galena, and local chalcocite alteration in some of the cubic grains (Figures 5.27, 5.28). In an attempt to avoid these areas, data collection was limited to the centre of botryoids, and areas that appeared homogeneous.

Analysis of remobilized, vein-type U4 and U5 uraninite presented significantly greater challenges, given their propensity to form as finely laminated heterogeneous uraninite, sometimes with coffinite (Figure 5.31). Furthermore, identification of the U4 phase relative to U5 or possibly even other later vein-type phases is impossible to do without cross-cutting relationships, which is why both phases were analyzed together.

Despite attempts to select only analysis spots from homogeneous areas within some veins, the resulting concordia diagram indicates that this may not have always been the case (Figure 7.19). The heterogeneity and fine-grained nature of remobilized uraninite rendered it extremely difficult to accurately date. The mean age for remobilized vein-type uraninite is 262±24 Ma, with a high MSWD of 5.2. This remobilization age is not inappropriate, but the range in obtained ages resulted in an unreliable standard deviation.
Table 2: SIMS data from primary (U1) and remobilized (U4/U5) uraninite (U1; RB31039; U4 - U5; RB31048) used to construct concordias

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<th>Sample</th>
<th>( ^{207}\text{Pb}/^{206}\text{Pb} )</th>
<th>Error % (1σ)</th>
<th>( ^{235}\text{U}/^{238}\text{U} )</th>
<th>Error % (1σ)</th>
<th>( ^{207}\text{Pb}/^{235}\text{U} )</th>
<th>Error % (1σ)</th>
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Figure 7.18: Concordia intersected by discordant line created from U/Pb isotope measurements taken from SIMS analysis of primary euhedral U1 sample RB31039. (Original in colour)

Figure 7.19: Concordia intersected by discordant line created from U/Pb isotope measurements taken from SIMS analysis of remobilized vein-type U4 & U5 from sample RB31048. (Original in colour)
The varied range could be associated with the inadvertent analysis of uraninite veins that were misidentified as U4 or U5 veins, or it could be associated with the inadvertent analysis of more than one phase of uraninite, due to their heterogeneous nature.

7.6.2 Chemical age dating

Chemical ages were obtained for uraninite from five samples while conducting EPMA on primary and remobilized uraninite from RWZ (data attached in Appendix D). Of the samples analyzed, two contain primary euhedral U1 or U2 (RB31010: 218.0 m, DDH 09-101; RB31039: 248.5 m, DDH 09-116), and two comprise primary euhedral U1 and U2, as well as secondary remobilized vein-type U4 and U5 (RB31006: 207.5 m, DDH 09-094; RB31024: 249.5 m, DDH 10-197A). The final sample consists solely of remobilized vein-type U4 and U5 (RB31048: 239.2 m; DDH 09-131). The chemical ages obtained for primary U1 are consistent with, although sometimes older than, the ages obtained from SIMS – especially for sample RB31039, which was analyzed using both methods. The chemical age data, comprising 110 data points returns an average age of 1,167±2.1 Ma (Figure 7.20). The data is variable overall, ranging between 677±1.7 Ma and 1,482±1.9 Ma, which may be associated with lead loss, or the inadvertent analysis of nearby coffinite or chalcocite alteration.
Uraninite that was identified as U2 returned a significantly younger average age of 743±2.1 Ma. The 51 data points analyzed returned fluctuating results between 261±1.4 Ma and 1,395±1.9 Ma, which indicates either that nearby remobilized uraninite may sometimes have analyzed, or perhaps that the U2 phase may not have always been correctly identified.

Remobilized uraninite samples were more difficult to analyze accurately due to their heterogeneity and fine-grained nature. These problems are further reflected in the low number of reliable samples that were obtained for U3 and U4 over the course of EPMA. The anhedral, heterogeneous U3 phase returned a narrow spread of eleven chemical ages between 107±1.1 Ma and 237±1.3 Ma, with an average age of 174±1.8 Ma (Figure 7.20). This range is consistent with
and younger than the U/Pb isotopic SIMS age for uranium remobilization and is younger than expected for primary uranium remobilization.

As discussed in the section on SIMS age dating, vein-type U4 and U5 phases were extremely difficult to analyze given their inclination to form as heterogeneous thinly-banded laminations (Figure 5.31). Five chemical ages from U4 veins that are cross-cut by later, often more heterogeneous veins, returned a mean age of 693±1.7 Ma, maintaining a narrow range between 630±1.7 Ma and 756±1.7 Ma (Figure 7.20). This data suggests that the U4 veins are older than the first identified remobilization phase, and in fact, that they are older than the chemical ages of primary U2 uraninite. Careful inspection of the data point locations and the resultant data suggest that it is likely these data are contaminated, as pure uraninite only accounts for 75% or less of the analysis, which has been removed as erroneous data in all other datasets, and will therefore be disregarded. Later U5 veins returned 83 chemical ages, averaging 246±1.8 Ma with a substantial range between 35±1.5 Ma and 523±1.5 Ma, which is in accordance with the discordant age obtained from SIMS analysis of remobilized uraninite (Figure 7.19). The large spread of chemical ages for U5 veins could be due to misidentification of the vein phases, perhaps due to the presence of more than two remobilized uraninite vein phases that could not be accurately identified as separate phases without cross-cutting relationships. The range of ages could also be attributed to incidental analysis of more than one phase of uraninite, due to its heterogeneous and fine-grained nature. The lowermost age suggests potential for remobilization of uraninite by recent fluids.
7.7 Geochemical characteristics of uraninite

The data obtained from EPMA of uraninite was used to explore the relationship of uraninite to iron, calcium, and silicon in the RWZ, and compare these results to published data on other unconformity-type uranium deposits in the Athabasca Basin (Appendix D; Fayek & Kyser, 1997; Cloutier et al., 2009, 2011). The bivariate plots of primary U1 & U2 vs. FeO indicate that U at RWZ is associated with a range of FeO concentrations between 0%wt and 0.9%wt (Figure 7.21). This is likely due to the dilution effect, as the sample analyzed contains > 80% UO₂, however it also implies that uranium mineralization at RWZ is not significantly affected by or associated with FeO. Similar trends are observed in many of the other unconformity-type uranium deposits, such as the nearby McLean Lake Sue C and Midwest deposits, as well as the more distal Eagle Point and Millennium deposits. Slightly dissimilar is the McArthur River deposit, which appears to be associated with a range of FeO around primary uraninite. Remobilized U3 – U5 at RWZ is associated with similar FeO concentrations as outlined for primary mineralization (Figure 7.22), whereas other deposits show somewhat limited FeO concentrations around remobilized uraninite, between 0 – 0.35 %wt, except at Cigar Lake, where one data point reaches 0.68%wt. Unfortunately, there is an overall lack of data with respect to remobilized uranium mineralization from other deposits.
Figure 7.21: Bivariate plot of primary uranium mineralization vs. FeO at RWZ (Roughrider), plotted with data obtained from previous research on the McArthur River, Key Lake, Midwest, McLean Lake Sue C (Fayek & Kyser, 1997), Millennium (Cloutier et al., 2009), and Eagle Point deposits (Cloutier et al., 2011). (Original in colour)

Figure 7.22: Bivariate plot of remobilized uranium mineralization vs. FeO at RWZ (Roughrider), plotted with data obtained from previous research on the McArthur River, Cigar Lake, Midwest, McLean Lake Sue C, Eagle Point (Fayek & Kyser, 1997). Yellow box indicates location of primary uraninite vs. iron data points for RWZ. (Original in colour)
The relationship between U1 & U2 at RWZ and CaO is similar to that observed between U and FeO above (Figure 7.23). The data plotted from RWZ samples show a range of CaO concentrations between 0.5%wt and 2.7%wt, which agrees most with the Key Lake, Millennium, and Midwest deposits, and to a lesser degree, with the M\textsuperscript{1}Lean Lake Sue C deposit. The range of CaO values associated with primary uraninite may provide evidence for its minor alteration, which may have caused some of the younger isotopic and chemical ages obtained. Remobilized U3 – U5 at RWZ displays the association of U to a wider range of CaO concentrations between 1.1%wt and 4.95%wt, which is dissimilar to the other deposits as, despite the relative lack of data points, they all show a narrower range of CaO associated with remobilized uraninite (Figure 7.24). The increased range of CaO values in remobilized uraninite at RWZ may be due to its alteration to uranophane. Conversely, the Eagle Point shows a wider range of CaO concentrations associated with what was identified as primary uraninite, and a significantly narrower range associated with remobilized uraninite. This is explained perhaps as a function of the remobilized uraninite becoming increasingly pure as it is carried away to precipitate as U2 at the expense of primary U1 (Cloutier et al., 2011). Furthermore, primary U1 at Eagle Point has been identified to contain some uranophane alteration, which was not identified in remobilized U2 (Cloutier et al., 2011).
Figure 7.23: Bivariate plot of primary uranium mineralization vs. CaO at RWZ (Roughrider), plotted with data obtained from previous research on the McArthur River, Key Lake, Midwest, McLean Lake Sue C (Fayek & Kyser, 1997), Millennium (Cloutier et al., 2009), and Eagle Point deposits (Cloutier et al., 2011). (Original in colour)

Figure 7.24: Bivariate plot of remobilized uranium mineralization vs. CaO at RWZ (Roughrider), plotted with data obtained from previous research on the McArthur River, Cigar Lake, Midwest, McLean Lake Sue C, Eagle Point (Fayek & Kyser, 1997). Yellow box indicates location of primary uraninite vs. calcium data points for RWZ. (Original in colour)
Contrary to the other bivariate plots, the relationship between primary U1 & U2 and SiO₂ at RWZ is clearly defined in Figure 7.25. Primary uraninite only coincides with low to absent values of SiO₂ (0 – 2.2%wt), which is similarly exemplified by the Key Lake, M⁶Lean Lake Sue C, Midwest, and M⁶Arthur River deposits. The data from the Millennium deposit shows a similar relationship, with a higher range of just below 4%wt, whereas Eagle Point data suggests that primary uraninite is associated with highly variable SiO₂ concentrations of up to 10.2%wt (Figure 7.25).

Remobilized U³ – U⁵ at RWZ shows a significantly larger variation in SiO₂ concentrations, reaching up to 7.9%wt, whereas the few data obtained from other unconformity-type uranium deposits in the Athabasca Basin highlight an association of remobilized uraninite with a substantially smaller range of SiO₂, typically between 0.5%wt and 3.7%wt (Figure 7.26). This trend at RWZ may again be linked to the alteration of remobilized uraninite to coffinite and uranophane, or may reflect the heterogeneous nature of remobilized uraninite.

The relationship between the chemical ages of primary and remobilized uraninite and their respective SiO₂, FeO, and CaO content was also explored (Figure 7.27). The primary uraninite grains that were analyzed were not associated with elevated concentrations of SiO₂ (Figure 7.25) and this trend is further reflected for the oldest uraninite data in Figure 7.27A. Remobilized younger uraninite displays the same variation in silica content as observed in Figure 7.26, likely due to the association outlined between remobilized uraninite and uranium alteration minerals such as coffinite and/or uranophane.
Figure 7.25: Bivariate plot of primary uranium mineralization vs. SiO₂ at RWZ (Roughrider), plotted with data obtained from previous research on the McArthur River, Key Lake, Midwest, McLean Lake Sue C (Fayek & Kyser, 1997), Millennium (Cloutier et al., 2009), and Eagle Point deposits (Cloutier et al., 2011). (Original in colour)

Figure 7.26: Bivariate plot of remobilized uranium mineralization vs. SiO₂ at RWZ (Roughrider), plotted with data obtained from previous research on the McArthur River, Cigar Lake, Midwest, McLean Lake Sue C, Eagle Point (Fayek & Kyser, 1997). Yellow box indicates location of primary uraninite vs. calcium data points for RWZ. (Original in colour)
Figure 7.27: Bivariate plots of chemical ages obtained for primary (blue data points) and remobilized (red data points) vs. (A) SiO$_2$\%$_{wt}$; (B) FeO\%$_{wt}$ and; (C) CaO\%$_{wt}$. (Originals in colour)

As noted in Figures 7.21 and 7.22, uraninite at RWZ does not appear to be significantly affected by varying concentrations of FeO, which is further reflected in the bivariate plot of chemical ages for primary and secondary uraninite vs. FeO (Figure 7.27B). Both primary and remobilized uraninites have similar, only slightly variable, iron content, implying perhaps that iron is not associated with alteration.
at RWZ. This relationship is not observed in the bivariate plot of uraninite chemical ages vs. CaO (Figure 7.27C), as primary uraninite is clearly associated with lower concentrations of CaO, and remobilized uraninite is associated with high concentrations. This is likely a function of the alteration of some uraninite into rutherfordine during remobilization, which is commonly seen in mineralized samples that contain remobilized U3, U4, and U5 (Figures 5.24, 5.32).
8. DISCUSSIONS

8.1 Similarities and differences between RWZ and other unconformity-type uranium deposits in the Athabasca Basin

The Roughrider deposit, comprising three mineralized pods that are separated from one another by approximately 50 m barren zones, is a complex, basement-hosted unconformity-type uranium deposit that exhibits some characteristics that are typical of sandstone-hosted deposits. In an attempt to better understand the controls on mineralization in the RWZ, it is compared to other unconformity-type uranium deposits in the Athabasca Basin, such as the sandstone-hosted Cigar Lake, Midwest, Collins Bay, and Key Lake deposits, as well as basement-hosted McArthur River, Millennium, Dawn Lake, and Rabbit Lake deposits.

8.1.1 Comparison with sandstone-hosted unconformity-type uranium deposits

The well documented above-mentioned sandstone-hosted deposits are commonly associated with topographic basement highs and are characterized by elongate cigar-shaped pods that contain a massive high-grade uranium core that is surrounded by a low-grade uranium shell and a massive clay cap (Sibbald, 1985; Kyser & Cuney, 2008). These deposits are located at or within 50 m of the unconformity, within the Athabasca Group quartzose sandstones (Kyser & Cuney, 2008). Uraninite and minor coffinite comprise the mineralogy, which often precipitate alone or, rarely, with minor syn-ore chlorite (Kyser & Cuney, 2008). These deposits are typically also associated with anomalous concentrations of
Ni, As, Cu, and Co, which are paragenetically associated with alteration of the primary uranium ore (Sibbald, 1985; Fayek & Kyser, 1997). Some of the polymetallic sandstone-hosted uranium deposits display a distinct zonation between uranium and nickel across the ore deposit, as at Collins Bay and Key Lake (Sibbald, 1985). All of these deposits are genetically linked to dilational jogs caused by the intersection of brittle faults with a larger pre-existing reactivated reverse fault. The only exception to this is the atypical Midwest deposit, which is associated with normal faults, defined by offset and sag of the Marker Conglomerate directly above uranium mineralization (Sibbald, 1985). Clay alteration associated with these deposits is extensive in the sandstone, forming a cone shape that is best developed around the unconformity. Distal to mineralization, the sandstone lacks pyrite and chlorite, and is characterized by the regional diagenetic dickite-dominant illite-subordinate clay in the sandstone matrix (Jefferson et al., 2007; Kyser & Cuney, 2008).

The RWZ shares many of these characteristics, especially those associated with the proximal Midwest deposit, likely because they share the same primary structure (Section 2.2). The RWZ is a somewhat elongate, pancake-shaped pod that is characterized by a high-grade uranium core with a low grade shell and a surrounding clay cap (Figure 4.7). Similar to other sandstone-hosted unconformity-type uranium deposits, U1 in the RWZ is considered to have precipitated by itself, however U2 is interpreted as a primary mineralization phase that precipitated with illite and was closely followed by the
sulphides and arsenides, rather than as a remobilization or alteration phase (Figure 5.38).

Uranium mineralization at RWZ is spatially related to the intersection of brittlely reactivated reverse faults that offset the unconformity and have thrust underlying granitoid basement rocks several metres into the sandstone. As described at Midwest, the Marker Conglomerate overlying the RWZ displays downward sag and offset that is related to brittlely reactivated faults (Keller et al., 2011). Furthermore, the Roughrider deposit is spatially associated with a topographic high, identified as the Midwest Dome (Figure 4.7; Keller et al., 2011).

An extensive, chimney-shaped sandstone alteration halo is present above the RWZ, characterized by illite-chlorite-pyrite±galena, similar to other sandstone-hosted unconformity-type uranium deposits (Figures 5.15, 5.38, 6.2, 6.3, 6.4). As documented in other research, strong mineralization-associated alteration at RWZ is most expansive along the unconformity (Figures 6.3, 6.4); however, as outlined in Chapter 4, the alteration is only visibly represented in core up to the Marker Conglomerate, and becomes trace to weak above it. The geochemical relationships identified between uranium and iron, calcium, or silicon in uraninite support the similarity of the RWZ to the sandstone-hosted Midwest deposit. The uraninite in both deposits exhibit variable iron content, relatively restricted low concentrations of CaO, and a lack of SiO₂ associated with primary uraninite (Figures 7.21, 7.23, 7.25). The geochemical trends are further supported by the petrographic study in the form of pre-ore quartz dissolution (Section 5.2; Figure 5.38), the alteration of uraninite to uranophane and
rutherfordine (Figures 5.24, 5.32, 5.38), and variable pre-ore and post-ore remobilization of hematite from the paleoweathering profile (Section 5.2, Figures 5.16, 5.19, 5.38).

8.1.2 Comparison with basement-hosted unconformity-type uranium deposits

The basement-hosted deposits are generally located in the WSPG, with minor overlap into the granitoids and pegmatites (Kyser & Cuney, 2008). Uranium mineralization in the basement occurs primarily as fracture linings and veins, but may form elongate cigar-shaped pods with similar high-grade cores and low-grade haloes as observed in the sandstone-hosted deposits (Kyser & Cuney 2008; Cuney, 2009). Basement-hosted unconformity-type uranium deposits are characterized by a geochemically simple mineralogy of uraninite, with lesser coffinite and uranium alteration minerals (Kyser & Cuney, 2008). Some basement deposits (e.g., Dawn Lake, Rabbit Lake, McArthur River), however, also contain trace Cu, Ni, and As minerals (Sibbald, 1985). The simple mineralogy that defines these deposits is interpreted to reflect more oxidizing conditions than those found in the sandstone-hosted deposits (Kyser & Cuney, 2008). Illite is the only syn-ore mineral identified to have precipitated with primary uraninite (Alexandre et al., 2007; Kyser & Cuney, 2008). These deposits are typically focussed along fractures and faults in the basement, especially those that have been exacerbated by the presence of graphitic pelitic units (Kyser & Cuney, 2008), and are sometimes defined by fluid or collapse breccias, as at Rabbit Lake (Sibbald, 1985). Basement mineralization-associated alteration is defined by a fault-controlled inverted cone of clay alteration that is widest near
the unconformity, consisting of pervasive illitization and strong chlorite alteration immediately proximal to mineralization (Jefferson et al., 2007; Kyser & Cuney, 2008).

The RWZ also shares many of the above-listed characteristics that define basement-hosted unconformity-type uranium deposits. Uranium mineralization is predominantly hosted in the WSPG, and less commonly, in the intruding pegmatites, and in the nearby HWW and FWW granitoids. As described in Section 5.3, some uranium mineralization at RWZ locally occurs as fracture linings, veins, or breccias associated with brittle reactivation of regional structures, which is likewise documented at Rabbit Lake (Sibbald, 1985). Mineralization at RWZ however is overall defined by a high grade core surrounded by a low grade shell, which is also comparable to basement-hosted mineralization at Rabbit Lake (Figures 4.7, 6.1; Section 5.2; Hoeve & Sibbald, 1978). The RWZ is also locally monometallic, associated only with trace amounts of chalcopyrite or rare brecciated fragments of skutterudite that are not in-situ (Figures 5.28, 5.29A, 5.30, 5.31). The Roughrider deposit is spatially associated with a series of cross-cutting faults at 30° and 70° TCA (Figure 4.7) that dominantly preserve a reverse sense of displacement, as is the case for most unconformity-type uranium deposits. Mineralization-associated alteration, dominated by illite with subordinate mineralization-proximal chlorite localized in the WSPG is extensive in the basement rocks surrounding the segment. Similar to previously-documented basement-hosted deposits, clay alteration at RWZ defines an inverted cone that is most pervasive proximal to the unconformity,
however it reaches significant depth into the basement (Figures 6.2, 6.3). Furthermore, the geochemical relationships of uranium relative to iron, calcium, or silicon in uraninite at RWZ indicate that primary uraninite exhibits geochemical relationships similar to the basement-hosted Key Lake, McClean Lake Sue C, and to a lesser extent, Millennium deposits (Figures 7.21, 7.23, 7.25). Primary uraninite in these deposits is associated with an absence of SiO₂, low concentrations of CaO, and variable iron content. As stated above, this is suggested by pre-ore quartz dissolution (Section 5.2; Figure 5.38), the mobilization and/or alteration of uranium by calcic brines (Pagel et al., 1975; Kotzer & Kyser, 1995), and variable pre-ore and post-ore remobilization of hematite from the paleoweathering profile (Section 5.2, Figures 5.16, 5.19, 5.38).

The similarity of controlling structures, styles of mineralization, and alteration at RWZ to those discussed in previously studied basement-hosted and sandstone-hosted unconformity-type uranium deposits in the eastern Athabasca Basin suggest that uranium mineralization at Roughrider represents a hybrid system. Such a system has also been documented at McArthur River (McGill et al., 1993). The McArthur River deposit, in the southeastern Athabasca Basin, is composed of three sandstone-hosted uraniferous pods and one basement-hosted ore body (Kyser & Cuney, 2008). It is monometallic and transitions from being hosted at the unconformity in the south, to depths > 500 m at its northeastern extent (Tuncer et al., 2006). The string of uraniferous pods at McArthur River along the P2 fault have been interpreted as a hybrid sandstone-to-basement-hosted system as the oxidizing uranium-bearing fluids were able to
attain greater depth into the basement (McGill et al., 1993; Kyser & Cuney, 2008). In similar fashion, when the basement-hosted RRE and RRFE zones are considered in conjunction with the RWZ and Fission Energy's proximal sandstone-hosted J-zone uranium mineralization to the west, the hybrid nature of RWZ becomes more evident. These uraniferous pods create a west to east transition from sandstone-hosted to basement-hosted uranium mineralization, which may reflect the ability of mineralizing fluids to attain greater depth into the faulted basement rocks. This situation could be explained if mineralization was associated with bi-directional fluid flow that takes advantage of the network of cross-cutting structures as a fluid conduit. In this scenario, the basement-hosted pods precipitate from an oxidized basinal brine that travels downward into the WSPG along a network of faults. Conversely, the sandstone-hosted segments precipitate after a reduced “basement fluid” travels upward into the sandstone and interacts with an oxidized uranium-bearing basinal brine at or above the unconformity. In either case, as the RWZ occurs at the junction between sandstone- and basement-hosted pods of uranium mineralization, it can be interpreted as the transition from the western sandstone-hosted deposit type (the J-zone, or the Midwest deposit to the southwest) to the eastern basement-hosted deposit type end-members, represented by the RRE and RRFE zones. These factors explain the ability of the RWZ to display characteristics that define both end-member unconformity-type uranium deposit styles, such as its high-grade core and low-grade shell with veinlets and fracture-hosted mineralization, locally
polymetallic and monometallic nature, and extensive basement and sandstone alteration halos.

8.2 Model of uranium mineralization for the Roughrider deposit

The integration of data collected over the course of this study has culminated in the development of a model for the genesis of uranium mineralization at Roughrider (Figure 8.1). The data used in the formulation of the model include: (1) the extent of the clay alteration halo in the sandstone and basement at Roughrider (Figures 6.3, 6.4); (2) prevailing structures encountered in core; (3) information obtained regarding all of the uraniferous segments that comprise the Roughrider deposit from core logging and communications with the staff at Hathor Exploration Ltd.; (4) paragenetic and geochemical relationships identified for the RWZ (Figure 5.38) and; (5) the plethora of pre-existing research on unconformity-type uranium deposits in the Athabasca Basin.

The RWZ is located 20 – 30 m below the unconformity, whereas the RRE segment is approximately 50 – 75 m below the unconformity, and the RRFE segment comprises two zones, one that is approximately 20 m below the unconformity, and another approximately 125 m below the unconformity. The two segments of the RRFE zone are separated from each other by about 100 m of relatively unaltered basement rocks. All of the mineralized segments preserve evidence of the two dominant brittle structures that created dilational jogs along their intersections, allowing the mineralizing fluid to move into and out of the basement (Section 2.2). The deeper portion of the RRFE segment is sandwiched between locally fractured silicified zones of variable thickness, which is
interpreted to have acted as an aquitard, preventing the upward migration of mineralizing fluids along the 70° TCA fault at RRFE (Figure 8.1).

The originally ductile to brittle-ductile faults are inferred to be the result of deformation related to the Trans-Hudson Orogeny (Card et al., 2007). Brittle reactivation of these interconnected structures post-dating deposition of the Athabasca Group may have been the result of post-orogenic tectonic relaxation and/or to a lesser extent, fluid overpressure in the basement, resulting from graphite dissolution. Potential heat sources include the Moore Lakes olivine diabase lopolith, emplaced in the southeastern Athabasca Basin at 1.1±0.1 Ga (MacDougall & Williams, 1993), and/or the 1772±88 Ma locally uraniferous radiogenic granitic pegmatites that intrude the basement throughout the eastern Athabasca Basin (Annesley et al., 2000). Geothermal gradient or heat anomalies can create convection cell style circulation of the basin fluid and motivate it to travel downward into the faulted underlying basement rocks (Raffensperger & Garven, 1995; Cui et al., 2012). Furthermore, the greatest flow velocities during convection style flow have been associated with the basal conglomerate and unconformity (Cui et al., 2012), which explains why alteration is greatest in this region (Figures 6.2, 6.3, 6.4), illustrating the ability of mineralizing fluids to overprint the paleoweathering profile, and outlines lithological and structural controls on the scale of alteration.
Figure 8.1: Conceptual model of fluid flow and uranium mineralization for the Roughrider deposit. Model is not shown to scale. Blue arrows indicate possible flow direction associated with mineralization and are not representative of the number of fluids involved. Question marks and dashed lines indicate uncertainty, and/or potential for another uraniferous pod. (Original in colour)
The basinal brine at Roughrider is presumed to travel from west to east in the genetic model presented here, as it fits best with the formation of the three uraniferous segments discovered to date, and there is no way to determine where the Midwest NorthEast property sits with respect to the eastward flowing or westward flowing fluid cells in the free flow convection style model constructed for the Athabasca Basin (Raffensperger & Garven, 1995). The fluid, travelling predominantly along the poorly consolidated Basal Conglomerate proximal to the unconformity, has been identified in some research to be a saline NaCl and/or CaCl$_2$–rich brine (Pagel et al., 1975, Kotzer & Kyser, 1995, Derome et al., 2005, Mercadier et al., 2010). The source of salinity may be related to evaporated seawater, as suggested by the presence of an evaporite unit in the Carswell Formation in the western Athabasca Basin (Ramaekers et al., 2007) and by fluid geochemistry (Richard et al., 2011). The absence of significant sulphides and mudstone layers and the development of red beds in the quartz-dominant sandstones that fill the basin suggest that the brine was oxidizing. The pre-ore oxidizing brine travels along the lower MFb causing significant quartz dissolution and local mobilization of hematite and yellow-beige goethite. It may also leach and mobilize uranium from detrital zircon and monazite in the sandstone.

As the oxidizing brine moves into the basement along faults, it reacts with mafic minerals in the relatively unaltered pelitic gneisses and less commonly, granitoids, to form illite and lesser sudoite (Figures 5.13, 5.20), increasing the porosity of these rocks, exacerbating the scale of fluid flow, and creating space for the precipitation of uraninite (Figure 8.1). The oxidized brine may also leach
and mobilize uranium and some of the nickel, arsenic, copper, cobalt, and sulphur from the basement rocks. Given the relatively small fluid to rock ratio and limited recharge, the reaction between the basinal brine and the basement rocks can be considered to have occurred in a closed system. The mobilization of sulphides and arsenides dispersed in the basement rocks, dissolution of graphite (Figures 5.2, 5.3, 5.6, 5.7), and replacement of biotite, garnet, feldspars, and cordierite by illite may have altered the chemistry of the uranium-bearing brine to a more reduced condition, thereby causing the precipitation of uraninite, locally with minor chalcopyrite (Figure 5.29). The fluid-rock interaction may also have caused minor depletion of potassium relative to the original basinal brine as a result of argillization, as discussed in Chapter 6. The reduced fluid may then follow another structure back upward and eastward into the sandstone, remobilizing hematite and dissolving quartz along its path. Upon reaching the sandstone, the fluid precipitates mobilized potassium and iron by altering diagenetic dickite into illite and precipitating hematite (Figure 8.1). Considering the traceable outline of illitization to the current erosional basin surface (Figures 6.2, 6.3, 6.4), the reducing fluid may have reached the current basin surface.

The free convection cell flow system created by the oxidized and subsequently reduced fluids along the fault network at Roughrider allows for the remobilization of primary uraninite and the remobilization and alteration of base metal sulphides and arsenides, which is supported by the pseudomorphic replacement of uraninite botryoids by covellite and chalcocite, uraninite grains by skutterudite and nickeline, and the replacement of skutterudite, nickeline, and/or
pyrite by late remobilized uraninite (Figures 5.27, 5.29, 5.33, 5.37, 5.38). The cyclic fluid cell cycle may also have sometimes reversed its flow direction over time, and traveled from east to west. This cyclic bi-directional fluid flow would stimulate movement of the horizon between the oxidized hematized and argillized rocks and the uranium and base metal mineralized, reduced basement rocks, creating a reduced zone proximal to the unconformity around RWZ and the upper portion of RRFE, while creating a deeper zone of oxidation around the RRE and the lower portion of RRFE (Figure 8.1). This explains the occurrence of pyrite and galena in the sandstone above the RWZ segment (Figure 5.15), its occurrence proximal to the unconformity, and the deeper location of the RRE and lower RRFE segments. Increasing the zone of oxidation in the basement allows remobilization of primary uranium and base metal arsenides and sulphides. The fluid would inevitably become reduced again, re-precipitate uraninite, and locally, the base metal sulphides and sulpharsenides proximal to or within the reduced zone around the RWZ (Figures 5.33, 5.37, 8.1). The mobilization of ferrous iron in the fluid would have aided the local downward migration of the zone of oxidization, allowing the oxidized brine to travel deeper into the basement, perhaps leaching uranium from the basement rocks, as well as causing post-ore alteration, uranium remobilization, and perhaps the concentration of the deeper RRE and lower RRFE segments.

The addition of volatiles (CO$_2$ and CH$_4$) in the circulating basement fluid, caused by graphite dissolution, may result in fluid overpressure and brittle reactivation of faults and fractures, as the addition of gas(es) to an aqueous
solution increases its volume (Figure 5.22). As the basement rocks are crystalline, the increased volume would result in a local increase of fluid pressure in the basement, which could cause fracturing/brecciation of the surrounding rocks as the gas(es) try to escape. These late structures brecciate and remobilize primary uraninite, are associated with late carbonate alteration and silicification, and facilitate alteration of uraninite into rutherfordine and uranophane (Figures 5.23, 5.24, 5.32, 5.34, 5.38). The post-ore fluid subsequently precipitates late carbonate veins of sphalerite and ankerite, with marcasite and gersdorffite in the pelitic gneisses (Figure 5.23), fine grained disseminated siderite, and quartz-carbonate-pyrite veinlets (Figure 5.14).

Primary U1 returned an isotopic U/Pb age of 1,188±52 Ma, and an average chemical age of 1,167 Ma, as outlined in Section 7.6. These ages are considerably younger than the ages obtained for other Athabasca unconformity-type uranium deposits, which are often dated between 1471 – 1593 Ma (e.g.: Fayek & Kyser, 1997; Fayek et al., 2002a, 2002b; Alexander & Kyser, 2005; Alexandre et al., 2007; Cloutier et al., 2009, 2011; Alexandre et al., 2012). This suggests that perhaps an episode of lead loss and possible alteration has affected U1 and U2 in the RWZ, as a result of post-primary fluid alteration, and that the young ages obtained in this study may in fact reflect the age of this early resetting event. A possible cause for lead resetting that coincides with this age is the distal Grenville orogeny to the south east at 1,166±84 Ma (Hoffman, 1990; Mosher, 1996). In further support of this theory, one of the oldest chemical ages obtained on U1 was 1,482±1.9 Ma, which is more in accordance with the average
ages recorded for unconformity-type uranium mineralization elsewhere along the WMTZ (Appendix D). This older age may have been poorly represented in the U/Pb ages obtained, as it represents only one of several data points collected to define the discordant line that intersects the Concordia. Furthermore, the geochemical analyses of uraninites in Section 7.7 highlight the presence of minor Ca and Fe in primary U1 and U2, supporting the concept that primary uraninite at RWZ may have been affected by later fluid(s), causing isotopic resetting (Figure 7.27). Complementary to this theory, the identification of a minimum of six uranium precipitations events and therefore at least five fluid (resetting) events, described in Chapter 5 and substantiated by Figure 7.6, it is likely that uranium mineralization at RWZ is older than the obtained data suggests, and that the ages obtained for primary mineralization may actually record a lead resetting/fluid alteration event at RWZ.

The six phases of uraninite identified in the course of this study preserve evidence of at least six cycles of fluid flow that have created and affected the RWZ segment. Geochronology suggests that episodic uranium mineralization and remobilization took place over at least 900 Ma. Free convection-style fluid flow has been proven possible over extended periods of time with a sufficient thermal gradient or anomaly (Raffensperger & Garven, 1995; Cui et al., 2012). The linking of the dominant structures identified at Roughrider explains the pervasive, widespread alteration halo encountered in the RWZ, the less extensive alteration halo observed at RRE, and the spatial separation of uraniferous pods at RRFE by up to 100 m of unaltered basement rocks (Figure
8.1). As the RWZ rests between the sandstone-hosted Midwest deposit to the southwest and the basement-hosted RRE and RRFE segments to the east-northeast, it marks the hybrid transition between these two end-member deposit types. As such, RWZ is characterized by traits that define both of the end-member unconformity-type uranium deposit styles encountered in the eastern Athabasca Basin. This genetic model for mineralization at Roughrider also suggests potential for the discovery of other uraniferous pods or segments below currently discovered, conventional sandstone-hosted unconformity-type uranium deposits in the eastern Athabasca Basin, provided the same linking structures are present.

8.3 Future work

The function of this project was to characterize the RWZ uranium segment, and provide a model for its genesis. Several new problems were identified over the course of this study that fell outside of its scope, including:

- Metallogenic modelling of potential zonation relationships between uranium and nickel, arsenic, cobalt, and/or copper, including a detailed investigation of the geochemical and spatial relationship identified between uranium and copper. Geochemical zonation relationships have been identified for Ni and As across uranium mineralization and/or alteration in several other deposits (McLean Lake, Key Lake, and Collins Bay; Sibbald, 1985). Outlining any potentially similar relationships in the RWZ or within the Roughrider deposit as a whole may assist in better
understanding paleoredox conditions, or perhaps delineate another pathfinder source for future exploration.

- A petrographic, geochemical, and geochronological study of the RRE and RRFE uraniferous segments, and their comparison to Fission Energy’s J-zone uranium mineralization to decipher their temporal relationship with the RWZ and confirm the mineralization model presented in this study.

- Stable isotope and fluid inclusion studies would assist in determining the nature and source of mineralizing fluids, better outline the genetic and geochemical conditions present on the Midwest NorthEast property during uranium mineralization, and confirm the fluid and mineralization model hypothesized for the Roughrider deposit. A major issue with this research in the RWZ was the inability to find quartz- or carbonate-bearing samples within or immediately proximal to uranium mineralization.

- A geochemical investigation of iron speciation at Roughrider to examine its potential to behave as a reducing agent for the precipitation of uranium from solution would improve the current knowledge regarding the genesis of these deposits. Iron is abundant in host rocks at Roughrider, in its reduced form in the unaltered basement minerals and as pre- and post-ore pyrite, and in its oxidized form as hematite in the upper portion of the saprolitic paleoweathering profile, liesegang bands in the MFc and MFb sandstones, and around uranium mineralization.
Limonite is also present in the sandstones and in the basement around uranium mineralization. A project of this nature could help determine if the vast amount of iron that has been identified in this work to have close spatial and temporal relationships to uranium mineralization may in fact play a large role in the formation of these deposits. This work could further be expanded to include sulphur isotopes in the polymetallic portions of the RWZ, RRE, and/or RRFE segments for the same purpose.

- A paragenetic analysis and U/Pb isotopic age dating of alteration-associated rutile in the RWZ could provide more accurate ages for pre-ore and post-ore alteration. If present, syn-ore rutile could also provide a more accurate age for primary mineralization at RWZ, or further substantiate the results obtained in this study. Rutile may serve as a good age dating mineral given its ability to retain uranium and lead, thus perhaps rendering it more reliable than uraninite age dating, provided good paragenetic relationships can be identified (Zack et al., 2011).
9. CONCLUSIONS

The goal of this project was to provide a detailed petrographic and geochemical characterization of the West Zone of the Roughrider unconformity-type uranium deposit, with a secondary aim of deciphering its formation mechanisms, and advancing uranium exploration in the Athabasca Basin, particularly in the area surrounding the Roughrider property. Some questions remain without a clear answer, such as the explicit source of uranium, or of reduction of the mineralizing fluids, as they are outside of the scope of this study and cannot be conclusively determined here. The main conclusions of this study are summarized as follows.

- The RWZ is characterized by components that define both end-member styles of unconformity-type uranium deposits, as it is hosted in the basement rocks and is locally monometallic, yet is also locally polymetallic, and associated with an extensive halo of clay alteration.

- The Roughrider deposit is intersected by a series of brittle reactivated cross-cutting 30° and 70° TCA reverse faults and fractures that have locally displaced the Marker Conglomerate, thrust altered basement rocks a few metres into the Athabasca Group sandstones overlying the RWZ, and created dilation jogs that increase basement porosity and permeability. Many of these structures have preferentially intersected planes of weakness defined by graphitic pelitic gneisses, allowing the mineralizing fluids to react with and dissolve graphite.
• Pre-ore alteration associated with uranium mineralization comprises deg
graphitization, argillization, chloritization, hematization, desilicification, minor goethitization, and bleaching.
• At least six generations of uranium mineralization have been identified in the RWZ, meaning at least six fluid circulation events that resulted in five lead resetting events have affected the RWZ, which is supported by the linear relationships exhibited by uranium and thorium. Primary U1 has been identified to have precipitated as a singular phase, potentially locally replacing pre-existing chalcopyrite. Fine-grained primary U2 co-precipitated with illite and local sudoite, as well as skutterudite, nickeline, vaesite, and gersdorffite, locally concentrating them together.
• Post-ore alteration comprises at least four generations of uranium remobilization, copper-enrichment, remobilization of hematite, local minor carbonatization, alteration of uraninite, local silicification, pyritization, late precipitation of base metal sulphides and sulpharsenides, and trace rutile, and kaolinite.
• Primary uranium mineralization returns a discordant U/Pb age of 1,188±52 Ma and a similar average chemical age of 1,167±2.1 Ma, which may represent Pb resetting associated with the Grenville orogeny. Remobilized U4 – U5 uraninite yields a highly discordant U/Pb age of 262±24 Ma, and a compatible average chemical age of 246±1.8 Ma, which implies periodic alteration and remobilization of uraninite at RWZ over at least 900 Ma.
• Uranium mineralization at RWZ is geochemically similar to both the basement-hosted McClean Lake Sue C and Millennium deposits, and the sandstone-hosted Key Lake and Midwest deposits. The similarities between RWZ and the Midwest deposit suggest that together they form part of a hybrid system, where RWZ marks the transition between the sandstone-hosted mineralization to the west-southwest (Midwest deposit), and the basement-hosted mineralization to the east-northeast (RRE and RRFE segments).

• The transition from shallow, sandstone-hosted to deeper basement-hosted uranium mineralization reflects the ability of the oxidized mineralizing fluid to attain greater depth in the basement, circulating along the network of interconnected, reactivated brittle faults and taking advantage of hematite to maintain its oxidized state. Gently-dipping fractures may have played a critical role in the fluid flow networks in the basement and in the formation of uranium mineralization below the deposits formed near the unconformity.
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Appendix A: Thin Section Petrography

RB26001:
Composition:
- Quartz: 10 – 15%
  - Weakly fractured
  - Mostly monocrystalline, some polycrystalline
  - Many have sutured grain contacts
  - Appear to weakly follow dominant foliation, sometimes deviates to define weaker secondary foliation with rutile → 2 quartz episodes?
- Cordierite: 5 – 10%
  - Clear in PPL, looks like quartz but lacks undulose extinction
  - First order dark grey interference colours
  - Strongly fractured
  - Most occurs as pinnite (95% of all cordierite)
  - No apparent preferred orientation
- Feldspars: 5 – 10%
  - Strongly clay/sericite altered.
  - Undifferentiated due to degree of alteration
  - No apparent preferred orientation
- Chlorite: 5%
  - Pleochroic bluish-green – green – clear
  - Some appears to be partially altered to sericite (?)
  - First order yellow interference colours
- Hematite: 3%
  - Transmitted light (TL): dark reddish brown in both PPL and XPL
  - Reflected light (RL): light bluish-grey in PPL, and reddish-pink to blue-grey anisotropy in XPL
  - Generally conforms to foliation
- Rutile: 2%
  - Many internal reflections (yellow, green, blue, red)
  - Skeletal grains; subhedral to anhedral
  - Some grains appear squished (pre-syn-tectonic?), some appear to overprint primary mineralogy (post-tectonic – hydrothermal?)
- Illite: 55%
  - Fine grained alteration of pre-existing mineralogy
  - Lath-shaped to acicular
  - Some second order pink and blue interference colours, and slightly larger grains size suggest presence of sericite as well
- Graphite: 2 – 3%
  - Opaque in TL; goldeny-brownish grey in RL (PPL)
  - Elongate sheaves are 0.4 mm (avg)
  - Subparallel to foliation defined by quartz and hematite grains
  - Usually microfolded, unless protected by quartz
- Pyrite: << 1%
  - Found one tiny grain
Weakly graphitic cordierite-pelitic gneiss was originally composed of quartz, plagioclase, cordierite, biotite, graphite and tiny trace amounts of pyrite. Hydrothermal alteration produced some hematite, chlorite after biotite, and illite/sericite after plagioclase and cordierite. Brittle deformation is suggested by microfractured quartz and cordierite. Rutile appears to be corroded. Dominant foliation is defined by graphite, hematite, and some quartz. Secondary foliation is defined by the same minerals as the first, and is weaker than the dominant foliation, as the minerals defining it overprint the first (dominant) foliation. Fractures are typically either subparallel to one of the foliations, or oblique at shallow angles (30° to one of the foliations). A late precipitated chlorite is relatively unaltered and overprints some quartz grains (late hydrothermal). Some quartz grains suggest recrystallization (grain size reduction).

RB26003:
Composition:
- Quartz: 20%
  - Undulose extinction
  - Weakly to moderately microfractured
  - 2 phases: coarse (2 – 4 mm) quartz crystals are brittle deformed; fine (~0.15 mm) quartz crystals are relatively undeformed, with rare inclusions and no undulose extinction
- Dark brown clay alteration: 30%
  - Tartan twin appearance is faintly visible in some crystals (Kfs?)
  - Opaque minerals are replacing the core
  - Few fractures, but less than seen in quartz
  - No visible preferred orientation
- Pale beige clay mineral: 15%
  - Lamellar twins are rare, but faintly visible in some crystals
  - May be strongly altered cordierite or plagioclase
  - Rutile and hematite have precipitated in the core of some
  - No obvious preferred orientation
- Feldspars: 20%
  - Dusty-looking in PPL
  - 2 cleavages at 90° used to ID relative to quartz
  - Some illite alteration is present along cleavages and edges
  - No obvious preferred orientation
- Biotite: 10%
  - Clear to pale brownish-red in PPL
  - Pleochroic from pinkish-brown to bluish-green
  - Partially altered to chlorite, with rutile and hematite precipitating along cleavages
  - Weak, discontinuous alignment of crystals defines foliation
- Rutile: 5%
  - Present exclusively as alteration of biotite
- Pyrite: 1 – 2%
o Whitish-yellow subhedral to cubic habit
o No visible anisotropism, internal reflections, or bireflectance
o Finely disseminated throughout the section
o Almost exclusively hosted in clay

Weakly altered granitic pegmatite is relatively undeformed, likely originally composed of k-feldspar, quartz, plagioclase, and biotite. Feldspars have been altered and replaced by illite/sericite. Some quartz crystals are weakly microfractured, while most exhibit undulose extinction, indicating fracturing/faulting. Biotite is partially to completely altered to chlorite, with rutile and hematite precipitated along its cleavage planes. Pyrite is finely disseminated in the illite – precipitated from hydrothermal alteration (?)

RB26004:
Composition:
- Quartz: 90%
  o ~1 – 2% as quartz overgrowth cement
  o Some dissolution has created secondary porosity
  o Long and concave-convex grain boundaries
  o Subround to subangular
  o Poorly sorted
  o Moderate to good sphericity
  o Both monocrystalline (90%) and polycrystalline (10%)
- Illite: 7%
  o As pervasive cement/replacement of pore space and dickite
- Zircon: <1%
  o Detrital
  o Fractured
  o Weakly to moderately corroded
- Monazite: <1%
  o Detrital
  o Fractured
  o Weakly to moderately corroded
- Sericite: 2%
  o As pervasive cement/replacement with illite
- Muscovite: << 1%
  o As rare detrital grains included in or protected by quartz
  o Variably altered
- Chlorite: <1%
  o As fine-grained cement with illite and sericite
  o Also occurs as alteration of biotite/muscovite grains
- Biotite: <<<<1%
  o Saw one chlorite grain that appeared to be replacement of biotite
- Leucoxene: ~1%
  o Rutile needles in pore space of what was probably ilmenite grain
  o Detrital – alteration associated with diagensis
- Anatase: <<< 1%
  o One equant, round, anhedral grain found
  o Pre-dates illite

Quartz arenite has been weakly hydrothermally altered. Quartz dissolution is minor, evidenced by secondary porosity and corroded grain edges. Illite & sericite replace pre-existing dickite and infill pore space. Chlorite alters and replaces muscovite and biotite, rarely occurring as hydrothermal cement with illite and sericite. Leucoxene and anatase have replaced detrital ilmenite, suggesting that leucoxene is related to late diagenesis or early hydrothermal fluid alteration.

RB26005:
Composition:
- Quartz: 95% (~10% as polycrystalline quartz)
  o Subrounded to subangular
  o Moderate to good sphericity
  o Avg grain size is 0.7 – 1 mm
  o Most have concavo-convex or sutured grain contacts
  o Moderately sorted
  o Most grains exhibit undulatory extinction
  o Some overgrowth cement present
  o Some dissolution – corrosion of edges and secondary porosity in some grains
- Zircon: 2%
  o Euhedral
  o Corroded and microfractured, unless they are included in quartz
- Muscovite: < 1%
  o Rare grains occur with sericite and illite cement, or around/within quartz
- Rutile: < 1%
  o Rare inclusions in quartz, and grains floating in illite cement
- Monazite: <1%
  o Subhedral to euhedral
  o Pale yellowish – green in ppl or colourless
  o Small (5 µm), rounded, anhedral detrital grains
- Galena?: << 1%
  o Disseminated in illite cement
  o Euhedral to subhedral and very fine grained
- Hematite: < 1%
  o Small bladed grains, or as reddish stain of clay
- Illmenite: << 1%
  o Inclusion in quartz
  o Micron-sized anhedral illmenite grain has hematite exsolution
  o Fractured/altered
- Pyrite: < 1%
  o Disseminated anhedral grains in illite
Secondary porosity: < 1%: from partial dissolution of quartz, and around illite

**Quartz arenite** has experienced strong compaction, evidenced by sutured grain contacts and quartz overgrowth cement (2%). Illite and sericite cements make up the remainder of cement and mineral composition of this sample. Partial desilication is evidenced by eroded quartz grain boundaries and open pore space within grains. Galena and pyrite are associated with hydrothermal alteration, as they occur exclusively in the illite/sericite cement, which is also a product of hydrothermal alteration. Hematite blades, and rarely, pink – reddish hematite stain of illite and around quartz grains is observed. Approximately 1% secondary porosity has been created by quartz dissolution and illitization.

**RB26006**: (Analyzed with SEM)
Composition:
- **Quartz**: 95% (~5% as polycrystalline quartz)
  - Round to subround
  - Good sphericity
  - Avg grain size is 0.75 – 1.5 mm
  - Most have sutured grain contacts (65%)
  - Well sorted
  - Most grains exhibit undulose extinction (80%)
  - Some grains indicate dissolution (secondary porosity)
- **Zircon**: 2%
  - Subhedral – euhedral
  - Most are metamict, contain nearly no U or Th
  - Brownish-clear in PPL
  - Avg grain size is 0.15 mm
- **Rutile**: 3%
  - In dissolution vugs in quartz, and as rare inclusions in quartz
  - Sometimes pleochroic brown to greenish-brown
  - Average grains size ~ 0.25 mm
  - Sometimes anhedral and round, sometimes bladed and acicular
- **Monazite**: <1%
  - Subhedral to euhedral
  - Pale yellowish-green in PPL or colourless
  - Small (5 µm), rounded, anhedral grains
- **Alumino-phosphate-sulphate mineral (APS)** (Carnelite?): <<<<1%
  - Found one grain in illite/chlorite cement
  - ID’d using SEM

**Cement**: 35%
- Quartz overgrowths are rare and hard to find
- Illite-dominant (fibrous/micaceous) some areas are incomplete replacement of dickite by illite
- Some sericite (rare)

Secondary porosity: 1%
- Partial dissolution of quartz, and around illite cement
Quartz arenite has experienced strong compaction, evidenced by sutured grain contacts. Quartz overgrowth cement is rarely visible (2%). Hydrothermal clay alteration is dominated by illite, which has replaced diagenetic dickite. Partial desilicification is evidenced by eroded grain boundaries and open pore space in some grains. There are 2 phases of rutile: one appears to be detrital, occurring as small (10 µm), round, corroded grains; a later hydrothermal (?) acicular rutile is euhedral to subhedral (5 – 15 µm), and occurs in the eroded earlier rutile grains or with illite. Red earthy hematite occurs only as stain of illite. Approximately 3% secondary porosity has been created by quartz dissolution.

RB26008:
Composition:
- Illite: 20%
  - Fine grained
  - Pervasive replacement of pre-existing minerals
  - Overprints quartz grains
- Sericite: 30%
  - Appears late-syn to early post-illite
  - Locally replaces original mineralogy
  - Randomly oriented
- Rutherfordine: 10%
  - Nearly radiating masses
  - Micaceous – euhedral
  - Second order blue interference colours
  - Paragenetically late relative to all other minerals
- Amphibole: 5%
  - Strongly altered – mostly skeletal fragments of grains
  - Biotite has replaced it sometimes, which is then chloritized
  - Identified by remnant cleavage – preserved by rutile sometimes
- Cordierite (?): 10%
  - Paragenetically early; overprinted by illite/sericite/chl
  - Strongly altered to pinnite
  - ID’d based on alteration - could otherwise have been quartz
- Garnet: < 1%
  - 1 - 2 potential grains
  - Strongly altered, somewhat euhedral outline
  - Chloritized; preserves grain outline with chlorite blades
- Quartz: 2 – 3%
  - Randomly oriented grains
  - Rarely appears relatively unaltered \(\rightarrow\) late recrystallization/silicification (?)
- Tourmaline: <<1%
  - Micron-sized subhedral to euhedral crystals
  - Blue – clear pleochroism
  - Rare, hosted in illite/sericite/chlorite
  - Second order yellow interference colours
Zircon: 1 – 2%
- Corroded
- Rounded subhedral grains
- Randomly oriented inclusions around the micaceous material

Hematite: 2 – 3%
- Red stain in clay
- Metallic (paragenetically late) euhedral blades near rutile
- Possible alteration product of garnets with rutile and chlorite (?)

Pyrite: << 1%
- Weakly to moderately corroded
- Some rounded small grains
- Only found 2 grains, obviously formed quite early – remobilized (?)

Garnetiferous amphibole-cordierite-pyrite pelitic gneiss has been moderately hydrothermally altered. Original mineralogy likely consisted of hornblende, quartz, cordierite, garnet, biotite, pyrite, and plagioclase. Hornblende has been eroded and locally altered to biotite, which was then chloritized and overprinted by sericite. Garnets appear to have been replaced by chlorite, hematite, and rutile. Quartz has been dissolved, and fine-grained illite, sericite, and chlorite have infilled its space. Cordierite is dusty looking due to pinnite/illite, chlorite, and sericite alteration. Zircons are round and fractured. Tourmaline is rare and strongly fractured. Pyrite appears to be early (pre-alteration), showing evidence of corrosion around edges, caused by hydrothermal fluids. Hematite appears zoned – with skeletal/strongly eroded edges, and euhedral to subhedral cores. Illite has pink stain from hematite, and has pervasively replaced/alter ed everything else, with lesser coeval sericite and chlorite (barely identifiable except for ghosts). Rutherfordine is paragenetically late, euhedral, and overprints the illite/chlorite.

RB26009:
Composition:
- Quartz: 30%
  - Corroded around edges - minor dissolution
  - Euhedral drusy quartz marks outer edge of pyrite veins
  - Some appear augened - weakly define foliation
  - Inclusions in eyes are oriented parallel to foliation
- White to pale tan clay: 15%
  - Sericite and illite - original minerals not identifiable
  - No obvious preferred orientation
- Beige clay (feldspar): 5%
  - Remnant mineral outlines replaced by illite and sudoite
  - Remnant graphic intergrowths with quartz → was a feldspar
- Chlorite: 20%
  - After biotite – partial to total replacement
  - Contains inclusions of rutile
  - Spatially associated with graphite
Best defines original foliation, is slightly folded by later foliation

- Pyrite: 25%
  - Weakly to moderately fractured euhedral to subhedral grains
  - Some grains are corroded
  - Appears that more brittle fracturing occurred after the vein – fracturing and eroding pyrite

- Chalcopyrite: <1%
  - Yellowish-green colour (RL)
  - Very fine grained
  - Finely disseminated throughout the groundmass

- Gersdorffite: <1%
  - Encrusted on the side of pyrite grain in vein
  - No bireflectance or anisotropy
  - Tested on SEM

- Graphite: 5%
  - Elongate sheaves
  - Some are folded in the stress directions associated with 2 foliations
  - Close spatial association to chloritized biotite

- Rutile: 1%
  - As inclusions in chloritized biotite

**Weakly graphitic pyrite-chalcopyrite pelitic gneiss** originally contained quartz, feldspar, biotite and graphite +/- pyrite (?). Feldspars were altered to illite, sericite and sudoite. Biotite was replaced by chlorite, and rutile, along cleavage. Graphite preserves evidence of two deformational stresses, suggesting that it was an original component of the pelite. S1 was strong, as some quartz grains are augen and have a halo of graphite around them. This is also true of another mineral, which has been entirely replaced by chlorite (garnet?). Hydrothermal alteration resulted in the pyrite-quartz vein, outlining reactivated brittle deformation, as pyrite is fractured and squished locally, with the beginning of triple point contacts, and some minor recrystallization possible. Gersdorffite encrusted the edge of vein pyrite. Chalcopyrite is earlier than graphite, as it occurs as inclusions within it, and along its edges (2 chalcopyrite phases?). Chalcopyrite also formed slightly after the quartz-pyrite vein, as it is finely disseminated inside the quartz veined area.

**RB26012:**
Composition:
- Quartz: 40%
  - Fractured
  - Undulose extinction
  - ~5% as recrystallized microquartz in veins and with illite and chlorite alteration
- Illite: 25%
  - As replacement of feldspars (or garnet?) around quartz
- Chlorite: 30%
As replacement of biotite and muscovite
- As alteration of feldspars with illite (~5% of it)

- Zircon: 1%
  - As inclusions in quartz
  - Randomly disseminated

- Monazite: <<1%
  - Randomly disseminated

- Anatase: 1%
  - As large strongly altered, anhedral grains
  - As fine grained disseminations in the clay
  - Fairly pervasive

- Hematite: <<1%
  - As stain around some quartz grains

- Muscovite: 5%
  - Partially to completely replaced by iron-poor, colourless chlorite

- Siderite: <<1%
  - As randomly disseminated aggregates (late) in the clay

- Tourmaline: <1%
  - Randomly disseminated in the clay, and sometimes as inclusions in quartz

**Moderately argillized granite** originally composed of feldspars, quartz, biotite, muscovite, monazite, dravite. Hydrothermal alteration produced illite, chlorite, and late siderite±tourmaline

**RB26013:**
**Composition:**

- Quartz: 57%
  - Moderately to strongly fractured
  - Fractures have microcrystalline quartz veins infilling them
  - 2 dominant brittle fracture sets: (1) sub-parallel the short side of the section first, and (2) A later cross-cutting event ~75° oblique to that angle (~ subparallel to the long side of the section)
  - Some is fine, possibly polycrystalline quartz – possible late silicification

- Chlorite: 25%
  - Replaces (pseudomorphs in some cases) garnets (?) and biotite
  - Very fine grained
  - Pale green pleochroism
  - Slightly anomalous interference colours

- Sericite: 3%
  - Replaces feldspars and garnets

- Rutile: <1%
  - One ~15 µm round grain noted near specular hematite

- Pyrite: <1%
  - 1 anhedral grain noted around hematite
The possible presence of chloritized garnets suggests that this sample is a moderately to strongly chloritized garnet-pyrite pelitic gneiss. The original mineralogy is suggested to include quartz, feldspar, garnet, pyrite, and biotite. The feldspars, garnet, and biotite have been altered to chlorite, illite, and sericite. Quartz has been stretched, fractured and recrystallized, evidencing several deformation events. A late secondary brittle event is oriented sub-perpendicular to the first, evidenced by locally displaced fractures associated with S_a due to S_b fractures. S_b appears to have been stronger; creating a foliation that follows the fracture pattern. Only the weak outlines of the original minerals are present, making them not confidently identifiable. Later hematite stains edges of quartz and clay minerals.

RB26017:
Composition:
- Quartz: 25%
  - Weakly fractured
  - Inclusions of zircon/biotite
  - Undulose extinction
  - Many surtured grain boundaries
  - Half or more is polycrystalline
- Pale Beige Mineral (illite/sericite): 45%
  - Dominantly illite, with minor sericite and fine grained chlorite(?)
  - Appears to have 2 cleavages at 90° and grain outlines
- Brownish-beige altered mineral (illite?): 20%
  - Illite and chlorite, maybe hematite stained?
  - One possible weak cleavage, and grain outlines
- Biotite: 2 – 5%
  - Alteration of remnant amphibole and as mineral being chloritized
  - Contains inclusions of rutile and hematite
  - Defines foliation
- Amphibole: 1%
  - Very high relief
  - Contains black fibrous/acicular rutile alteration – defines cleavage
- Pyrite: << 1%
- Rare tiny grains are subhedral and corroded
- One grain is being pseudomorphed by cpy
- **Chalcopyrite**: 1%
  - Randomly disseminated anhedral blebs
  - Very fine grained
  - Appears to be pseudomorphing earlier pyrite
- **Hematite**: 3%
  - Randomly dispersed small grains
  - Slightly fractured
  - Some as inclusions in biotite

**Granitic gneiss** originally contained K-feldspar, quartz, plagioclase, hornblende and biotite. Metamorphism/deformation appears to have altered hornblende to biotite, then chloritized all biotite. Metamorphic biotite is the only mineral that defines a weak foliation. Quartz is weakly fractured, with tiny biotite and zircon inclusions. Feldspars (?) are completely hydrothermally altered to illite, sericite, and chlorite. Pyrite is early, as it is being replaced by hydrothermal chalcopyrite, and hematite also appears to be locally replacing it as well. Hematite is late, as inclusions in biotite, and randomly disseminated inclusions. Hematite may also be responsible for staining some of the clay in this slide to a dark maroonish-brownish colour. Also contains late kaolinite veins (?) that crosscut some quartz and clay alteration.

**RB26020: BAD SLIDE**
Can only see quartz, chloritized mica, and sericite veins.

**RB26021:**
**Composition:**
- **Quartz**: 60%
  - Undulose extinction
  - Moderately fractured
  - Crosscut by veinlets of hematite and illite, or polycrystalline quartz
  - Some contain dissolution vugs
  - Local stretching of grains, though this is not very evident
  - Weak alignment of some quartz
- **Illite**: 35%
  - Replaces ghost minerals – interpreted to have been feldspars
  - Outlined by red hematite
- **Biotite**: 5%
  - Completely replaced by chlorite/sericite/hematite
  - Appears to follow weak alignment of quartz on one side of slide
- **Specular hematite**: <1%
  - Occurs proximal to reddish hematitic clay
  - Appears late relative to the rest of the rock
  - Euhedral to anhedral
  - No preferred orientation observed
This sample is a **Granite** which has been strongly altered and replaced by illite and chlorite, and to a minor extent, hematite. This is a relatively poorly cut thin section, due to abundance of clay. Originally composed of quartz, K-feldspar, plagioclase, and biotite. Quartz has been fractured (2 dominant orientations sub- perpendicular to each other). Hematite-stained kaolinite vein divides the thin section and may represent the contact of or increased proximity to a fault:

- The longer side is more deformed, fractured, and altered relative to shorter side. Minerals are weakly aligned to define a foliation. Quartz is fractured and has been squished and stretched.
- The shorter side is weakly to moderately fractured with no foliation or mineral alignment whatsoever.

There is also a late sericite-illite-hematite vein that crosses the section parallel to the short side of the slide and to the hematite vein above.

**RB26024:**

**Composition:**

- **Quartz:** 35%
  - As microquartz in veins cementing fractures in quartz phylloclasts
  - Some preserve quartz side of myrmekitic texture
- **K-feldspar:** 35%
  - Almost entirely replaced by illite, chlorite, and sericite
  - Sometimes just ghost outline with faint cleavage
- **Plagioclase:** 20%
  - Strongly altered to illite
  - Mostly only visible as a ghost outline
  - Less common than K-feldspar and quartz
- **Chlorite:** 15%
  - As replacement of original biotite and muscovite
  - In groundmass with illite
  - As partial replacement of feldspars
- **Muscovite:** 2%
  - Variably to completely chloritized
- **Rutherfordine:** 3%
  - As late hydrothermal fresh overprinting micaceous laths on one side of slide
- **Illite:** 10%
  - As pervasive replacement of feldspars with chlorite
  - In veins cutting quartz (May be kaolinite)
- **Anatase:** <1%
  - As late fine grained anhedral disseminations
  - As early alteration of biotite, ilmenite? (as leucoxene) and possibly hornblende, preserving cleavages, or twin planes for ilmenite
- **Hematite:** <<<1%
As random disseminations of earthy red extremely fine grained hematite
Late, rarely noted in this slide

**Granite** has been moderately to strongly hydrothermally altered to illite, sericite, with minor chlorite and hematite. Trace rutherfordine and veinlets of quartz and illite (or kaolinite) attests post-ore alteration.

**RB26025:**
Composition:
- **Quartz:** 20%
  - Strongly fractured
  - Undulose extinction
  - Strongly corroded
  - 2 dominant fracture orientations – one is subparallel to slide (S<sub>a</sub>), other is ~ 20° - 25° oblique to first (S<sub>b</sub>)
  - Commonly intersected by veins of kaolinite or illite (?)
- **Chlorite:** 15%
  - ~ 5% of chlorite as alteration of biotite
  - Much appears late, as overprint of quartz, within clay
  - Micaceous habit, first order yellow interference colours
  - Some appears to be overprinted by hematitic clay?
- **Cordierite/Other alteration?:** 10%
  - Yellowish in PPL
  - Strongly altered to illite, sericite, chlorite
  - Commonly overprints quartz
- **Reddish-brown mineral:** 1%
  - Spatial association to cordierite
  - Probably illite and chlorite altered mineral that has been stained by hematite
- **Rutherfordine:** 15%
  - Euhedral, well formed micaceous bladed crystals
  - Late hydrothermal forming in clay and void space
  - Sometimes has close association to chlorite
- **Illite:** 20%
  - Cannot see outline of previous minerals – has been completely hydrothermally overprinted
- **Hematite:** 15%
  - Stains illite and chlorite
  - Metallic (specular) hematite is elongate, bladed, and extremely fine grained
  - Occurs after 1<sup>st</sup> pyrite
- **Pyrite:** <1%
  - Sometimes strongly fractured, with corroded edges – appears framboidal
o Finely disseminated cubes throughout the slide, and within kaolinite(?) veins – multiple episodes?
  o Sometimes closely associated with hematite
• Chalcopyrite: <1%
  o As tiny anhedral grains randomly disseminated throughout the slide
• Kaolinite (?): 3 – 5%
  o As late veins that crosscut everything else
  o Clay has booklet-like appearance

Psammo-pelitic gneiss (?) sample likely originally contained quartz, K-feldspar, plagioclase, and biotite. Does not appear to have significant metamorphic overprint, no foliation. Hydrothermal alteration has rendered biotite to chlorite and feldspars to illite and chlorite. Much of original quartz has been dissolved, void space replaced by illite and chlorite. Some quartz is shattered or strongly fractured in two dominant directions. Cordierite and the reddish-brown mineral have been hydrothermally altered to chlorite, illite +/- sericite. Hematitic reddish brown stain of clay appears late to everything. Late veinlets of illite-pyrite crosscut everything else, suggesting they were last to form. Metallic minerals are extremely fine grained and generally appear randomly disseminated throughout the sample, only maintaining a close spatial association with chlorite.

RB26026:
Composition:
  ▪ Quartz: 40%
    o Moderately fractured
    o Undulose extinction
    o No preferred orientation
    o Some trace dissolution
  ▪ Feldspar (?): 25%
    o Replaced by sericite and illite
  ▪ Biotite: 5%
    o Completely chloritized
    o Appear randomly oriented
  ▪ Sericite/illite: 25%
    o More sericite in this section than in most – possibly just a better slice
    o Undifferentiated minerals – original mineralogy not determinable
  ▪ Carbonaceous clay stain (?): 5%
    o Opaque clay in TL and RL
    o Likely responsible for overall grey colour of sample
    o Super fine-grained graphitic clay?

This sample is hydrothermally altered massive clay, containing quartz, sericitized feldspars, and chloritized biotite. The differentiation of K-feldspar relative to plagioclase is not possible as they are completely replaced by sericite and illite. Biotite has been replaced by chlorite. Quartz shows undulose extinction
and same two fracture patterns oriented sub-perpendicular to each other, infilled with illite and fine quartz. There is significant evidence throughout this slide of 2 brittle deformational events.

**RB26027:** very similar to **RB26017**

**Composition:**
- **Quartz:** 20%
  - Weakly fractured
  - Inclusions of zircon/biotite
  - Undulatory extinction in some
  - Very little is polycrystalline
- **Dark brown-stained illite and chlorite (?):** 75%
  - Outline of replaced grains is sometimes visible
  - Stain renders differentiation of chlorite and illite difficult
  - Extremely fine grained and pervasive
- **Biotite:** 2 – 3%
  - Chloritized
  - Contains inclusions of rutile and hematite
  - Defines a foliation
- **Chalcopyrite:** << 1%
  - Randomly disseminated anhedral blebs
  - Very fine grained
  - Appears to pseudomorph earlier pyrite
- **Hematite:** 2%
  - Randomly dispersed small grains
  - Slightly fractured
  - Some as inclusions in biotite

**Granitic gneiss** originally contained K-feldspar, quartz, plagioclase, and biotite. This sample is very similar to RB26017, although it is slightly more altered with many more veinlets of kaolinite or illite. Metamorphic biotite is the only mineral that defines a weak foliation. Quartz is weakly fractured, with some zircon and tiny biotite inclusions. Other minerals are completely hydrothermally altered to illite, sericite, and chlorite. Clay minerals are stained a dark brownish colour (hematite). Chalcopyrite is rare, as disseminated tiny grains. Hematite is also present as inclusions in biotite, and randomly disseminated grains. Sample has late kaolinite or illite (?) veinlets that crosscut quartz, in a random orientation, while some follows main foliation.

**RB26028:**

**Composition:**
- **Quartz:** 25%
  - Some are strongly fractured
  - Undulose extinction
  - Inclusions of biotite
- **Chlorite:** 20%
As replacement of biotite grains
- As alteration of sillimanite
  - Illite: 40%
    - As pervasive replacement of entire slide
  - Hematite: 2%
    - Has specular habit
    - Also occurs as red grains less commonly in this section
  - Cordierite (?): 10%
    - Extremely altered
    - Usually smaller grains around and altered to chlorite, sericite, and illite
  - Sillimanite?: 2%
    - As yellowish “fireplace” fibrous grains
    - Associated only with chloritized section of slide
  - Arsenopyrite?: 1%
    - Elongate pyrite-looking grain, but whiter
    - Weak pleochroism (whitish – bluish – yellowish)
    - Appears to occur mostly in veins, or is replacing pyrite?
    - Reddish and bluish anisotropy
  - Pyrite: < 1%
    - Most grains are eroded around edges
    - Very few, extremely small euhedral grains disseminated in sample

This sample is suspected to be a sillimanite-pyrite-cordierite-garnet (?) pelitic gneiss. Originally mineralogy comprised quartz, biotite, plagioclase, garnet, cordierite, sillimanite, and pyrite. This thin section is too thin to see any metamorphic or deformation fabrics. Quartz is strongly fractured in all directions (like a broken egg), evidencing cataclasis. Hydrothermal alteration is extensive, as it would appear that fractured quartz and very strongly altered cordierite are surrounded by chlorite and illite, or illite +/- some sericite. Sometimes other grain outlines can be seen (cubes, rhombs), leading to the suspicion that garnets may have been present at one point, but have now be replaced by chlorite. Hematite is very well formed as acicular blades, and stain of clay. Pyrite appears to be corroded and sometimes is being replaced by hematite or arsenopyrite. Pyrite appears to have formed early - before hematite. Arsenopyrite looks extremely similar to pyrite, but also shows weak pleochroism and anisotropy. It appears to be late - forming in veins or as replacement of cubic to subhedral pyrite grains, and is fresh.

**RB26029:**
Composition:
- Quartz: 35%
  - Undulose extinction
  - Moderately fractured (2 orientations @ ~90°)
  - Crosscut by veins of illite and microcrystalline quartz
  - Some weak evidence of stretching
• Illite±chlorite: 45%
  o Cannot differentiate – believe it may have been feldspar
  o Weakly fractured
  o Only ghost outline of grains remain
• Biotite/muscovite: 15%
  o Completely replaced by chlorite, sericite, and rutile
  o Appears to weakly define 2 separate foliations (oriented in the
    same direction as the 2 fractures)
• Rutile: 1%
  o As alteration in altered biotite/muscovite
  o Occurs along cleavage
• Sericite: 3%
  o Usually filling fractures, or occurring as blades disseminated
    through the thin section, generally following first brittle fracture
    orientation (~25° – 30° from the long side of section)
• Hematite:
  o As fine disseminations in clay
  o Usually associated with illite and sericite alteration (stain)

This sample is interpreted as Granite. It was composed of quartz, feldspars, biotite, and muscovite. Biotite has been replaced by chlorite and rutile (along cleavages). The feldspars have been replaced by illite and sericite, leaving only the outline of their grains. Two brittle deformations are visible – one that fractures quartz ~ 10° from the short side of the section, and another later event that is ~20° – 30° from the long side of the section that shares its orientation with several kaolinite veinlets, and appears to have been stronger than the first.

RB26033:
Composition:
• Sericite/illite: 35%
  o Ghost grains – possibly feldspar
• Quartz: <5%
  o RARE very uncommon, strongly corroded
• Chlorite (sudoite): 20%
  o Replacement of biotite/muscovite, garnet, with illite
• Sericitized/chloritized garnet (?): 5%
  o Totally replaced, ID based on habit of ghost outline
• Illite: 10%
  o Replacement of pre-existing mineralogy
• Rutherfordine: 10%
  o Late hydrothermal
  o Forms with graphite
  o Overprints everything, is very fresh
• Hematite: <<1%
  o As rare earthy red disseminations/stain
• Anatase: <1%
Coarse anhedral to subhedral grains that are pre-metallic minerals
  * Anhedral blebs infilling altered mica cleavages

- **Graphite: 5%**
  * Well formed laths
  * Early relative to skutt, cpy, nick, etc

- **Skutterudite: 5%**
  * Euhedral to subhedral
  * Corroded
  * Altering to nickeline sometimes, possibly cobaltite too

- **Nickeline: ~1%**
  * Similar timing to skutt, slightly later as it occurs as alteration?

- **Gersdorffite?: <1%**
  * Similar to skutt, but slightly more creamy yellowish tint

- **Chalcopyrite: 5%**
  * Anhedral disseminations throughout the slide
  * Common around graphite

- **Pyrite: < 1%**
  * Could be mistaking this for Gersdorffite, or other way around

Pyrite first, then Graph, then Skutt/Nick, cpy, then rutile

**RB26039:**
Composition:
  * **Quartz: 20%**
    * Most grains exhibit undulose extinction
    * Weakly to moderately fractured
    * Equant crystals follow foliation, but do not define it well
    * Some contain inclusions of zircon and rutile

- **Dark beige – brown mineral: 20%**
  * Completely altered to sericite/illite
  * Outlines of crystals still visible
  * Impossible to identify → presumed to have been feldspar

- **Pale tan mineral: 20%**
  * Completely altered to sericite/illite
  * Outlines of crystal still visible
  * Impossible to identify → presumed to have been feldspar

- **Garnet: 20%**
  * Euhedral to subhedral
  * Replaced by illite/chlorite
  * Moderately fractured (alteration most obvious in fractures)
  * Appear to define weak foliation?

- **Biotite: 15%**
  * Is both chloritized and relatively unaltered
  * Many contain inclusions of rutile along cleavage plane
o 2 phases – one that follows the foliation, and appears to be slightly more altered to chlorite, and another, later, coarser grained orientation perpendicular to the foliation
o Both phases overprint or grow around all other minerals except graphite

- Hematite: 1%
  o Anhedral grains that are partially corroded
  o Disseminated throughout the section

- Graphite: 1%
  o Dominantly as fine sheaves, rarely as roundish grain
  o 2 orientations – same as biotite – one defines and follows foliation, one crosses it

- Pyrite: <1%
  o Subhedral to anhedral
  o Slightly corroded
  o Disseminated throughout the sample

This Weakly graphitic garnet-pyrite pelitic gneiss contains both early and retrograde biotite, as indicated by 2 different orientations. Graphite also occurs in both orientations however these are the only minerals to define a second fabric. Quartz is well formed and weakly fractured. Feldspars are presumed to be the medium beige-brown sericite-illite and the pale tan and black/white (XPL) sericite-illite-sudoite(?) alteration. Some of the biotite is partially altered to chlorite. The garnets are moderately to strongly fractured, most oriented subparallel to foliation, with a lesser set perpendicular to that. The fractures are infilled with illite, which they are also moderately altered to. Pyrite and hematite have corroded cores and are randomly disseminated throughout the sample. Both appear to be late relative to everything else.

RB26040:
Composition:

- Ankerite: 50%
  o Both as euhedral rhombs growing in vein, and as anhedral fine grained groundmass
  o Drusy lining around metallic sphalerite and galena
  o SEM’d to ID

- Sphalerite: 5%
  o As weakly zoned brownish colloform masses
  o Rimmed by galena, marcasite, graphite and ankerite

- Muscovite (?) : 5%
  o Partially chloritized
  o Late, occurring as euhedral micaceous laths in fine grained ankerite – this may be Rutherfordine
  o Also earlier, as strongly chloritized laths and knots in calcite

- Quartz: 5%
  o Euhedral drusy minor vein fill between Ankerite and metallics
- Chlorite: 3%
  o Occurs exclusively as alteration of micas (muscovite)
- Galena: 15%
  o As massive anhedral grains
  o Earliest metallic mineral
- Marcasite: 5 – 10%
  o As elongate prismatic laths and sub-cubic equant grains
  o Later than sphalerite, galena, and (pseudomorphs?) pyrite
- Gersdorffite: 1%
  o Encrusts pyrite and galena
  o Possibly rims cobaltite as well
- Graphite: 1%
  o Randomly disseminated micaceous laths
- Unknown mineral (Cobaltite?): 2 - 5%
  o Creamy white with brownish-purplish tint
  o Poor polish
  o VERY weak B/P and anisotropy → hard to see: creamy yellowish grey to creamy pinkish grey
  o Altering/replacing marcasite along fractures
- Pyrite: 2%
  o As cubic grains that are being replaced by galena locally
  o Not common
  o May have been pseudomorphed by marc

Timing: micas + pyrite + graphite → carbonate (Ankerite) → quartz → galena → sphalerite → cobaltite → marcasite + gersdorffite → muscovite?

RB26041:
Composition:
- Quartz: 15 – 20%
  o Almost equally split between being poly and mono-crystalline
  o Undulose extinction
  o Fractured
  o Some grains between 2 – 4 mm, most are 0.5 – 1.0 mm
  o Grains are all fractured parallel to dominant foliation, with some fractured sub-perpendicular to this
- Chlorite: 10 – 15%
  o 0.25 mm blades
  o Pleochroic pale yellowish green to colourless or pale green
  o Forms both parallel to and perpendicular to foliation
  o Appears relatively undeformed – formed post-deformation, hydrothermal?
- Biotite: ~5%
  o Medium brown
  o Typically folded
  o Defines foliation
- Very thin cut, hard to determine outside of brown colour in PPL, cleavage, and crystal habit – completely chloritized?
- Appears to have rutile inclusions/alteration

- Hematite: 2%
  - Fine grained bright red clay in fractures and in cracks in quartz
  - Some specular (bright whitish grey in RL) occurs less commonly

- Rutile: 1 – 2%
  - Strongly corroded
  - Yellowish anisotropism with yellow internal reflections
  - Generally elongate parallel to foliation, although some cut it sub-perpendicular

- Garnet: 2%
  - Strongly altered
  - Hard to ID except for tweed-like cleavage planes, and pale pinkish red colour in PPL and isotropism in XPL
  - Usually ~ 0.5 mm

- Galena: << 1%
  - On edge of slide near centre on convex edge
  - Small, whitish-blue grey in RL, isotropic, no bireflectance
  - Triangular equant euhedral grain

- Illite/Sericite: 55%
  - As replacement of feldspars, garnet, pre-existing minerals
  - In some areas, crystal shape is loosely preserved – most were likely garnets or feldspars

* a cluster of siderite was observed, as well as a few laths of graphite, although neither in sufficient concentration to amount to anything representative of the sample.

This **garnet pelitic gneiss** has been moderately to strongly illitized, weakly hematized, and weakly chloritized. Original mineralogy likely included quartz, feldspars, biotite, garnet, muscovite, and possibly amphibole. Pervasive illitization has left original mineralogy impossible to ID for sure. Hematite concentrates in fractures around quartz and along foliation around remnant garnets and biotite. Metallic minerals are rare, and include rutile, rare specular hematite, pyrite, and galena. One dominant foliation is visible across the centre of the slide, while edges have no visible fabric. A weak brittle fracture set can be seen in some quartz and by orientation of chlorite, however this is discontinuous, and was either transposed to the strong foliation, or was not strong enough to alter it.

**RB26046:**
Composition:
- Quartz: 25%
  - Undulose extinction
  - Moderately fractured
  - Loosely follows/defines foliation
Some appears stretched parallel to foliation

- Sericite/illite replaced grains (?): 15 – 20%
  - Possibly originally feldspar?
  - Only grain shape remains

- Muscovite: 30%
  - Larger grains appear to be weakly folded toward foliation, while smaller grains define it
  - Possibly 2 phases (coarser grained phase first, then finer grained phase)
  - Usually contains inclusions of rutile
  - Some oriented subperpendicular to foliation – weaker secondary foliation perhaps

- Graphite: 10%
  - Golden in RL
  - Appears undeformed
  - Defines foliation
  - Another (less common) phase occurs perpendicular to foliation
  - Contains inclusions of yellow chalcopyrite

- Sericite/illite: 10%
  - Replaces/alters most minerals

- Garnet: < 1%
  - Altered to sericite/illite/chlorite
  - Only outer grain shape remains, and pale reddish tint in some
  - Appear unaffected by foliation

- Galena: < 1%
  - Isotropic
  - Whitish – grey in RL
  - Fine grained and randomly disseminated in section

- Rutile: 1 – 2%
  - Corroded
  - Yellow in crossed polars (RL)
  - Yellow IR
  - Randomly disseminated and as inclusions in muscovite or biotite

- Pyrite: < 1%
  - Euhedral to subhedral
  - Occurs as inclusions in or around graphite and biotite
  - Finely disseminated

This weakly graphitic garnet-pyrite pelitic gneiss originally contained quartz, plagioclase, biotite, graphite, garnet, and muscovite (?). Original minerals were altered to sericite/illite/sudoite; biotite was also partially altered to rutile. Graphite looks brighter and “cleaner” than in previous sections.

RB26048:
Composition:
- Quartz: 25%
- Mostly either fine grained monocrystalline or polycrystalline
- Some appears stretched a bit, but not very fractured
- Some grains exhibit undulose extinction

- Cordierite: 15%
  - In little (2 mm) pocket clusters with significant clay alteration
  - Subhedral grain outlines have quartz, illite, pinnite

- Illite/sudoite: 50%
  - Pervasive – most grains no longer recognizable
  - Different colours – darker/browner stuff hematite-stained

- Biotite: 3%
  - Altered to chlorite

- Tourmaline: 1 – 2%
  - Pleochroic blue – clear – palest yellow
  - Max 1st order red and yellow interference colours
  - Fractured
  - Often zoned

- Chalcopyrite: < 1%
  - Anhedral or subhedral skeletal grains
  - Finely disseminated
  - Medium yellowish colour – almost greenish
  - Contains a sphalerite inclusion (?) (md grey, no anisotropy, not observed outside of this one inclusion)

- Rutile: <1%
  - Medium grey equant anhedral to subhedral blebs (RL)
  - Bright yellow IR

- Pyrite: <1%
  - Bright whitish yellow subhedral blocks
  - Randomly disseminated
  - Somewhat corroded edges

This Pyrite-chalcopyrite-cordierite pelitic gneiss is strongly altered. Most minerals have been illitized/serecitized/chloritized. Fine grained tourmaline (dravite?) occurs around edges of altered cordierite. Some remnant biotite is visible, but has been altered to chlorite. No distinct obvious foliation left. Pyrite appears early, while chalcopyrite may be late, brought in with hydrothermal fluids.

RB26049:
Composition:
- Quartz: 15%
  - Undulose extinction
  - Some occurs as late growths within biotite cleavage planes
  - Contains some zircon inclusions

- Biotite: 15%
  - Has quartz growing between cleavages
  - Weakly defines a foliation (most obvious in one corner of slide)
  - Contain many inclusions
Based on pleochroism, some is phlogopite

- Amphibole: 25%
  - Strongly altered
  - Identified by crystal habit, and mostly, cleavages
  - Some is altered to biotite, which is altered to chlorite
  - More than one episode – strongly biotite altered large grains that follow weak foliation, and strongly corroded smaller sub-idioblastic grains that are weakly oriented sub-perpendicular

- Cordierite: ~5%
  - Strongly altered to pinnite
  - Remnant sub-idioblastic grains

- Garnet: 1%
  - Strongly altered
  - More of a brownish alteration, and otherwise is similar to cordierite
  - Isolated grains are strongly fractured and altered

- Tourmaline (Dravite): 2%
  - Subhedral
  - Pleochroic blue – clear – yellow
  - Commonly as inclusions in quartz, and around biotite
  - Late – possibly last to form (?)

- Pale tan mineral (Feldspar?): 10%
  - Strongly altered
  - Too thin relative to rest of thin section – pervasive clay replacement
  - ID’d based on pale tan colour (alteration) and 2 cleavages @ 90°

- Hematite: 3 – 5%
  - Fine medium grey inclusions in biotite, or medium grey skeletal grains randomly disseminated
  - Early hydrothermal alteration

- Pyrite: 2 - 3%
  - Framboidal, or strongly corroded
  - Randomly disseminated sub-cubic grains, sometimes skeletal
  - Also occurs as growth between cleavage planes in bio
  - Bright whitish- pale yellow

**Cordierite-garnet-pyrite pelitic gneiss** originally composed of amphibole, quartz, biotite, feldspar(s), cordierite, garnet, and pyrite. Amphibole occurs as an early syn-tectonic event and as a post-tectonic event. Syn-tectonic amphibole defines foliation, and has been almost entirely altered to biotite. Post-tectonic amphibole is sub-perpendicular to foliation, and appears to be corroded. Early quartz is stretched. Biotite is pre-tectonic, defining foliation, and almost totally replaced by chlorite and illite, and as retrograde alteration of amphibole, both of which are variably altered to chlorite and illite, and contain inclusions/alteration of quartz, hematite, and pyrite. Cordierite and garnet are illite and chlorite altered nearly beyond recognition. Neither appear to have any specific orientation or follow foliation. Hydrothermal alteration produced pervasive illite and chlorite alteration, corroded pyrite and precipitated minor hematite.
RB26050: Similar to RB26049

Composition:
- Quartz: 15%
  - Undulose extinction
  - Appears as late growths within biotite/hornblende cleavage planes
  - Only one phase is visible
- Biotite: 10%
  - Fairly large grains, and late very small grains as inclusions in quartz
  - Has quartz growing between cleavages
  - Weakly defines a foliation with amphibole
  - Partially altered to chlorite
  - Based on reddish – yellowish pleochroism, dominantly phlogopite
- Amphibole: 25%
  - Strongly altered
  - ID’d by crystal habit, and mostly, cleavages
  - Some is altered to biotite, which is altered to chlorite and illite
  - Subidioblastic
  - More than one episode – biotite altered large grains follow weak foliation, and corroded smaller sub-idioblastic grains that are oriented slightly perpendicular to weak foliation
- Zircon: ~1%
  - Fractured
  - Subhedral
  - Usually occur near or as inclusions in biotite/amphibole
- Tourmaline (Dravite?): 2%
  - Subhedral
  - Pleochroic blue – clear – pale yellow
  - Late – possibly last to form
- Illite±fine-grained chlorite: 47%
  - Likely altered feldspars
  - No visible grain ghosts - unidentifiable mineralogy
- Hematite: 3 – 5%
  - Fine medium grey inclusions in biotite, and disseminated grains
  - Early hydrothermal alteration
- Pyrite: 2 - 3%
  - Framboidal or strongly corroded
  - Randomly disseminated sub-cubic grains, sometimes skeletal
  - Also occurs as growth between cleavage planes in biotite
  - Bright whitish-yellow

Cordierite-garnet?-pyrite pelitic gneiss. Very similar to previous section.

RB26053:

Composition:
- Quartz: 85 – 90%
  - Poorly to moderately sorted
- Subrounded
- Good sphericity
- Forms moderately defined graded beds of coarse (>4 mm) and fine (0.1 – 0.25 mm) grained quartz
- Most grains exhibit sutured contacts, some are concavo-convex
- Quartz overgrowth cement (1%) is uncommon
- Exhibits evidence of dissolution around edges
- Most grains are stained with brick red hematite

- **Illite**: 7 - 10%
  - As cement between quartz grains
  - Also occurs within vugs in quartz with sericite (post-dissolution)
  - Replaces dickite

- **Chlorite**: 2%
  - As replacement/alteration of muscovite/biotite?
  - Some small grains intergrown with illite

- **Muscovite**: < 1%
  - Partially to completely chloritized
  - Sericite occurs sometimes with illite cement, or between/around quartz grains

- **Zircon**: 1%
  - Detrital grains included in and around quartz
  - Less common than in fresh sandstone

- **Hematite**: 2%
  - As stain around quartz
  - 2 round grains that are the replacement of detrital ilmenite
  - Mostly late hydrothermal

- **Kaolinite**: <<<1%
  - As wormy veinlets in illite and chlorite cement

- **Anatase**: 1%
  - As late hydrothermal alteration
  - Typically fine grained, probably co-precipitated with pyrite
  - 2 distinct precipitation events – 1) as aggregates of 0.25 mm grains pre-hematite that are stained/coated by it, and 2) as < 0.1 mm grains within illite cement around quartz and in dissolved grains pores infilled by illite that are not stained by hematite, therefore post-hematite

- **Pyrite**: << 1%
  - Yellowish, and is isotropic, but has a triangular pluck mark?
  - Cubic
  - Late – after illite, but before hematite, as it rims grains

Original quartz arenite contained quartz, dickite, zircon, ilmenite and rare biotite/muscovite. Hydrothermal alteration dissolved the edges of some quartz grains, produced vugs within the grains, and dissolved some overgrowth cement. Precipitation of hydrothermal illite in void spaces in quartz grains with sericite, and occurs as replacement of dickite. Chlorite also precipitated with illite, or
possibly just a touch later. Diagenetic alteration of ilmenite liberated iron and titanium, produced pyrite grains, and then brick red hematite stain on quartz and pyrite. Last to precipitate in this sample is late fine grained anatase in the illite.

**RB26055:**
Composition:
- **Hematite:** 20 – 25%
  - Specular hematite needles, anhedral grains, and as fine red stain
  - Forms as bizarre ellipsoidal semi-round oddly shaped clusters, with carbonate cores
- **Ankerite:** 5 - 10%
  - ID’d using SEM
  - Zoned – usually evidenced by red hematite stain
  - Typically occur as clusters of euhedral subhedral grains
  - Surrounded by specular hematite in matrix of illite and fine grained carbonate (ankerite?)
  - Sometimes stained orangish-red from hematitic clay
- **Illite/Sericite:** 45%
  - As pervasive replacement of pre-existing mineralogy
  - Intergrown with ankerite
- **Chlorite:** 10%
  - As micaceous hydrothermal replacement
  - Original minerals not visible
  - Weak pleochroism and first order interference colours
- **Tourmaline (Dravite):** 1%
  - As minor randomly disseminated very small accessory mineral
  - Subhedral to euhedral
  - Blue – yellow pleochroism
  - Fractured
- **Pyrite:** 1%
  - As subhedral to anhedral finely disseminated grains in specular hematite around coarse euhedral ankerite
  - Late relative to hematite, filling in space around needles

This is a hydrothermally altered **Illite-ankerite-hematite-pyrite rock.** Protolith is probably a calcareous pelitic gneiss. All that remains is (in paragenetic order): illite and chlorite pervasively altered pre-existing minerals. Then specular hematite precipitated in void space created by mineral alteration and dissolution. Euhedral ankerite grains infilled remaining central void space, and precipitated as fine grained alteration in void space around illite/chlorite, while hem was still precipitating, as it is zoned, with some hem staining outlining the zonation. Late pyrite precipitated around specular hematite, and tourmaline and trace siderite in the clay... May represent early, unmineralized wormrock formation?

**RB26059:**
Composition:
Quartz: 1 – 2 %
- Remnant from alteration
- Mostly eroded
- Overprinted by illite and chlorite
- Undulose extinction still weakly visible

Chlorite: 30%
- As large (0.75 – 1 mm) grains and as smaller grains with illite
- Some is replacement of pre-existing biotite
- Some is well formed and relatively late

Illite: 50%
- Disseminated throughout the sample
- Sometimes overprints remnant quartz
- Hard to say anything about it, section is too thin

Chalcopyrite: 3%
- Euhedral to subhedral
- Finely disseminated throughout the slide
- Some looks fragmented – breccia fragments carried in late fluid?
- Occurs as inclusion in late galena and with pyrite

Hematite: 3%
- Euhedral to subhedral
- Finely disseminated throughout the slide
- Some looks altered/eroded

Skutterudite: 2%
- Euhedral to subhedral colloform grains with cores of purpleish cobaltite, rimmed with nickeline, then skutterudite

Cobaltite: <1%
- As core of skutterudite grains

Nickeline: <1%
- As rim around cobaltite in core of skutterudite

Graphite: 1%
- Thin micaceous elongate sheaves
- Very fine grained and hard to see
- Close relationship to pyrite sometimes

Pyrite: 1%
- As fragmented brecciated grains carried in fluid with chalcopyrite

Rutile: <1%
- Anhedral to sub-cubic
- Lots of yellowish internal reflections
- Forms in fractures and veins, as well as being disseminated everywhere

This weakly graphitic pelitic gneiss has been hydrothermally altered to illite, chlorite, and sericite. Original mineralogy is not determinable, except trace remnant quartz and graphite. It would appear that quartz dissolution and clay alteration were first. Graphite is thin and appears weakly corroded. Pyrite, chalcopyrite, and hematite appear to have been brought in with alteration fluids –
look like they are brecciated fragments that are not an original component of this sample.

RB26065:
Composition:
- Quartz: 35%
  - Undulose extinction
- Biotite: 15 – 20%
  - Three phases define 1 dominant foliation, and another ~49° from it
  - Lots of pleochroic haloes from zircon inclusions
  - Some grains are very clean and fresh, others are subhedral at best, and up to 30% chloritized
- Garnet: 10%
  - Subhedral to euhedral
  - Most are unaltered to weakly altered around fractures and edges
  - Some up to 75% altered to chlorite and illite
  - Vary in size from 0.5 mm to 2 cm
  - Generally conform to dominant foliation with biotite
- Feldspars: 30 - 35%
  - Most are 95 – 100% illitized, preserving ghost outlines only
- Zircon: 2%
  - Dominantly as inclusions in quartz and biotite
  - Sometimes around garnets
- Pyrite: 2%
  - Subhedral to euhedral
  - Fractured, fine grained (<1mm)
  - Weakly corroded possibly
- Graphite: < 1%
  - Around biotite
  - Two phases; subparallel to two biotite orientations
  - Sometimes wrapped around garnet

Weakly graphitic garnet-pyrite pelitic gneiss is relatively unaltered (except feldspars). Cordierite may have been present – was not differentiated from argillized plag if so.

RB26070:
Composition:
- Quartz: 25%
  - As desilicified anhedral crystals
  - Illite and chlorite infill vugs
  - 1% or less as hydrothermal veinlets with illite-sericite
- Feldspars (Illite): 30%
  - Rough estimate as all is completely replaced by sudoite, illite/sericite
  - Identified based on ghost grains and visible/remnant cleavage
- Muscovite: 22%
  o Partially to completely altered to illite and sudoite
- Rutherfordine: 3%
  o As late hydrothermal radiating micaceous laths (small) in clays
- Chlorite (Sudoite): 20%
  o Mostly as replaced biotite and amphibole (?), some fine grained sudoite intergrown with illite
  o Occurs rarely as random knots in illite as well – could be replaced garnets? (<2%)
- Amphibole: <<1%
  o Observed only a few grains for sure
  o ID’d based on habit of ghost grains and one grain has rutile needles preserving cleavage
  o completely altered to sudoite and illite
- Anatase: 1%
  o As alteration of micas and amphibole – preserves cleavage
  o Anhedral round grains randomly disseminated throughout the slide

**RB26071:**
Composition:
- Quartz: 30 – 35%
  o As large crystals with feldspars and as fine-grained drusy quartz vein with pyrite, chalcopyrite and galena (25%)
- Feldspars: 65 – 69%
  o 100% argillized (illite and sudoite), only ghost grains are visible
- Rutherfordine: 1%
  o Small radiating laths randomly dispersed in illite and sudoite
- Pyrite: <1%
  o Micron sized euhedral to subhedral grains in clay and in qtz vein
- Chalcopyrite: < 1%
  o Micron sized anhedral blebs mostly in qtz vein
- Galena: < 1%
  o Very pale grey-white cubes
  o micron sized... nearly impossible to see

This was a *pegmatite*, likely in **contact with a pelitic gneiss**? Rock is moderately argillized as feldspars are no longer individually recognizable. Quartz vein is interpreted as late post – mineralization as it carries pyrite, chalcopyrite, and galena fragments (gn). Late rutherfordine also observed as the last alteration phase.

**RB26080:**
Composition:
- Hematite: 10%
  o As bright red stain over clay
  o As randomly occurring specular or anhedral grains
- Illite: 25%
  - As pervasive replacement of feldspars and some micas (ghost outlines and some cleavage planes still visible)
  - Intergrown with sudoite
- Rutherfordite: 5%
  - As late hydrothermal grains in clay, and minor veinlets
  - Very weak yellowish pleochroism
  - Well formed euhedral micaceous laths
- Sericite: 10%
  - As strongly altered remnant crystals with illite
- Garnet: <<1%
  - Noted one grain that has preserved subhedral shape and reddish brownish colour
  - Hematite stained
  - Replaced by carbonate and illite-sudoite
- Sudoite: 10%
  - As replacement of micas, feldspars, garnet
  - Intergrown with illite
  - As late veins
- Tourmaline (Dravite): << 1%
  - As randomly disseminated grains in clay
  - Very few observed, pleochroism is weak
- Anatase: 1%
  - As randomly disseminated grains around hematite and within micas
- Monazite: <<1%
  - One detrital grain found in clay
- Pyrite: 1%
  - As fine grained disseminations carried in late fluids and precipitated in veins and vugs – likely result of faulting as they are all angular fragments
  - One anhedral altered grain found as well

RB26083:
Composition:
(Pelitic Side)
- Quartz: 25%
  - Moderately fractured
  - Average ~1mm
  - Evidence of dissolution around edges
  - Many inclusions of biotite and zircon
- Biotite: 20%
  - Partially to completely altered to anatase and chlorite (chamosite)
  - Defines 3 different mineral alignments
  - At least 2 possibly 3 phases
- Sudoite: 15%
  - As replacement of some biotite and amphibole
Intergrown with illite as well

- Cordierite: 5%
  - Completely altered to pinite (illite, sericite, and chlorite)

- Feldspars: 15%
  - Completely replaced by illite and sudoite
  - ID’d based on remnant grain outline, twinning, and cleavage

- Amphibole: 5%
  - Completely altered to combination of sudoite and anatase
  - Anatase preserves cleavage planes
  - Also ID’d by ghost outline

- Zircon: << 1%
  - Noted as inclusions in quartz

- Anatase: 2%
  - As alteration of amphibole and micas

- Pyrite: 1%
  - As tiny disseminated somewhat rounded equant grains
  - Core sometimes looks more creamy pinkish, and is v. weakly anisotropic – could have skutterudite/gersdorffite core with pyrite rim?
  - As inclusions in cleavage planes of micas with anatase

- Chalcopyrite: <<1%
  - As tiny anhedral accessory grains in the clay

- Covellite: <<<1%
  - As alteration of chalcopyrite

- Graphite: ~1%
  - As inclusions in altered biotite
  - Usually only occurs proximal to and along contact between pelitic gneiss and migmatite
  - Always closely associated with biotite

(Pegmatite/migmatite side)
- Same mineralogy, but quartz dominated, possibly some K-feldspar on one side of slide, and fewer metallic minerals.

**RB26094:**
Composition:
- Quartz: 95%
  - Round grains
  - Moderately to well sorted
  - Good sphericity
  - Dissolution around grain boundaries
- Illite: 3%
  - As cement around some quartz grains
  - Could be more pervasive and just didn’t survive slide creation
- Hematite: <<1%
  - As stain around quartz grains
• Anatase: <1%
  o As random anhedral subround grains
• Zircon: <1%
  o As inclusions in quartz
• Sericite: 1%
  o As hydrothermal alteration around quartz grains

Quartz Arenite is moderately argillized and hydrothermally altered, with minor quartz dissolution, and trace hematite staining. No obvious dickite.

RB26100:
Composition:
• Quartz: 45%
  o Undulatory extinction
• Plagioclase: 30%
  o Approximately 75% altered to sericite
• K-Feldspar: 15%
  o Approximately 10 - 15% altered to sericite
  o Hard to ID – many lack characteristic tartan twins
• Biotite: 5%
  o Red pleochroism – most likely phlogopite
  o Almost every grain has a pleochroic halo from zircon inclusions
  o At least 2 phases visible, one altered, one recrystallized, defining foliations ~35° from each other
  o Fairly pristine – no obvious chloritization
• Zircon: 2 – 3%
  o As μm sized subhedral inclusions in biotite and plagioclase
• Rutile: <1%
  o Accessory minerals around biotite, along cleavages, very small (<1mm)
• Pyrite: <1%
  o One 0.25 mm subhedral grain noted around quartz and plag

Granodioritic gneiss is relatively unaltered – for reference.

RB26101:
Composition:
• Quartz: 85%
  o Subround to angular
  o Poorly to moderately sorted grains range from 0.3 -5 mm
  o Both polycrystalline (coarse pebbles) and monocrystalline (small grains) quartz
  o Sutured and concavo-convex grain contacts
  o Good sphericity
  o Some large grains have inclusions of chloritized biotite and zircon
  o Overgrowth cement is present, but as a minor component (~1%)
• Zircon: <1%
  o As accessory mineral in the clay or included in quartz
  o Fractured
• Illite: 5%
  o As dominant mineral between quartz grains
• Dickite (cement): 3%
  o Less common than illite – booklets and isolated grains with illite
• Chlorite (mica replacement): 1%
  o Occurs as replacement of biotite/muscovite grains (2%)
  o Also (less commonly) intergrown with illite and dickite
• Sericite: 1%
  o As rare grains between quartz pebbles
• Ilmenite: <1%
  o Altering to hematite (>90% altered)
  o Is also altering to leucoxene
  o Defines a heavy mineral lamination on one end
  o Rounded, altered, fractured
  o 0.1 – 0.25 mm grains
• Anatase/leucoxene: <<1%
  o As rare accessory grains, and as alteration of ilmenite
• Hematite: <1%
  o As rare red stain around quartz, in clay, and around ilmenite
  o As replacement of ilmenite
• Quartz Cement: 1%
  o Rare, occurs around some quartz grains

Dirty quartz arenite contains quartz grains and rare chloritized biotite and muscovite-sericite grains. Most pre-existing primary pore space has been infilled by dickite/illite/chlorite. Quartz overgrowth cement occurs around most grains in a very small amount. Dickite cement appears to be being replaced by illite, while chlorite appears to be replacing detrital minerals. Hematite is uncommon, and occurs late relative to illite and chlorite. Ilmenite occurs as a lens of heavy minerals in the arenite. Detrital ilmenite is being replaced by anatase/leucoxene, and has a halo of hematite around it.

RB26103:
Composition:
• Plagioclase: 33%
  o Partially sericitized
  o Sometimes forms myrmekitic texture with quartz
• K-Feldspar: 40%
  o Partially sericitized
• Quartz: 25%
  o Sometimes forms myrmekitic texture with plag around k-feldspars
• Muscovite: 1%
  o Partially altered to chlorite
One crystal at edge of slide has chalcopyrite along cleavage

- Sericite: 1%
  - As alteration of feldspars

- Hematite: << 1%
  - Included in plagioclase
  - No IR or B/P
  - weak blue-grey – yellow-grey anisotropism

- Rutile: <<1%
  - As one equigranular crystal that is slightly brown in transparent light
  - Some internal reflections
  - Near hematite

- Pyrite: ~1%
  - As veinlets that crosscut feldspars and quartz
  - As cubic crystals in K-feldspar

- Chalcopyrite: <1%
  - As disseminated veinlet around pyrite in one edge of slide
  - As alteration of muscovite in cleavage planes, and replacing it along edges

Granite is unaltered, with equal parts plagioclase and K-feldspar, both of which are weakly to moderately sericitized, quartz (forming myrmekitic texture with plag), and trace muscovite. Rutile inclusions or veinlets are rare, but noted once. Pyrite is also uncommon, but unmistakeably present as inclusions in feldspars. Chalcopyrite occurs as alteration of muscovite along cleavage and as disseminated micron-sized veinlets that rim pyrite and crosscut feldspars and quartz. Pyrite and chalcopyrite are suggested to be original components of this rock → this could aid in providing source for reduced iron prior to mineralization.

RB26104:
Composition:

- Quartz: 35%
  - Undulose extinction

- Plagioclase: 55%
  - Large anhedral crystals
  - 5 – 25% sericitized

- Biotite: 5%
  - 3 distinct phases defining two foliations, approximately 30° - 40° apart
  - Fairly unaltered

- Muscovite: 1 – 2%
  - Few mm sized laths noted between plag or quartz crystals

- Zircon: <1%
  - Included quartz, rarely in biotite
  - << 1 mm – hard to find

- Garnet: <1%
  - Almost 100% altered to chlorite
ID’d based on ghost grain crystal habit, and isotropism where not altered

- **Pyrite**: 2%
  - Anhedral grains that are paragenetically late
  - Appear in void space between quartz and/or plagioclase
  - Especially concentrated in leucosome

- **Carbonate**: <1%
  - Observed as random, late < 1mm-sized veinlets that crosscut plagioclase and quartz

Relatively unaltered **leucotonalitic gneiss**. Has minor carbonate alteration? Related to metamorphic alteration from nearby calc-silicates?

**RB26105:**

**Composition:**

- **Quartz**: 30%
  - Undulatory extinction
  - Myrmekitic texture with plagioclase
  - Two phases – one recrystallized fine grained quartz with amphibole, one anhedral mm- to cm-sized crystals

- **Plagioclase**: 35%
  - Variably sericitized – sometimes only 5% - around crystal edges, sometimes up to 90%
  - Often displays myrmekitic texture with quartz

- **Biotite**: 5%
  - Deep red to pale tan pleochroism – phlogopite?
  - Very few pleochroic haloes
  - Two definite phases
  - Defines dominant foliation

- **Garnet**: 2 – 3%
  - Anhedral blebby crystals
  - Weakly chloritized to unaltered
  - Late overprinting – potentially related to alteration associated with Hudsonian pegmatite intrusions

- **K-Feldspar**: 10%
  - Hard to distinguish – often lacks twins
  - Generally 80 – 95% sericitized

- **Amphibole** (*Tremolite/actinolite?):** 10%
  - Prisms/elongate blades (subhedral to euhedral)
  - Only one visible cleavage
  - 1st order yellow to red interference colours
  - Rare crystals exhibit lamellar twins
  - Colourless in PPL – no pleochroism
  - Late overprint with small euhedral recrystallized quartz, graphite, rutile, pyrite – defining earlier biotite foliation

- **Pyrite**: 3 – 5%
• Blebby, anhedral
• Spatially associated with garnet, rutile, and biotite

• Chalcopyrite: 1%
  • Anhedral blebs
  • Late – similar timing to pyrite

• Rutile: 3 – 4%
  • Acicular needles to round subhedral crystals
  • Nearly opaque in transmitted light
  • Follows biotite, closely associated to pyrite and amphibole

• Graphite: <1%
  • Small laths around biotite
  • Late relative to feldspars, quartz, and biotite

• Zircon: 1 – 2%
  • Very small (<< 1mm) subhedral to euhedral crystals
  • Some greenish pleochroic haloes in biotite and plag

This granodioritic gneiss, composed of quartz, plagioclase, K-feldspar, biotite, zircon, possibly some of the garnet, and perhaps some of the rutile. Metamorphism or intrusion by Hudsonian pegmatites caused partial melting and recrystallization, which has imparted some of the mineralogy from the metasedimentary gneisses onto the granodioritic gneiss – which has been recognized as a transitional zone between the two rock types – thus the presence of garnet, pyrite, chalcopyrite, and graphite that overprint it.

RB26106:
Composition:

• Quartz: 10%
  • 2 phases – one early, polycrystalline, corroded episode that appears smeared and fractured, and a later (and less common) coarse “fresh” looking episode
  • Also occurs as veins of polycrystalline microquartz in feldspar cleavage or twins?

• Plagioclase: 15%
  • Strongly altered to sericite – crystal habit is visible
  • Some have exsolution lamellae of quartz? Along cleavage
  • Thin section is cut too thin

• Biotite: 12 - 15%
  • All is partially to completely chloritized
  • Defines 3 foliations, 1 (first) subparallel to long side of slide, with 2 others oblique to either short side of the slide, making an x across the first
  • 2 phases: one is retrograde after amphibole (which is chloritized); one that is chloritized

• Amphibole: 15 – 20%
  • Most is altered to biotite and then chloritized
  • Rutile has grown in cleavage planes, thus preserving them
- **Graphite:** 7 – 10%
  - Well formed elongate sheaves
  - Oriented in all 3 foliation directions
  - Evidences that last foliation was post-pyrite vein – crosscuts it

- **Sericite/illite:** 15 – 20%
  - As alteration of feldspars, garnet, and cordierite
  - Random orientation → hydrothermal alteration
  - Appears to be pre-pyrite veins, is overprinted by it

- **Tourmaline:** < 1%
  - Occurs very late, overprinting everything else
  - Very small (<< 1 mm), subhedral, relatively unaltered grains
  - Randomly disseminated throughout

- **Pyrite:** 1%
  - As veins with quartz – cut by graphite
  - Some is also disseminated throughout sample

- **Chalcopyrite:** << 1%
  - Saw one anhedral bleb
  - Included in a quartz crystal

- **Hematite:** < 1%
  - As inclusions in biotite, sometimes replaces biotite
  - As randomly disseminated anhedral grains in clay

- **Cordierite:** 2 – 5%
  - Completely altered to pinnite

**Weakly to moderately graphitic pyrite-cordierite-garnet pelitic gneiss**

originally contained quartz, amphibole, biotite, graphite, plagioclase, cordierite, garnet, chalcopyrite, and pyrite. Three deformational events are visible, with pyrite veins post-dating all of them. Quartz occurs both as pre-deformation dusty, altered, locally micro-vuggy grains that are sometimes slightly stretched with dominant foliation, while some quartz grains appear fresh and unaltered, and are larger than the earlier grains. Most amphibole has back-reacted to biotite, while original biotite was replaced by chlorite. Plagioclase is strongly altered to sericite, and sometimes has veinlets of microcrystalline quartz growing along cleavage or twin planes. Trace cordierite is altered to pinnite. Hydrothermal alteration is limited, resulted in quartz-pyrite veins that crosscut everything else. Pyrite also appears to replace some biotite grains, anhedral chalcopyrite occurs in quartz vugs, and hematite and quartz are present along chloritized biotite cleavage. Illite occurs only as alteration of feldspars, cordierite, and garnet, but grain outlines are visible, and illite accounts for <20% of rock.

**RB26107:**

Composition:

- **Plagioclase:** 30%
  - Partially altered to sericite or calcite (up to 30% altered)
  - Segregated in leucosome-defining foliation
  - Large euhedral crystals
• Zircon: <1%
  o As inclusions in quartz and biotite (pleochroic haloes)
• Biotite: 5%
  o Unaltered
  o Two phases – one more altered than the other
  o Defines dominant foliation with plagioclase, quartz, pyroxene, and amphibole
• Clinopyroxene (Augite?): 25%
  o Two good cleavages
  o 2\textsuperscript{nd} order blue interference colours
  o Classic basal sections
  o Defines foliation with plagioclase, amphibole, and biotite
• Muscovite: 2 – 3%
  o Follows dominant foliation
• Orthoamphibole (Cummingtonite – Grunerite?): 15 – 20%
  o ID’d based on interference colours and habit when cleavage wasn’t visible
  o Defines foliation with pyroxene, plagioclase and biotite
  o Most crystals are up to 30% altered to illite and chlorite
• Quartz: 15 – 20%
  o Undulose extinction
• Garnet: 3%
  o Rare
• Calcite: <1%
  o As alteration of plagioclase
  o As anhedral blebs growing between pyroxene and amphibole
• K-Feldspar: 1 – 2%
  o Up to 45% altered to illite and sericite
  o ID’d based on tartan twins
• Titanite: <1%
  o Euhedral,
  o In foliation with amphibole, pyroxene

**Garnetiferous Calcareous pelitic gneiss** is relatively unaltered.

**RB31002**

Composition:

• Illite: 15%
  o Replaced all pre-existing minerals
  o Sometimes occurs as coarser grained sericite proximal to ore
• Hematite: 10%
  o As deep red stain of illite
  o Sometimes as specular needles growing in spaces with illite
  o Never in contact with uranium minerals
  o Appears that mineralizing fluids bleach hematized area and carry it away
• Skutterudite: 30%
  o Creamy whitish grey with pink tint
  o Anhedral to colloform masses to zoned? Euhedral crystals
  o No B/P
  o Yellowish I/R around cracks
  o Is altering/being pseudomorphed nickelite and cobaltite and possibly gersdorffite

• Cobaltite: 5%
  o Occurs as alteration around fractures of skutterudite
  o VERY weak purpleish grey pleochroism
  o Creamy pinkish grey to dark purplish grey anisotropy
  o Has a satin-like texture

• Nickeline: 10%
  o Anhedral
  o Strong B/P deep medium orange to pale creamy orange
  o Looks like it alters skutterudite along fractures and around edges
  o Strongly anisotropic from whitish greenish bluish to dark orange

• Uraninite: 25%
  o Replacement of micas and clay or botryoidal colloform masses
  o Medium brownish grey, no B/P, isotropic
  o Appears to be intergrown with pale bluish grey mineral (chalcocite?)

• Rutile: 3 – 5%
  o As rhombs, acicular needles, and anhedral grains
  o Close association to uraninite
  o Appears post-mineralization, but may have more than one phase

Semi-massive wormrock has been thoroughly hydrothermally altered to illite-chlorite. Chlorite, illite, muscovite and remnant biotite are then pseudomorphed by uraninite. Early rutile is dissolved, and reprecipitated shortly after uraninite, and again later as larger rhombs in available space. Pervasive illite/sericite alteration was first, and this was then stained by hematite. Uraninite appears to pseudomorph micas, and precipitate and anhedral grains. Late skutterudite is the altered or exsolves to nickeline and cobaltite.

RB31003
Composition:
• Illite: 7%
  o Well formed, micaceous
  o Pervasive replacement – no remnant ghosts
  o Stained by hematite

• Chlorite?: ~5%
  o Greenish-brownish stained with illite and sudoite around uraninite
  o Intergrown with illite

• Sericite/Muscovite: 5%
  o Appears to be intergrown with illite
- Occurs in close proximity to uraninite, sulphides/arsenides and hematite
  - Hematite: ~13%
    - Appears to have been relatively early
    - Stains illite/chlorite
    - Locally removed by mineralizing fluids
  - Skutterudite: 38 - 40%
    - Subhedral to anhedral crystals in clusters throughout the slide
    - Commonly partially to completely pseudomorphed by nickeline or less commonly cobalite
    - Locally pseudomorphs illite/sudoite
  - Cobaltite: 2%
    - Late euhedral cubes and partial pseudomorph of skutterudite
    - Violet
    - Isotropic, and weak Bireflectance
    - Sometimes lath-shaped
  - Vaesite: 3%
    - Pale violet – blue
    - Alters nickeline around edges
    - Isotropic, weak possible bireflectance, but no distinct pleochroism
  - Nickeline: 25%
    - Commonly as replacement of or co-precipitated with skutterudite
  - Rutile: <1%
    - Fine grained

The protolith is undeterminable. Hydrothermal alteration is as follows: Illite was first (with sericite and sudoite) and was later stained by red hematite. Illite was then pseudomorphed by skutterudite first, and possibly contemporaneous nickeline, or else it occurred as alteration right afterward. Cobaltite and vaesite were last. Illite + sericite → Hematite + sericite → Chlorite → Skutterudite + nickeline → Cobaltite + vaesite + rutile

RB31004
Composition:
- Illite: 5%
  - Intergrown with chlorite
  - Randomly disseminated around uraninite
  - Sometimes stained or overprinted by limonite
  - Overprinted by uraninite and sulphides/arsenides
  - Could be more – hard to tell as slide is missing significant portions
- Chlorite: 15 - 20%
  - 2 phases: coarser grained chlorite after biotite; later, finer chlorite phase is syn- to post-ore replacement of illite?
  - Overprinted by uraninite in several areas
  - Appears to overprint illite in many areas
  - Coarse chl laths exhibit pale green pleochroism in PPL
Much of finer chl has close spatial association with limonite

- Sericite/Muscovite: 2%
  - Close association to limonite?
  - Late relative to uraninite
  - Interference colours differentiate it from chlorite
  - Timing of replacement relative to everything else is questionable

- Limonite (Goethite?): 10 – 15%
  - Pale yellowish-orange fine grained dull granular masses
  - Appears to be late relative to everything else
  - Occurs as a late stain of illite and chlorite
  - Proximal to euhedral rutile

- Hematite: 5%
  - Medium brownish reddish fine grained stain of clays

- Skutterudite: 40%
  - As fine-grained massive disseminations, or colloform to anhedral grains
  - Locally altering to chalcocite, which then alters to covellite
  - Appears to be the primary (dominant) ore mineral in this section
  - May be some cobaltite alteration

- Chalcopyrite: < 1%
  - As anhedral masses near one edge of slide
  - Very fine-grained
  - Partially to completely altered to chalcocite
  - Found in and around the yellow limonite

- Chalcocite: 10 – 15%
  - Occurs as alteration of chalcopyrite and possibly skutterudite?
  - Sometimes has micaceous habit → replacing chlorite and illite?
  - Is both light grey and pale blue
  - Is locally altered to covellite along fractures and edges
  - May be pseudomorphed pyrite? Some cubic grains, though this could also have been skutterudite

- Uraninite: 3 – 5%
  - Anhedral inclusions in skutterudite
  - Fine-grained, disseminated in skutterudite and illite and chlorite
  - Difficult to see

- Covellite: 1%
  - Occurs only as local alteration of chalcocite

Hydrothermally altered Cu-Ni-Co weakly mineralized rock has an indeterminable protolith. Early hydrothermal alteration rendered all pre-existing mineralogy to illite, which was then locally chloritized. Syn-ore chlorite replaced most of the remaining illite, and then post-ore limonite appears to stain illite and chlorite. Timing of ore minerals is difficult to determine – chalcopyrite and skutterudite are not found in contact, but it is presumed that chalcopyrite occurred first (as it is seen in unmineralized rocks as well), then skutterudite precipitated as replacement → some preserved texture of illite/chlorite, or may
have pseudomorphed uraninite botryoids (explains uraninite inclusions). Later hydrothermal alteration caused chalcocite and covellite alteration of skutterudite and chalcopyrite, and may have precipitated late limonite and sericite. **This sample is tricky.**

**RB31005**

**Composition:**

- **Illite:** 53%
  - Stained red → from hematite (common → 25 - 30%)
  - Stained olive green → from uraninite (most common → 50%)
  - Stained yellowish → from goethite (least common → 10%)
- **Chlorite:** < 5%
  - As alteration of biotite
  - Not commonly seen in this thin section
  - Intergrown with illite as well
- **Sericite:** 10%
  - Along fractures
- **Hematite:** 10 – 15%
  - As stain of illite
  - Sometimes specular
  - Never contacts uraninite
- **Limonite (goethite):** 2 – 5%
  - As stain of illite/sericite
  - Most commonly along fractures
  - Closer to uraninite than hematite
- **Uraninite??:** <1%
  - Alteration around fractures to darker grey mineral
  - Sometimes looks like it pseudomorphed biotite
  - Some acicular fine grained (µm) disseminations in clay
- **Skutterudite:** 10%
  - Not in contact with visible uraninite
  - Most commonly replaced by nickeline
  - Sometimes pseudomorphed by galena
- **Nickeline:** 25%
  - As anhedral to colloform grains
  - As replacement of skutterudite
- **Cobaltite:** <1%
  - Replacement/exsolution of skutterudite with nickeline
  - Isotropic
  - Pale purpleish grey
  - No tints, no pleochroism
- **Pyrite and Chalcopyrite:** < 1%
  - As very fine grained disseminated veinlets
  - Anhedral
  - Some of the larger grains are corroded
  - Otherwise, looks very late
o Close proximity to hematite
  • Galena: < 2%
    o Euhedral to subhedral large grains in and around skutterudite
    o One very large anhedral grain has inclusions of nickeline?

This sample is very similar to RB31002, RB31003, and RB31004. Some uraninite also appears to be later remobilized, as they are anhedral fragmented (?) grains, and randomly disseminated. Uraninite may have stained illite green, and appears to pseudomorph/replace illite locally. Hematite is pre-ore, as there appears to always be a bleached zone of illite between hematite and Ni-As-Co-U mineralization. Limonite is always in very close proximity to fractures near mineralization, and stains illite/sudoite around it, suggesting it is syn- to very early post-ore. I suspect that the PS is as follows: Illite + sudoite → Hematite → Uraninite → Skutterudite → Limonite + Nickelite + Cobaltite → Pyrite → Galena +/- remobilized Uraninite?

Hydrothermal alteration starts as pervasive illite replacement of minerals, which is then hematized. Prior to or during precipitation of uraninite, hydrothermal fluids bleach the area, and carry away hematite. That’s why there is a progressive transition from wormrock to semi-massive wormrock, to massive mineralization.

RB31006
Composition:
  • Hematite: 2 – 5%
    o Late stain of illite
    o Partially replacing uraninite botryoids?
  • Uranophane: 2 - 5%
    o Rims hematite
    o Sometimes replaces/is intergrown with illite and sudoite
    o Fracture/vein infill crosscuts U1
    o Does not contact U4 or U5 to determine timing
  • Illite: 3%
    o Pervasive replacement of pre-existing minerals – is replaced by mineralization
  • Uraninite A (U3 as it turns out): 45%
    o Massive
    o Botryoidal
    o Grades into grains?
    o Crosscut by uranophane, U4 and U5
  • Coffinite: 10%
    o As alteration of U3 along fractures
    o Difficult to see
  • Uraninite B (U2 as it turns out): 20%
    o Elongate fibrously looking uraninite that pseudomorphs illite maybe
  • Galena: <1%
    o As inclusions in U2 and U4/5
• Uraninite C (considered to be U2 as well): 5%
  o As equant small grains included in U2 – these have same timing,
    just slightly different growth habit
• Uraninite 4/5: 5%
  o Both as veins/veinlets
  o Crosscut U2 and U3
  o Earlier than hematite it would appear – no obvious timing
    relationships, but hematite seems to occur around veins – no
    contact
• Chalcocite: <1%
  o As core of an eroded botryoid, or else a vug

U2/U3 seem to have VERY similar crystal habit to some of the nickeline noted in
other samples – is this a pseudomorphic relationship.... late reducing fluids
replace uraninite with nickeline

RB31010:
Composition:
• Calcite: 1%
  o Infilling vugs and void space around uraninite, nickeline, and
    skutterudite
  o Late (paragenetically)
• Illite: 1%
  o Appears to be intergrown with some nickelinie
  o Stained green by uraninite ?
• Chlorite: 4%
  o Occurs in void spaces, intergrown with hematite and/or illite
• Hematite:
  o Occurs as reddish brownish stain of chlorite, and rims calcite and
    uranophane
  o Also occurs as veins that cross uraninite
• Uraninite (U1 and U2 as it turns out): 30%
  o Pale to medium grey
  o Occurs as botryoids/colloform bands that are being replaced by
    nickeline?
  o Also occurs as replacement of illite and sudoite (This is U2 → 10%)  
    o Being altered to darker grey uraninite → coffinite
• Nickeline: 20%
  o As colloform replacement of uraninite ?
  o As fine grained anhedral fragment inclusions in U3
  o Possibly replaces pre-exisiting pyrite
  o Intergrown with skutterudite
• Coffinite: 5%
  o Darker grey
  o Alteration of pale grey U1
  o Contains inclusions of nickeline and chalcopyrite
• Uranophane: 1 – 2%
  o Looks similar to calcite, but yellow
  o Occurs in void spaces and vugs
  o Late, similar timing to or later than calcite
• Skutterudite: 5%
  o Intergrown with nickeline
• Chalcopyrite: <1%
  o As rare anhedral inclusions in U2
  o Around nickeline, so after it and skutterudite

Clearly U1 was first, followed by U2, which replaced illite and sudoite, and bleached away pre-ore hematite. Then hydrothermal alteration probably remobilized some U1, while precipitating later hematite, nickeline and skutterudite simultaneously. Late calcite, uranophane, and chalcopyrite then precipitated.

RB31012
Composition:
• Quartz: 25%
  o Strongly fractured
  o Edges show dissolution
• Chlorite: 20%
  o Based on presence of coarse grained micaceous clear clay mineral with first order yellow interference colours, but lacks green pleochroism and anomaluous blue interference colours
• Illite: 50%
  o Assuming it is pervasive throughout the sample (cut too thin – hardly any left)
• Goethite: 1%
  o Nice prismatic crystals, or granular masses
  o Pale yellow to brownish yellow in PPL (TL)
  o Interference colours masked by colour
• Rutile: 1%
  o Pale to medium grey in RL, with anisotropy masked by bright white and yellow internal reflections
  o As a late overprinting of clays
• Hematite?: 5%
  o Earthy red
  o Medium to pale grey in RL, with twins, and slight bluish tint
  o LOTS of internal reflections (red)
  o Appears around edges of fractures in quartz, or along corroded grain boundaries
  o Stains illite/chlorite red

This sample is a **hematized, illitized, cataclastic rock**. Quartz occurs in 2 phases – one is early - microvuggy with corroded edges and is strongly fractured.
The other occurs as veins with hematite and illite, differentiated from cataclastic fragments by its lack of fracturing. Illite appears to have been the first (earliest) hydrothermal alteration phase, possibly contemporaneously with some hematite, replacing all pre-existing mineralogy. Chlorite may have occurred in 2 phases – one as mineral replacement, which was then surrounded by hydrothermal illite, preserving ghost grain outlines, and one that appears later, and forms/defines the fracture zone through quartz grains, replacing or intergrown with illite. Hematite occurs as lining around edges of corroded quartz, veins, and stain of illite and chlorite. Some [phase 1 – this thin section] hematite precipitated contemporaneously with or immediately after illite (stains), while later hematite [phase 2] is associated with fractures, staining edges of quartz – representing the early stage of vein infill (remainder after illite or possibly some kao), while a later phase of hematite [phase 3 ➔ or 0!] was infilled central voids after illite? Later veins associated with fractured zone crosscut early quartz, and appear to be infilled by hematite ➔ sericite, illite ± chlorite ➔ illite with a possible later overprinting of hematite! Fracture-associated fluid(s) are also responsible for late rutile.

**RB31014**
Composition:
- **Chlorite**: 45%
  - 2 phases – 1) earlier replacement of biotite (25%), and 2) later fine-grained intergrown with illite
  - Variably stained brownish-red (hematite) or yellowish (goethite)
  - Some replaced biotite grains are rimmed by veinlets of carbonate
- **Rutherfordine**: 25%
  - SEM confirmed
  - Late relative to chlorite and carbonate
  - Replaces chlorite?
- **Zircon**: 5%
  - Strongly fractured/altered
  - Sometimes contain cubic inclusions of skutterudite?!
- **Carbonate**: 10%
  - ID’d based on changing relief with stage rotation
  - Rhombic, or as fine-grained alteration in chlorite and illite
  - Sometimes as drusy micro-veinlets parallel to foliation
  - Late
- **Sericite**: < 1%
  - Occurs only really on one edge of slide, where it has replaced a mineral (feldspar probably)
  - Being replaced by chlorite
- **Rutile**: 5%
  - Anisotropy masked by white internal reflections most of the time
  - Anhedral masses to euhedral laths
  - In cleavage planes in micas
- **Hematite**: 5%
o Sometimes has red outline around edge of grain (hematite)
  o Anhedral masses to euhedral laths
  o Randomly disseminated throughout slide, and concentrated specifically along cleavages of micas
  o Some show yellowish to violet purple anisotropy
  • Skutterudite?: 1 – 3%
    o Anhedral masses disseminated throughout the sample
    o Closely associated with brownish-reddish hematite stains in chlorite
    o Sometimes as tiny euhedral cubic inclusions in metamict zircons?!
  • Brownish mineral with pink tint (Nickeline?): << 1%
    o Creamy brownish mineral with pinkish-orangish tint (RL)
    o Acicular or skeletal
    o Very fine grained
    o Anisotropy hard to see (so fine grained): brownish yellow-orange to dark bluish grey-brown?
    o No B/P

**Hydrothermal chloritized calcareous pelitic gneiss** is composed of chlorite, rutherfordine, carbonate, and zircons in fine-grained intergrown chlorite-calcite, and possibly illite. Original components of rock other than biotite are not identifiable. Original components of rock were pervasively replaced by sericite, except some biotite, which was replaced by chlorite. The last alteration product is carbonate microveinlets and fine-grained disseminations in chlorite, and rutherfordine.

**RB31015**
Composition:
- **Uraninite**: 90%
  - Fine grained, 2 different colours suggest 2 phases... this is a TERRIBLE slide.
- **Galena**: 10%
  - As micron-sized subcubic inclusions in uraninite
- **Illite**: <1%
  - Rims vuggy space in thin section where minerals were plucked during making
- **Uranophane?**: <1%
  - Rims “vuggy space” in thin section where minerals were plucked out

Bad slide, no decent information can be obtained from this.

**RB31016**
Composition:
- **Rutherfordine**: 5%
  - Late alteration
  - Close to or within uranophane alteration
- Illite: 10%
  - Rims uraninite
  - Stained and/or replaced by uranophane and carbonate

- Hematite: 1%
  - As brecciated fragments
  - Sometimes rimmed by calcite
  - As veinlets and stain of uranophane and rutherfordine

- Carbonate: 5%
  - Rims uranophane, hematite, uraninite
  - Veinlets
  - Late, similar timing to rutherfordine and uranophane

- Goethite: <1%
  - Post-hematite only in one small area, rimming fragmented hematite
  - Post-uranophane

- Uranophane: 60%
  - Pervasive replacement and stain of illite with carbonate – essentially makes up the matrix
  - Sometimes exhibits boytryoidal habit
  - Also occurs as veinlets that crosscut hematite and uraninite, and are crosscut themselves by later episodes of uraninite!!!!

- Uraninite (U4/U5/U6): 10%
  - As remobilized fragments from faulting (U6)
  - As veins remobilized with faulting (U4/U5)
  - As mini-subhedral botryoids (U6)
  - Both pre-uranophane (U4/U5) and post-uranophane - cutting a vein (U6)

- Chalcocite: <1%
  - As partial replacement of uraninite

- Covellite: <1%
  - As alteration of chalcocite included in uraninite grains

- Galena: 7%
  - As euhedral to subhedral inclusions in uraninite

RB31018
Composition:
- Sericite ?: 55%
  - Partially chloritized
  - Replaced bleached biotite?
  - Partially stained brownish grey
  - Has oxidation stains common to biotite

- Illite: 25%
  - With sericite
  - Replacement of other minerals
  - Sometimes stained greyish colour

- Chlorite: 3%
  - As alteration of some muscovite
Replacement of biotite

- Hematite: 5%
  - Stain of sericite and chlorite
- Rutile: 5%
  - As inclusions in sericite and chloritized biotite along cleavages
- Galena: < 2%
  - As altered subhedral grains (seen at edge of slide)
- Uraninite (U3?): < 1%
  - As hairy fibrous medium brownish grey mineral?
  - Opaque
  - Near slightly paler purpleish grey mineral (cobaltite or vaesite?)
- Purpleish blue opaque mineral (Cobaltite or vaesite?): 5%
  - Isotropic
  - Purpleish-bluish white
  - Always has tiny cores of pinkish nickeline?
  - Occurs near rutile and hematite
- Nickeline?: 2%
  - At cores of purpleish mineral
  - Can’t see anisotropism (too fine-grained)

Sample has been strongly hydrothermally altered to sericite and illite, with some odd greyish stains. Some clay has pseudomorphed biotite. There is not much left of this section. Contains several rutile inclusions in chloritized biotite. Hematite is randomly disseminated throughout the section, some of which has replaced the illite – possible that uraninite replaced illite as well. To summarize: illite → chlorite → sericite → hematite → uraninite +/- rutile → nickeline → cobaltite or vaesite.

**RB31019**

Composition:

- Quartz: 10%
  - Strongly fractured
  - Partially corroded
  - Contains veins of goethite and sericite that crosscut it
  - Some fractures have specular or dull red hematite infilling them
  - Some fractures are filled with black sooty uraninite?
- Goethite: 40%
  - As stain of illite
  - As veins that crosscut fractured quartz
- Hematite: 25%
  - As stain of illite
  - As veins that cut quartz, and are then cut by goethite
  - Sometimes looks like pseudomorphed biotite?
  - Sometimes more concentrated darker red
- Illite: 30%
  - As pervasive replacement of everything except quartz
No ghost grains remain
Often stained either red (hematite) or yellow (Goethite) or rarely dark greyish-green (uraninite?)

- Zircon or Monazite: < 1%
  - Strongly fractured
  - Brownish to clear (PPL), 2nd order blue (XPL)
- Rutile: < 2%
  - As anhedral disseminations within hematite
  - Closely intergrown. Interesting relationship
- Galena: <1%
  - Fine grained
  - Isotropic
  - Sometimes strongly fractured
  - Subhedral to euhedral
  - Sometimes in veins cross-cutting quartz

Hydrothermally replaced illitic hematite-goethite rock contains pervasive illite replacement, with no remaining ghost grains with which to identify pre-existing mineralogy. Illite has been pervasively stained red (hematite) or yellowish-brown (goethite). Remnant quartz is present, strongly pitted and fractured. Many quartz grains are subrounded and have veins of red hematite crossing them, while veins of yellow goethite cross quartz and hematite veins. Some quartz grains also have uraninite (?) infilling fractures. Timing relationships suggest that quartz and monazite or zircon are remnant, while illite was first alteration mineral. Then hematite stained illite and infilled fractures in quartz, then limonite did the same, with galena precipitating in fractured space last.

**RB31021**

Composition:

- Graphite: < 1%
  - As rare thin randomly oriented laths
  - Appear fractured and strongly corroded
  - Is being overprinted by later hematite
  - Is remnant component of rock, as illite alteration wraps around it, and is trying to replace it
- Chlorite: 5 – 7%
  - As small laths intergrown with illite
  - As replacement of biotite
- Quartz: 15%
  - Strongly fractured
  - Undulose extinction
  - Anhedral
  - Pitted and corroded
  - Contains veins of illite filling fractures
2 phases of quartz precipitation: 1) anhedral strongly fractured and partially eroded large remnant quartz grains; 2) as late product from hydrothermal alteration (veinlets)

- Sometimes myrmekitic texture is preserved

- Cordierite: 10%
  - Strongly altered
  - Replaced by sericite, illite, chlorite (pinnite)

- Illite: 45%
  - As pervasive mineral replacement
  - Most mineral outlines (ghosts) are still visible, but mineral is not ID-able
  - Sometimes stained by hematite

- Kaolinite: 5%
  - As booklet veinlets cross-cutting illite and chlorite

- Plagioclase: 15%
  - Mostly as small corroded grains in a matrix of sericite, chlorite, and rutile/hematite
  - Also taken to be the yellowish coloured clay alteration
  - Sometimes ID’d by remnant quartz mermykitic texture in clay
  - Is sometimes stained by hematite

- Rutherfordine: 35%
  - Late hydrothermal alteration
  - Replaces illite, and chlorite
  - Is general coarse grained, and relatively fresh
  - Coarse laths take advantage of open space from dissolved grains

- Rutile: 5%
  - As subhedral to euhedral grains in corroded chloritized biotite
  - As anhedral grains that cross-cut quartz grains
  - Corroded and partially dissolved
  - Likely early alteration product associated with breakdown of biotite, cordierite, and garnet

- Hematite: 5 – 7%
  - As leopard spotty dark red rounded stains in clay
  - In fractures and along corroded grains edges
  - Appears to also be somewhat dissolved
  - In RL, euhedral acicular wispy needles that are µm-sized

- Zircon: < 1%
  - Strongly corroded and altered

Hydrothermally altered **Weakly graphitic cordierite-garnet? pelitic gneiss** originally contained quartz, plagioclase, biotite, graphite, cordierite, and zircon, and possibly garnet (hexagonal mineral)? Early hydrothermal alteration rendered biotite to chlorite and rutile. Then mineralogy replaced by illite and minor chlorite. Hydrothermal hematite stains illite and chlorite. Hematite is also found in cleavage of sericite grains, crosscutting them, therefore occurring later. Minor carbonate alteration in clays also possible? Carbonate would be late, alongside
rutherfordine, which took advantage of dissolved grains and pore space to precipitate large euhedral crystals.

RB31022
Composition:
- Illite/sudoite/sericite: 30%
  - As pervasive replacement of pre-existing mineralogy
  - Very few ghost grains remain
  - Almost entirely stained by hematite and goethite
- Hematite: 50%
  - As pervasive stain of illite/sudoite/sericite
  - Grows in cleavage of biotite
  - Possibly 2 phases: one as the dominant stain and wispy needles, and another later episode of equant µm-sized grains peppered throughout the section, overprinting everything
  - Occurs in RL as fine wispy hairs of specular hematite
  - Closely intergrown with earlier and partially corroded rutile
- Goethite: 5 – 7%
  - As stain of illite/sericite/sudoite
  - Mostly stains micas, rarely as equant µm sized grains
- Rutile: 3 – 5%
  - Corroded, partially dissolved grain fragments
- Chlorite: 2 – 5%
  - As replacement of micas and intergrown with illite
- Uraninite/galena?: < 1%
  - As extremely fine µm-sized brecciated fragments disseminated along fluid path in the sample, noted by their black colour in TL-PPL, and white and medium grey angular anhedral grains in RL

Sample is a hydrothermal hematized–illite rock with disseminated uraninite. Was probably originally a pelitic gneiss, some remnant ghosts of plag and biotite are still visible. Entire mineralogy has been replaced by illite/sericite/sudoite, which has been stained by 2 phases of hematite and one phase of goethite. The timing between oxidized iron oxides is nearly impossible to determine in this sample. Chlorite is early hydrothermal as it is being replaced by sericite/illite. Uraninite and galena are very closely associated with hematite. Uraninite and galena are late remobilization, as they are extremely fine-grained fault breccia → primary mineralization was fractured, fragments were carried elsewhere in fluid, and deposited where there was space.

RB31023
Composition:
- Illite: 25%
  - As replacement of original mineralogy
  - Some ghost grains are still visible, but are subround and not useful
  - Intergrown with chlorite/sericite locally
• Brown clayish mineral (fine-grained carbonate?): 45%
  o Occurs with illite
  o Cannot see grains or crystal habit, brown colour masks any possible interference colours
• Chlorite: 2 - 5%
  o Intergrown with illite around edges of grain ghosts and along fractures, and as replacement of biotite
• Sericite/chloritized biotite: 25%
  o Same as chlorite above
  o Appears along fractures as replacement of illite?
  o Looks like it is altering to chlorite?
• Rutile: 1 - 2%
  o Likely late, as occurs in well-formed prisms that appear unaltered
  o Randomly disseminated in the clay
• Goethite: <1%
  o Occurs as rare yellowish/brownish stain of clay
• Hematite: < 1%
  o As randomly disseminated fractured and corroded grains in the rock
  o Fine-grained, anhedral
  o Likely early in alteration sequence to be so altered and fractured
• Pyrite?: < 1%
  o Replacing hematite? Locally
  o As fine disseminations throughout the rock
• Chalcopyrite: <1%
  o As fine disseminations throughout the rock
  o Maybe occurs with (rimming) hematite
  o Sometimes altering to covellite/chalcocite
• Covellite: << 1%
  o As alteration of chalcopyrite/chalcocite
• Chalcocite: < 1%
  o As alteration of chalcopyrite
  o Being altered to covellite

This is a strongly hydrothermally altered micaceous rock. Original components are no longer identifiable. Sample is moderately to strongly micro-fractured, and sericite/chlorite alteration is most common around these fractures. Late yellowish brownish goethite alteration stains the clay. Timing of metallic minerals is impossible to determine as they are too fine grained, never in contact with each other (except chalcopyrite which is being replaced by chalcocite and covellite and in one area where chalcopyrite is replacing hematite). Fine-grained disseminated nature of this section makes it difficult to work with.

**RB31024:** VIP for role of calcic brines remobilizing/altering uraninite – maybe responsible of copper mineralization?
Composition:
  • Carbonate: 5%
- As veinlets that crosscut everything else (including uranophane sometimes)
  - Veinlets sometimes grade into uranophane
  - Sometimes are stained by hematite, or have hematite inclusions
  - Cross-cut by later uranophane and carbonate veinlets

**Uranophane: 5%**
- As euhedral to anhedral grains
- Most commonly as fibrous looking veinlets that grade into carbonate
- Veinlets cross-cut everything else, except later carbonate veinlets

**Hematite: 10%**
- As stain in veinlets of carbonate and uranophane
- As colloform-shaped stain in illite and fine-grained chlorite

**Biotite: <1%**
- Have hematite and rutile growing in cleavage
- Chloritized
- One has hematite stain

**Chlorite: 15%**
- Intergrown with illite
- Replaced biotite

**Anatase: <1%**
- As late subhedral grains disseminated throughout slide

**Galena: 15%**
- As tiny cubes in veinlets
- As inclusions in uraninite
- As partial alteration/replacement of some uraninite grains
- As rim of some uraninite veinlets with chalcocite cores

**Chalcocite: 5%**
- Actively altering uraninite!!!
- Altering or closely associated with pyrite grains
- As veinlets (cores) with galena

**Covellite: <1%**
- Alteration with chalcocite

**Pyrite: 5%**
- As inclusions in U3
- As tiny anhedral to euhedral cubes
- Altering to chalcocite, sometimes rimmed by galena
- One grain has chalcocite at core!?

**Uraninite A (U3): 20%**
- As large anhedral grains
- No botryoids
- As anhedral clay replacement in the groundmass
- Sometimes forms equant wispy agglomerates
- Commonly has inclusions of galena and pyrite

**Coffinite: 15%**
- Replacement of U3 → coffinite
- Commonly rimmed by galena
- Frequently being replaced by chalcocite/covellite
- Sometimes overprinted by little cubic to subcubic pyrite inclusions

- **Uraninite B (U4/U5):** 5%
  - As veinlets that cross cut U3, but are cross-cut by hematite veinlets
  - Cross-cuts a uranophane veinlet, but is cross-cut by a calcite veinlet

This sample is great for showing timing relationships between various minerals and calcite, as well as the role of calcic fluids in uraninite alteration and remobilization. After primary alteration of minerals to illite/chlorite, uraninite was precipitated. Alteration of uraninite is associated with hematite (?). Then came calcite veinlets, pyrite, uraninite veinlets, and probably also alteration of some uraninite to uranophane and chalcocite/covellite, as well as mobilization of galena.

**RB31025**

**Composition:**
- **Illite:** 10%
  - Replaced all pre-existing mineralogy
- **Hematite:** 60%
  - As pervasive stain of illite
  - Hydrothermal fluids appear to leech it while precipitating uraninite
  - Earlier than previous minerals, except illite
- **Goethite:** 5%
  - As stain of illite
  - Appears to be earlier than hematite, as it is cross-cut by hematite veinlets and locally overprinted by hematite
- **Uraninite (U3):** 10%
  - Brownish grey
  - Anhedral – intergrown with or replacing clays
  - Has inclusions of galena
  - Partially replaced by secondary light greyish coffinite
- **Coffinite:** 5%
  - Slightly darker greyish brown mineral
  - Altering uraninite – very difficult to see
- **Galena:** 1%
  - As tiny μm-sized grains included in uraninite
  - Fractured sometimes

Mineralizing fluids bleach out hematite, leaving behind the illite that it had stained. Uraninite pseudomorphs micaceous minerals, leaving ghosts of biotite. So, minerals were hydrothermally altered to illite and sericite, which was then stained with hematite, pseudomorphed by uraninite, then stained by goethite, then hematite again. Lastly, the fragmented μm-sized metallic minerals that likely
resulted from cataclastic deformation of mineralization elsewhere are carried away and deposited in void space here?

**RB31026:** similar to RB31025

Composition:

- **Illite:** 75%
  - Pervasive replacement of everything
  - Some sparsely preserved plagioclase ghosts
- **Zircon:** 2%
  - Fractured
  - Randomly disseminated
- **Monazite:** 1%
  - Fractured
  - Randomly disseminated
- **Sericite:** 15%
  - With illite
  - Hematite-stained
- **Rutherfordine:** 2%
  - Extremely late
  - Euhedral micaceous laths
  - Overprints illite, sericite
- **Quartz:** 1%
  - As remnant grains that are strongly fractured
  - Only 2 noted in the sample
- **Hematite?:** 3%
  - No red stain
  - Specular hematite
- **Rutile:** 5%
  - As small subhedral to euhedral grains
  - Not primary → secondary, these are fresh, relatively unaltered, unfractured, some are very fine grained
- **Uraninite:** <1%
  - One grain seen
  - Has inclusions of white fragmented metallic (galena?), which kind of crosses it like a vein
  - Also has inclusions of chalcocite, and chalcopyrite?
- **Hematite:** 5%
  - As disseminated grains
  - No red, no red I/R, appear almost zoned
- **Chalcopyrite:** 2%
  - Appears isotropic
  - Anhedral
  - Altering to chalcocite and covellite
- **Gersdorffite:** <1%
  - Only noticed twice
  - Fractured
Appears to be corroded around edges
Isotropic
Cubic

- Covellite: <1%
  - As alteration of chalcopyrite
  - As inclusions in uraninite?
- Chalcocite: <1%
  - As alteration of chalcopyrite
  - As inclusions in uraninite

This sample is very similar to RB31025, except with visible covellite and chalcocite, and no red hematite or goethite. Ghost grains are rare, and original mineralogy is not identifiable. Illite has been locally dissolved to make space for precipitation of euhedral coarse grained rutherfordine, but this is the latest stage of alteration, as it is fresh and unaltered. Illite, sudoite, and sericite replaced everything first, then hematite stained it, was subsequently removed by mineralizing fluids, rutile is almost always a late phase that follow disseminated uranium minerals. 2 grains of uraninite are observed, altering around fractures and edges to another mineral, and containing late (brecciated and mobilized?) inclusions of chalcopyrite, chalcocite, covellite, and galena.

RB31028: similar to RB31021
Composition:
- Illite: 25%
  - No ghost grains remain
- Sericite: 10%
  - Around edges of uraninite, where hematite has been removed
- Hematite: 40%
  - As pervasive stain of illite and sudoite
- Chlorite: < 3%
  - As alteration of biotite (?) and intergrown with illite
- Uraninite: 10%
  - As massive anhedral void space filling in areas where original minerals have been dissolved away
  - Preserves some ghost grain outlines of pre-ore mica that has been partially replaced by wispy to semi-massive anhedral uraninite
  - Has secondary grey coffinite in fractures
  - Has inclusions of chalcopyrite
- Coffinite: 5%
  - As veinlets of alteration within uraninite
    - Slightly paler colour
    - Isotropic
- Galena: 1 - 2%
  - Around edges of uraninite
    - Sometimes as inclusions in uraninite
- Chalcopyrite: < 1%
As anhedral bleby inclusions in uraninite

This sample is very similar to RB31021, and same paragenesis is less obvious here.

**RB31029:**

**Composition:**
- Illite: 45%
  - As replacement of original mineralogy
  - Many grain outlines are well preserved, though the original mineral can only be speculated on
- Chlorite: 10%
  - Intergrown with illite
  - No distinct grain shape
- Sericite: 10%
  - Intergrown with illite
  - Random orientation
  - Sometimes weakly chloritized
- Rutherfordine: 15%
  - Late alteration feature
  - Euhedral micaceous laths
  - Random orientation
  - Most common in the illite portion of the slide
  - Pleochroism is weak yellowish to clear, and interference colours are middle 2nd order
- Leucoxene/anatase: 2%
  - Most commonly as acicular needles crossing each other to look like amphibole cleavage
  - Most are within altered micas
- Hematite: 2 – 3%
  - Replacing biotite (cleavage)
- Chalcocite: < 1%
  - As fragmented remobilized grains
  - Replaces chalcopyrite
- Covellite: <1%
  - As alteration of chalcocite
- Gersdorffite: <<1%
  - As fragmented remobilized grains found in fluid paths throughout the slide with chalcocite
- Uraninite (U3?): 1 – 2%
  - As dull sooty randomly dispersed grains
  - Poor reflectance, black in TL and dull blackish-grey with hardly any reflectance in RL
  - Rims the outer edge of tiny fragmented anatase in hydrothermal fluid areas
  - Fine-grained and disseminated – does not look primary
Galena: << 1%
  o As fragmented euhedral grains that have been remobilized with copper minerals

Original feldspars (plagioclase), biotite, and garnet (?) ghosts are still visible, having been completely replaced by illite/sericite and chlorite. Biotite has also been locally altered to hematite and anatase along cleavages, as well as chlorite. Anatase occurs as late anhedral grains throughout the section. Anatase also has a special association with the uraninite mineralization, as it is either rimmed by uraninite, or close to it. When rimmed by fine grained disseminated uraninite, the uraninite is a late remobilization phase. Chalcocite, covellite, gersdorffite, and galena are late brecciated fragments that were carried in fluids from a different area (all are angular fragments).

RB31030:
Composition:

- Illite: 25%
  o As replacement of pre-existing minerals
  o Intergrown with chlorite and sericite
- Sercite: 45%
  o Intergrown with illite
  o No preserved ghost of pre-existing mineralogy
- Rutherfordine: 2 – 3%
  o Hydrothermally late
  o In sericite/illite
  o Coarse euhedral laths
- Sillimanite?: 1%
  o Noted in one edge of slide
  o Based on low relief, yellowish fireplace interference colours
- Pyrite: 5%
  o As fine grained euhedral to subhedral disseminations
  o Sometimes closely associated with hematite
  o Common in altered biotite, along cleavage
  o Altering from hematite ?
  o Late in hydrothermal alteration scheme
- Hematite: 5%
  o As alteration within biotite cleavage
  o Altering to pyrite ?
  o Close to rutile as well
- Quartz: < 1%
  o Strongly corroded
- Rutile: 15%
  o As euhedral to subhedral late grains
  o Randomly disseminated throughout the slide
  o Close association to hematite
- Nickeline: <5%
- White - pinkish
- Weak B/P
- Moderate to strong anisotropy → blue, orange, reddish...
- Skeletal grains left, some are fragmented
- Some tiny grain fragments are disseminated throughout the slide → this is remobilization of this mineral that makes it look like the result of cataclasis!

- **Skutterudite**: 1 – 2%
  - Bright white
  - Otherwise occurs with nickeline
  - Same situation → skeletal, and fragmented

- **Uraninite (U3)**: 1- 2%
  - As partially altered fractured grains with inclusions of galena
  - Occurs as wispy edged grains with galena

Sample seems to tell the same story as all the rest.

**RB31032**

Composition:

- **Chlorite**: 30%
  - Intergrown with illite

- **Illite**: 60%
  - As pervasive replacement
  - No ghosts

- **Sericite**: 5%
  - Intergrown with illite

- **Zircon**: 1%
  - Strongly fractured
  - Corroded and rounded

- **Chalcopyrite**: 1 – 2%
  - Fractured
  - Anhedral and fragmented
  - Appears isotropic
  - Close proximity to rutile

- **Rutile**: 3%
  - 3 phases probably: 1) early alteration phase, forming elongate blades in chloritized biotite cleavage; 2) as late alteration, as fine elongate anhedral grains, and; 3) as coarse-grained euhedral very late crystals
  - With exception to biotite cleavages, is always late relative to other minerals

- **Gersdorffite?**: <1%
  - Skeletal grains and colloform masses
  - Sometimes is partially altering from cobaltite and skutterudite
  - Core of skutterudite is purple cobaltite, and then another rim of gersdorffite
• Skutterudite?: <1%
  o As skeletal grains fragments
  o As the core of a colloform mass with a rim of cobaltite and a further
    rim of gersdorffite
• Cobaltite: <1%
  o Only seen as a rim between skutterudite (inner) and gersdorffite
    (outer)

Significantly hydrothermally altered sample contains evidence that rutile was the
first opaque mineral to form, with chalcopyrite, along cleavage planes of
chloritized biotite. Chlorite is also intergrown with illite and sericite. It would then
appear that euhedral skutterudite precipitated, and was altered to cobaltite and
gersdorffite, then precipitating rutile. Fragmented chalcopyrite appears to have
been sourced from fracturing in another rock and sometimes rims a core of
skutterudite, suggesting it may have precipitated in-situ from the HTF after
skutterudite, and probably after the cobaltite and gersdorffite alteration. The last
phase that appears to have precipitated is euhedral, 0.5 mm clusters of rutile
rhombs, randomly dispersed throughout the sample.

RB31033
Composition:
• Illite: 60%
  o Pervasive replacement of pre-existing minerals
  o Some anhedral grain ghosts still preserved
  o Probably replaced feldspar, biotite, maybe garnet?
• Biotite: 10%
  o As replacement of biotite/chlorite during early HT alteration
  o Partially replaced by chlorite
  o Has rutile needles in the cleavages
• Chlorite: 1 – 2%
  o As alteration of biotite, garnet?
  o Possibly intergrown with illite
• Garnet?: < 1%
  o One euhedral rhombic grain noted
  o Appears to have been replaced by chlorite and calcite maybe?
    Then illite
  o High relief in RL
• Hematite: 2 – 3%
  o Acicular needles randomly dispersed around uranium minerals
  o Does not contact uraninite
• Zircon: 2%
  o Strongly fractured
• Rutile: 5%
  o Closely associated with uraninite
  o Some are very late, as blades and acicular needles in the illite
• Chalcopyrite: < 1%
- As radiating acicular mass → pseudomorphed something?
- As core of arsenopyrite?

**Gersdorffite?**: 3%
- Slightly yellowish tinted white mineral with no B/P
- Isotropic
- Occurs as large fractured mm-sized euhedral to subhedral grains
- Alteration to creamy pink nickeline along fractures and along edges

**Arsenopyrite**: 3 – 5%
- As subhedral fractured grains throughout the slide
- Close spatial association to uranium minerals
- Alteration with Gersdorffite and nickeline
- Bright white rhombs with possible twins sometimes noted?
- Weak B/P → creamy whitish to creamy pinkish yellowish
- STRONG anisotropy → bluish greenish whitish grey to yellowish blue to reddish violet
- Is altering the edges of some of the gersdorffite?

**Nickeline**: <<< 1%
- Noted as pink pleochroic alteration in gersdorffite

**Uraninite (U3?)**: 2%
- Medium grey anhedral disseminated grains
- Very close spatial association to rutile and aspy?

Looks like the timing of metallic minerals is as follows: rutile → hematite → uraninite → gersdorffite → chalcopyrite, nickeline → arsenopyrite → rutile

**RB31034:**
Composition:
- Illite: 45%
  - Pervasive replacement of original mineralogy
  - Is locally replaced by kaolinite – looking booklets?
  - Sometimes stained greeny-brownish colour
- Sericite: 2 – 5%
  - Most commonly around fractures
  - Sometimes in illite-replaced grains near kaolinite
- Chlorite: 30%
  - As replacement of biotite and other mafic minerals
  - Frequently noted as coarse micaceous grains around fractures
  - Lacks green colour – ID’d based on interference colours and coarse grained micaceous habit
- Tourmaline (Dravite?): 2%
  - High relief
  - Strongly fractured
  - Partially altered/corroded
  - Yellowish – clear in PPL
  - Prismatic
- Dark greenish brown muddy clay: 5%
- Outlines veins and fractures
- Usually associated with hematite – stain!
- Very wormy texture – kaolinite alteration?
  - Kaolinite?: <1%
    - As wormy booklets randomly dispersed through illite altered grains
    - Appears very late relative to everything else
  - Chalcopyrite: 3%
    - As anhedral to subhedral grains
    - Engulfs pyrite grains, and encrusts skutterudite – in cracks around it
    - Strongly fractured and sometimes strongly corroded
  - Pyrite?: 1%
    - As small pale whitish yellow cubes included in chalcopyrite
  - Skutterudite: 3%
    - Fractured
    - Euhedral to subhedral
    - Sometimes partially altering to cobaltite or nickeline
  - Uraninite: 1 – 2%
    - Dark greenish-brown clayish mineral in TL
    - Medium grey around edges, paler grey in middle
    - Looks like there are flecks galena inclusions
    - Isotropic
    - No B/P
    - No I/R
    - Sometimes looks altered, with dusty brownish isotropic inclusions
    - Partially corroded
    - Typically follows fractures with skutterudite and corroded early chalcopyrite
  - Rutile: 2 – 3%
    - Early as anhedral masses disseminated throughout the rock
    - Late as euhedral fine grained needle like prisms that cross-cut everything else – except uraninite
  - Nickeline and cobaltite: << 1%
    - As an alteration by product noted around skutterudite

This **Pyrite pelitic gneiss** is strongly altered. Pervasive illite/sudoite/sericite alteration was first, leaving some rutile (?). Chlorite altered mafic minerals, is intergrown with illite and around fractures. Skutterudite precipitated in void space. Cobaltite and nickeline are later alteration or exsolution products from skutterudite, and likely precipitated around the same time as chalcopyrite, which rims pyrite. Uraninite is suggested to be with or just after skutterudite, nickeline, cobaltite, and chalcopyrite, following veinlets. Late fine-grained euhedral rutile grows into the skutterudite-nickeline-cobaltite, indicating it is late, with veinlets of kaolinite booklets.

**RB31035:**
Composition:
- **Chlorite:** 25%
  - As alteration of biotite
  - Has inclusions of rutile, pyrite and hematite along cleavage planes
  - 2 weak alignments ~30° apart from each other
- **Feldspars:** 25%
  - Is totally beige or medium brownish dusty colour
  - Has preserved grain boundaries and some cleavage (2 @ 90°)
  - Thoroughly clay altered
  - Has many inclusions of chalcopyrite, rutile, hematite
  - Relief changes on stage rotation – carbonate alteration as well?
- **Illite:** < 1%
  - Fine-grained replacement of minerals – with fine-grained carbonate
- **Carbonate:** 35%
  - Fine-grained
  - ID’d based on cleavage, relief change (PPL) and interference colours
  - Looks like it is replacing/intergrown with illite and altering minerals
- **Zircon:** 1%
  - Noted best in RL
  - Zoned
  - Corroded
- **Chalcopyrite:** 7%
  - After pyrite → pyrite cube inclusions, or partial pseudomorphism
  - Some occurs as disseminated anhedral grains
  - Some in cleavage of biotite
- **Pyrite:** 1%
  - Pale creamy yellowish white colour
  - Most frequently skeletal
  - No B/P, isotropic
  - Some is being replaced by cpy (which leads me to believe its pyrite), some is being pseudomorphed by gersdorffite
  - Cubic to pseudocubic or round
- **Skutterudite:** <<1%
  - As micron-sized cores of some pyrite/chalcopyrite
- **Rutile:** 5%
  - As inclusions in altered grains and along cleavage in biotite
  - Pale to medium grey in RL
  - Anisotropy masked by white and yellowish I/R
  - Elongate blades
- **Gersdorffite:** <1%
  - As alteration around pyrite
  - Skeletal blades
  - Weakly anisotropic → bluish greenish gray to dark purplish grey
  - Pseudocubic to orthorhombic
- **Hematite:** < 1%
  - As metallic inclusions in biotite
Differentiated by red I/R and anisotropism

Sample is a hydrothermally altered carbonate-cemented cataclasite which may have originally been pelitic gneiss (?). Evidence of grain outlines and cleavage suggest that sample originally contained feldspar(s), biotite, zircons, and likely quartz, although there is no longer any evidence of the last. The grains that are present are angular, brecciated, and appear to be cemented by carbonate. Grains are replaced by light-medium browny-beige clay – either too fine grained to see, or the thin section is too thin to identify grains. Metallic grains appear to be fractured and occur dominantly as inclusions in altered biotite, or as micron-sized angular fragments in carbonate cement. This suggests that the precipitation of pyrite, gersdorffite, and chalcopyrite was pre-late brittle deformation. Where rutile and hematite are disseminated in the clay, they appear fractured, therefore they were probably also precipitated pre-brittle deformation. Hematite and rutile were probably early alteration, then skutterduite, then pyrite and chalcopyrite (around fragments of skutterudite), then gersdorffite (as pseudomorph of pyrite), and probably carbonate during these last phases. These minerals also look to have been brought in from post-ore alteration fluids, not original components in the rock.

RB31036:
Composition:
- Pale creamy beige clay: 60%
  - Preserved outline of grains, original mineralogy is not recognizable
  - Most is fine-grained, with some chlorite around fractures and grain boundaries, or just randomly dispersed in the altered grains
- Kaolinite: 15%
  - Occurs as late very fine-grained veinlets with odd wormy shape
  - Cross-cut all other clay alteration
- Chlorite: 5%
  - Intergrown with sericite/illite
  - Most obvious in the coarse grains
  - Also occurs as replacement of some round (ghost; garnets?)
- Quartz: <<1%
  - As a late small (0.1 mm) grains cross-cutting sericitized grains
  - Contains μm-sized euhedral pyrite cubes
- Brownish stained clay: 2%
  - Along fractures and around grain edges
  - Maybe hematite-stained illite and chlorite
- Tourmaline (Dravite?): < 1%
  - Weakly yellow – green pleochroism
  - Up to 2nd order red interference colours
  - One good cleavage visible, high relief
  - Strongly fractured
  - Partially altered/corroded
  - Prismatic crystals
- Skutterudite: 8%
  - Anhedral creamy yellowish – white
  - Exsolving violet tinted cobaltite and edges are altering to white gersdorffite
  - Extremely difficult to differentiate from arsenopyrite
  - Appears often in veinlets
- Cobaltite: < 1%
  - As alteration in skutterudite
  - No observed anisotropy, but fine grained
- Gersdorffite: < 1%
  - Appears to be replacing edges of skutterudite grains
- Arsenopyrite: 7%
  - No B/P
  - Rhombic habit
  - Appears to replace some pyrite ± gersdorffite
  - Has bluish-reddish to greenish-yellowy anisotropism
- Pyrite: < 1%
  - White-yellow
  - No B/P
  - Isotropic
  - Cubic, fine-grained
  - Appears late, disseminated throughout the slide
  - Usually in veins (with quartz)

**Hydrothermal illite/sericite breccia** contains grain ghosts of minerals that are entirely replaced by illite, sericite, and chlorite. Late wormy kaolinite veinlets with random orientation cut across grain ghosts, and along fractures. One late quartz veinlet occurs along the edge of 2 fractured grains, with micron-sized euhedral pyrite. Skutterudite is skeletal, fractured, and is sometimes altered to cobaltite, and is almost always rimmed by, or has its edges replaced by gersdorffite. Arsenopyrite, which also appears to sometimes replace skutterudite, is also randomly disseminated throughout the slide. I believe that skutterudite was present early on, and has been altered by later migrating fluids. Gersdorffite and arsenopyrite appear to be slightly later than skutterudite, as they are less corroded and altered, and locally replace it.

**RB31037**
Composition:
- Chalcopryite: 2 – 3%
  - After skutterudite/gersdorffite
  - Before uraninite
  - Being replaced by galena
  - Small disseminated grains
  - Some pseudomorph skutterudite
  - Many are fractured
- Galena: 2 - 3%
Within and around uraninite
- Also disseminated throughout the slide, but more common with uraninite
- Replaces chalcopyrite (?)
- Cubic with good cleavage

- **Uraninite (U4/U5): 2 – 5%**
  - Secondary fracture fill
  - Only occurs within and along fractures in the rock
  - Contains many µm-sized equant euhedral grains of galena and anhedral fragments of chalcopyrite
  - Wispy

- **Skutterudite: 1 – 2%**
  - As fragmented and partially replaced grains (by chalcopyrite)
  - Mostly as anhedral grains or colloform masses
  - Early HT → overprinted by uraninite and altering to cpy

- **Gersdorffite: 1 - 2%**
  - Fragmented subhedral grains
  - Partially altered anhedral grains between skutterudite and cobaltite

- **Cobaltite: 1 – 2%**
  - Alteration of or intergrown with skutterudite

- **Illite: 70%**
  - As pervasive replacement of mineralogy

- **Chlorite: 10%**
  - Intergrown with illite along fractures
  - Proximal to uraninite
  - Alteration to chalcopyrite along cleavages

- **Zircon: < 1%**
  - As subhedral grains
  - Corroded

- **Kaolinite: 5%**
  - As late booklet veinlets cutting across illite
  - Late
  - Particular association to chalcopyrite and skutterudite and cobaltite

This sample is **massive clay with disseminated uraninite** - very similar to RB31033. It contains no primary uraninite. The dominant opaque mineral is chalcopyrite, which rims and locally replaces skutterudite/cobaltite, making it late in the sequence. It is also being pseudomorphed by galena, occurs in chlorite cleavage planes, and as fine-grained disseminations around and within uraninite. Uraninite is clearly late in the sequence, and strictly follows fracture planes throughout the slide. The slide has ghost grains that are fractured and displaced, evidence fracturing. A small quartz-filled (?) vein occurs very near to uraninite, but does not cross-cut it, making timing difficult to determine definitively, but it truncates chalcopyrite. I believe it to be the last alteration in this slide.

**RB31039**
Composition:

- Uraninite (U1): 93%
  - Euhedral botryoids
  - Pseudocubic with alteration zones of chalcocite (?)
- Galena: 1%
  - As veinlets cross-cutting botryoidal uraninite
  - As cement around edges of botryoids
- Chalcocite: 1%
  - Medium greyish-blue
  - Some yellowish to greyish anisotropy
  - Some B/P
  - Alteration around some uraninite cubes
- Covellite: 1%
  - As alteration with chalcocite, around some uraninite
  - Bright blue
- Chalcopyrite: <1%
  - As tiny veinlets at core of uraninite botryoids
- Pyrite: < 1%
  - Only noticed in fractures or between botryoids
  - Isotropic
- Coffinite: < 1%
  - Alteration around some botryoids

Massive uraninite is coarse-grained, radiating botryoids and pseudocubes that are “cemented” by galena with trace chalcocite/covellite. Chalcopyrite appears at the core of some botryoids, suggesting that it was present before uraninite. Some pseudocubic uraninite also appears to have some chalcocite alteration zones, suggesting that either these were originally chalcopyrite as well, or perhaps that uraninite was pseudomorphing earlier pyrite, which was altered to chalcopyrite and then chalcocite (?). Galena is interpreted as radiogenic product of early primary mineralization. This euhedral uraninite is primary, void space infilling. Very nice.

RB31040:
Composition:

- Illite (and minor sericite): 65%
  - As dominant pervasive alteration of all pre-existing mineralogy
  - Earliest
- Chlorite: 20%
  - As colourless fine grained alteration with illite
  - Replaces biotite and garnet
  - Sometimes appears to replace illite?
- Hematite: 10%
  - As late overprinting stain
  - One of the last phases of HT alt present in this sample
  - Stains illite and wraps around anatase
- Zircon: <<1%
  o Strongly fractured
- Anatase: 2%
  o As multiple phases
  o Readily seen preserving ilmenite twins and cleavage
  o Also as coarse grains, and as alteration of biotite (cleavage)
- Pyrite?: < 1%
  o Tiny grain fragments, rarely seen
  o Remobilized in a fault above or below this sample, and relocated with the fluid traveling in fractures

**Massive clay** is composed of illite and chlorite that replace all pre-existing minerals. Chlorite occurs in 2 phases: (1) As replacement of biotite and garnet and (2) as fine-grained clay intergrown with illite. Sericite appears to be intergrown with illite locally. Hematite is late hydrothermal, precipitating as overprinting stain over pre-existing illite/sericite/chlorite, with a random leopard spot-like appearance. Hematite occurs as extremely fine-grained wispy hair-like fibrous masses. Anatase alteration is before hematization in this sample, but appears to have 3 phases: (1) as leucoxene alteration on one edge of the slide that represents original mineralogy, (2) as strongly fractured/altered coarse grains that are pre-hematite, pre-chlorite, and post-illite alteration, and; (3) as fine-grained equant grains sitting in illite. Pyrite occurs as tiny fragmented grains in fractures that appear to be the remobilized remnants of grains from a fault zone.

**RB31041**: Poor slide
Composition:
- Illite/chlorite: 35%
  o Fine-grained replacement
- Hematite: 30%
  o Stains illite
- Uraninite (U2?): 35%
  o Fine-grained replacement of clays? Intergrown with clays
- Galena: 1%
  o Randomly disseminated throughout the section

Section is cut too thick? Can’t see much... uraninite appears to be the clay intergrown phase (U2?), and has inclusions of euhedral to subhedral galena randomly disseminated throughout. Illite and hematite are pervasive, both appear to be pre-uraninite.

**RB31042**:  
Composition:
- Illite: 40%
  o As pervasive replacement of minerals
- Sericite: 10%
Intergrown with illite – as replacement of pre-existing minerals

- Chlorite: 15%
  - Intergrown with illite as replacement of pre-existing minerals

- Uraninite (U3): 20%
  - Massive fine-grained pseudomorph/replacement of clays (U3: 15%)
  - May rim anatase (?)
  - U4/U5 veinlets (fracture-lining) also present (5%)

- Hematite: 5%
  - Stain of clay
  - Around uraninite, never touching it

- Goethite: 5%
  - Stain of clays
  - Around uraninite, never touching it

- Anatase: 5%
  - Disseminated fine-grained late precipitation
  - Earlier coarse grain – possibly rimmed with uraninite (?)

- Galena: <<< 1%
  - Rare micron-sized grains with uraninite

- Pyrite: <<<1%
  - Rare micron-sized grains in clay

**Massive clay with disseminated uraninite.** Uraninite appears to be attached to a rutile needle (?). Preserved cleavage (if that’s what it is) in illitized ghost grains suggest they were feldspars (but I don’t know which one). Sericite occurs as vein infilling fractures and faults, which have one dominant orientation, and a weaker one sub-perpendicular to that. These fractures cross-cut uraninite and everything else, causing obvious displacement of the ghost outlines and sometimes displacing uraninite. Uraninite lines several fractures (U4/U5). Uraninite has 3 phases: (1) Whitish-grey-brownish uraninite is less common, as rounded grains (U3), (2) Dull earthy medium grey-brown uraninite (most common) represents the majority of uraninite in the slide (U3), and 3: Dull earthy black mineralization that is opaque in TL and RL, just black. These are usually somewhat round elliptical grains most frequently seen in fractures (U4/5) – may be due to the slide being too thin?

**RB31044:**
Composition:

- Chlorite: 5%
  - Occurs around edges of plucked out areas – could be more if the plucked area was presumed to be filled with chlorite → could be chloritized garnets?
  - Fine grained, no distinctive green colour

- Illite/sericite/chlorite: 85%
  - Looks like may be intergrown with microcrystalline calcite
  - Generally stained dark brownish – hematite?
  - Looks like it has replaced all of the minerals
Slide cut too thick

- Carbonate: 5%
  - Alteration – late void space filling around clays?

- Graphite: <1%
  - Small micaceous laths
  - Random orientation
  - Some are squished
  - Looks like it is being altered/corroded away

- Galena: <1%
  - Saw a tiny cubic grain that looked like it had pluck marks
  - White, isotropic
  - Late relative to everything

- Rutile: 1%
  - Occurs as skeletal grains, euhedral needle-like prisms, and anhedral blebs
  - 2 coarse grains are partially fractured and corroded, while elsewhere, grains appear “fresh” and unfractured → pre-hydrothermal rutile and a post-ore rutile

- Hematite: <1% → other than stain (?) of illite
  - Presumed to be grains that had red outline around edge and were pale grey in RL
  - Far less common that rutile, though both are fairly uncommon
  - Some grains have red outline, but were not opaque in TL, and were brownish, these were taken to be rutile?
  - Appear to be corroded/ altersed, possibly pre- to syn-D?
  - Randomly disseminated throughout the slide

- Rutherfordine: <1%
  - Micaceous
  - Green-yellow pleochroism
  - 2nd order interference colours (green-blue)
  - Smallish, but coarse relative to sericite/illite/chlorite mix

This is a hydrothermal **Massive clay-altered weakly graphitic calcareous pelitic gneiss**. All other minerals have been replaced dominantly by brown-semi opaque clay (illite, chlorite, and sericite) with no visible minerals (slide cut too thick?). Some late laths of rutherfordine are noted. Some grain outlines are loosely preserved, suggesting the original presence of biotite and probably feldspar and quartz. Graphite appears to be corroded and fractured. Some semi-round to elliptical plucked out areas with chl/illite around the edges could have been chloritized garnets. Rutile appears to have been both an original constituent in the rock (fractured and corroded anhedral grains), as well as a later precipitate from hydrothermal alteration (fresh euhedral to subhedral fine crystals and grains randomly disseminated in the clay).

**RB31045**
Composition:
- Illite/chlorite: 30%
  - Stained by hematite, uraninite, and goethite
  - Replacement of pre-existing minerals
- Hematite: 15%
  - As rim around uraninite – not touching
  - Stains illite
  - As 2 separate veinlets that cross-cut everything else
  - As core of some veins that have rims of U5?
  - Sometimes contains fine-grained fragments of pyrite or skutterudite, and galena
- Uranophane: 2 – 5%
  - As replacement of illite, or fills pore space between
- Goethite: 5%
  - Rims hematite, late
- Zircon: <1%
  - Found 2 grains
  - Corroded
  - Hematite-stained
- Uraninite (U2/U3? and U4/U5): 35 – 40%
  - Pervasive replacement of illite – has fine-grained wispy habit (U2/U3?)
  - Has veinlets of hematite and of U4 and U5 cross-cutting it
  - Sometimes has inclusions of galena
  - U4/U5 veinlets (15% of U in slide) have tiny fragmented pyrite and galena inclusions
- Anatase: 1%
  - As small subhedral to anhedral grains and fragments most commonly within the hematite, but also occur as inclusions in U3/4
  - Late
- Pyrite: <1%
  - As tiny fragmented grains remobilized after faulting in U4/U5 and hematite veinlets
- Galena: <1%
  - As tiny fragmented grains remobilized after faulting in U4/U5 and hematite veinlets

RB31047
Composition:
- Illite/sericite: 45%
  - Pervasive replacement of pre-existing mineralogy
  - Ghosts are hard to find, except for biotite
  - Some boxy feldspars (?) are possible
- Chlorite: 15%
  - As replacement of biotite
  - Intergrown with illite
- Hematite: 15%
As leopard spot stain of illite
  o Occurs in cleavages of altered biotite
  o Small round equant disseminated spots that stain the clays
  o Wrap around zircons and rutile

- Goethite: 20%
  o As stain of most of the clay minerals, when not stained by hematite
  o Appears to be syn- to post-hematite

- Zircon: << 1%
  o Fractured relict round grains
  o Disseminated in the sample

- Rutherfordine: 5%
  o Pristine euhedral micaceous laths
  o Is late relative to everything else, including hematite

- Anatase: 1%
  o As alteration in chloritized biotite cleavages
  o As large anhedral to subhedral equant fractured and corroded grains

This **massive clay** sample was most likely pelitic gneiss, as the amount of biotite originally in this rock is > 15 – 20%. There are multiple generations of biotite, all of which have been chloritized, then replaced by illite, chlorite, and sercite like the rest of the original mineralogy, with anatase and hematite precipitating in the cleavages. Hematite stains clay, which is later also stained by yellowish beige goethite. Late sericite veins are present, but appear to be pre-Rutherfordine. Anatase occurs as original coarse grains along with zircons, and as late hydrothermal fine-grained, elongate needles in biotite cleavages with hematite.

**RB31048**: very good sample for timing/U phases!!!!

**Composition**:

- Hematite: 5%
  o Stains clays

- Goethite: 3%
  o Stains clays

- Illite/sercite: 15 – 25%
  o Pervasive replacement of pre-existing minerals
  o Replaced by uraninite (pseudomorphed?)

- Rutherfordine: 1 – 2%
  o As micaceous laths disseminated throughout the section
  o Both within and around uraninite, where ever space was available

- Chlorite: 2 – 3%
  o Intergrown with illite/sercite
  o Not readily ID’d in this slide

- Uraninite A (U3?): 45%
  o Black in TL and in RL
  o Dull, sooty
  o Replaces (pseudomorphs) clays
Dominant phase
- Contains micron sized galena inclusions
- Locally also contains rounded equant grains of non-transparent anatase which is late relative to the uraninite as it is growing in void space along fractures of uraninite grains

- **Uraninite B (U4/U5):** 5%
  - Medium bluish grey colour in RL
  - Occurs as disseminated veinlets that cross-cuts U3
  - Also contains inclusions of galena and chalcopyrite
  - Cross-cuts and is cross-cut by hematite

- **Anatase:** 1%
  - As inclusions in U3?
  - As late hydrothermal alteration

- **Galena:** 1%
  - As inclusions in uraninites

**Fracture-hosted semi-massive uraninite** contains U3 which appears to have pseudomorphed or replaced the clays, and rarely, large (1.8 – 2 mm) subhedral to anhedral anatase grains. It forms as fine wispy elongate blades. Anatase is both pre-uraninite (U3) and is post-U as well, having precipitated in the clays, or void space. Galena is post-everything pretty much, as euhedral micron-sized cubes which occur as inclusions in U3, and U4, as well as in the clays as well. U4 veins cross-cut U3, but appear to be earlier than some hematite, as it is locally cross cut by hematite alteration, although it also cuts hematite alteration. U5 is last, crosscutting illite, U3, U4, illite, hematite, goethite, etc. At least 2 veinlet episodes of uraninite, probably more, but can't tell without cross-cutting relationships.

**RB31049**
Composition:
- **Illite and sericite:** 35%
  - Pervasive replacement of pre-existing minerals
  - Ghost grain boundaries are nearly impossible to see
- **Rutherfordine:** 5%
  - Late alteration
- **Chlorite:** 20%
  - As replacement of biotite, with rutile in cleavage
  - Replaces garnets
  - Intergrown with illite
- **Anatase:** 2%
  - As randomly oriented anhedral equant grains of varying size
  - Coarse grains (0.15 – 0.4 mm) appear to be earlier than small micron-sized grains
  - Micron sized grains follow fractures in the thin section and are obviously a very late phase
- **Zircon:** << 1%
- Corroded
  - Arsenopyrite: 5%
    - Late, following fractures
    - Subhedral grains
    - Especially concentrated on one side of slide
  - Covellite: << 1%
    - As equant grains near arsenopyrite
    - Disseminated near fractures
    - Late
  - Uraninite A (U3?): 25%
    - Medium grey colour
    - Appears to pseudomorph or be intergrown with illite
  - Chalcopyrite: << 1%
    - As micron-sized anhedral grains with covellite and arsenopyrite near fractures
  - Galena: < 1%
    - As micron-sized cubes randomly disseminated within uraninite and clay
  - Pyrite: << 1%
    - As anhedral grains disseminated around the edge of the slide

Very similar to RB31048 – but worse for timing of minerals.

**RB31050:**

**Composition:**

- Hematite: 25%
  - Deep red
  - Specular grains within clay
  - Stains clays
  - Looks like maybe it was the first alteration? And perhaps the last?
  - Surrounds uraninite
- Goethite: 5%
  - Stains clay
  - Occurs dominantly as outline around hematite, and sometimes on its own
- Illite/sericite: 35%
  - As pervasive replacement of pre existing mineralogy
  - Stained greenish-grey sometimes (uraninite)
  - Stained red sometimes (hematite) or orange-yellow (goethite)
  - Hydrothermally very early
- Chlorite: 15%
  - Intergrown with illite
- Kaolinite: < 1%
  - Late wormy vein that cross hematite
  - Locally stained red from hematite → evidences a late hematite?
- Uraninite (U2/3?): 20%
- Isotropic
- No B/P
- No I/R
- Anhedral to colloform fine-grained wisps after illite
- Large anhedral grains – more pervasive replacement of clays
- Corroded

- Arsenopyrite: < 1%
  - As skeletal grains
  - Strong anisotropy – bluish green to reddish brown
  - Appears to be replacing skutterudite

- Skutterudite: < 1%
  - Is surrounded by arsenopyrite
  - Occurred first
  - Anhedral
  - No B/P
  - Extremely strange anisotropy → twinned? Changes slightly...?

**Wormrock** has completely replaced mineralogy. Gangue minerals are: illite with minor sericite and chlorite that is stained by hematite and goethite. Hematite appears to have been early (pre-ore), stains clays. Then it is rimmed by later goethite. Greenish-grey/black stain of clays appears to be uraninite stain. Hematite and skutterudite appear to be locally intergrown, and occur as anhedral to subhedral fractured grains. Skutterudite appears to be rimmed by or altered to arsenopyrite locally. These minerals are post-uraninite, which is locally corroded around the edges, and is being altered/rimmed by skutterudite.

**RB31051:**
Composition:
- Illite/Sericite: 70%
  - As pervasive replacement of pre-existing mineralogy
  - Some ghosts are still visible
  - Intergrown
  - As cement for brecciated rock
- Rutherfordine: 10%
  - Last stage of alteration – relatively fresh
  - Micaceous
  - 3rd order interference colours (green and pink)
  - Pleochroic – pale lemon yellow to deep yellow
  - 1 visible cleavage
  - High relief
- Zircon: 2 – 5%
  - Fractured
  - High relief
  - Colourless
- Kaolinite: < 1%
  - As late veins that crosscut pre-existing ghost grains
Appendix B: Conditions for electron probe microanalysis of uraninite and clay minerals

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<th>Crystal</th>
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Operating conditions were 40 degrees takeoff angle, and a beam energy of 20 keV. The beam current was 20 nA, and the beam diameter was fully focused.

Elements were acquired using analyzing crystals LLIF for Hf Ia, V ka, As ka, La Ia, Ce Ia, Nd Ia, Dy Ia, Mn ka, Fe ka, Co ka, Ni ka, Cu ka, Zn ka, LPET for Y Ia, P ka, Ca ka, Mo Ia, Sb Ia, S ka, PET for Th ma, U ma, Ti ka, Pb ma, LPET for Y Ia, P ka, Ca ka, Mo Ia, Sb Ia, S ka, PET for Th ma, U ma, Ti ka, Pb ma, LPET for Y Ia, P ka, Ca ka, Mo Ia, Sb Ia, S ka, and LTAP for Mg ka, Al ka, Si ka.

The counting time was 30 seconds for P ka, Si ka, Ti ka, Hf Ia, Al ka, V ka, As ka, Y Ia, La Ia, Ce Ia, Nd Ia, Dy Ia, Mg ka, Ca ka, Mn Ia, Fe ka, Co ka, Ni ka, Cu ka, Zn ka, Mo Ia, Sb Ia, S ka, and 60 seconds for Th ma, U ma, Pb ma.

The MAN background intensity data was calibrated and continuum absorption corrected for P ka, Si ka, Ti ka, Hf Ia, Th ma, U ma, Al ka, V ka, As ka, Y Ia, La Ia, Ce Ia, Nd Ia, Dy Ia, Mg ka, Ca ka, Mn Ia, Fe ka, Co ka, Ni ka, Cu ka, Zn ka, Pb ma, Mo Ia, Sb Ia, S ka.


Unknown and standard intensities were corrected for deadtime. Standard intensities were corrected for standard drift over time.

Interference corrections were applied to P for interference by Mo, and to Si for interference by Hf, and to Ti for interference by La, and to Hf for interference by Cu, and to U for interference by Sb, Th, and to V for interference by Ti, and to As for interference by Pb, Hf, and to La for interference by Nd, and to Nd for interference by Ce, and to Dy for interference by Nd, Ce, Fe, and to Mg for interference by Nd, and to Ca for interference by U, and to Co for interference by Hf, Nd, and to Pb for interference by Th, Y, S, and to Mo for interference by S, and to Sb for interference by U, and to S for interference by Pb, Mo,

See J.J. Donovan, D.A. Snyder and M.L. Rivers, An Improved Interference Correction for Trace Element Analysis in Microbeam Analysis, 2: 23-28, 1993

The matrix correction method was ZAF calculations and the mass absorption coefficients.

The ZAF algorithm utilized was Armstrong/Love Scott (default).

See J. T. Armstrong, Quantitative analysis of silicates and oxide minerals: Comparison of Monte-Carlo, ZAF and Phi-Rho-Z procedures, Microbeam Analysis—1988, p 239-246
## Appendix C: Data obtained from electron probe microanalysis of clay minerals

(III = Illite, Sud = Sudoite, Chl = Chlorite, Hm = Hematite)

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<tr>
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<th>SiO₂</th>
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<th>Al₂O₃</th>
<th>FeO</th>
<th>MgO</th>
<th>MnO</th>
<th>NiO</th>
<th>CaO</th>
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