

Geological Setting, Petrology, and Geochemistry of Granitic Pegmatites and Leucogranites Hosting U-Th-REE Mineralization at Fraser Lakes Zone B, Wollaston Domain, Northern Saskatchewan, Canada

CHRISTINE L. MCKECHNIE^{1,*}, IRVINE R. ANNESLEY^{1,2}, AND KEVIN M. ANSDELL¹

(Received March 25, 2011; accepted June 6, 2012)

Abstract — The U-Th-REE mineralization at Fraser Lakes Zone B is hosted by granitic pegmatites and leucogranites, which lie along the deformed contact between Paleoproterozoic metasedimentary gneiss of the Wollaston Group and Archean orthogneiss, approximately 25 km from the southeastern edge of the Athabasca Basin. The pegmatites/leucogranites are subcordant to concordant with the regional foliation and are concentrated within a northeast-plunging antiformal fold nose, the study area, which lies west of Fraser Lakes. The mineralized pegmatites/leucogranites in the western part of the study area (Group A) are typically enriched in U ($\pm$ Th) with Th/U $\sim$ 1, and contain uraninite, thorite, zircon, and allanite. Those intruding the central part of the study area (Group B) are generally enriched in Th and LREE, with Th/U $>$ 2, and contain monazite, thorite (commonly U-enriched), and zircon. The pegmatites and leucogranites in Group A tend to be slightly enriched in SiO₂ and depleted in TiO₂ relative to those in Group B and are interpreted to represent more evolved crustal melts. Both groups are peraluminous and show varied chemistry. Partial melting ($\sim$ 850°C and 9 kbar) of a metasedimentary rock-dominated source, entrainment of accessory minerals as xenocrysts, and assimilation–fractional crystallization processes combined to enrich the granitic pegmatites/leucogranites in U, Th, and REE elements. Transfer of melt from the source region to the crystallization sites was assisted by deformation within and along major structural zones, such as the folded Archean–Paleoproterozoic discontinuity. The character of mineralization and structural control in the study area is reminiscent of the alaskite-hosted deposits at Rössing, Namibia. © 2012 Canadian Institute of Mining, Metallurgy and Petroleum. All rights reserved.

Key Words: U-rich pegmatites, Th-REE-rich pegmatites, Fraser Lakes Zone B, Wollaston Domain, Athabasca Basin, U metallogeny

Sommaire — La minéralisation en U-Th-ÉTR de la Zone B de Fraser Lake est contenue dans des pegmatites granitiques et des leucogranites localisés le long du contact déformé entre des gneiss métasédimentaires d'âge paléoprotérozoïque du Groupe de Wollaston et des orthogneiss d'âge archéen, à environ 25 km de l'extrémité sud-est du bassin d'Athabasca. Les pegmatites / leucogranites sont subcordants à concordants avec la foliation régionale et se concentrent dans la charnière d'un antiforme plongeant vers le nord-est dans la zone d'étude, laquelle est située à l'ouest de Fraser Lake. Les pegmatites minéralisées / leucogranites de la partie ouest de la zone d'étude (Groupe A) sont généralement enrichis en U (Th $\pm$), présentent un rapport Th / U $\sim$ 1, et contiennent de l'uraninite, de la thorite, du zircon et de l'allanite. Celles faisant intrusion dans la partie centrale de la zone d'étude (groupe B) sont généralement enrichies en Th et en terres rares légères, avec un rapport Th / U $>$ 2, et contiennent de la monazite, de la thorite (communément enrichie en U), et du zircon. Les pegmatites et les leucogranites du groupe A tendent à être légèrement enrichis en SiO₂ et appauvris en TiO₂ par rapport à ceux du groupe B et proviendraient de liquides plus évolués d'origine crustale. Les deux groupes sont hyperalumineux et présentent des compositions chimiques variées. La fusion partielle (à $\sim$ 850 ° C et à 9 kbar) d'une source dominée par des roches métasédimentaires s'est combinée à l'entraînement de minéraux accessoires en tant que xénocristaux, ainsi qu'aux processus d'assimilation et de cristallisation fractionnée expliquerait l'enrichissement des pegmatites granitiques / leucogranites en U, Th, et en éléments des terres rares. La déformation à l'intérieur et en périphérie de zones structurales majeures, tel la discordance plissée entre l'Archéen et le Paléoprotérozoïque, a contribué à la migration des liquides de fusion partielle de la région source aux sites de cristallisation. La nature de la minéralisation et le contrôle structural dans la zone d'étude rappellent les gîtes contenus dans des alaskites à Rössing, en Namibie. © 2012 Canadian Institute of Mining, Metallurgy and Petroleum. All rights reserved.

¹ Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, SK, Canada, S7N 5E2

² JNR Resources, Inc., 204-315 22nd Street East, Saskatoon, SK, Canada, S7K 0G6

* Corresponding author: e-mail – christine.mckechnie@usask.ca

Introduction

Economic concentrations of uranium can be found in a wide variety of geological environments, although the highest average grades, up to 18.3% U_3O_8 (Cigar Lake Deposit; Cameco, 2012), are typically found in the unconformity-related deposits of the Athabasca Basin, northern Saskatchewan, Canada (Fig. 1a, 1b; e.g., Kyser and Cuney, 2008). In contrast, some of the lowest grade uranium deposits (as low as 0.01% U) are hosted in granitic pegmatite and/or leucogranite, although they can be economically significant if of large enough tonnage. For example, the largest of this type currently being mined is the Rössing deposit in Namibia (Berning et al., 1976; Basson and Greenway, 2004); in 2010 it produced 3077 tU (~6% of the global uranium production for that year) and was the world's third largest uranium producer (World Nuclear Association, 2011).

In Canada, some of the best understood mineralized pegmatite bodies occur within the Grenville Province (Fowler and Doig, 1983; Lentz, 1991, 1996). Uranium-enriched granitic pegmatites (from 100 ppm up to %-level enrichment) are known from numerous locations in northern Saskatchewan, including the Charlebois Lake pegmatite (Mudjatik Domain), and many occurrences within the Wollaston Domain (e.g., Mawdsley, 1952, 1953, 1955; Parslow and Thomas, 1982; Parslow et al., 1985; Annesley and Madore, 1999; Annesley et al., 2000; Madore et al., 2000). These latter occurrences are assigned to the Paleoproterozoic Wollaston Group and underlying Archean rocks that form the basement to the eastern Athabasca Basin.

Uranium-enriched granitic pegmatites are associated with many unconformity-related uranium deposits, such as Moore Lakes (Annesley et al., 2000), McLean Lake, and P-Patch (Key Lake: see Madore et al., 2000). Uranium-enriched granitic pegmatites are considered to be an import-

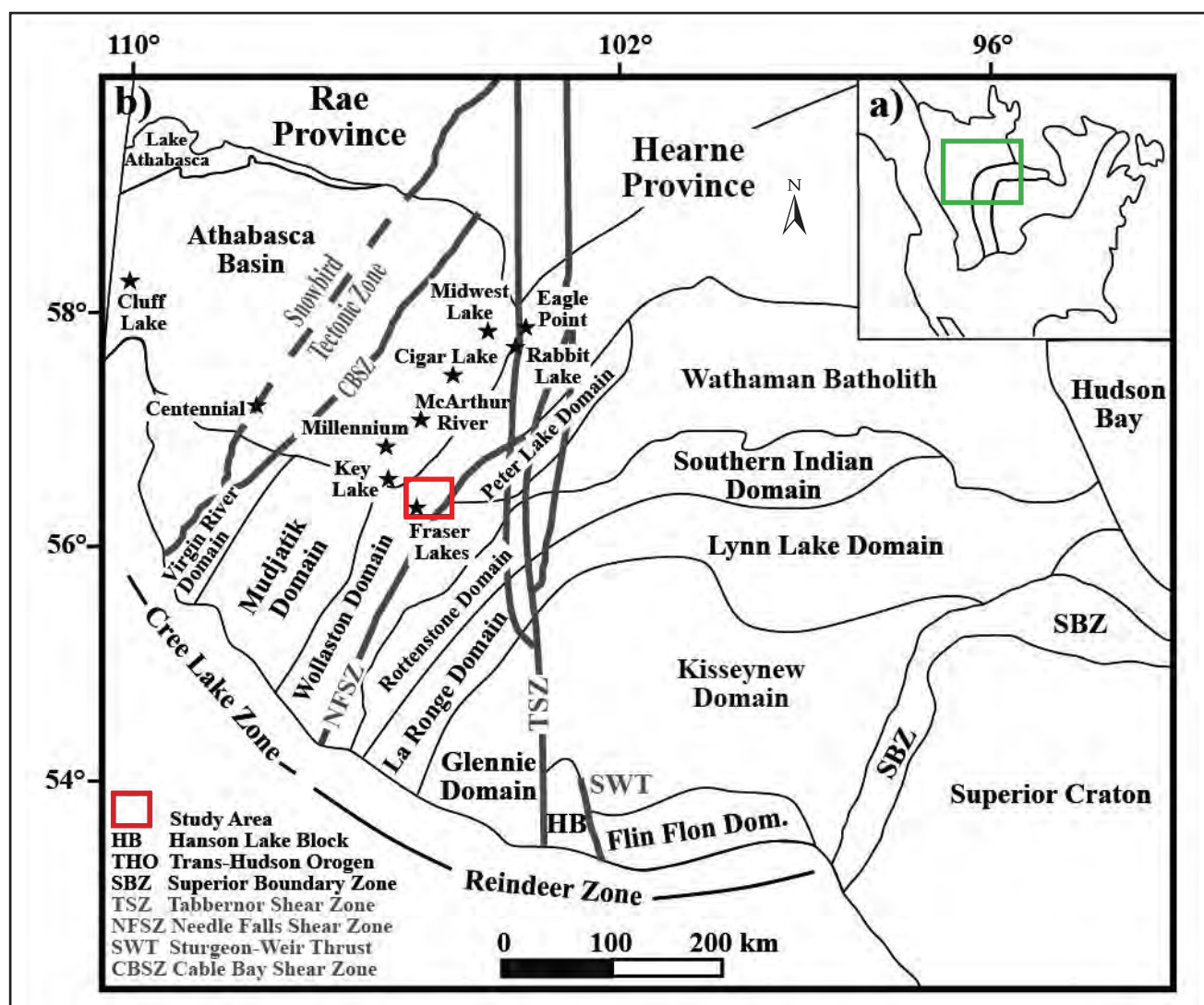


Figure 1. a) Map of North America, showing the Archean Hearne-Rae and Superior cratons, welded by the Paleoproterozoic Trans-Hudson Orogeny. Green box shows the location of Figure 1b. b) Lithotectonic domains in northern Saskatchewan and Manitoba, showing the location of several unconformity-type uranium deposits within the Athabasca Basin. Red box shows the location of Figure 2. Figure after Annesley et al. (2005).

Lewry and Sibbald (1980) and Tran (2001) initially considered the boundary between the Wollaston and Mudjatik domains to be gradational, although Annesley and Madore (1989, 1994) postulated that a significant crustal-scale shear zone lies along this boundary. The Needle Falls Shear Zone (Fig. 1b) marks the southeastern boundary of the Wollaston Domain, separating it from the 1.865 Ga Wathaman Batholith and the Peter Lake Domain (Tran, 2001; Annesley et al., 2005; Tran et al., 2008, and references within). The Hearne Province and the Reindeer Zone to the southeast underwent multiphase deformation and metamorphism during the collisional stages of the ca. 1.9–1.8 Ga Trans-Hudson Orogeny, which produced a Himalayan-scale mountain belt that welded Archean cratons together to form the core of Laurentia (Hoffman, 1990; Lewry and Collerson, 1990; Ansdell, 2005; Corrigan et al., 2009).

The Wollaston Domain has been the subject of numerous studies focusing on its stratigraphy, structure, metamorphism, geochronology, and mineral potential (cf. Tran, 2001; Tran et al., 2003, 2008; Annesley et al., 2005; Yeo and Delaney, 2007, and references therein). Overall, the domain contains Archean orthogneisses (predominantly granitic gneiss) that are unconformably overlain by metasedimentary rocks of the Paleoproterozoic Wollaston Group, which was deposited in rift, passive margin, and foreland basin environments. Hudsonian granites, amphibolites, leucogranites, migmatites, and granitic pegmatites are also locally abundant. The area of Figure 2 was originally mapped by Ray (1980) and is representative of the eastern Wollaston Domain (Annesley et al., 2005). It contains the Fraser Lakes Zones A and B and is described in detail below.

The Fraser Lakes Inlier and Johnson River Inlier (Fig. 2) of the Wollaston Domain consist of granitic orthogneisses and are dated by U-Pb zircon geochronology at 2593 ± 13 Ma and 2574 ± 3 Ma, respectively (Hamilton and Delaney, 2000). The inliers are overlain by metasedimentary rocks of the Wollaston Group; in the eastern Wollaston Domain, these metasedimentary rocks comprise two subgroups: an upper calc-silicate-rich subgroup, and a lower pelitic to psammitic subgroup (Tran et al., 1998, 2008; Tran, 2001).

The upper subgroup (Geikie River Group of Yeo and Delaney, 2007), consisting of calcareous and calc-silicate gneisses, is interpreted to be particularly thick in the Fraser Lakes area (Delaney et al., 1996), although the thickest sections lie to the east of the study area. The lower subgroup contains six units as described by Annesley et al. (2005); these are 1) graphitic pelitic gneiss, 2) partly calcareous, pelitic gneiss interlayered with garnetite-metatactite and tourmalinite, 3) psammopelitic gneiss, 4) metasedimentary calc-silicate gneiss, 5) psammitic gneiss, and 6) sillimanite-bearing metatactite. In the Fraser Lakes area, the lower subgroup (Daly Lake Group of Yeo and Delaney, 2007) consists of pelitic and quartz-feldspathic psammitic gneisses (Table 1). Graphite-bearing pelitic gneiss occurs immediately adjacent to the Archean inliers and is delineated by electromagnetic (EM) conductors (Fig. 2, 3a).

The Wollaston Group was intruded in various places by biotite-bearing monzogranite, granodiorite, and tonalite that range in age from 1840 Ma to 1810 Ma; rare metagab-

bro and amphibolites that range from 1830 Ma to 1820 Ma; and granitic pegmatites that range from 1820 Ma to 1800 Ma (Annesley et al., 2005). These intrusions document two main phases of melting at 1835 Ma and 1815 Ma, the latter being more voluminous, as observed elsewhere in the western margin of the Trans-Hudson Orogen (Clarke et al., 2005; Schneider et al., 2007; van Breeman et al., 2007; Tran et al., 2008). The rocks were metamorphosed under upper amphibolite to granulite facies conditions and were strongly deformed ca. 1.86–1.78 Ga (Annesley et al., 2005; Yeo and Delaney, 2007). Annesley et al. (1997, 2005) and Tran (2001) have introduced P-T-t paths for this metamorphism, which show that the gneissose fabric developed before or at peak pressure and before peak temperature in the western Trans-Hudson Orogen.

The dominant, generally northeast-trending structural fabric in the Fraser Lakes area formed by tight folding of this gneissose fabric; for example, a mapped EM conductor bordering the Fraser Lakes Inlier delineates northeast-plunging isoclinal folds (Fig. 2). North- to north-northwest-trending brittle faults offset lithological units in the area, which may be associated with the Tabernor Shear Zone (Fig. 1b).

The area in the immediate vicinity of the Fraser Lakes A and B mineralized zones is underlain by metasedimentary gneiss (including graphitic and non-graphitic pelitic gneisses, psammopelitic gneiss, and calc-silicate gneiss) of the Wollaston Group and underlying Archean orthogneiss of the Fraser Lakes Inlier (Fig. 2; Ray, 1980; Delaney and Tisdale, 1996). The contact between the Wollaston Group and Archean orthogneiss is marked by a 65 km long, folded EM conductor that defines northeast-plunging regional folds with shallow to moderately plunging fold axes and highly sheared and transposed fold limbs (Fig. 2, 3a; Annesley et al., 2009). An aeromagnetic map (Fig. 3a) emphasizes the northeast-trending regional structural trend but also shows the location of younger brittle faults.

The granitic pegmatites hosting the U-Th-REE mineralization are located in a ~500 m by 1500 m area west-northwest of the Fraser Lakes within an antiform fold nose cross-cut by a number of east-west-trending ductile-brittle structures, and north-northwest- and north-northeast-trending brittle faults (Fig. 3a, 3b). The granitic pegmatites intrude the highly deformed, folded, northeast-plunging, unconformable contact zone between pelitic gneiss of the basal Wollaston Group, which is graphitic in places, and Archean granitic and tonalitic gneisses of the Fraser Lakes Inlier (Fig. 3b, 3c).

Field Relationships and Petrography

Archean Orthogneiss

The orthogneiss in the Fraser Lakes area is grayish to reddish pink in drill core, and typically is fine to medium grained, with local coarse-grained and pegmatitic leucosome sections (Fig. 4a). It is relatively equigranular and tends to approach granoblastic polygonal texture in biotite-poor rocks. The orthogneiss ranges in composition from granodiorite to syenogranite and locally is gradational into tonalitic to quartz dioritic gneiss at its margins. Because

Table 1. Comparison of lithostratigraphic units in the Wollaston Domain, Hearne Province, Saskatchewan.

This paper	Wollaston supergroup (Yeo and Delaney, 2007)	Western Wollaston Domain (Yeo and Delaney, 2007)	Eastern Wollaston Domain (Coombe, 1994)	Annesley et al. (1997, 2005)
Calcareous metasedimentary & calc-silicate gneisses	Calc-silicate rocks & marble	Geike River Group	Hidden Bay Assemblage	
	Calc-silicate-bearing arkose		Fraser Lakes Formation	
	Arkose, conglomerate, wacke, & calc-silicate breccia		Rafuse Lake Formation	
	Conglomerate & arkose		Janice Lake Formation	
Psammopelitic gneiss	Arkose & quartzite	Daly Lake Group	Burbridge Lake Formation	Metaquartzite
	Arkose & psammopelite		Roper Bay Formation	Psammopelitic gneiss–psammitic gneiss
	Psammopelite & pelite		Thomson Bay Formation	Calc-pelitic gneiss
Pelitic gneiss ± Sil ± Grt ± Crd	Cordierite-sillimanite psammopelite & pelite		Bole Bay Formation	
	Garnet pelite & psammopelite ± iron formation	Karin Lake Formation	Spence Lake Formation	Garnetite, thin metaquartzite
	Pelite & psammopelite		George Lake Formation	Pelitic gneiss with amphibolite or quartzite
Graphitic pelitic gneiss ± Sil ± Grt ± Crd	Garnet-Graphite pelite & psammopelite ± quartzite			Garnetite, thin metaquartzite
	Garnet-Orthopyroxene-Graphite-Amphibolite gneiss			Graphitic pelitic gneiss
	Quartzite & psammopelite		Souter Lake Group	Marginal rocks including skarn, amphibolite, pegmatite
	Conglomerate & arkose ± volcanic rocks		Courtney Lake Group	
Archean granitic to granodioritic orthogneisses	Granitoid rocks			Undivided granitoids (Archean)
				Granite to granodiorite, foliated–gneissic (Archean)
Archean tonalitic to quartz dioritic orthogneisses				Tonalite–Trondhjemite–Granodiorite Suite (Archean)

Notes: 1. Granitic pegmatites/leucogranites and leucosomes of this study are age-equivalent to inlier marginal rocks of Hudsonian age of Annesley et al. (2005).

2. The position of lithological units in this table is based on their relative stratigraphic position, not their relative ages.

the tonalitic orthogneiss and the basal pelitic gneiss of the Wollaston Group are both dark gray in color, it can be difficult to distinguish the two rocks in drill core, especially where they have a protomylonitic to mylonitic fabric.

In the granitic orthogneiss, quartz, plagioclase, and K-feldspar are the dominant minerals (>75%), with biotite being the most common mafic mineral; perthitic feldspar intergrowths occur locally. Hornblende, magnetite, ilmenite, and pyrite are minor minerals, and accessory minerals include zircon, apatite, and rare allanite and uraninite. The granitic orthogneiss has undergone weak retrograde alteration, comprising chlorite and fluorite alteration of biotite (typically along cleavage planes), and sericite and saussurite alteration of feldspar. Ductile deformation has led to the development of a moderately intense foliation, plagioclase deformation twins, and undulose extinction in quartz.

The tonalitic orthogneiss is dominated by plagioclase and quartz, with significant amounts of hornblende, biotite, ilmenite, and magnetite, and varied amounts of clinopyroxene and orthopyroxene (Fig. 4b). Accessory minerals include zircon, apatite, and rare epidote and spinel. Most thin sections show evidence of weak retrograde metamorphism

or alteration, indicated by the presence of chlorite, clay, and sericite. Locally, a weak, fracture-controlled carbonate and hematite alteration is present. Textures exhibited by the tonalitic to quartz dioritic orthogneiss include myrmekitic intergrowths, plagioclase deformation twinning, undulose extinction in quartz, and symplectite textures formed by quartz and hornblende on the edge of hornblende crystals. This gneiss is moderately foliated with the foliation defined primarily by biotite and/or pyroxene and hornblende (Fig. 4b).

Wollaston Group Gneisses

In the larger Fraser Lakes area, the Wollaston Group consists of a number of units (Table 1), but in the study area, it is composed mainly of pelitic gneiss that can be subdivided into graphitic and non-graphitic varieties.

The graphitic gneiss is commonly porphyroblastic (garnet and/or cordierite), and the grain size ranges from very fine to medium grained, with an average size of <2 mm (Fig. 5a). This gneiss consists mostly of quartz, plagioclase, K-feldspar, biotite, and graphite (up to a maximum of 10–15% in thin section). It also contains varied amounts of cordierite, sillimanite, garnet, pyrite, chalcopyrite, and

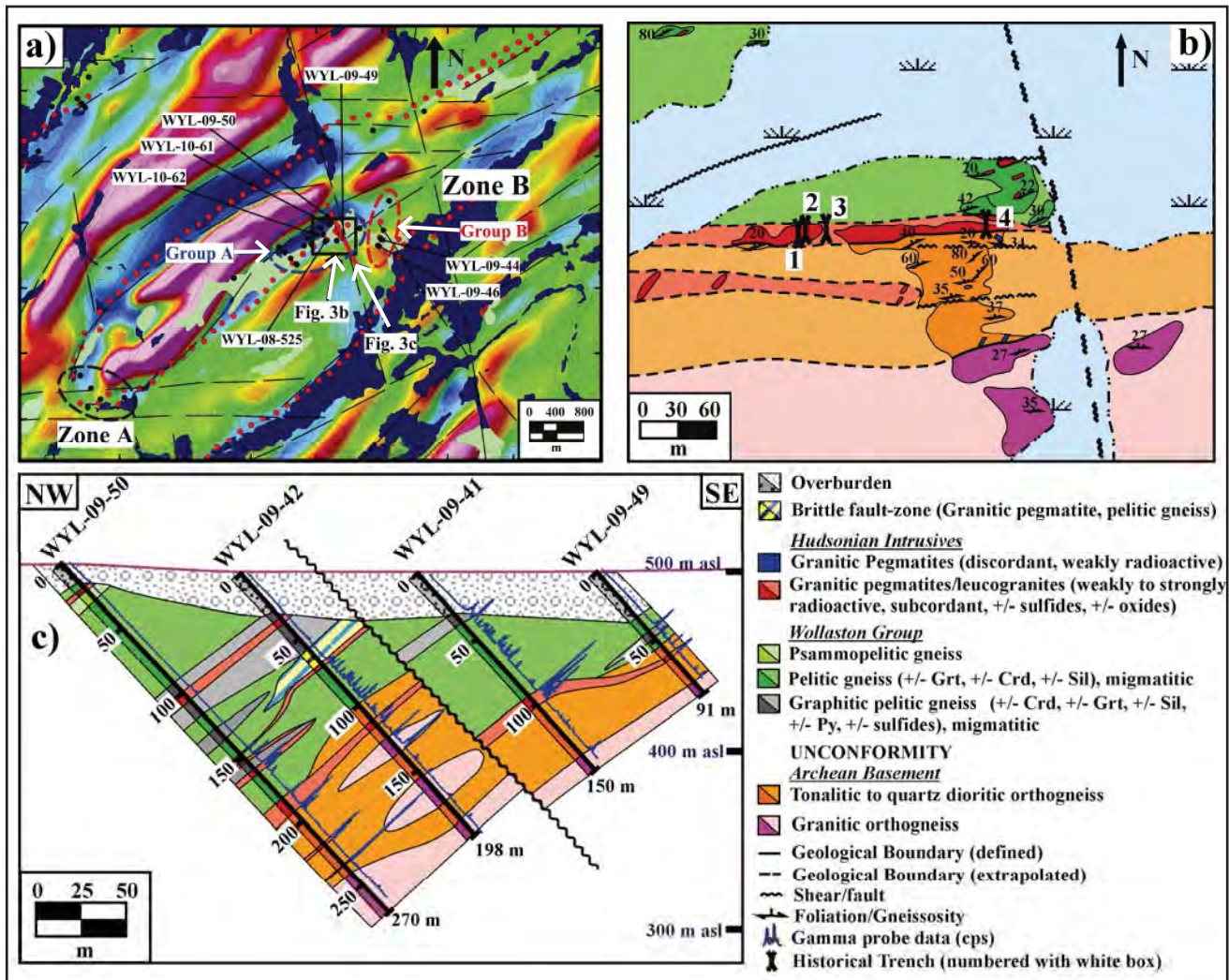


Figure 3. Geophysical and geological characteristics of the Fraser Lakes Zone B area. **a)** First vertical derivative total field aeromagnetic map of the Fraser Lakes area. Pink/red = areas of high magnetic potential field; blue/green = low magnetic potential field. Black dots = drill holes (study samples are labeled). Red dots = regional-scale electromagnetic conductor. Figure also shows the location of Groups A and B pegmatites/intrusives, Figure 3b, and Figure 3c. **b)** Geological map of the Fraser Lakes Zone B outcrop, showing Trenches 1 to 4. The uraniferous granitic pegmatites (in red) intruded at or near the contact zone between Archean orthogneiss and metasedimentary rocks of the Wollaston Group. Modified from Ko (1971). **c)** Geological cross-section showing drill holes WYL-09-41, -42, -49, and -50. Many pegmatites intrude both pelitic gneiss and orthogneiss. Blue lines represent the downhole gamma probe results, and the largest peaks coincide with the location of pegmatites. The largest peak (in WYL-09-50) corresponds to ~5800 counts per second (cps) of radioactivity.

ilmenite; accessory minerals include apatite, monazite, and zircon (Fig. 5b). The graphitic gneiss tends to be quite heterogeneous in composition and is generally interlayered (Fig. 5c) with the non-graphitic pelitic gneiss, especially near the contact with Archean orthogneiss, which is the locus of most of the mineralized pegmatites (Fig. 3b, 3c).

Non-graphitic gneiss is common in the Fraser Lakes area, where it forms extensive layers of varied thicknesses (up to tens of meters). It is fairly heterogeneous in composition, commonly exhibits layering, and is gradational into other units of the Wollaston Group (see Table 1). The non-graphitic gneiss is typically dark gray, fine to medium (and, locally, coarse) grained, and is generally inequigranular. Porphyroblasts are common within this gneiss and typically are composed of inclusion-rich cordierite and/or garnet (Fig. 5d, 5e). The gneiss is composed of quartz, plagioclase,

K-feldspar (generally subordinate), biotite, $\pm$ garnet, $\pm$ cordierite, $\pm$ sillimanite, $\pm$ ilmenite, $\pm$ rutile, $\pm$ pyrite, and $\pm$ chalcopyrite. Accessory minerals include zircon, monazite, apatite, titanite, uraninite, and allanite. The two main alteration assemblages are an early, retrograde chlorite, muscovite, leucosene, clay, and epidote alteration; and a late, fracture-associated hematite, chlorite, and clay mineral alteration.

Both the graphitic and non-graphitic gneisses are generally tightly folded and are typically well banded with a gneissic to mylonitic fabric. Migmatitic textures are common. They include evidence of small-scale melt reactions (Fig. 5e); deformed, boudinaged felsic leucosome bands (Fig. 5f); and dikelets of remobilized felsic leucosome that lie parallel to, and cross-cut, the gneissosity. Stromatic and diatexite migmatite are present. The fabric is defined by the

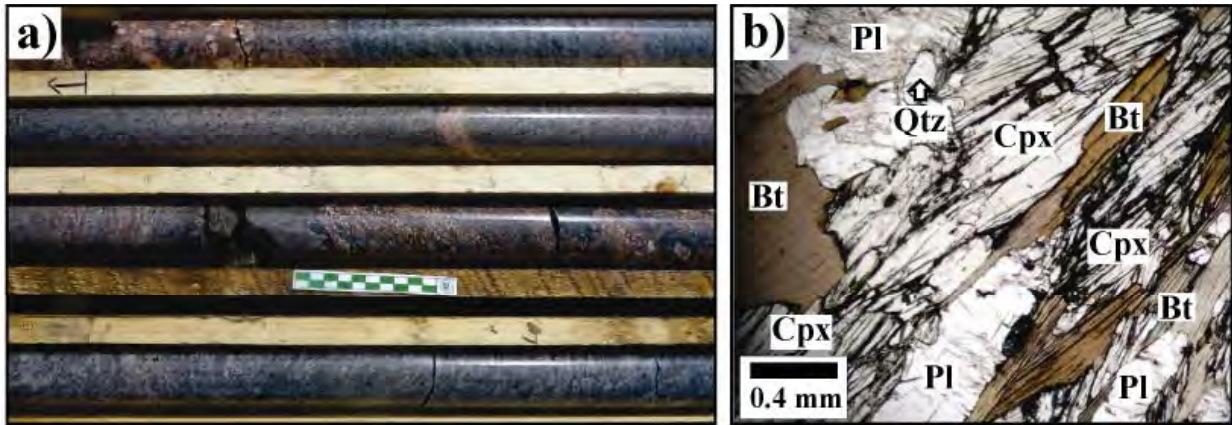


Figure 4. Archean orthogneissic rocks of the Fraser Lakes Inlier. **a)** Layered granitic and tonalitic orthogneisses intruded by granitic pegmatite (drill core from WYL-09-46). Scale bar in cm. **b)** Photomicrograph of clinopyroxene- and biotite-bearing tonalitic orthogneiss (WYL-09-49-53.9). Bt = biotite, Cpx = clinopyroxene, Pl = plagioclase, Qtz = quartz. Abbreviations for all mineral names after Kretz (1983).

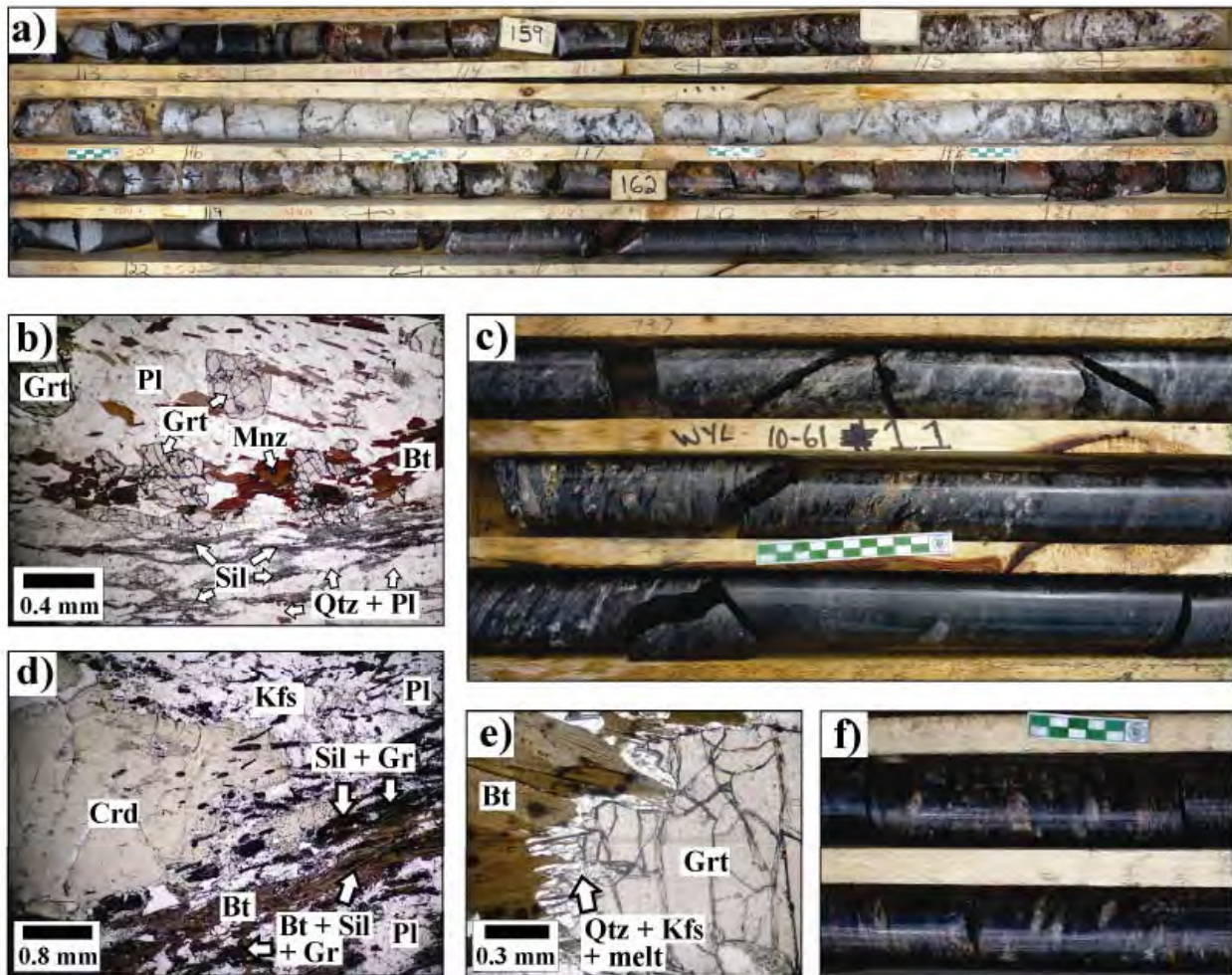


Figure 5. Pelitic gneisses hosting the Fraser Lakes Zone B pegmatite. **a)** Graphitic pelitic gneiss intruded by zoned quartz- and K-feldspar-rich, weakly mineralized granitic pegmatite parallel to gneissosity (WYL-09-50). **b)** Pelitic gneiss containing biotite, garnet, sillimanite, monazite, quartz, and feldspars (WYL-09-49-36.1). **c)** Pelitic gneiss showing its compositional variation, including graphite-cordierite-sillimanite-rich layers (WYL-10-61). **d)** Pelitic gneiss with altered cordierite, biotite, sillimanite, feldspar, and quartz (WYL-10-61-78.1). **e)** Garnetiferous pelitic gneiss with melt microtextures at the contact between garnet and biotite (WYL-09-44-61.4). Biotite was consumed in the melt-generating reaction. **f)** Boudinaged, lighter colored leucosomes (K-feldspar + quartz-dominated) accentuating the dominant gneissosity and foliation shown by the darker pelitic gneisses (WYL-09-37). Scale bar in cm. Bt = biotite, Crd = cordierite, Fsp = feldspar, Grt = garnet, Kfs = K-feldspar, Mnz = monazite, Pl = plagioclase, Qtz = quartz, Sil = sillimanite.

preferred orientation of biotite, sillimanite, and graphite, where present (Fig. 5b, 5d). Porphyroblasts of cordierite tend to be flattened, stretched, and elongated parallel to the fabric. Garnet porphyroblasts rarely are slightly flattened, but more typically are round to irregular in shape (Fig. 5b).

Other rocks of the Wollaston Group in the Fraser Lakes area include garnetite, quartzo-feldspathic gneiss, calcareous metasedimentary rocks, and calc-silicate gneiss. These units were rarely intersected in drill core and are gradational into each other and the more voluminous graphitic and non-graphitic pelitic gneisses. The psammopelitic gneiss and calc-silicate gneiss are concentrated near the top of several drill holes (e.g., WYL-09-50: Fig. 3c) and generally overlie the pelitic $\pm$ graphite gneiss that lies closer to the contact with the Archean orthogneiss. However, due to their subordinate presence in the Fraser Lakes drill core, the psammopelitic gneiss and calc-silicate gneiss were not examined in detail for this study.

Granitic Pegmatites and Leucogranites

The two types of granitic (*sensu lato*) pegmatites/leucogranites in the Fraser Lakes area can be distinguished on the basis of their cross-cutting relationships. For brevity, the rocks are herein termed ‘pegmatites’ and ‘intrusions,’ although they are properly classified as granitic pegmatites and leucogranites.

The first type of pegmatites is weakly radioactive, typically showing less than two times background radioactivity as measured by a Radiation Solutions RS-125 handheld scintillometer. It features a simple mineralogy of quartz, K-feldspar, plagioclase, and rarely biotite. These intrusions are inequigranular, typically pink, and coarse grained to pegmatitic; they commonly show graphic textures and perthitic intergrowths in quartz and feldspars. They occur sporadically in drill core and outcrop as discordant dikes and sheets, which significantly post-date the main phase of ductile deformation in the Fraser Lakes area. These intrusions were not examined in detail during the present study.

The second type of pegmatites is weakly to strongly radioactive, typically showing greater than two to three times background radioactivity. These radioactive pegmatites have a varied primary mineralogy, including quartz, plagioclase, K-feldspar, biotite, $\pm$ magnetite, $\pm$ ilmenite, $\pm$ zircon, $\pm$ U-Th-REE-bearing accessory minerals, $\pm$ fluorite, $\pm$ titanite, $\pm$ apatite, $\pm$ graphite, $\pm$ garnet (Table 1, Fig. 6a–6f, 7a–7d). The pegmatites range in width from a few centimeters to a decameter or more in both outcrop and drill core; the thicker bodies are concentrated close to fold noses, and the thinner bodies are on the limbs. The rocks are inequigranular, with grain size ranging from coarse grained to pegmatitic (Fig. 5a, 6a).

The majority of the radioactive accessory minerals in this second type of pegmatites tend to be associated with biotite, quartz, and magnetite (Fig. 6b–6d, 7a–7d). Quartz, feldspar, biotite, and magnetite grains tend to be much larger and form crystals up to a few centimeters in size (Fig. 5a, 6a). The individual pegmatite bodies are subcordant to concordant with the dominant gneissosity/foliation of the host rocks (Fig. 7a) and thus are interpreted to have been

intruded syn-tectonically with respect to the Trans-Hudson Orogeny.

The highly radioactive intrusions can be further subdivided into two subgroups on the basis of their general location, geochemistry, and mineral assemblages:

- a U-enriched group, the ‘Group A pegmatites/leucogranites,’ hereafter referred to as the Group A intrusions, and
- a Th- and LREE-enriched group, the ‘Group B pegmatites/leucogranites,’ hereafter referred to as the Group B intrusions.

The composition of the host rocks also influences the mineral assemblages of both groups, as magnetite is found only in pegmatites that intruded the Archean orthogneiss, whereas graphite and garnet occur sporadically in pegmatites hosted by rocks of the Wollaston Group.

The U-Th-REE accessory minerals in Group A intrusions include uraninite, U-enriched thorite, zircon, allanite, and apatite (Fig. 6b–6f; Table 2), with rare monazite. These intrusions occur within the western part of the study area (Fig. 3a) and crop out at the original showing (Fig. 3b) that was initially described by Foster (1970) and later mapped by Ko (1971). Biotite grains in these pegmatites exhibit strong red-brown pleochroism (Fig. 6b, 6c). Low-Ca plagioclase (albite to oligoclase) is common. Zircons are typically zoned with distinct cores and rims that generally have different colors and birefringence (Fig. 6c). Uraninite (Fig. 6b, 6d) is typically present as small, altered cubic grains containing small galena (radiogenic?) and pyrite inclusions. Thorite and allanite are generally strongly altered, making them difficult to recognize in thin section.

The Group B intrusions are located mainly in the central part of the study area (Fig. 3a). The U-Th-REE accessory minerals include monazite and U-enriched thorite (commonly with pyrite inclusions), as well as thorite; and zircon, with rare allanite, xenotime (surrounding monazite), and apatite (Fig. 7a–d; Table 2). A single grain of an unusual Nb-rich mineral was also observed in one thin section from drill hole WYL-09-46. Monazite grains are commonly altered to hematite and partly rimmed by a mixture of chlorite $\pm$ clay (Fig. 7a–7c). Allanite is also strongly altered and difficult to recognize in thin section. The monazite crystals are up to 1–2 mm in size and are typically associated with thorite, biotite, and zircon. The biotite exhibits slightly brownish to greenish pleochroism and commonly contains inclusions of rutile.

Zoning is common in most of the intrusions and varies among different bodies. Typical zoning patterns include plagioclase or quartz-rich cores with K-feldspar more predominant at the margins, but a consistent pattern has not been established. However, the highest radioactivity (as determined by a handheld scintillation counter) in both groups of intrusions is associated with biotite-rich zones. Quartz-rich zones in some intrusions also tend to contain significant concentrations of uranium and thorium.

The radioactive pegmatites show a variety of igneous textures, including occasional granophyric, graphic, perthitic, and myrmekitic intergrowths. They also tend

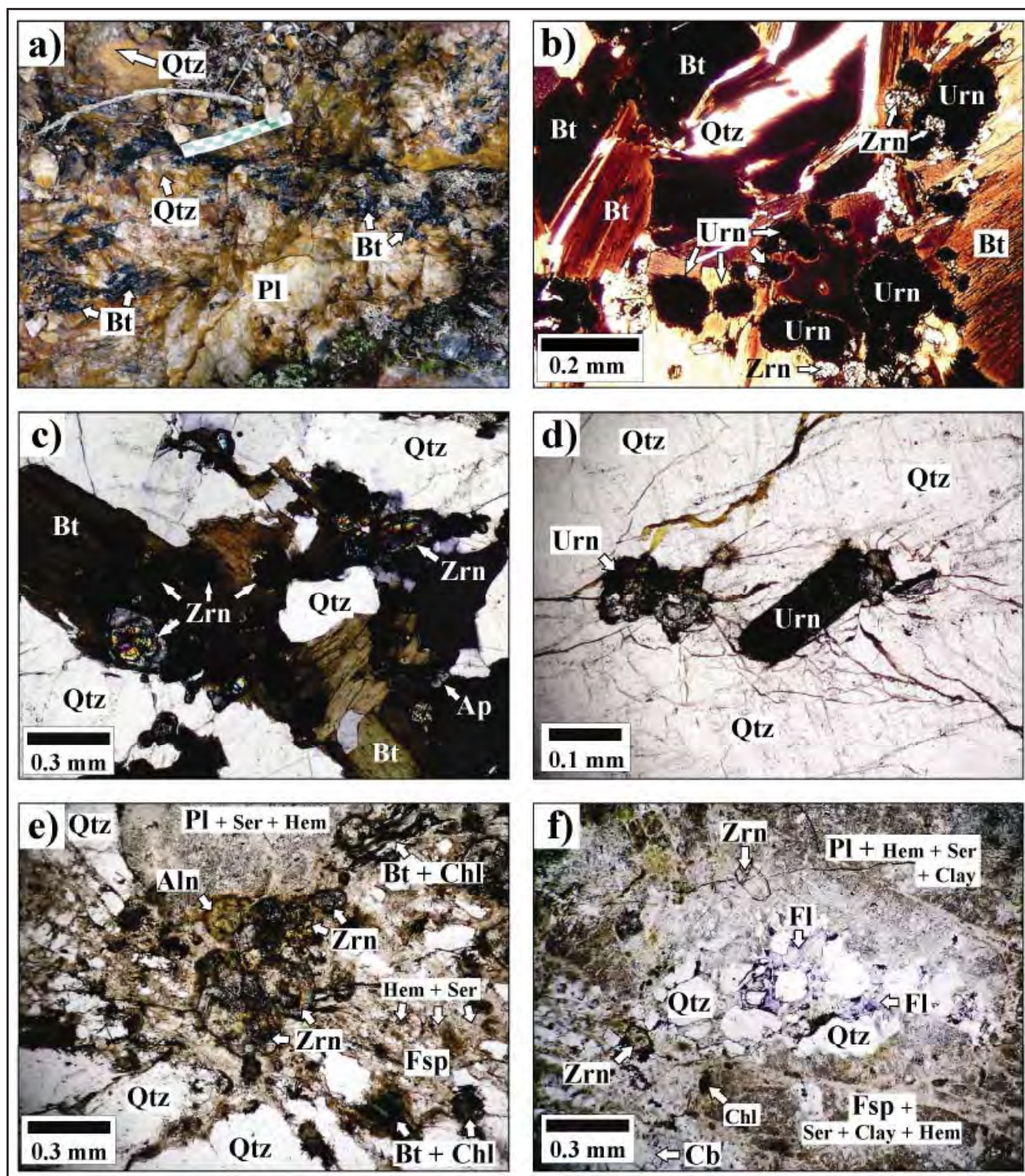


Figure 6. Field photograph and photomicrographs of Group A granitic pegmatites and leucogranites from Fraser Lakes Zone B. **a)** Typical U-rich granitic pegmatite showing coarse grain size of plagioclase-, biotite-, and quartz-rich mineralogy; from outcrop at Trench 2 (see Fig. 3b). Scale bar in cm. **b)** Granitic pegmatite, rich in biotite, zircon, and uraninite (sample Trench 2-2). **c)** Granitic pegmatite with abundant zoned zircon, and apatite in a cluster of biotite (WYL-09-50 at ~191.6 m). **d)** Quartz-rich granitic pegmatite sample containing partially altered uraninite (Sample QTZPEG 0004-2). **e)** Moderate to strongly altered (hematite, chlorite, and sericite) quartz-plagioclase pegmatite containing zircon and a strongly altered mineral that is possibly allanite (WYL-09-50-215.8). **f)** Altered pegmatite showing fluorite, carbonate, and strong clay mineral (Clay) + sericite + hematite + chlorite alteration of feldspar (WYL-09-50-215.8). Aln = allanite, Ap = apatite, Bt = biotite, Cb = carbonate, Chl = chlorite, Fl = fluorite, Fsp = feldspar, Hem = hematite, Pl = plagioclase, Qtz = quartz, Ser = sericite, Urn = uraninite, Zrn = zircon.

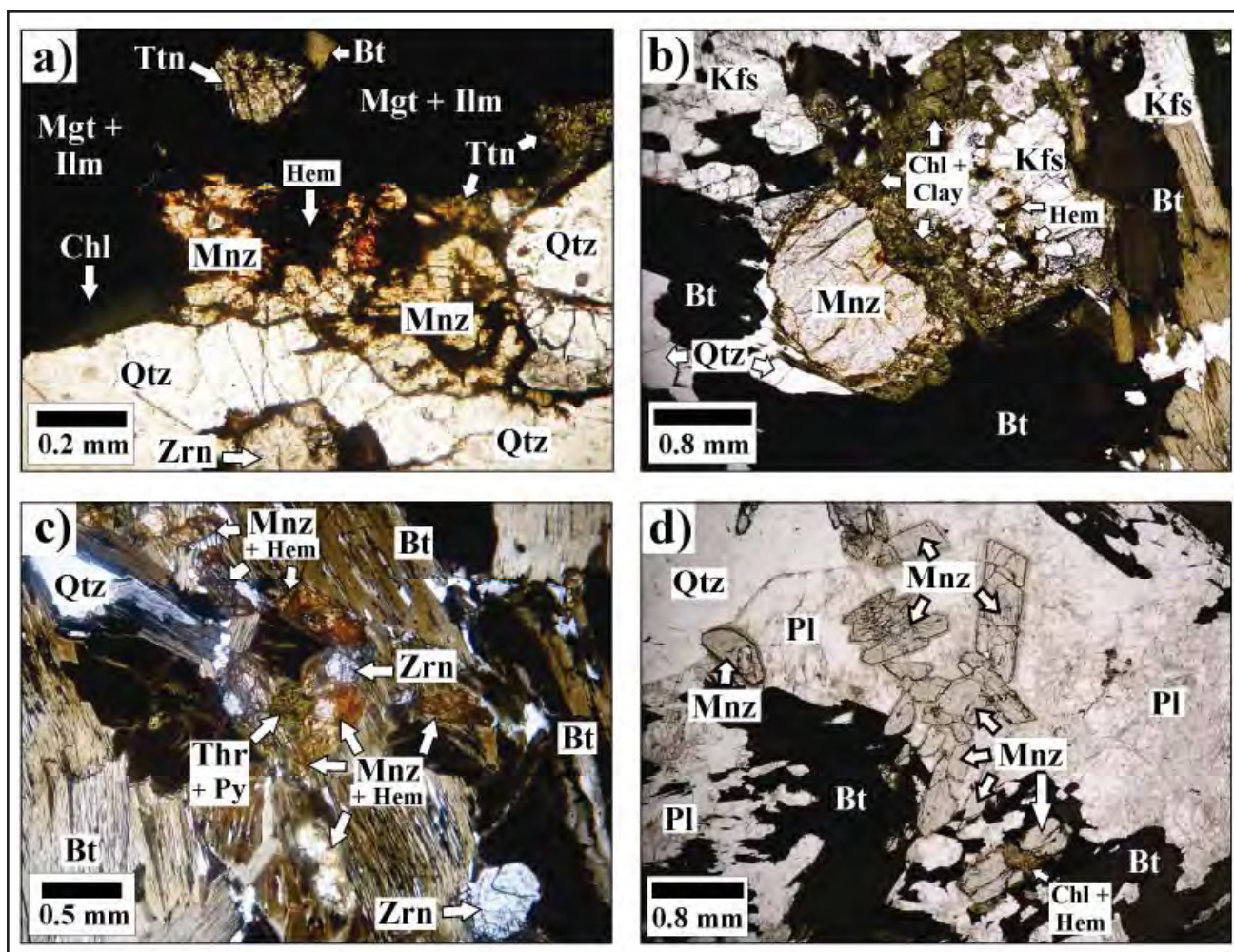


Figure 7. Photomicrographs of Group B pegmatites and leucogranites from Fraser Lakes Zone B. **a)** WYL-09-46-83.0, and **b)** WYL-09-46-42.8, both of which show monazite, zircon, ilmenite, magnetite, and titanite mineralization. **c)** Biotite-rich section of a granitic pegmatite (WYL-09-46-36.1) with hematite-altered monazite, U-enriched thorite with pyrite inclusions, and zoned zircon. Note weakly chloritized biotite. Monazite typically is weakly (a) to strongly (c) altered to hematite, chlorite, and clay minerals (Clay). **d)** Monazite-rich granitic pegmatite (WYL-09-46-32.6). Bt = biotite, Chl = chlorite, Hem = hematite, Ilm = ilmenite, Kfs = K-feldspar, Mgt = magnetite, Mnz = monazite, Py = pyrite, Qtz = quartz, Thr = thorite, Ttn = titanite, Zrn = zircon.

to show a hypidiomorphic granular texture overall, with euhedral to subhedral grains, especially in early-formed accessory minerals. Radial cracks are accompanied by the development of reaction rims and pleochroic damage haloes in the surrounding minerals (Fig. 6c, 6d, 7c). These features are interpreted to be the result of metamictization and associated crystal volume changes of radioactive minerals.

Ductile deformation of the radioactive intrusions is strongly dependent on their size, with the largest bodies showing only weak ductile deformation in their cores. Small intrusions and the margins of larger bodies exhibit signs of ductile deformation, including folding and the development of a weak foliation (defined by the alignment of biotite). Quartz and K-feldspar typically show undulose extinction due to strain, and deformation twins are common within plagioclase. Brittle deformation in the radioactive intrusions is common and consists of cross-cutting fractures and fault zones. Brittle deformation is highly var-

ied in intensity and is likely related to large-scale ductile-brittle and brittle faulting that took place in the Wollaston Domain at 1760–1700 Ma (Annesley et al., 2005). The most prominent fault in the Fraser Lakes area is the north-northwest-striking Tabernor Shear Zone (Fig. 1), a major fault that extends for many kilometers.

All of the pegmatites commonly show weak sericite, saussurite, and clay mineral alteration of feldspar and rare chloritization of biotite (Fig. 6e, 6f, 7a–7c). Carbonate and hematite alteration of the intrusions is typically very late and is generally related to brittle fractures running through the pegmatites and their host rocks. The carbonate and hematite alteration is locally associated with fluorite, clay minerals, and chlorite (Fig. 6e, 6f). It affects not only the major minerals in the pegmatites and their host rocks, but also the U-Th-REE-bearing accessory minerals—in particular monazite, uraninite, and U-enriched thorite, which show weak to locally strong alteration (Fig. 7a–c). In some drill holes in the Fraser Lakes Zone B area, this alteration

Table 2. Pegmatite mineralogy, with minerals listed in order of abundance. Yellow = major minerals. Green = U-Th-REE-bearing accessory minerals.

U-rich pegmatites	Th-REE-rich pegmatites
Quartz	Quartz
K-feldspar	K-feldspar
Plagioclase	Plagioclase
Biotite	Biotite
Magnetite	Magnetite
Ilmenite	Ilmenite
Pyrite	Pyrite
Fluorite	Fluorite
Zircon	Monazite
Rutile	Zircon
Uraninite	Rutile
Thorite	U-enriched thorite
Allanite	Thorite
Titanite	Allanite
Molybdenite	Xenotime
Garnet	Molybdenite
Apatite	Titanite
Sphalerite	Apatite
Chalcopyrite	Sphalerite
Pyrrhotite	Garnet
Graphite	Chalcopyrite
	Pyrrhotite
	Graphite
	Nb-oxide

is strong and resembles hydrothermal alteration typical of unconformity-related uranium deposits of the nearby Athabasca Basin (Annesley et al., 2010b; JNR Resources Inc., 2012).

Rarely, the pegmatites cut calc-silicate rocks, which resulted in the development of skarns along the margins of these intrusive bodies, a phenomenon common elsewhere in the Wollaston Domain (Annesley et al., 2005).

Sampling and Analytical Techniques

Diamond drill cores from more than one dozen holes were logged to determine the macroscopic features of the granitic pegmatites and their host rocks, and to focus sampling for the petrographic study and geochemical analysis. In addition, one outcrop previously mapped by Ko (1971; Fig. 3b) was examined; representative samples of relatively unweathered pegmatite and pelitic gneiss were taken from this outcrop and from trenches dug by

JNR Resources Inc. Polished thin sections were prepared in the Thin Section Laboratory in the Department of Geological Sciences at the University of Saskatchewan. Transmitted and reflected light petrography were performed at the University of Saskatchewan and JNR Resources Inc.

The definitions of rock types, rock classification, nomenclature, and other terms used in this study follow those of the International Union of Geological Sciences (IUGS) Subcommittee on the Systematics of Igneous Rocks (Le Maître, 2002) and the Subcommittee on Metamorphic Rocks (Fettes and Desmons, 2007). In addition, this study used the definitions, textural terminology, and genetic models of pegmatites, migmatites, and metamorphic rocks put forth by London (2008), Sawyer (2008), and Vernon and Clarke (2008), respectively.

Sample preparation and geochemical analysis were performed at the Saskatchewan Research Council (SRC) Geoanalytical Laboratories. Detailed descriptions of procedures at SRC Geoanalytical Laboratories can be found on their website (SRC, 2012). A total of 87 samples, most of which were from drill core, were analyzed for major- and trace-element chemistry.

Whole-rock major-element oxides, loss on ignition (LOI), and selected trace elements (Ba, Cr, Sc, Sr, Y, and Zr) were analyzed by a Perkin Elmer inductively coupled plasma-optical emission spectrometer (ICP-OES) after lithium metaborate fusion. Detection limits were ~0.01% for the major elements (except SiO₂), 0.1% for LOI and SiO₂, and 2 ppm for the trace elements. The remaining trace elements, with the exception of B, were analyzed by ICP-OES or ICP-MS following acid digestion of the rock powder; the detection limit was ~1 ppm. Samples for B analysis underwent NaO₂/NaCO₃ fusion prior to analysis by ICP-OES; the detection limit was ~2 ppm. Carbon and sulfur concentrations were determined by combusting pulverized sample material in a LECO induction furnace supplied with oxygen. Instrument calibrations were used to determine the weight percent concentrations of both elements in the sample. Detection limits for both carbon and sulphur were ~0.01%. As part of the quality control and assurance procedures at the SRC, in-house standards and the United States Geological Survey GSP-2 standard (Wilson, 2009) were routinely analyzed, along with duplicate sample pulps and blanks.

Representative samples of pelitic gneiss, orthogneiss, and granitic pegmatite were also analyzed by X-ray Fluorescence (XRF) to determine fluorine, chlorine, and sulphur contents, as well as major- and trace-element concentrations. The sample preparation involved the formation of pressed pellets, which were analyzed in a vacuum using a Bruker S8 TIGER XRF spectrometer. Detection limits varied depending on the element; they ranged from 0.005% to 0.10% for the major elements; were 0.01% for F, S, and Cl; and ranged from 1 ppm to 10 ppm for the remaining elements.

Reanalysis of samples previously done by ICP-OES provided constraints on analytical accuracy, and the results from both techniques were very similar (see Supplementary Data Table (SDT). Readers interested in this full geochemical data set (the SDT) may e-mail the corresponding author for a copy of the Excel file.) Titration analysis was performed on selected samples to obtain a value for FeO_{total} in the rocks. The amounts of ferrous and ferric iron in the samples were calculated from the values obtained using ICP-OES, XRF, and titration.

Geochemical Results

Gneissic Host Rocks

The three analyzed samples of Archean granitic orthogneiss show consistent major-element compositions, as typified by Sample WYL-09-50-252.7 (Table 3, Fig. 8a–e, SDT). The samples are also enriched in U (av. 7 ppm), Th (av. 29 ppm), and Zr (av. 444 ppm) relative to average continental crustal values of 1.3 ppm, 5.7 ppm, and 210 ppm, respectively (Weaver and Tarney, 1984). The less abundant tonalitic to dioritic orthogneiss shows a more varied chemical composition, due to its more diverse primary mineralogy; it tends to have higher concentrations of V, Cr, Co, Ni, and Zn, and lower total REE than the granitic orthogneiss (Table 3, SDT), reflecting its more mafic composition. All of the Archean orthogneiss samples have major- and trace-element characteristics that indicate they are calc-alkaline, similar to other Archean inliers in the Wollaston Domain (e.g. Tran, 2001).

Pelitic gneiss samples show considerable variation in chemical composition, with SiO_2 ranging from 37.3 wt. % to 64 wt. %, and Al_2O_3 from 10.5 wt. % to 21.2 wt. % (Table 3, Fig. 8b, SDT); the compositional variation reflects their mineralogical variation. The two samples with the lowest SiO_2 content (<40 wt. %) also have the highest $\text{Fe}_2\text{O}_{3\text{tot}}$ (23.1–25.1 wt. %) and high K_2O (5.5–6.2 wt. %), indicating they are biotite-rich. The range in major-element compositions is similar to that presented by Tran et al. (2003) in their study of metasedimentary rocks from other parts of the Wollaston Domain.

Samples of graphite-bearing pelitic gneiss contain up to 6.64 wt. % C, and some also contain up to 15.6 wt. % S (Table 3). They have varied metal concentrations. However, the highest Ni (2600 ppm in one sample: SDT), Cu (307 ppm), and Co (137 ppm) contents are in rocks with the highest S content, suggesting a relationship with sulfides; whereas the highest Cr (259 ppm) and V (566 ppm) contents occur in rocks with the highest $\text{Fe}_2\text{O}_{3\text{tot}}$, suggesting a relationship with iron oxide minerals. U (up to 49 ppm, av. 15 ppm) and Th (up to 557 ppm, av. 42 ppm) are enriched relative to typical values for fine-grained sedimentary rocks, as exemplified by the North American Shale Composite (NASC) of Gromet et al., 1984, which has values of 2.66 ppm U and 12.30 ppm Th. Such enrichment in U and Th is expected, due to the graphitic nature of this gneiss.

Granitic Pegmatites and Leucogranites

Whole-rock geochemical analysis of pegmatites is fraught with difficulty because of the coarse grain size of minerals and common internal zoning. These features make determination of the bulk composition of the pegmatite-forming melt almost impossible (e.g., Stilling et al., 2006) but may allow determination of the melt composition of specific zones within a pegmatite. At Fraser Lakes Zone B, samples were collected predominantly from drill core, but a few were collected from the only outcrop (Fig. 3b, 6a). However, the small volume of each sample, especially the drill core samples, means that any individual sample may not accurately reflect the modal mineralogy of the

pegmatite/leucogranite at that specific location. Nevertheless, the two groups of strongly radioactive granitic pegmatites (Group A and Group B, introduced earlier) show differences in their U and Th contents and Th/U values (Fig. 9a); the compositions of two samples from each group are shown in Table 3.

Group A intrusions are enriched in U and Th and have Th/U values of ~ 1 (Table 3, Fig. 9a), reflecting the presence of uraninite and U-enriched thorite; they contain up to 2460 ppm U and 1100 ppm Th. In contrast, Group B intrusions are typically enriched in Th and LREE with Th/U values of >2 (commonly greater than the crustal average ratio of 4; see Fig. 9a); they contain up to 701 ppm U, 7310 ppm Th, 4410 ppm La, 9050 ppm Ce, 1060 ppm Pr, 3590 ppm Nd, and 607 ppm Sm (Table 3).

Group A intrusions on average tend to be more SiO_2 -rich (Fig. 9b) than Group B intrusions, except where the former intrusions contain magnetite and ilmenite. Group B intrusions, in contrast, have elevated P_2O_5 (Fig. 9c); this is related to the presence of monazite as the dominant accessory mineral, as it hosts most of the light REEs (LREEs). The Th/U vs log Ce emphasizes the high LREE content of Group B pegmatites, especially those high in Th, which in turn reflects their monazite content (Fig. 9d). U-enriched thorite contains much of the U and some of the Th in Group B intrusions, with xenotime being one of the main heavy REE (HREE) hosts. Group A intrusions have elevated Pb concentrations of up to 847 ppm and Group B intrusions, up to 674 ppm (Table 3).

The pegmatites show variation in their major-element chemistry related to the relative amounts of quartz, plagioclase, K-feldspar, biotite, magnetite, and ilmenite in each specific sample. Group A intrusions tend to be slightly more enriched in silica and depleted in titanium relative to Group B; however, their chemistry overlaps considerably (Fig. 8a–e). The high- SiO_2 intrusions are quartz-rich, whereas samples with the lowest SiO_2 have the highest proportion of biotite, magnetite, and/or ilmenite. The contents of Al_2O_3 , MgO, and $\text{Fe}_2\text{O}_{3\text{tot}}$ tend to decrease as SiO_2 increases (Fig. 8b–d), whereas CaO, Na_2O , and K_2O contents are more varied with respect to SiO_2 (Table 3, SDT).

Group A and Group B intrusions are peraluminous to weakly metaluminous and represent S-type and marginal I-type granitoids (Fig. 10). They overlap the pelitic gneiss and orthogneiss on major-element Harker variation diagrams (Fig. 8a–e), with Group A intrusions tending to be more distinct in composition from the pelitic gneisses and orthogneisses than Group B intrusions. Some of the low-MgO pegmatites define a linear trend toward higher TiO_2 with constant MgO: that is, away from the granitic orthogneiss compositions (Fig. 8e). These pegmatites intrude Archean granitic orthogneiss, and thus their composition may be controlled by melting or assimilation of the host rocks.

The pegmatites contain varied amounts of F and Cl. Group A intrusions typically contain <0.20 wt. % F, but a few samples have up to 0.42 wt. % F. Chlorine is present in small amounts as well (up to 0.11 wt. % Cl). In contrast, Group B intrusions contain 0.07–0.45 wt. % F (typically

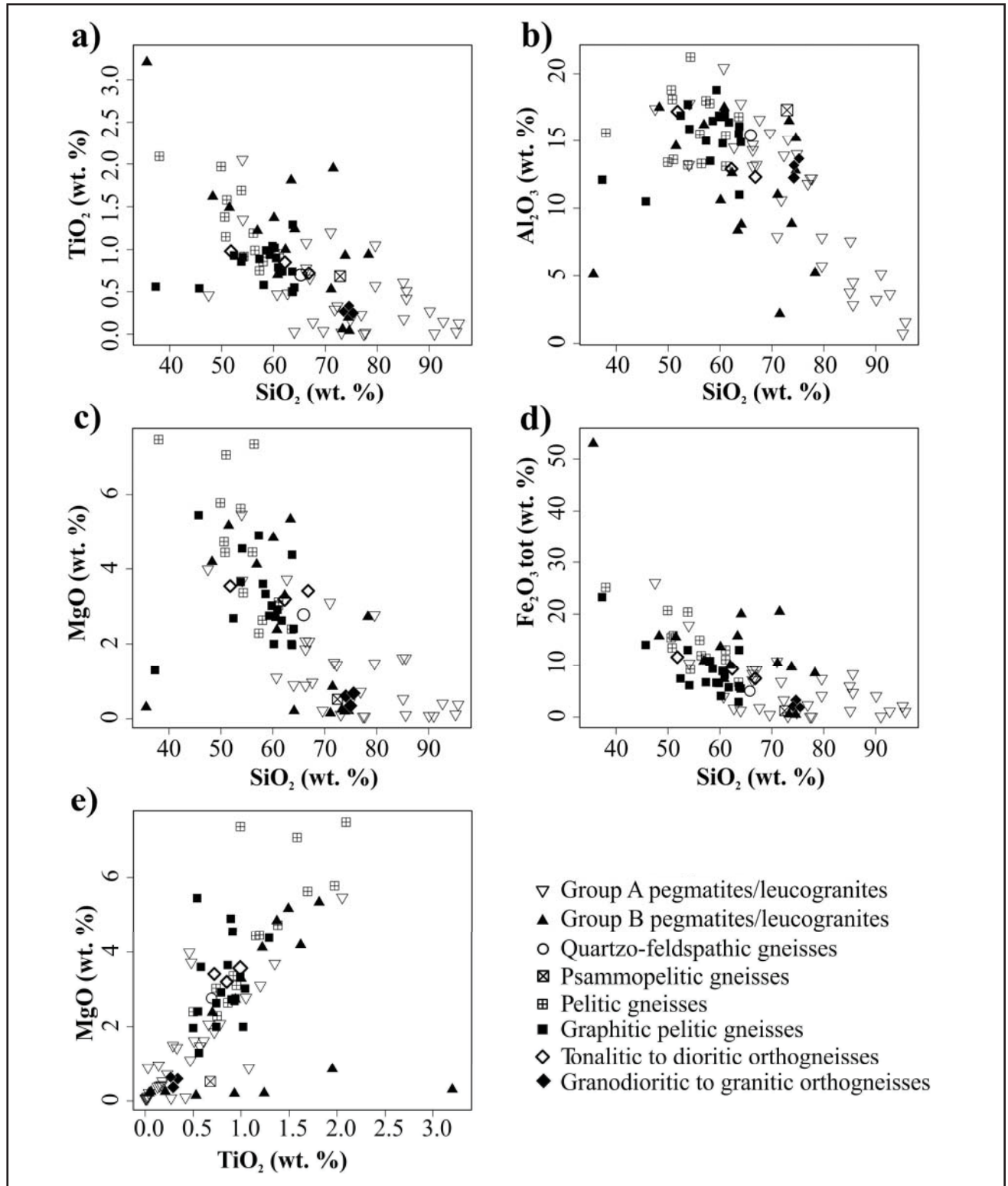


Figure 8. Major-element Harker diagrams for granitic pegmatites and leucogranites, pelitic gneiss, and orthogneiss. **a)** TiO_2 vs SiO_2 , **b)** Al_2O_3 vs SiO_2 , **c)** MgO vs SiO_2 , **d)** Fe_2O_3 tot vs SiO_2 , and **e)** MgO vs TiO_2 . The major-element compositions of Group A and Group B pegmatites show some overlap with those of the pelitic gneiss and orthogneisses, suggesting a possible compositional influence (i.e., the pegmatites possibly formed from melting of similar rocks and/or assimilation of host rocks). Group A pegmatites define weak trends towards higher SiO_2 contents with decreasing TiO_2 , Al_2O_3 , MgO , and Fe_2O_3 , suggesting they formed from more evolved melts. Group B pegmatites show compositions more similar to the pelitic gneiss; they could represent more primitive melts or restitic melts, or may reflect more assimilation of the host rocks. See text for details.

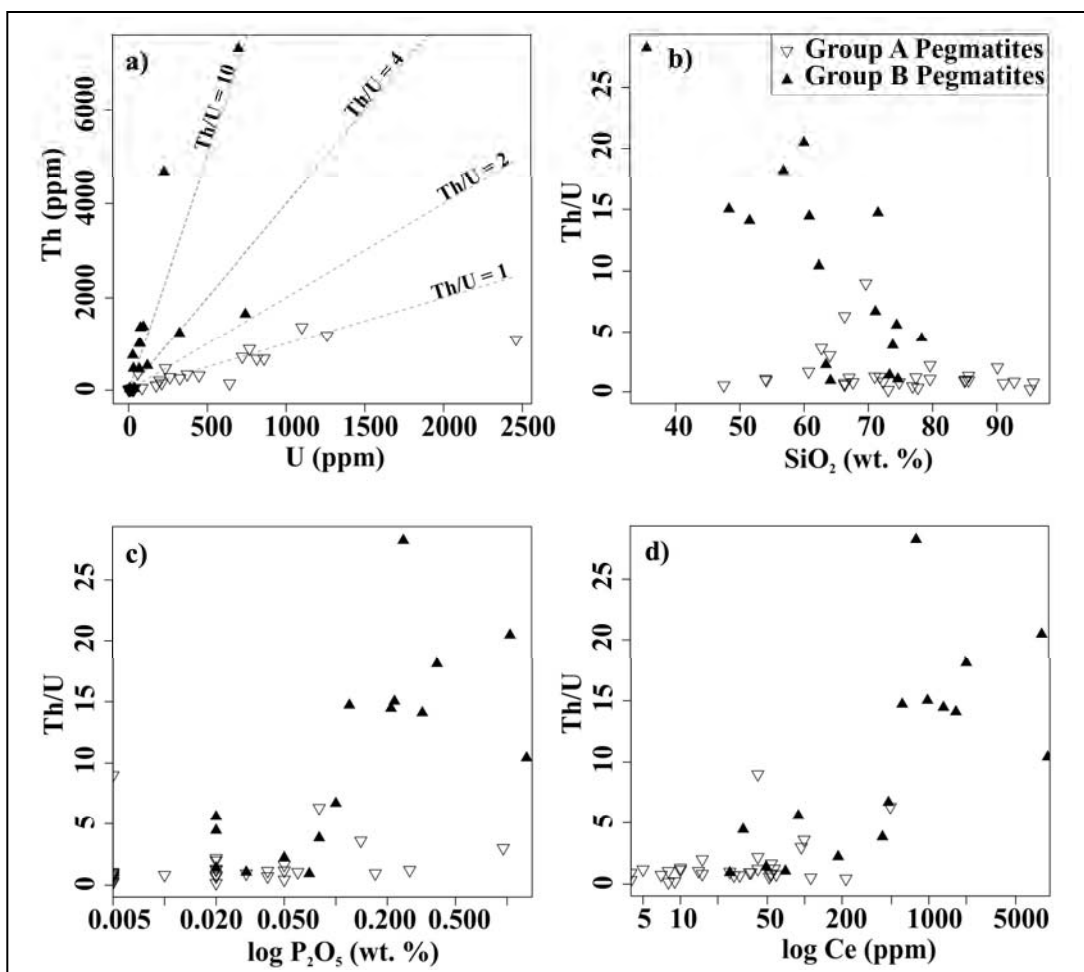


Figure 9. Trace-element diagrams for the Fraser Lakes Zone B granitic pegmatites. **a)** Th vs. U, in which the diagonal lines show different Th:U ratios. The Group A pegmatites have Th/U ~1, and the Group B pegmatites generally have Th/U >2. **b)** Th/U vs. SiO₂, which shows that the Group A pegmatites generally have higher SiO₂ contents than do the Group B pegmatites, with some overlap between the two groups. **c)** Th/U vs. P₂O₅ to emphasize the importance of monazite in the Group B pegmatites. **d)** Th/U vs. log Ce, emphasizing the high LREE content of the Group B pegmatites, especially those high in Th, which in turn reflects their monazite content.

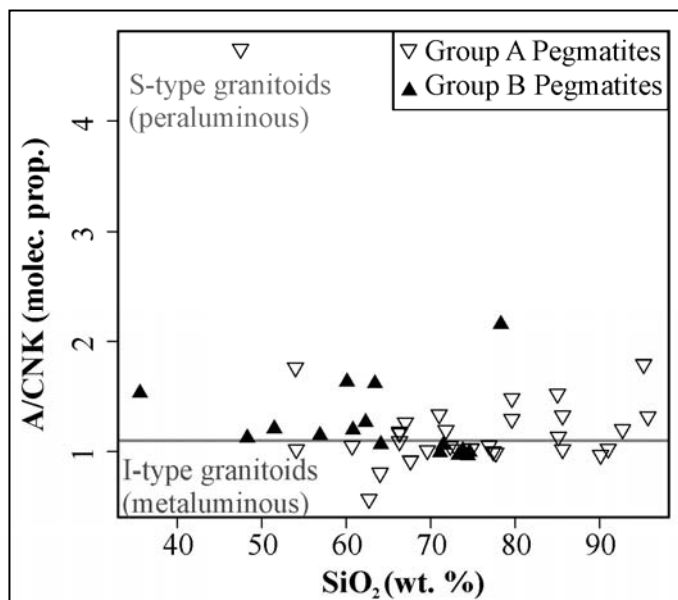


Figure 10 (to left). A/CNK vs. SiO₂ diagram (Chappell and White, 1974), showing that the granitic pegmatites have A/CNK values similar to those of S-type granitoids with some overlap into the I-type granitoid field. $A/CNK = Al_2O_3 / (CaO + Na_2O + K_2O)$.

>0.20 wt. % F) and up to 0.40 wt. % Cl. Zirconium ranges markedly in Group A intrusions (249–4060 ppm) and in Group B intrusions (64–11,700 ppm), depending on the modal proportion of zircon. The concentrations of Be (<6 ppm) and Li (<54 ppm) are low for both groups of intrusions (Table 3, SDT).

The total REE contents in Group A intrusions tend to be lower (~35–500 ppm) than in Group B intrusions (~1000–19,000 ppm) (Fig. 11a, 11b, Table 3, SDT). Chondrite-normalized patterns of Group A intrusions (Fig. 11a) have flatter and more complex patterns than Group B intrusions (Fig. 11b). Group B intrusions are LREE-enriched (Fig. 11b), with La_n/Yb_n values up to 200 and significant negative Eu anomalies.

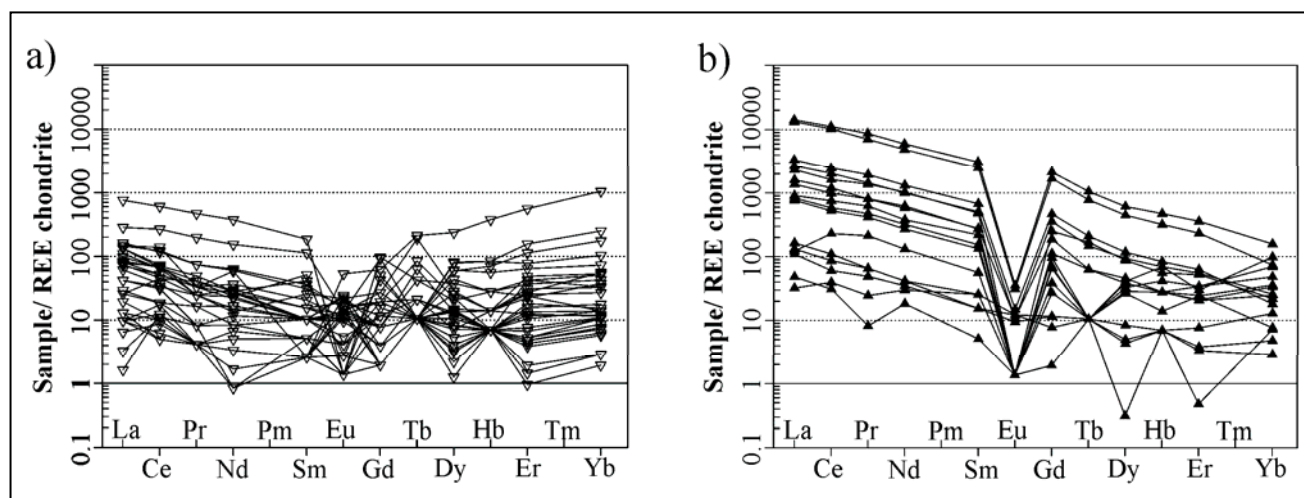


Figure 11. Chondrite-normalized (Boynnton, 1984) REE plots for the ‘radioactive’ granitic pegmatites, showing the differences between **a)** Group A, and **b)** Group B granitic pegmatites and leucogranites.

Discussion

Classification of Granitic Pegmatites and Leucogranites

The granitic pegmatites and leucogranites at Fraser Lakes are generally subcordant to lithological and structural contacts of their metamorphosed and locally migmatitic host rocks. These intrusions are aligned subparallel to the dominant fabric in the upper amphibolite to lower granulite facies metamorphic rocks (Fig. 3a, 3b, 5a). The presence of migmatite indicates that rocks in the area attained conditions suitable for melts to form and suggests that the intrusions were formed by partial melting.

On the basis of U-Th-Pb dating of uraninite (Annesley et al., 2010b), Group A intrusions are interpreted to have crystallized in their present position ca. 1810–1775 Ma, a time interval similar to that interpreted for other uranium-enriched granitic pegmatites in the Wollaston Domain (Annesley et al., 2000; Mercadier et al., 2010). No granitic plutons of this age are known in the Wollaston Domain, especially in the vicinity of Fraser Lakes Zone B. The similarities in intrusive contacts suggests that Group B rocks were intruded at roughly the same time as Group A rocks, however, reliable primary magmatic ages for these intrusions have not yet been obtained.

The metamorphic grade of the host rocks, structural relationships (concordant to subcordant contacts), and lack of any relationship to coeval granitic rocks all suggest that the Fraser Lakes pegmatites/leucogranites can be classified as Abyssal-class pegmatites (Černý and Ercit, 2005). Group A pegmatites/leucogranites at Fraser Lakes contain abundant zircon and uraninite (Table 2) and have the highest U concentrations. These Group A intrusions are assigned to the U-subclass of Abyssal pegmatites of Černý and Ercit (2005), whereas the LREE-enriched pegmatites/leucogranites of Group B intrusions that contain ubiquitous monazite (Table 2) are assigned to the LREE subclass.

The lack of contemporaneous granitic plutons suggests that the Fraser Lakes pegmatites were derived by melting

during peak thermal metamorphism along an essentially isothermal decompression path. Mechanisms driving partial melting may have included (but are not limited to) isothermal decompression, large amounts of high heat-producing elements in the crust (in particular U and Th in the Fraser Lakes area), shear heating, thinning of the mantle lithosphere, and a high crustal geothermal gradient (Nabelek and Liu, 2004).

The Fraser Lakes pegmatites are interpreted to be the same age and/or younger than the leucosomes (generated by in situ melting and crystallization) in the immediate host rocks. However, the large size of the pegmatite bodies indicates that they were generated ‘off-site’ at depth as anatectic melts, which migrated to and crystallized at their present location. The geochemical and mineralogical characteristics of these pegmatites are thus a function of the composition of the source rock, the nature of melt reactions, and the assimilation and fractional crystallization processes that might have operated during melt migration and/or final solidification.

Petrological and Geochemical Constraints

The Fraser Lakes pegmatites are peraluminous to slightly metaluminous S-type to marginally metaluminous I-type granitoids (Fig. 10), implying that the source area where partial melting occurred was dominated by sedimentary rocks. This was also suggested by previous studies of leucogranites and granitic pegmatites in the Wollaston Domain (Annesley et al., 2000, 2005). The overlapping compositions of pelitic gneiss, orthogneiss, and pegmatite (Fig. 8a–e) suggest that the pegmatites are compositionally related to their host rocks, especially the pelitic gneisses, and that they may be derived by partial melting of such rocks, or that the melt may have assimilated rocks of a similar composition. The ranges in major- and trace- element compositions of the pelitic gneisses (Fig. 8a–e, 9a–d) reflect the wide range of original bulk compositions, which makes modeling of melting or assimilation processes difficult.

Table 3. Representative whole-rock, major- and trace-element geochemical analyses of pegmatites and gneissic host rocks (cont'd on next page).

Sample No.	WYL-09 -50-237	WYL-09 -50-252.7	WA-08-0 -0046	WYL-10 -62-68.9	WYL-09 -50-37.5	WYL-10 -62-87.1	WYL-09 -49-36.1	WYL-10 -61-190.3	WYL-10 -62-93.5	WYL-09 -46-31.1	WYL-09 -46-32.6
Lithology	Dioritic orthogneiss	Granitic orthogneiss	Tonalitic orthogneiss	Pelitic gneiss (Crd-Sil-Grt)	Pelitic gneiss (Grt-Crd-Sil-Spn-Grt)	Pelitic gneiss (Grt-Crd)	Pelitic gneiss (Grt-Sil)	Group A Pegmatite/Leucogranite	Group A Pegmatite/Leucogranite	Group B Pegmatite/Leucogranite	Group B Pegmatite/Leucogranite
SiO ₂	51.80	74.80	62.20	63.60	59.30	51.00	58.00	85.60	71.00	62.30	56.90
TiO ₂	0.98	0.25	0.85	0.74	0.94	1.58	0.86	0.42	1.20	1.00	1.22
Al ₂ O ₃	17.20	13.50	12.90	15.50	18.80	13.60	17.80	2.83	7.89	12.60	16.20
Fe ₂ O ₃ ^{tot}	11.60	1.70	9.52	2.92	6.64	15.80	10.80	8.36	10.80	10.00	10.80
MnO	0.14	0.04	0.16	0.08	0.03	0.17	0.22	0.04	0.08	0.12	0.13
MgO	3.54	0.60	3.20	2.00	2.76	7.05	2.64	0.10	3.10	3.29	4.12
CaO	8.62	1.08	6.79	1.08	1.28	2.40	1.03	0.47	0.28	1.30	1.80
Na ₂ O	4.48	4.70	2.86	3.46	3.70	1.57	1.79	0.99	0.57	2.74	3.81
K ₂ O	1.72	3.80	1.11	5.08	4.78	4.64	5.49	0.27	4.12	2.84	4.21
P ₂ O ₅	0.23	0.01	0.17	0.07	0.07	0.22	0.13	0.03	0.02	1.30	0.39
LOI	0.20	0.30	0.60	5.90	1.70	2.20	0.80	0.30	0.80	2.50	1.10
SUM	100.51	100.77	99.98	100.37	100.00	100.15	99.56	99.38	99.84	99.99	100.68
C%	0.01	0.12	0.08	3.95	0.33	6.09	0.06	0.11	0.04	0.07	0.03
S%	0.01	0.01	0.02	0.99	0.01	15.60	0.04	0.01	0.17	0.08	0.01
F%	-	-	0.16	0.12	-	0.34	-	0.09	0.42	0.20	0.34
Cl%	-	-	0.08	0.01	-	0.09	-	0.02	0.14	0.10	0.10
B	6	6	4	55	10	7	10	15	4	37	10
Br	-	-	1	16	-	1	-	14	1	5	5
Sc	24	2	28	17	21	38	28	4	14	26	20
V	192	16	244	132	134	328	133	32	91	156	201
Cr	4	7	137	80	89	264	120	16	72	49	33
Co	40	1	28	18	15	47	40	2	23	23	32
Ni	26	3	75	72	41	130	52	4	79	59	55
Cu	1	1	53	97	38	55	4	7	57	157	1
Zn	95	25	127	61	39	353	82	85	483	128	321
Cs	-	-	3	6	-	18	-	3	18	3	12
Rb	61	153	18	208	139	435	280	12	402	334	643
Sr	300	43	187	75	186	82	68	18	27	174	65
Ba	173	394	144	783	1160	660	1390	32	435	263	331
Nb	1	13	2	10	14	38	14	13	141	174	166
Zr	99	422	121	203	215	258	200	3090	2210	2700	64
Hf	2	9	1	4	5	6	3	95	76	89	1

Table 3 (cont'd). Representative whole-rock, major- and trace-element geochemical analyses of pegmatites and gneissic host rocks.

Sample No.	WYL-09 -50-237	WYL-09 -50-252.7	WA-08-0 -0046	WYL-10 -62-68.9	WYL-09 -50-37.5	WYL-10 -62-87.1	WYL-09 -49-36.1	WYL-10 -61-190.3	WYL-10 -62-93.5	WYL-09 -46-31.1	WYL-09 -46-32.6
Y	21	30	20	28	38	47	45	149	92	1190	228
La	27	61	18	65	74	131	55	8	24	4410	1040
Ce	48	107	31	105	137	279	149	36	57	9050	2000
Pr	3	11	2	12	12	30	11	5	6	1060	238
Nd	25	39	17	44	52	126	39	14	17	3590	796
Sm	5	6	3	7	8	21	6	10	8	607	132
Eu	3	1	1	1	2	1	2	0	0	3	1
Gd	3	5	2	4	6	14	7	13	11	553	121
Tb	1	1	1	1	1	1	1	1	1	50	10
Dy	3	5	4	3	5	8	6	20	14	197	38
Ho	1	1	1	1	1	1	1	4	2	34	6
Er	2	3	2	1	4	3	3	13	9	75	13
Yb	3	3	3	1	3	3	4	15	11	33	4
Pb	13	11	22	30	11	38	24	324	709	559	153
Th	2	23	1	21	17	410	23	1190	1370	7310	1360
U	1	8	5	11	4	44	4	1260	1100	701	75
Li	15	23	9	45	74	89	34	10	66	54	53
Be	1	4	1	2	2	2	1	1	0	6	5
Ga	23	21	18	22	30	30	21	26	27	12	28
As	-	-	13	16	-	12	-	23	21	6	6
Mo	1	1	1	8	1	50	3	1	1	144	9
Ag	0	0	1	1	0	0	0	13	13	0	0
Cd	1	1	2	2	1	2	1	1	1	1	1
Ta	1	1	1	1	1	1	1	1	3	12	9
Bi	-	-	1	1	-	1	-	13	1	3	3
Sb	-	-	1	1	-	1	-	1	1	1	1
Se	-	-	39	1	-	42	-	1	27	5	44
Sn	1	12	1	1	1	1	1	9	3	13	10
W	1	1	1	10	1	1	1	1	1	1	1
Th/U	2.0	2.9	0.1	1.9	4.3	9.3	5.8	0.9	1.2	10.4	18.1
Eu/Eu*	2.7	0.4	1.4	0.7	1.1	0.1	0.8	0.0	0.1	0.0	0.0
Lan/Ybn	7.3	13.7	4.7	31.3	14.7	27.6	10.6	0.4	1.5	89.8	184.5
Sum REE	124	242	83	245	305	618	283	139	159	19662	4399
A/NK	1.86	1.14	2.18	n/a	n/a	n/a	n/a	1.47	1.46	1.66	1.50
A/CNK	0.69	0.98	0.71	n/a	n/a	n/a	n/a	1.02	1.34	1.27	1.15

Notes: n/a = not applicable; - = not analyzed.

As the actual source rock for the granitic pegmatites is unknown, we assume that conditions during the partial melting of the Fraser Lakes pelitic gneisses and the formation of the migmatites were equivalent to those leading to the formation of the Fraser Lakes granitic pegmatites/leucogranites. Annesley et al. (2005) determined that partial melting of pelitic gneisses in the Wollaston Domain occurred at ca. 1815 Ma by fluid-absent melting at temperatures of up to 850°C and pressures of up to 9 kbar. The rocks then underwent essentially isothermal decompression over the next 20–35 Ma, during which time the rocks remained within the appropriate conditions for partial melting, by biotite-dehydration reactions, until pressures decreased to ~4–5 kbar. Migmatite development was coeval with peak thermal metamorphism in the Fraser Lakes area. The migmatites at higher levels were intruded by pegmatitic melts that were being continually generated at greater depths in the crust.

The crystallization conditions of the Fraser Lakes pegmatites may be recorded by the metamorphic mineral assemblages of their host rocks, which are indicative of upper amphibolite to granulite facies metamorphism (Fig. 5a–f). Group A and Group B intrusions are not pure anatectic melts (e.g., Patiño Douce, 1999), because they contain varied amounts of peritectic minerals such as garnet, zircon, biotite, and monazite, some of which were entrained as xenocrysts from the source rocks. These assemblages indicate that the granitic pegmatites were emplaced at mid-crustal depths (15–20 km). After generation, the melts likely evolved due to changing pressure, temperature, or volatile content.

Weakly defined trends and clusters of analyses on Harker major-element variation diagrams (Fig. 8a–f) could be explained by varied degrees of partial melting and amounts of crystal fractionation, causing differences in modal mineralogy. For example, the depletion in Al_2O_3 , CaO , and K_2O of the most siliceous pegmatites (Fig. 8b, Table 3) is consistent with the fractionation of plagioclase and alkali feldspar; and the decrease in Fe_2O_3 , MgO , and TiO_2 with increasing SiO_2 implies fractionation of biotite. Crystal fractionation of the major minerals (Table 2) is important as the pegmatites are commonly zoned (Fig. 5a), with quartz-rich and plagioclase-rich internal zones and K-feldspar-rich margins. In addition, some zones are preferentially enriched in biotite (Fig. 6a, 7c).

The gneissic rocks in the Fraser Lakes area are enriched in U, Th, and Zr relative to the NASC, as would be expected for graphite-bearing rocks, and thus they could generate melts enriched in these elements. Bea (1996) emphasized the importance of accessory minerals as the reservoir of REE, U, and Th in metamorphic rocks but also reported that large volumes of the accessory phases occur as inclusions in biotite. Thus, the concentrations of REE, U, and Th in any melt may depend on the efficiency of the reactions that lead to the breakdown of biotite and which can release accessory minerals into the melt.

Annesley et al. (2005) emphasize that biotite-dehydration reactions are important in the generation of migmatites in the Wollaston Lake area (e.g., Pow Peninsula, McClean Lake, among others). The U-Th-REE-bearing accessory

minerals within source rock biotites would not be liberated during early melt-generating reactions that did not involve biotite dehydration. This lack of liberation would enrich the remaining source rocks in these elements and in turn would increase the likelihood that late melts would be enriched in U-Th-REE (see Nabelek and Liu, 2008; Villaros et al., 2009; and Brown, 2010 and references therein).

Evidence for biotite-dehydration reactions, in the form of melt textures (Fig. 5e) and the metamorphic assemblages, is visible in the pelitic gneisses of the Fraser Lakes area. Accessory minerals in the granitic pegmatites, in particular zircon and monazite, are commonly found in clusters (Fig. 6c, 6e, 7d) rather than uniformly distributed. In addition, many zircons in the pegmatites appear to have cores (Fig. 6c) that are inherited.

Thus, the textural relationships suggest that some accessory minerals were entrained as xenocrysts in the melt at the source and then transported within the melt to the region of final crystallization. However, zircons are present in the pegmatites/leucogranites that have overgrowths with typical magmatic zoning, suggesting that Zr was also available in the melt. The uraninite grains in Group A intrusions also show primary igneous characteristics. Thus, it is likely that the U-Th-REE-bearing minerals formed due to a combination of inheritance (from the source rock and/or assimilation of host rocks) and igneous fractionation and crystallization processes.

The spatial association between zircon, monazite, and biotite suggests that these minerals share a common evolution during the formation of the granitic pegmatites/leucogranites. This implies that these minerals would have been incorporated into the melt to a similar extent if partial melting and entrainment processes dominated or, alternatively, that they would have been fractionated from the melt to a similar extent if crystal-liquid fractionation processes dominated.

Overall, the large-scale zoning, observed geochemical variations, and character of the U-Th-REE-Zr-bearing accessory minerals all suggest that these pegmatites represent a combination of processes: that is, partial melting of an enriched pelitic gneiss source; entrainment of accessory phases (inherited from the magma source and assimilated during transport) in the resultant peraluminous magma; fractionation of the melt with respect to U, Th, REEs, and Zr; and the growth of U, Th, REE, and Zr-bearing minerals from the melt.

Zr and REE contents in zircon and monazite have been used to calculate crystallization temperatures, under the assumption that they represent the saturation temperatures of those minerals. Petrological studies have shown that the temperature estimates are relatively close to the temperature of segregated melts, provided the accessory phases grew from the melt and were not inherited (Watson and Harrison, 1983; Montel, 1993; Miller et al., 2003). Calculated temperature estimates for the Fraser Lakes granitic pegmatites range between 825°C and 700°C. The highest temperature of 825°C is close to the estimate for peak thermal metamorphism in the Wollaston Domain (Annesley et

al., 2005), and the range indicates that the melt potentially cooled and crystallized during transport and emplacement, if the temperatures were derived from magmatic crystals.

The decrease in Zr, Th, and LREE with increasing SiO₂ (see SDT) in the granitic pegmatites probably reflects the growth and fractionation of zircon and monazite from the melt due to decreasing solubility of these phases, given that Zr and REE occur mainly in these accessory minerals; thus, not all of the zircon and monazite in these pegmatites was inherited. This also implies that some uraninite probably crystallized after zircon and monazite formation from the most fractionated melts, which would have had the highest SiO₂ contents.

Role of Deformation

Annesley et al. (2010c) recently suggested that the identification of target areas with major structures and accumulation of peraluminous S-type granites within the basal metasedimentary rocks of the Wollaston Group can be used as an exploration tool for predicting the potential location of unconformity-type uranium deposits in the eastern Athabasca Basin. They outlined five key criteria for identifying these areas: a) structurally complex zones with a history of, and evidence for, reactivations, b) multiple sets of faults with various orientations, c) a higher than normal volume of S-type granite, d) migmatitic metasedimentary rocks (in part graphitic) near the base of the Wollaston Group, and e) an inlier of Archean rocks (antiformal core or ridge) in close proximity to the base of the Wollaston Group. All five conditions apply at Fraser Lakes Zone B, which raises the following questions.

- What is the relationship between deformation and S-type granites?
- What relationships exist between or among the mineralized granitic pegmatites and the host pelitic gneisses?
- What is the role of deformation in magma extraction, migration, differentiation, and emplacement of the granitic pegmatites and associated leucogranites?
- What is the role of the folded and sheared Archean–Paleoproterozoic contact (i.e., the tectonized discontinuity or décollement)?

Opinions differ on the cause and effect of strain localization in melt-bearing continental crust, and on how magma is transferred from the source region to the sink region (Ward et al., 2008; Weinberg and Mark, 2008; Brown, 2010). In the last fifteen years, however, researchers have reconciled this by considering that deformation and melts interact in a positive feedback loop (see Brown, 2010, and references therein). Still, different processes are ascribed to explain the positive feedback loop (e.g., Kisters et al., 1998; Brown and Solar, 1999; Handy et al., 2001; Solar and Brown, 2001; Brown, 2010). According to others in-

cluding Weinberg (1999), Weinberg and Mark (2008), and Kisters et al. (2009), the geometry of the magma network in the source region provides the ultimate control on the transfer process.

At Fraser Lakes, we observed fertile, radioelement-enriched pelitic to psammopelitic rocks in both outcrop and drill core that have undergone syn-kinematic melting and subsequent crystal fractionation at upper amphibolite to granulite facies conditions in the presence of a volatile H₂O-F-rich phase. We also observed veinlets, dikes, and sheets of granitic pegmatites up to tens of meters wide, which are located along a folded, sheared Archean–Paleoproterozoic discontinuity that marks an inferred transfer zone of magma from deeper crustal levels.

Similarly to Weinberg and Mark (2008), we see the following important structural indicators of the sense of melt migration within the rocks (upward): 1) development of a cauliflower-shaped upper contact with host rocks, 2) preferential segregation into fold hinge zones, and 3) development of cusped fold hinges with destruction of synformal features.

We also see on a large scale the preferential movement of high volumes of melt into antiformal structures, similar to what is observed within the area of the Rössing uranium deposit (Nex et al., 2001; Basson and Greenway, 2004). It appears that folding of the rocks led to pressure gradients, causing melt to migrate preferentially along ductile, high-temperature layers and parallel to the axial plane of the folds. In addition, melt migration may have led to attenuation of the folding, in turn causing disaggregation of the rocks with a preferential destruction of synformal structures (see Weinberg and Mark, 2008, their Fig. 3, 4, 13).

Summary of Model

The granitic pegmatites at Fraser Lakes Zone B are interpreted to be lower to middle crustal melts that were derived from a crustal source similar to the migmatitic metasedimentary gneiss units cropping out in the immediate Fraser Lakes area and the nearby Walker River area (Annesley et al., 2009). This interpretation implies crustal thickening and associated overthrusting at Fraser Lakes along a clockwise P-T-t path with large-scale structures facilitating crustal melt transfer, as proposed by Weinberg and Mark (2008).

The peak metamorphic mineral assemblages of these metasedimentary rocks on petrogenetic grids yield P-T estimates similar to those reported from other parts of the Wollaston Domain, in which maximum P-T conditions (i.e., peak thermal metamorphism) reached 6–9 kbar and 800–850°C (Annesley et al., 2005) at ca. 1815 Ma (Annesley et al., 1997, 2005; Tran, 2001). Considering an elevated gradient of ~30–40°C/km, partial melting may have occurred at a depth of approximately 20–30 km, which is consistent with previous estimates made by Annesley et al. (2005) for melting in the Wollaston Domain.

The model presented here has many similarities to models proposed for the formation and evolution of leucogranites in the Paleoproterozoic Svecofennian Orogen of Sweden, Finland, and western Russia, in particular, the ur-

anum potential of late orogenic potassic granites (Lauri et al., 2007; Cuney et al., 2008; Skyttä and Mänttari, 2008; Kukkonen and Lauri, 2009; Kurhila et al., 2011).

Metasedimentary migmatites exposed in the Fraser Lakes area are cross-cut by numerous vertical to subvertical granitic pegmatite and leucogranite bodies that could represent transfer zones for melts from a deeper partial melting zone. (It is assumed that accumulation of relatively low-density melts triggered vertical migration through the crust.) Continuous deformation within and along major structural zones, including large-scale folds, is believed to have helped crustal melt ascent by creating alternative zones of dilation and compression within the anastomosing shear/fault zone system of the Wollaston fold-and-thrust belt. This led to the expulsion of crustal melts to upper crustal levels. At Fraser Lakes, we envisage the exposed high-grade migmatitic terrane as being the former mid-crustal melt transfer zone between the deeper crustal source region and the middle to upper crustal sink region.

An important assumption in this paper is that the sources of the granitic pegmatites and leucosomes were partially melted pelitic to psammopelitic rocks of the Wollaston Group near and below their observed emplacement depth. However, it is also possible that a different melt source (or several sources) exists below and that the similarities in composition of the granitic pegmatites/leucogranites to that of their host rocks is due to assimilation only.

Emplacement of the granitic pegmatites in the middle crust in relation to the large-, kilometer-scale folds and associated shear zones (Fig. 12, 13) demonstrates the potential role of deformation in magmatic evolution. Mineral fractionation in magmas en route to the surface is likely enhanced by regional deformation, especially in the case of highly silicic mushes that are more readily affected by stress, so that liquids (melts) may be expelled from the rigid framework once the Rigid Percolation Threshold (RPT; Vigneresse et al., 1996) has been reached. This explains the extreme heterogeneity of Group A and Group B intrusions and indicates that Group B intrusions are still fairly close to their source area.

After reaching the RPT, the deformation and tectonic stress processes start to facilitate the discontinuous squeezing of residual liquids upward along the structural and metamorphic fabric toward the surface (i.e., smaller amounts of melt, as proposed by Bons et al., 2004). These same deformation and tectonic stress processes would also push the melt away from the limbs of the fold toward the fold nose area where they are emplaced; that is, melt migration would occur perpendicular to the fold axis and parallel to the stretching axis (see Weinberg and Mark, 2008).

Such a scenario implies that melt migration enhanced folding. Consequently, the Fraser Lakes granitic pegmatites may have crystallized from different pulses and compositions of crustal anatectic melts that experienced contrasting crystal–liquid fractionation, thus explaining their heterogeneous nature.

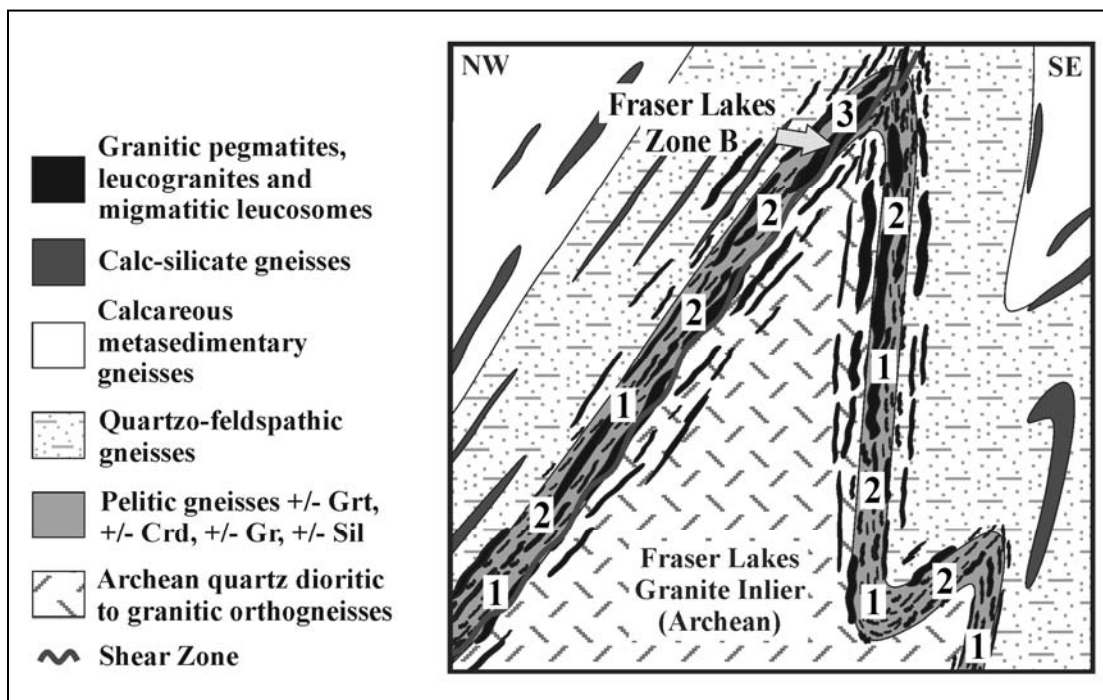


Figure 12. Schematic vertical cross-section (vertical scale is ~1 km) depicting the different levels of migmatization, transport, and emplacement of pegmatitic melts in the Fraser Lakes Zone B area. (See Fig. 2 for approximate location of Zone B in the report area.) Plunge of the antiformal fold noses is ~25–30°NE. **1)** Partial melting at depth/in situ of U-Th-REE-enriched metasedimentary rocks (Wollaston Group) during peak thermal metamorphism by biotite dehydration melting. **2)** Transport of melt upwards and laterally along ductile shear zones and parallel to gneissosity; during transport, the melt undergoes fractionation, becoming further enriched in U-Th-REE. **3)** Concentration of melt in fold noses, where it crystallizes to form pegmatites; during crystallization, the melt undergoes igneous assimilation–fractional crystallization processes.

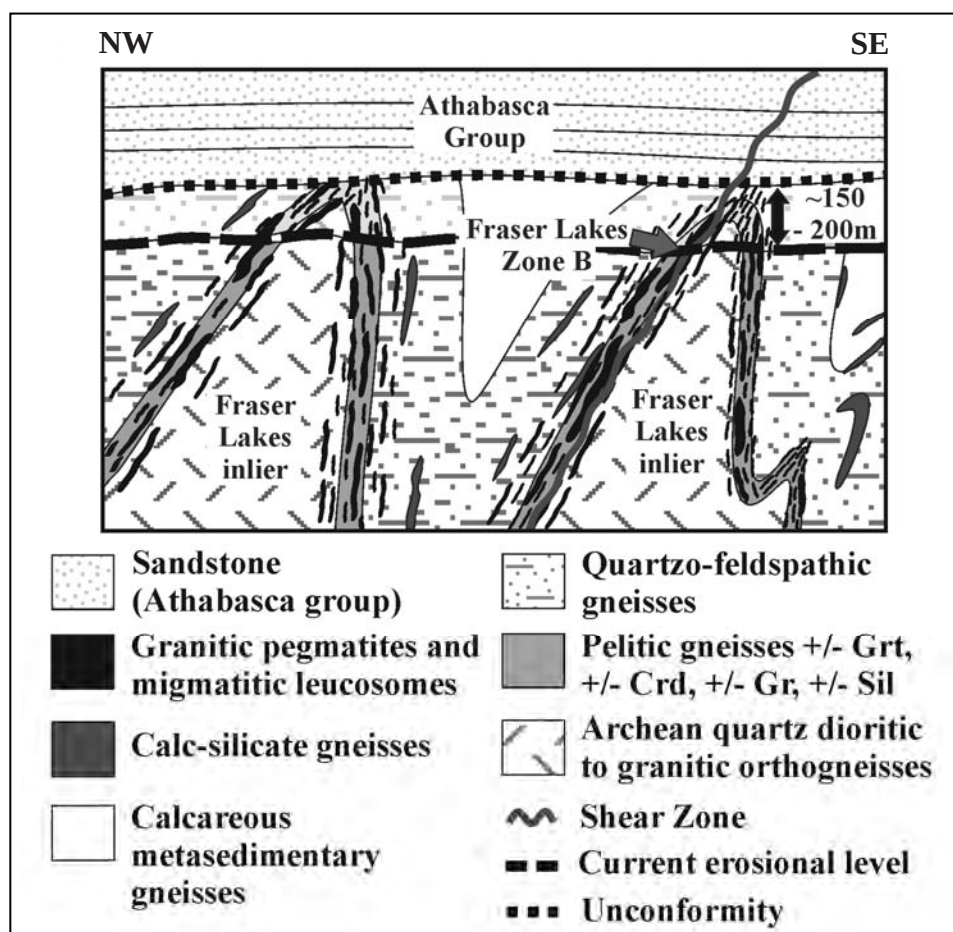


Figure 13. Idealized vertical cross-section of Fraser Lakes Zone B area prior to complete erosion of the overlying Athabasca group sedimentary rocks and ~150–200 m of basement rocks below the unconformity (Annesley et al., 2009). The thickness of basement eroded is estimated by eastward extrapolation of the sub-Athabasca Group unconformity slope to the Fraser Lakes area. Vertical scale is ~1 km. Antiformal fold noses plunge ~25–30°NE, as on Figure 12.

Link to Unconformity-Related Uranium Deposits

Unconformity-related uranium deposits are among the highest grade uranium deposits in the world, with grades of up to 18.3% U_3O_8 (Cigar Lake Deposit; Cameco, 2012) in the Athabasca Basin of northern Saskatchewan (Fig. 1). Typically, they are located along fault zones rooted in the underlying basement rocks that extend into overlying sandstones of the Athabasca Group. They result from the interaction between oxidizing fluids that transport uranium with either graphitic or ‘reduced’ rock types, or reduced fluids (Hoeve and Sibbald, 1978; Jefferson et al., 2007).

One of the still-debated questions concerning the origin of unconformity-related uranium deposits is the source of the uranium. Kotzer and Kyser (1995), for example, consider that oxidized fluids leached the uranium from detrital minerals in the sandstone. Such fluids then interacted with basement rocks to generate mineralization and alteration (Alexandre et al., 2005; Cloutier et al., 2009).

In contrast, Hecht and Cuney (2000) and Madore et al. (2000) suggest that oxidized basinal fluids interacted with basement rocks and obtained uranium from accessory minerals, such as monazite and uraninite. Pegmatites are im-

portant in this regard, as they may 1) have interacted with fluids that led to the in situ alteration of uranium-bearing accessory minerals, 2) have been a component of the regolith underlying the basin, the uranium having been remobilized during weathering and/or by fluids moving through the regolith, and/or 3) represent the source of uranium-bearing detrital minerals in the Athabasca Basin sedimentary rocks, the uranium having been remobilized later by fluids moving through the sandstone.

Several unconformity-related uranium deposits in the Athabasca Basin, including McArthur River, P-Patch, and Moore Lakes, contain uraniferous pegmatites in the basement underlying the deposits (Annesley et al., 2000, 2005). In many cases, these pegmatites have been altered to minerals similar to the alteration assemblages associated with the unconformity uranium deposits.

Annesley and Madore (1999), Hecht and Cuney (2000), and Madore et al. (2000), among others, suggest that monazite in the basement rocks and/or regolith were altered by hydrothermal fluids (the same fluids responsible for the unconformity-related mineralization) to different minerals including Th-silicates (thorite or huttonite?), chlorite, and

poorly crystalline, hydrous, Si-bearing Ca-Th phosphates (Hecht and Cuney, 2000). This alteration would have led to uranium redistribution and leaching, with the thorium remaining in the monazite alteration products due its lower solubility (Hecht and Cuney, 2000).

Calculations by Madore et al. (2000) using monazite (not taking into account uraninite, which is also easily altered by oxidizing fluids) suggest that large amounts of uranium may have been remobilized from monazite within the pegmatites/leucogranites, and may have provided a large amount of the uranium necessary for unconformity-related uranium deposits of the Athabasca Basin.

In the Fraser Lakes granitic pegmatites, especially in the highly fractured Th-rich varieties, there is evidence for low-T hydrothermal alteration in the form of moderately to strongly altered feldspars, biotite, thorite, allanite, uraninite, and monazite (Fig. 6e, 6f, 7a–c). Monazite in particular shows alteration to chlorite, hematite, and clay minerals (Fig. 7a–c), an assemblage with similarities to monazite alteration products related to uranium remobilization in the Athabasca Basin (Hecht and Cuney, 2000).

Thus, hydrothermal fluids may have passed through the rocks leading to remobilization of uranium from monazite in the Group B intrusions, similar to the model proposed by Annesley and Madore (1999), Hecht and Cuney (2000), and Madore et al. (2000) for uranium remobilization from monazites in the sandstones of the Athabasca Group and underlying regolith and/or basement.

In addition, the fluids responsible for altering the intrusions may have leached uranium from uraninite and thorite (including U-enriched thorite) from the Fraser Lakes Zone B pegmatites/leucogranites. Thus, the possibility exists that significant amounts of uranium may have been remobilized from these intrusions by the same fluids that altered the rocks.

As indicated earlier, the presence of radioelement-enriched pegmatites spatially associated with structures in this area may suggest increased potential for the discovery of unconformity-related uranium deposits in the Fraser Lakes area. This type of redox boundary is important for later geochemical reactions during reactivation of pre-existing basement structures at or near the Wollaston–Archean unconformity, ultimately leading to mineralization as the redox change at the boundary could cause a decrease in uranium solubility in the mineralizing fluids.

The most likely source of the low-T (<250°C) fluids responsible for the alteration assemblages at Fraser Lakes Zone B are the highly oxidizing, acidic basinal brines in the Athabasca Basin (Mercadier et al., 2010; Richard et al., 2010, 2011, 2012). These basinal fluids may have been efficiently circulated downward in fractures, where they altered the pegmatites/leucogranites at Fraser Lakes Zone B, analogous to the process proposed recently by Mercadier et al. (2010).

Strongly clay-altered pelitic gneisses with a clay mineral assemblage similar to that of unconformity uranium deposits occur within an interpreted fault zone northwest of the Fraser Lakes Zone B area (Annesley et al., 2010a; JNR

Resources, 2012). These gneisses offer further evidence that fluids similar to those responsible for the Athabasca Basin unconformity-related uranium passed through the Fraser Lakes Zone B area. The fluids may have remobilized uranium from the Fraser Lakes Zone B granitic pegmatites/leucogranites, ultimately leading to the formation of an as yet undiscovered, basement-hosted, unconformity-related uranium deposit near Fraser Lakes Zone B.

Conclusions

The U-Th-REE mineralization at Fraser Lakes Zone B consists of primary magmatic mineralization in granitic pegmatites, which is overprinted locally by later hydrothermal alteration. The pegmatites were emplaced into the highly deformed contact zone between Archean orthogneiss and metasedimentary rocks of the Wollaston Group, specifically within a regional fold nose.

The pegmatites in the central part of the fold nose are enriched in Th and LREE, whereas those on the west side are enriched in U ± Th. The pegmatitic melts were generated by partial melting of metasedimentary rocks with slightly elevated U and Th concentrations; and with U, Th, and REE-bearing accessory minerals that were entrained in the melt as xenocrysts. Subsequently, the melts underwent assimilation and fractional crystallization processes en route to the crystallization site. Melt migration and deformation are interpreted to have formed a positive feedback loop.

The character of the mineralization and structural control is consistent with that reported in research on similarly mineralized granitic pegmatites and leucogranites in the Rössing area of Namibia (Berning et al., 1976; Basson and Greenway, 2004) and in the Grenville Province of Canada (Fowler and Doig, 1983; Lentz, 1991, 1996).

The present study will form the framework for a future metallogenetic model of U-Th-REE mineralization in the Fraser Lakes area. It will aid in exploration for similar deposits in northern Saskatchewan and will help to determine the link between these pegmatite-hosted deposits and the high-grade, unconformity-related uranium deposits in the Athabasca Basin.

Acknowledgements

This work forms part of an M.Sc. thesis project by McKechnie. The authors acknowledge the financial support of JNR Resources Inc., Natural Science and Engineering Research Council (NSERC; Discovery Grant to Ansdell), and the University of Saskatchewan (Department Heads Research Grant to Ansdell and Graduate Scholarship to McKechnie).

Thanks to Blaine Novakovski for preparing the thin sections, Kimberly Bradley from JNR Resources Inc. for her assistance with petrography, and Rob Millar of the Saskatchewan Research Council for the geochemical analytical results. Critical reviews by C. Card, L. Lauri, and E. Potter are appreciated.

References

- Alexandre, P., Kyser, K., Polito, P. A., Sopuck, V., and Thomas, D., 2005. Alteration mineralogy and stable isotope geochemistry of Paleoproterozoic basement-hosted unconformity-type uranium deposits in the Athabasca Basin, Canada: *Economic Geology*, v. 100, p. 1547–1563.
- Annesley, I. R., and Madore, C., 1989. The Wollaston Group and its underlying Archean basement in Saskatchewan: 1989 fieldwork and preliminary observations, in *Summary of Investigations 1989: Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 89-4*, p. 87–91.
- Annesley, I. R., and Madore, C., 1994. A geological study of the Wollaston–Mudjatik domain boundary in the Wollaston Lake area, Hearne Province, Saskatchewan: Saskatchewan Research Council, Publication R-1230–6-C-94, 162 p. (plus appendices).
- Annesley, I. R., and Madore, C., 1999. Leucogranites and pegmatites of the sub-Athabasca basement, Saskatchewan: U protore? in Stanley, C.J. et al., eds., *Mineral Deposits: Processes to Processing*: Balkema, Vol. 1, p. 297–300.
- Annesley, I.R., Madore, C., and Shi, R., 1997. Thermotectonic evolution of the Wollaston EAGLE Project Area, in *Thermotectonic and uranium metallogenic evolution of the Wollaston EAGLE Project area*, in Annesley, I.R., Madore, C., Shi, R., and Quirt, D.H., eds. Saskatchewan Research Council, Publication R-1420–2-C-97, p. 1–62.
- Annesley, I. R., Madore, C., Kusmirski, R., and Bonli, T., 2000. Uraninite-bearing granitic pegmatite, Moore Lakes, Saskatchewan: Petrology and U-Th-Pb chemical ages, in *Summary of Investigations 2000, Vol.2: Saskatchewan Geological Survey, Saskatchewan Energy and Mines Miscellaneous Report 2000-4.2*, p. 201–211.
- Annesley, I.R., Madore, C., and Portella, P., 2005. Geology and thermotectonic evolution of the western margin of the Trans-Hudson Orogen: evidence from the eastern sub-Athabasca basement, Saskatchewan: *Canadian Journal of Earth Sciences*, v. 42, p. 573–597.
- Annesley, I. R., Cutforth, C., Billard, D., Kusmirski, R. T., Wasyluk, K., Bogdan, T., Sweet, K., and Ludwig, C., 2009. Fraser Lakes Zones A and B, Way Lake Project, Saskatchewan: Geological, geophysical, and geochemical characteristics of basement-hosted mineralization: *Proceedings of the 24th International Applied Geochemistry Symposium (IAGS)*, Fredericton, NB. Conference Abstract Volume 1, p. 409–414.
- Annesley, I.R., Austman, C.L., Creighton, S., Mercadier, J., Ansdell, K.M., Gittings, F., Bogdan, T.S., and Billard, D., 2010a. Fraser Lakes U-Th-REE mineralization, southeastern Athabasca basement: composition and U-Th-Pb chemical/isotopic ages with consequences for U protore and U/C-type mineralization, in *Open House 2010 Abstract Volume: Saskatchewan Geological Survey*, p. 8.
- Annesley, I. R., Creighton, S., Mercadier, J., Austman, C.L., and Bonli, T., 2010b. Composition and U-Th-Pb chemical ages of uranium and thorium mineralization at Fraser Lakes, northern Saskatchewan, Canada: *GeoCanada 2010 Conference CD*, Extended Abstract 815.
- Annesley, I. R., Wheatley, K., and Cuney, M., 2010c. The role of S-type granite emplacement and structural control in the genesis of the Athabasca Uranium deposits: *GeoCanada 2010 Conference CD*, Extended Abstract 649.
- Ansdell, K.M., 2005. Tectonic evolution of the Manitoba-Saskatchewan segment of the Paleoproterozoic Trans-Hudson Orogen, Canada: *Canadian Journal of Earth Sciences*, v. 42, p. 741–759.
- Basson, I.J., and Greenway, G., 2004. The Rössing Uranium deposit: a product of late-kinematic localization of uraniferous granites in the Central Zone of the Damara Orogen, Namibia: *Journal of African Earth Sciences*, v. 38, p. 413–435.
- Bea, F., 1996. Residence of REE, Y, Th, and U in granites and crustal protoliths: Implications for the chemistry of crustal melts: *Journal of Petrology*, v. 37, p. 521–552.
- Berning, J., Cook, R., Hiemstra, S.A., and Hoffman, U., 1976. The Rössing uranium deposit, South-West Africa: *Economic Geology*, v. 71, p. 351–368.
- Boiron, M.C., Cathelineau, M., and Richard, A., 2010. Fluid flows and metal deposition near basement/cover unconformity: lessons and analogies from Pb–Zn–F–Ba systems for the understanding of Proterozoic U deposits: *Geofluids*, v. 10, p. 270–292.
- Boynton, W.V., 1984. Cosmochemistry of the rare earth elements: meteorite studies, in Henderson, P. ed., *Rare Earth Element Geochemistry*: Elsevier, Amsterdam, p. 63–114.
- Bons, P.D., Arnold, J., Elburg, M.A., Kalda, J., Soesso, A., and van Milligen, B.P., 2004. Melt extraction and accumulation from partially molten rocks: *Lithos*, v. 78, p. 25–42.
- Brown, M., 2010. Melting of the continental crust during orogenesis: the thermal, rheological, and compositional consequences of melt transport from lower to upper continental crust: *Canadian Journal of Earth Sciences*, v. 47, p. 655–694.
- Brown, M. and Solar, G.S., 1999. The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm: *Tectonophysics*, v. 312, p. 1–33.
- Cameco, 2012. Cameco – Mining – Cigar Lake, http://www.cameco.com/mining/cigar_lake/
- Černý, P., and Ercit, T., 2005. The classification of granitic pegmatites revisited: *The Canadian Mineralogist*, v. 43, p. 2005–2026.
- Chappell, B.J., and White, A.J.R., 1974. Two contrasting granite types: *Pacific Geology*, v. 8, p. 173–174.
- Clarke, D.B., Henry, A.S., and Hamilton, M.A., 2005. Composition, age, and origin of granitoid rocks in the Davin Lake area, Rottenstone Domain, Trans-Hudson Orogen, northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 42, p. 599–633.
- Cloutier, J., Kyser, K., Olivo, G.R., Alexandre, P., and Halaburda, J., 2009. The Millennium uranium deposit, Athabasca Basin, Saskatchewan, Canada: an atypical

- basement-hosted unconformity-related uranium deposit: *Economic Geology*, v. 104, p. 815–840.
- Coombe, W., 1994. Sediment-hosted base metal deposits of the Wollaston Domain, northern Saskatchewan: Saskatchewan Energy and Mines, Report 213, 108 p.
- Corrigan, D., Pehrsson, S., Wodicka, N., and de Kemp, E., 2009. The Paleoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary processes: *Geological Society, London, Special Publications*, v. 327, p. 457–479.
- Cuney, M., Brouand, M., Lauri, L., Rämö O.T., Kister, P., and Caillat, C., 2008. Accessory mineral paragenesis and U potential of late orogenic potassic granites of southern Finland: 33rd International Geological Congress, 6–14 August 2008, Oslo, Norway, Abstract CD-ROM.
- Delaney, G., and Tisdale, D., 1996. Bedrock geology, Fraser Lakes area (part of NTS 74H-2): Saskatchewan Geological Survey, Summary of Investigations Map 96-4-7.3.
- Delaney, G., Tisdale, D., and Davies, H., 1996. Stratigraphic relationships and base metal mineralization in the Lower Proterozoic supracrustal assemblage along the Archean Johnson River Inlier, Wollaston Domain, Saskatchewan: Saskatchewan Geological Survey, Summary of Investigations 1996, Miscellaneous Report 96-4, p. 3–11.
- Derome, D., Cathelineau, M., Cuney, M., Fabre, C., Lhomme, T., and Banks, D.A., 2005. Mixing of sodic and calcic brines and uranium deposition at McArthur River, Saskatchewan, Canada: a Raman and laser-induced breakdown spectroscopic study of fluid inclusions: *Economic Geology*, v. 100, p. 1529–1545.
- Fettes, D. and Desmons, J., eds., 2007. *Metamorphic Rocks (A Classification and Glossary of Terms)*: Cambridge, Cambridge University Press, 244 p.
- Forster, R. W., 1970. A geological report on Dynamic Petroleum Products Ltd. Permit No. 1: Saskatchewan Geological Survey Assessment Report 74H02-0007, p. 1–36.
- Fowler, A. D., and Doig, R., 1983. The age and origin of Grenville Province uraniumiferous granites and pegmatites: *Canadian Journal of Earth Sciences*, v. 20, p. 92–104.
- Gromet, L. P., Dymek, R. F., Haskin, L. A., and Korotev, R. L., 1984. The 'North American shale composite' - Its compilation, major and trace element characteristics: *Geochimica et Cosmochimica Acta*, v. 48, p. 2469–2482.
- Hamilton, M.A. and Delaney, G., 2000. New U-Pb geochronological constraints on the age of basement and cover in the eastern Wollaston Domain, Saskatchewan, and evolution of the SE Hearne Province: GeoCanada 2000, Calgary, May 29-June 2, Conference CD-ROM, abstract 1103.
- Handy, M.R., Mulch, A., Rosenau, N., and Rosenberg, C.L., 2001. The role of fault zones and melts as agents of weakening, hardening and differentiation of the continental crust: a synthesis, in Holdsworth, R.E., Magloughlin, J., Knipe, R.J., Strachan, R.A., and Searle, R.C., eds., *The Nature and Tectonic Significance of Fault Zone Weakening*: Geological Society, London, Special Publication 186, p. 305–332.
- Hecht, L. and Cuney, M., 2000. Hydrothermal alteration of monazite in the basement of the Athabasca basin: implications for the genesis of unconformity related deposits: *Mineralium Deposita*, v. 35, p. 791–795.
- Hoeve, J., and Sibbald, T.I.I., 1978. On the genesis of Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada: *Economic Geology*, v. 73, p. 1450–1473.
- Hoffman, P.F., 1990. Subdivision of the Churchill province and extent of the Trans-Hudson Orogen, in Lewry, J.F., and Stauffer, M.R., eds., *The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada, Special Paper 37*, p. 15–39.
- Jefferson, C.W., Thomas, D.J., Gandhi, S.S., Ramaekers, P., Delaney, G., Brisbin, D., Cutts, C., Portella, P., and Olson, R.A., 2007. Unconformity-associated uranium deposits of the Athabasca Basin, Saskatchewan and Alberta, in Jefferson C.W., and Delaney, G., eds., *EXTECH IV: Geology and Uranium Exploration TECHNOLOGY of the Proterozoic Athabasca Basin, Saskatchewan and Alberta: Geological Survey of Canada Bulletin 588*, Saskatchewan Geological Society Special Publication 18, Mineral Deposit Division (GAC) Special Publication 4, p. 23–67.
- JNR Resources Inc., 2012. —Home Page— <http://www.jnrresources.com>.
- Kisters, A.F.M., Gibson, R.L., Charlesworth, E.G., and Anhaeusser, C.R., 1998. The role of strain localization for the segregation and ascent of anatectic melts, Namaqualand, South Africa: *Journal of Structural Geology*, v. 20, p. 229–242.
- Kisters, A.F.M., Ward, R. A., Anthonissen, C.J., and Vietze, M.E., 2009. Melt segregation and far-field melt transfer in the mid-crust: *Journal of the Geological Society*, v. 166, p. 905–918.
- Ko, C.B., 1971. Geological report on Dynamic Petroleum Products Ltd. CBS 1837: Saskatchewan Geological Survey Assessment Report 74H02-SW-0012, p. 1–23.
- Kotzer T.G., and Kyser, T.K., 1995. Petrogenesis of the Proterozoic Athabasca Basin, northern Saskatchewan, and its relation to diagenesis, hydrothermal uranium mineralization and paleohydrology: *Chemical Geology*, v. 120, p. 45–89.
- Kretz, R., 1983. Symbols for rock-forming minerals: *American Mineralogist*, v. 68, p. 277–279.
- Kukkonen, I.T., and Lauri, L.S., 2009. Modelling the thermal evolution of a collisional Precambrian orogen: High heat production migmatitic granites of southern Finland: *Precambrian Research*, v. 168, p. 233–246.
- Kurhila, M., Mänttari, I., Vaasjoki, M., Rämö, O.T. and Nironen, M., 2011. U-Pb geochronological constraints of the late Svecofennian Leucogranites of Southern Finland: *Precambrian Research*, v. 190, p. 1–24.
- Kyser, T.K., and Cuney, M., 2008. Unconformity-related uranium deposits, in Kyser, T.K., and Cuney, M., eds., *Recent and Not-So-Recent Developments in Uranium Deposits and Implications for Exploration: Mineralogical Association of Canada, Quebec*, vol. 39, p. 161–219.
- Lauri, L.S., Rämö, O.T., and Cuney, M., 2007. Source characteristics of U-enriched leucogranites of the Svecofen-

- nian orogen in southern Finland, in Andrew, C.J. et al. eds. *Digging Deeper*, Proceedings of the Ninth Biennial Meeting of the Society for Geology Applied to Mineral Deposits: Society for Geology Applied to Mineral Deposits, v. 2, p. 1165–1168.
- Le Maître, R.W., ed., 2002. *Igneous Rocks: A Classification and Glossary of Terms, Recommendations of the International Union of Geological Sciences Subcommittee on the Systematics of Igneous Rocks*: Cambridge, Cambridge University Press, 252 p.
- Lentz, D., 1991. Radioelement distribution in U, Th, Mo, and rare-earth-element pegmatites, skarns, and veins in a portion of the Grenville Province, Ontario and Quebec: *Canadian Journal of Earth Sciences*, v. 28, p. 1–12.
- Lentz, D., 1996. U, Mo, and REE mineralization in late-tectonic granitic pegmatites, southwestern Grenville Province, Canada: *Ore Geology Reviews*, v. 11, p. 197–227.
- Lewry, J.F. and Collerson, K.D., 1990. The Trans-Hudson Orogen: Extent, subdivision and problems, in Lewry, J.F., and Stauffer, M.R., eds., *The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada, Special Paper 37*, p. 1–14.
- Lewry, J.F., and Sibbald, T.I.I., 1977. Variation in lithology and tectonometamorphic relationships in the Precambrian basement of northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 14, p. 1453–1467.
- Lewry, J.F., and Sibbald, T.I.I., 1980. Thermotectonic evolution of the Churchill Province in northern Saskatchewan: *Tectonophysics*, v. 68, p. 45–82.
- London, D., 2008. Pegmatites: The Canadian Mineralogist Special Publication, v. 10, 347 p.
- Madore, C., Annesley, I.R., and Wheatley, K., 2000. Petrogenesis, age, and uranium fertility of peraluminous leucogranites and pegmatites of the McClean Lake/Sue and Key Lake/P-Patch deposit areas, Saskatchewan: *Geo-Canada 2000*, Calgary, May 2000, Conference CD, Extended Abstract 1041.
- Mawdsley, J.B., 1952. Uraninite-bearing deposits, Charlebois Lake area, northeastern Saskatchewan: *Canadian Institute of Mining and Metallurgy, Bulletin No. 482*, p. 366–375.
- Mawdsley, J.B., 1953. Uraninite-bearing fine-grained pegmatite of the Charlebois Lake area northeastern Saskatchewan: *Geological Society of America Bulletin*, v. 64, p. 1550.
- Mawdsley, J.B., 1955. Radioactive pegmatites of northern Saskatchewan: *Canadian Mining Journal*, v. 76, p. 53–56.
- Mercadier, J., Richard, A., Boiron, M.-C., Cathelineau, M., and Cuney, M., 2010. Migration of brines in the basement rocks of the Athabasca Basin through microfracture networks (P-Patch U deposit, Canada): *Lithos*, v. 115, p. 121–36.
- Miller, C.F., Meschter McDowell, S., and Mapes, R.W., 2003. Hot and cold granites? Implications of zircon saturation temperatures and preservation of inheritance: *Geology*, v. 31, p. 529–532.
- Montel, J.M., 1993. A model for monazite/melt equilibrium and application to the generation of granitic magmas: *Chemical Geology*, v. 110, p. 127–146.
- Nabelek, P.I., and Liu, M., 2004. Petrologic and thermal constraints on the origin of leucogranites in collisional orogens: *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 95, p. 73–85.
- Nex, P.A.M., Kinnaird, J.A., and Oliver, G.J.H., 2001. Petrology, geochemistry and uranium mineralization of post-collisional magmatism around Goanikontes, southern Central Zone, Damaran Orogen, Namibia: *Journal of African Earth Sciences*, v. 33, p. 481–502.
- Parslow, G. R., and Thomas, D. J., 1982. Uranium occurrences in the Cree Lake Zone: *Mineralogical Magazine*, v. 46, p. 163–171.
- Parslow, G. R., Brandstätter, F., Kurat, G., and Thomas, D. J., 1985. Chemical ages and mobility of U and Th in anatexites of the Cree Lake Zone, Saskatchewan: *Canadian Mineralogist*, v. 23, p. 543–551.
- Patiño Douce, A., 1999. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas?, in Castro, A., Fernandez, C., and Vigneresse, J.L., eds., *Understanding Granites: Integrating New and Classical Techniques: Geological Society, London, Special Publication 168*, p. 55–75.
- Ray, G.E., 1980. Geology of the Parker Lake-Nelson Lake vicinity: Saskatchewan Geological Survey, Report No. 190, 40 p.
- Richard, A., Pettke, T., Cathelineau, M., Boiron, M.-C., Mercadier, J., Cuney, M., and Derome, D., 2010. Brine-rock interaction in the Athabasca basement (McArthur River U deposit, Canada): consequences for fluid chemistry and uranium uptake: *Terra Nova*, v. 22, p. 303–308.
- Richard, A., Banks, D.A., Mercadier, J., Boiron, M.-C., Cuney, M., and Cathelineau, M., 2011. An evaporated seawater origin for the ore-forming brines in unconformity-related uranium deposits (Athabasca Basin, Canada): Cl/Br and $\delta^{37}\text{Cl}$ analysis of fluid inclusions: *Geochimica et Cosmochimica Acta*, vol. 75, p. 2792–2810.
- Richard, A., Rozsypal, C., Mercadier, J., Banks, D.A., Cuney, M., Boiron, M.-C., and Cathelineau, M., 2012. Giant uranium deposits formed from exceptionally uranium-rich acidic brines: *Nature Geoscience*, v. 5, p. 142–146.
- SRC, 2012. Uranium and Geochemistry: http://www.src.sk.ca/html/labs_facilities/geo_labs/uranium/index.cfm
- Sawyer, E.D. 2008. Atlas of Migmatites: The Canadian Mineralogist, Special Publication v. 9, 371 p.
- Schneider, D.A., Heizler, M.T., Bickford, M.E., Wortman G.L., Condie, K.C., and Perilli, S., 2007. Timing constraints of orogeny to cratonization: Thermochronology of the Paleoproterozoic Trans-Hudson Orogen, Manitoba and Saskatchewan, Canada: *Precambrian Research*, v. 153, p. 65–95.
- Skyttä, P., and Mänttari, I., 2008. Structural setting of late Svecofennian granites and pegmatites in Uusimaa Belt, SW Finland: Age constraints and implications for crustal evolution: *Precambrian Research*, v. 164, p. 86–109.
- Solar, G.S., and Brown, M., 2001. Petrogenesis of migmatites in Maine, USA: Possible source of peraluminous leucogranite in plutons: *Journal of Petrology*, v. 42, p. 789–823.

- Stilling, A., Cerny, P., and Vanstone, P.J., 2006. The Tanco Pegmatite at Bernic Lake, Manitoba: XVI. Zonal and bulk compositions and their petrogenetic significance: *Canadian Mineralogist*, v. 44, p. 599–623.
- Tran, H.T., 2001. Tectonic evolution of the Paleoproterozoic Wollaston Group in the Cree Lake Zone, northern Saskatchewan, Canada, unpublished Ph.D. thesis, U. Regina, 458 p.
- Tran, H.T., Yeo, G.M., Bradley, S., and Lewry, J.F., 1998. Geology of the Daly-Suttle-Middle Foster lakes area, eastern Wollaston Domain (NTS 74A-5, -11, and 12), in *Summary of Investigations 1998: Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 98-4*, p. 48–65.
- Tran, H.T., Ansdell, K., Bethune, K., Watters, B., and Ashton, K., 2003. Nd isotope and geochemical constraints on the depositional setting of Paleoproterozoic metasedimentary rocks along the margin of the Archean Hearne craton, Saskatchewan, Canada: *Precambrian Research*, v. 123, p. 1–28.
- Tran, H.T., Ansdell, K.M., Bethune, K.M., Ashton, K., and Hamilton, M.A., 2008. Provenance and tectonic setting of Paleoproterozoic metasedimentary rocks along the eastern margin of Hearne craton: Constraints from SHRIMP geochronology, Wollaston Group, Saskatchewan, Canada: *Precambrian Research*, v. 167, p. 171–185.
- van Breemen, O., Harper, C.T., Berman, R.G., and Wodicka, N., 2007. Crustal evolution and Neoproterozoic assembly of the central–southern Hearne domains: Evidence from U–Pb geochronology and Sm–Nd isotopes of the Phelps Lake area, northeastern Saskatchewan: *Precambrian Research*, v. 159, p. 33–59.
- Vernon, R.H. and Clarke, G., 2008. *Principles of Metamorphic Petrology*: Cambridge, Cambridge University Press, 460 p.
- Vigneresse, J.-L., Barbey, P., and Cuney, M., 1996. Rheological transitions during partial melting and crystallization with application to felsic magma segregation and transfer: *Journal of Petrology*, v. 37, p. 1579–1600.
- Villars, A., Stevens, G., Moyen, J.-F., and Buick, I.S., 2009. The trace element compositions of S-type granites: evidence for disequilibrium melting and accessory phase entrainment in the source: *Contributions to Mineralogy and Petrology*, v. 158, p. 543–561.
- Ward, R.A., Stevens, G., and Kisters, A., 2008. Fluid and deformation induced partial melting and melt volumes in low-temperature granulite-facies metasediments, Damara Belt, Namibia: *Lithos*, v. 105, p. 253–271.
- Watson, E.B., and Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types: *Earth and Planetary Science Letters*, v. 64, p. 295–304.
- Weaver, B., and Tarney, J., 1984. Empirical approach to estimating the composition of the continental crust: *Nature*, v. 296, p. 575–577.
- Weinberg, R., 1999. Mesoscale pervasive felsic magma migration: alternatives to dyking: *Lithos*, v. 46, p. 393–410.
- Weinberg, R., and Mark, G., 2008. Magma migration, folding and disaggregation of migmatites in the Karakoram Shear Zone, Ladakh, NW India: *Geological Society of America Bulletin*, v. 120, p. 994–1009.
- Wilson, S. A., 2009. Granodiorite, Silver Plume, Colorado, GSP-2, U. S. Geological Survey, Certificate of Analysis: http://minerals.cr.usgs.gov/geo_chem_stand/granodiorite.html
- World Nuclear Association, 2011. World Uranium Mining, <http://www.world-nuclear.org/info/inf23.html>
- Yeo, G.M., and Delaney, G., 2007. The Wollaston Supergroup, stratigraphy and metallogeny of a Paleoproterozoic Wilson cycle in the Trans-Hudson Orogen, Saskatchewan, in *Jefferson, C.W., and Delaney, G., eds., EXTECH IV: Geology and Uranium Exploration TECHNOLOGY of the Proterozoic Athabasca Basin, Saskatchewan and Alberta: Geological Survey of Canada Bulletin 588, Saskatchewan Geological Society Special Publication 18, Mineral Deposit Division (GAC) Special Publication 4*, p. 89–117.



Reprinted with permission of the Canadian Institute
of Mining, Metallurgy and Petroleum
www.cim.org

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/273694115>

Geological setting, petrology and geochemistry of granitic pegmatites hosting the Fraser Lakes Zone B U–Th–REE mineralization, Wollaston Domain, northern Saskatchewan, Canada

Article in *Exploration and Mining Geology* · January 2013

CITATIONS

26

READS

1,250

3 authors:



Christine Louise McKechnie

25 PUBLICATIONS 183 CITATIONS

[SEE PROFILE](#)



Irvine R. Annesley

Universite de Lorraine; University of Saskatchewan

172 PUBLICATIONS 1,250 CITATIONS

[SEE PROFILE](#)



Kevin M. Ansdell

University of Saskatchewan

101 PUBLICATIONS 1,395 CITATIONS

[SEE PROFILE](#)