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Fertile Peraluminous Granites and Related Rare-Element Mineralization in Pegmatites, Superior Province, Northwest and Northeast Ontario: Operation Treasure Hunt

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Fertile Peraluminous Granites and Related Rare-Element Mineralization in Pegmatites, Superior Province, Northwest and Northeast Ontario: Operation Treasure Hunt

by

F.W. Breaks, J.B. Selway and A.G. Tindle

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Abstract

Rare-element (Li, Cs, Rb, Tl, Be, Ta, Nb, Ga, and Ge) pegmatite mineralization associated with S-type, peraluminous granite plutons is distributed over a wide expanse of the Superior Province of northeastern and northwestern Ontario. Peraluminous granitic rocks were generated during low pressure, Abukuma-type regional anatexis of clastic metasedimentary rocks between 2.646 and 2.91 Ga and principally occur within and proximal to the Quetico and English River subprovinces. Modern, comprehensive geological databases for rare-element pegmatite mineralization exist for only a few localities, such as Separation Lake, Pakeagama Lake and the Dryden area. However, for most of the remaining occurrences, there are little existing data available that adequately characterize the field, mineralogical and bulk petrochemical features requisite for exploration conceptualization. The purpose of this study, therefore, is to upgrade the database of rare-element pegmatite and genetically linked, fertile, peraluminous granites for 20 localities mainly dispersed within a 65 000 km^2 area of northwestern Ontario. The mineral and petrochemical database developed in this study comprises 13 176 electron microprobe analyses of important pegmatite minerals, 184 bulk rock and 119 bulk mineral analyses. Several important areas that merit exploration focus for rare-element pegmatite deposits are recommended:

1. Uchi–English River subprovincial boundary zone
    - Allison Lake batholith and associated Jubilee Lake pegmatite group
    - Wenasaga Batholith
    - Root Lake pegmatite group
    - Eastern Lake St. Joseph–Pashkokogan Lake area
2. Wabigoon–English River subprovincial boundary zone
    - Seymour Lake pegmatite group
    - Crescent Lake pegmatite group
    - Falcon Lake pegmatite group
    - Linklater Lake area in vicinity of beryl-type pegmatites
3. Sioux Lookout domain
    - Dryden–Temple Bay (Eagle Lake) area
    - Graphic–Tower lakes area
4. Quetico Subprovince
    - Onion–Walkinshaw lakes area
    - Niobe–Nym lakes area
    - Wisa Lake pegmatite group
    - Area in vicinity of Lowther Township pegmatite
5. Opatica Subprovince
    - area in vicinity of Case pegmatite

Exploration techniques used in the above target zones include regional sampling aimed at detection of alteration (exomorphic) halos in the host rocks around rare-element pegmatites coupled with mineralogical and geochemical recognition of fertile, peraluminous, parent granites. Economic evaluation of prospective fertile granites and potential associated rare-element pegmatites is best undertaken by indicator mineral chemistry (potassium feldspar, muscovite and spessartine-rich garnet). Lake sediment geochemistry for Li, Cs, and Rb represents an additional useful tool in the generation of target areas for rare-element mineralization.

Fertile Peraluminous Granites and Related Rare-Element Mineralization in Pegmatites, Superior Province, Northwest and Northeast Ontario: Operation Treasure Hunt

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Introduction

During the past few years, there has been a significant increase in exploration interest for rare-element mineral deposits in Ontario. This interest has led to widespread claim staking in most areas of the province where rare-element occurrences had been previously documented (e.g., Separation Rapids and Pakeagama pegmatites) (Breaks and Tindle 1996, 1997a, 1997b; Breaks, Tindle and Smith 1999). The major impetus of this study was linked to the surging price of tantalum, which, in 2000, was the top-performing metal the price of which increased 420%. The price of tantalum-niobium-rich concentrate (approximately 35 to 38% Ta_2O_5) rose from US$106 to $444 per pound in 2000 (www.metalworld.com) due to rising demand from the high technology and hard-metal applications, coupled with a scarcity of supply. Approximately 60% of tantalum is utilized in the electronics industry, mainly in the form of tantalum capacitors (Tantalum-Niobium International Study Centre at www.tanb.org). The interest in tantalum as an exploration target in Ontario was heightened after publication of the article by A. Robinson "Little-known tantalum rare, but its future shines" (*The Globe and Mail*, January 5, 2001, p.B1-B2). The price of tantalum in the form of scrap vacuum solids (99.9% Ta) has retracted from its high of US$380 per pound, which was reached on December 19, 2000.

Past work in more localized areas of the Superior Province of Ontario has led to a proposed linkage between peraluminous, S-type, fertile parent granites and rare-element pegmatites (e.g., Dryden area (Breaks and Moore 1992); Separation Lake area (Breaks and Tindle 1996, 1997a, 1997b)). Recognition of peraluminous granites is critical in the exploration for rare-element pegmatites because delineation of such granite masses effectively reduces the target area of investigation. Most pegmatite swarms that can be linked with an exposed fertile, parent granite pluton are situated within approximately 15 km of such granites (e.g., Separation Rapids pluton and eastern and southwestern rare-element pegmatite groups: Breaks and Tindle, 1996, 1997a, 1997b). However, for much of the vast Superior Province, there are relatively little data available to chemically and mineralogically characterize potential peraluminous granite masses. Peraluminous, S-type granite masses are widespread in the English River, Quetico, and Opatica subprovinces, but also may occur in greenstone-rich subprovinces, such as the Wabigoon and Sachigo subprovinces (e.g., Raleigh Lake area (Breaks 1993; Stone, Hallé and Chaloux 1999) and in the North Caribou greenstone belt (Breaks, Osmani and deKemp 2001)).

The purpose of this project—supported by the Operation Treasure Hunt initiative—is to initiate the development of a comprehensive field, chemical, mineralogical and geochronological database for fertile granites and associated rare-element pegmatites for the entire Superior Province of Ontario. Such a database is critical to future exploration success from the private sector. The work in the 2001 field season focussed on northwestern Ontario augmented by a small amount of work in northeastern Ontario (Figure 1).

Several significant results have emerged from this study to date:

- discovery of rare-element mineralization in fertile granites the Quetico Subprovince (Onion–Walkinshaw lakes area along the Armstrong highway and Nym–Niobe lakes areas);
- delineation of the largest fertile granite mass in northwestern Ontario (Allison Lake batholith): a 15 by 50 km area is recommended for rare-element mineral exploration;
- recognition that clastic metasedimentary rock-hosted rare-element pegmatites are widespread in the Sioux Lookout domain: a 5 to 20 km by 160 km area is recommended for rare-element mineral exploration;
- reclassification of the McCombe dikes of Root Lake pegmatite group as complex-type, spodumene-subtype; and identification that the western Lake St. Joseph greenstone belt has high potential for tantalum mineralization;

- recognition, on the basis of evolved tantalum-bearing oxides and potassium feldspar chemistry, that the Onaman–Tashota greenstone belt of the Armstrong area represents an important new target area for tantalum and cesium deposits.

A total of 184 bulk whole rock, 98 bulk potassium feldspar samples and 21 bulk muscovite samples were analyzed at the Geoscience Laboratories, Ontario Geoservices Centre in Sudbury. Fertile granites, aplite, metasomatized host rock, potassium feldspar and muscovite were analyzed by bulk techniques. The study is also supported by 11 658 electron microprobe analyses conducted by A.G. Tindle at the Open University and 1518 analyses at the Geoscience Laboratories, Ontario Geoservices Centre. The microprobe analyses include tourmaline, garnet, tantalum-oxide minerals (i.e., columbite-tantalite, ferrotapiolite, microlite and strüverite), fluorapatite, micas, potassium feldspar, beryl, cassiterite and spodumene. All of the bulk and microprobe analyses and analytical methods for samples collected in summer 2001 as part of OTH are available on 2 Miscellaneous Releases—Data (MRD 90 and 111: Tindle, Breaks and Selway 2001; Tindle, Selway and Breaks 2002, respectively). Microprobe analyses of samples discussed in the text and plotted in the graphs, which were collected in previous field seasons (during the 1980s), will be published in a future Miscellaneous Release—Data once the location co-ordinates can be verified, as UTM co-ordinates were not recorded at the time of sampling.

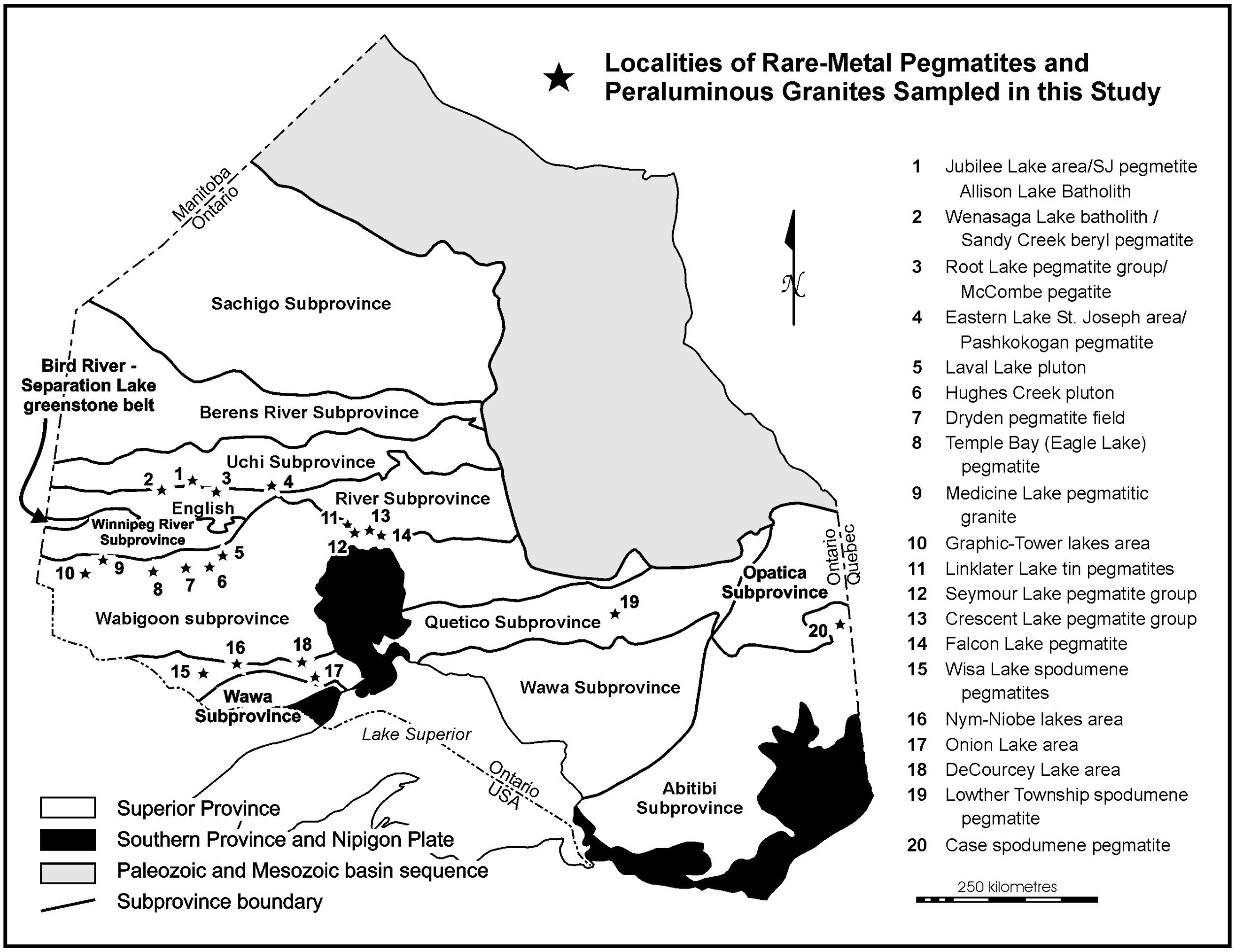


Figure 1. Location of peraluminous pegmatitic granite masses and rare-element pegmatites examined in this study.

Organization of the Open File Report

Due to the length of this Open File Report, the main descriptions have been divided into 11 sections based on subprovince boundaries or entire subprovinces:

1. Overview of fertile granites
2. Using bulk whole rock compositions as an exploration tool
3. Using mineral compositions as an exploration tool
4. Uchi–English River subprovincial boundary, which includes the Allison Lake batholith, the McCombe spodumene pegmatites and the East Pashkokogan spodumene pegmatite
5. Wabigoon–English River subprovincial boundary, which includes the North Aubry, the South Aubry and the Tebishogeshik spodumene pegmatites
6. Sioux Lookout domain, which includes the Fairservice, the Tot Lake and the Gullwing spodumene pegmatites
7. Quetico Subprovince, which includes the Armstrong highway cross-section and the Lowther Township pegmatite
8. Opatica Subprovince, which includes the Case spodumene pegmatites
9. Summary and Conclusions, which includes recommendations for future exploration
10. Appendix 1, at the end of the report, comprises Figures 32 to 82, the chemical plots for bulk and mineralogical data
11. Appendix 2, at the end of the report, includes several tables of reference information: definitions of common pegmatite terms (Table 2), conversion from ppm to element % to weight % for rare-elements (Table 3), formulae for pegmatite minerals examined during this study (Table 4) and the physical properties of pegmatite minerals (Table 5).

Overview of Fertile Granites

Identification of parental fertile granites is an important exploration tool in the search for rare-element pegmatites, as it greatly reduces the area of the search (Breaks and Tindle 1997a). Rare-element pegmatites derived from a fertile granite are typically distributed over 10 to 20 km^2 area within 10 km of the fertile granite (Breaks and Tindle 1997a). Examples of fertile granites and their associated rare-element pegmatites in the Superior Province of Ontario include the Ghost West batholith and Mavis Lake pegmatite group in the Sioux Lookout domain (Breaks and Janes 1991; Breaks and Moore 1992); and the Separation Rapids pluton and Separation Rapids pegmatite groups at the English River–Winnipeg River subprovincial boundary (Breaks and Tindle 1996, 1997a, 1997b). This report examines 2 significant, newly identified, fertile granites: the Allison Lake batholith at the Uchi–English River subprovincial boundary and the Onion–Walkinshaw lakes area along the Armstrong highway, Quetico Subprovince.

DEFINITION OF A FERTILE GRANITE

A fertile granite is the parental granite to rare-element pegmatite dikes. Many granitic melts have the capability to first crystallize a fertile granite pluton, and the residual melt from such a pluton can then migrate into the host rock and crystallize pegmatite dikes. The following discussion on fertile granites and their genetic relationship with rare-element pegmatites is based on work by Černý and Meintzer (1988) and Černý (1989a, 1989b, 1991b), and on field observations by the authors during the summers of 2001 and 2002.

CHARACTERISTICS OF A FERTILE GRANITE

Fertile granites differ from barren (common) granites by their geochemistry, mineralogy and textures. Fertile granites tend to be small in areal extent, typically greater than 10 km^2 (Breaks and Tindle 1997a). Fertile granites are silicic (quartz-rich) and peraluminous (A/CNK > 1.0), which results in crystallization of aluminum-rich minerals, such as muscovite, garnet and tourmaline. A/CNK is a molecular ratio of $Al_2O_3/(CaO + Na_2O + K_2O)$ calculated from bulk whole rock analyses. Fertile granites are also poor in Fe, Mg, Ca and have variable K_2O/Na_2O ratios (Černý and Meintzer 1988). Their rare-element content increases with increasing degree of fractionation/evolution: Sr, Ba, Ti and Zr decrease; Li, Rb, Cs, Be, Ga, Y, Sn, Nb, B, F, and P increase; and K/Rb, K/Cs, Rb/Cs, Ba/Rb, Sr/Rb, Mg/Li, Al/Ga, Th/U, Zr/Hf, Zr/Y and Zr/Sn ratios decrease (Černý and Meintzer 1988). The range of trace elements in a bulk whole rock analysis of a fertile granite are as follows: (445 to <1 ppm Sr, 900–6 ppm Ba, 4300 to <100 ppm Ti, 77 to <1 ppm Zr) and (1–3540 ppm Li, 32–5775 ppm Rb, 3–51 ppm Cs, 1–604 ppm Be, 19–90 ppm Ga, <1–112 ppm Sn, 3–102 ppm Y) (Černý 1989a). The range in trace element ratios for a fertile granite are 270 to 42 K/Rb, 15 400 to 1600 K/Cs, 48 to 18 200 K/Ba, 1.6 to 185 Rb/Sr, 3100 to 1180 Al/Ga, 64 to 14 Zr/Hf, 1.7 to 50 Mg/Li (Černý 1989a). The Mg/Li ratio for bulk whole rock analysis is one of the best indicators of the degree of fractionation of granites and pegmatites. An elevated Mg/Li ratio (e.g., Mg/Li = 50) indicates abundant Mg in a primitive rock, whereas a low Mg/Li ratio (e.g., Mg/Li <10) indicates elevated Li contents in a fractionated rock. Lithium-rich rocks have more economic potential than lithium-poor rocks. Rare-earth element (REE) abundances are low, usually less than 40× chondritic, and mostly between 20× and 1× (Černý and Meintzer 1988; Černý 1989a).

Rare-elements occur in quartz-rich pegmatites and include lithium, rubidium, cesium, niobium and tantalum. Rare-*earth* elements occur in quartz-poor pegmatites and syenites and include lanthanum, cerium and gadolinium. The pegmatites in this study are enriched in rare-elements, not rare-earth elements.

Fertile granites have more variety in accessory minerals than barren granites. Barren granites contain biotite and/or silver muscovite as their minor minerals, and apatite, zircon and titanite as accessory minerals, whereas fertile granites contain numerous possible accessory minerals: primary green lithium-bearing muscovite, garnet, tourmaline, apatite, cordierite and rarely andalusite and topaz (Černý 1989a; Breaks and Tindle 1997a). More evolved fertile granites contain beryl, ferrocolumbite (niobium-oxide mineral) and Li-tourmaline (Breaks and Tindle 1997a).

Graphic textures are common in fertile granites: graphic potassium feldspar + quartz intergrowth, plumose muscovite (muscovite + quartz intergrowth) and rarely tourmaline + quartz intergrowth. Sodic aplite may also be present in fertile granites (see below for description).

ROCK TYPES

According to Černý and Meintzer (1988), intrusions of fertile granites are typically heterogeneous consisting of several units, which are transitional to each other and, in most cases, have separated from a single intrusion of magma. Most of the rock types contain a characteristic assemblage of peraluminous accessory minerals. Černý and Meintzer (1988, p.178-180) have identified 5 possible rock types that may be part of a single fertile granite intrusion, which, from most primitive to most fractionated, are

1. fine-grained or porphyroblastic biotite granite
2. fine-grained leucogranite
3. pegmatitic leucogranite
4. sodic aplite
5. potassic pegmatite
6. rare-element-enriched pegmatite, which forms dikes external to the fertile granite pluton

Biotite granite is fine-grained to coarse-grained and, locally, potassium feldspar is megacrystic. The potassium feldspar is usually late and anhedral. Biotite granite is a minor component of a fertile granite pluton, as it is exposed only by erosion. Fertile biotite granite cannot be distinguished from barren biotite granite in hand sample.

Fine-grained leucogranite may contain biotite, two micas or muscovite alone. Garnet is a typical accessory mineral, especially in muscovite-bearing rocks. Leucogranites are usually massive with albite plagioclase and anhedral late potassium feldspar. Leucogranites are similar to some barren granites in that they contain 2 feldspars (plagioclase and potassium feldspar), quartz and mica. Leucogranites can be distinguished from barren granites in that their overall colour is usually white and they contain peraluminous minerals, such as garnet and tourmaline.

Pegmatitic leucogranite typically consists of megacrystic potassium feldspar (5 to 150 cm in size) intergrown with graphic quartz, embedded in a medium- to coarse-grained matrix of albite plagioclase, quartz and muscovite. Garnet and/or tourmaline are common minor minerals, whereas apatite, zircon and gahnite (zinc-oxide) are accessory minerals. The matrix can locally contain patches of plumose muscovite + quartz intergrowths with garnet or tourmaline in their centres.

Sodic aplite is mostly composed of fine-grained equant white albite (sodium-rich plagioclase) and quartz with accessory minerals of garnet, tourmaline, green muscovite, tantalum-oxide minerals and fluorapatite. An aplite has the texture of a bowl of sugar and may crumble easily. It may be layered with stringers of garnet or tourmaline alternating with layers of garnet- and tourmaline-free aplite.

Potassic pegmatite usually consists of blocky white potassium feldspar and local books of muscovite rimming a quartz core. The potassium feldspar typically lacks graphic quartz. Garnet, tourmaline, beryl, columbite (niobium-oxide) and molybdenite appear sporadically in the central parts of the potassic pegmatite. Potassic pegmatite differs from leucogranite in that it only contains one feldspar (potassium feldspar), whereas leucogranite contains 2 feldspars (plagioclase and potassium feldspar).

Rare-element-enriched pegmatite contains pegmatitic minerals such as spodumene (Li), petalite (Li), lepidolite (Li-mica), tourmaline (B), cesium-bearing beryl (Be), tantalum-oxide minerals (Ta) and pollucite (Cs).

FRACTIONAL CRYSTALLIZATION (GRANITES TO PEGMATITES)

Fractional crystallization of a granitic melt will first crystallize a barren granite composed of common rock-forming minerals (i.e., quartz, potassium feldspar, plagioclase, and mica). This type of granite is very common in the Superior Province, Ontario. As common rock-forming minerals crystallize, and separate from the granitic melt, the granitic melt will become enriched in incompatible rare-elements (such as Be, B, Li, Rb, Cs, Nb, Ta, Mn, Sn) and volatiles (H_2O and F). Incompatible elements do not fit easily into the crystal structures of common rock-forming minerals.

Several factors control whether or not a barren granite melt will fractionate to produce a fertile granite melt:

- presence of trapped volatiles: fertile granites crystallize from a volatile-rich granitic melt
- composition of melt: fertile granites are derived from a peraluminous (aluminium-rich) melt. S-type granite melts usually contain rare-elements, but I-type granite melts do not.
- source of magma: barren granite are usually derived from the partial melting of a igneous source (I-type), whereas fertile granites are derived from partial melting of a peraluminous sedimentary source (S-type)
- degree of partial melting: fertile granites require a high degree of partial melting of the source rock that produced the magma

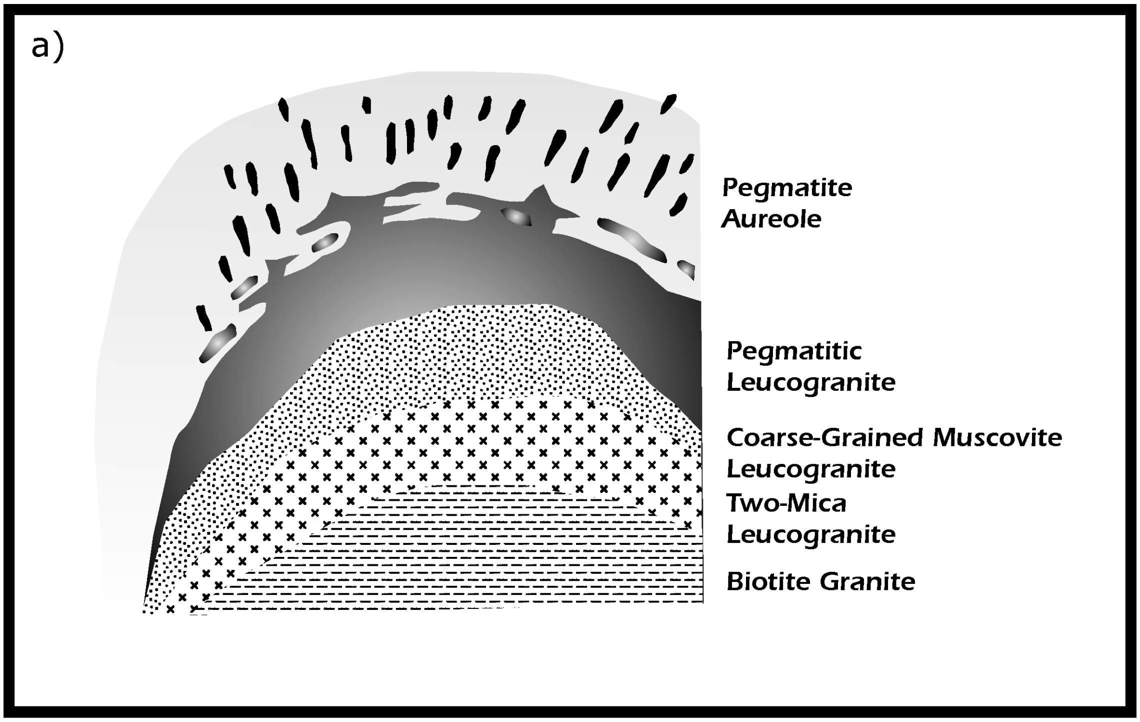
The fertile granite melt will continue to become enriched in incompatible rare-elements, as common rock-forming minerals crystallize. The incompatible elements will wait until the last possible moment to crystallize into pegmatitic minerals, such as spodumene (Li), tantalite (Ta) and cassiterite (Sn). Pegmatites are rich in rare-elements and the exotic minerals that result from crystallization of rare-elements.

REGIONAL ZONING IN FERTILE GRANITES AND PEGMATITE DIKES

Granite-pegmatite systems are largely confined to deep faults, pre-existing batholithic contacts or lithologic boundaries (Černý 1989b). They typically occur along subprovince boundaries within the Superior Province (e.g., Uchi–English River and Wabigoon–English River subprovincial boundaries and Sioux Lookout domain), the exception being those within the Quetico Subprovince. In Archean terranes, greenstone belts, metasedimentary gneissic troughs and metasedimentary–metavolcanic basins are the dominant units hosting rare-element pegmatites (Černý 1989a). Fertile granites that generate rare-element pegmatites are largely late tectonic to posttectonic, postdating the peak of regional metamorphism (Černý 1989b). Granite-pegmatite systems are located in host rocks of the upper greenschist and lower amphibolite facies of the Abukuma-type terranes (low pressure–high temperature) (Černý 1989b).

With increasing fractionation, the composition of the fertile granite changes from biotite granite, in the deepest parts, to two-mica leucogranite to coarse-grained muscovite leucogranite to pegmatitic leucogranite with intercalated layers of sodic aplite and potassic pegmatite at the intrusion roof (Figure 2a) (Černý and Meintzer 1988; Černý 1989a, 1991b). The pegmatite dikes in the host rock (pegmatite aureole) occur above or on the flanks of the fertile granite intrusion. The fertile granite changes in composition from biotite dominant to two-mica dominant to muscovite dominant and there is a noticeable increase in grain size. This entire sequence is rarely exposed in a single intrusion as the number of rock types exposed on the surface depends on the level of erosion.

The most fractionated part of the fertile granite closest to the derived rare-element pegmatite dikes contains accessory rare-element minerals. For example, the interior beryl zone of the Ghost West batholith, parent to the Mavis Lake pegmatite group, contains accessory beryl, and abundant tourmaline and rubdium-cesium-enriched potassium feldspar (Breaks and Janes 1991). The interior beryl zone of the Separation Rapids pluton, parent to the Separation Rapids pegmatite group, contains accessory beryl, cassiterite, ferrocolumbite, ferrocolumbite, and rare manganocolumbite and manganotantalite (Breaks and Tindle 1997a). The potassium feldspar in the interior beryl zone of the Separation Rapids pluton is enriched in rubdium (>4000 ppm Rb) and cesium (>50 ppm Cs) (Breaks and Tindle 1997a).



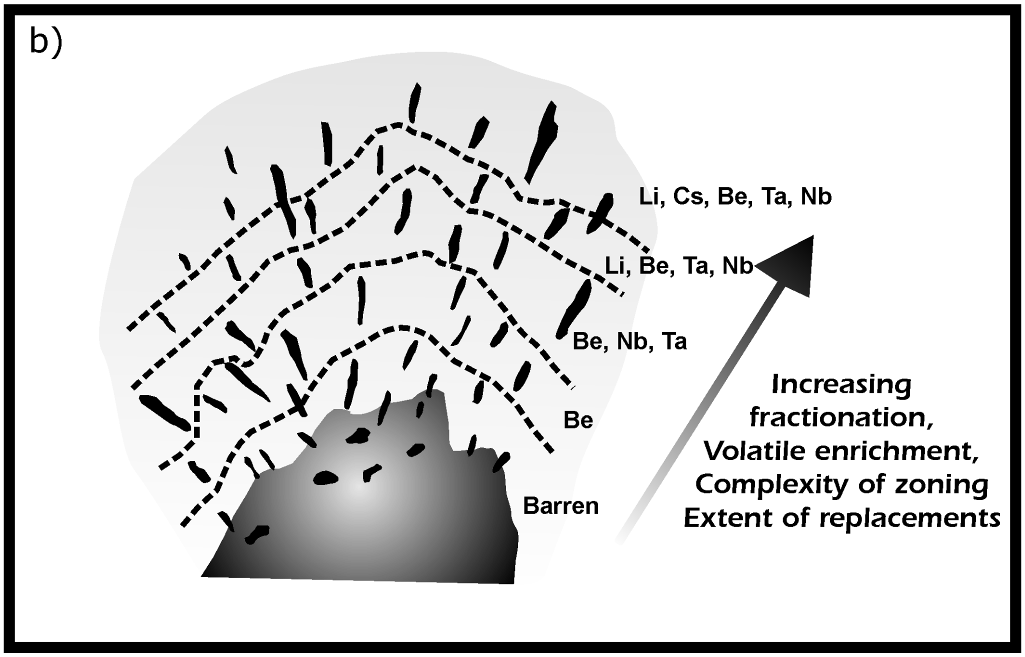


Figure 2. Regional zoning in fertile granites and pegmatites (Černý 1991b). a) Regional zonation of a fertile granite (outward-fractionated) with an aureole of exterior of lithium pegmatites. b) Schematic representation of regional zoning in a cogenetic parent granite + pegmatite group. Pegmatites increase in degree of evolution with increasing distance from the parent granite.

Table 1. Average abundances and ranges of rare-elements and selected ratios from upper continental crust values from Taylor and McLennan (1985, p.46), internal units of fertile granites in the Superior Province (Černý and Meintzer 1988, p.189) and Separation Rapids pluton, Ontario (the fertile parent granite of the Separation Rapids pegmatites) (Breaks and Tindle 2001).

	Average Upper Continental Crust (ppm)	Internal Pegmatitic Granite Unit						Separation Rapids Pluton
		Fine-Grained Leucogranite		Pegmatitic Leucogranite		Sodic Aplite		
		Mean (ppm)	Range (ppm)	Mean (ppm)	Range (ppm)	Mean (ppm)	Range (ppm)	Maximum (ppm)
Be	3	4	<0.5–61	27	<0.5–604	6	1–34	24
Cs	3.7	8	<0.5–39	14	<0.5–51	16	<0.2–67	272
Ga	17	38	<10–81	20	<10–90	9	45–73	94
Li	20	81	1–1400	51.7	6–288	82	7–324	1630
Nb	25	24	<1–81	18	<1–135	–	45–138	120
Rb	112	305	33–1050	473	32–5780	169	9–559	2310
Sn	5.5	9	<1–44	19	<1–112	13	2–25	652
Ta	2.2	4.5	2–8.5	2.7	0.5–8	–	3–435	68
K/Cs	7630	11 000	794–78 400	7880	246–38 500	3020	166–14 900	35–1526
K/Rb	252	159	42–418	165	13–576	85	24–332	0.5–61
Nb/Ta	11.4	5	0.1–11.9	1.71	0.1–7.17	–	0.32–0.62	0.82–8.4

The residual fractionated granitic melt that remains after the fertile granite intrusion has formed can intrude along fractures in the host rock to form pegmatite dikes. The pegmatite dikes increase in degree of fractionation, volatile enrichment, complexity of zoning within individual pegmatite dikes and extent of alteration (e.g., albitization of potassium feldspar) with increasing distance from their parent fertile granite (Figure 2b) (Černý 1991b). Pegmatite dikes increase in rare-element content with increasing fractionation, as rare-elements are incompatible in rock-forming minerals and will wait until the last possible moment to crystallize. With increasing distance from the parent fertile granite, the pegmatites will contain the following index minerals:

1. beryl
2. beryl and ferrocolumbite
3. beryl, tantalite and Li-rich aluminosilicates (such as petalite or spodumene)
4. beryl, manganotantalite, Li-rich aluminosilicates and pollucite.

Pegmatite dikes with the most economic potential occur the greatest distance (up to 10 km) from the parent granite.

Using Bulk Whole Rock Compositions as an Exploration Tool

Table 1 provides some petrochemical data that typify 3 of the most abundant units of fertile granite bodies in the Superior Province (pegmatitic leucogranite, fine-grained leucogranite and sodic aplite) and is a useful guide in the chemical assessment of potential fertile granite masses. Classification of rare-element class pegmatite types and subtypes follows that of Černý (1989a, 1991a). Table 3 (*see* Appendix 2) contains instructions on how to convert ppm to element % to weight % for key rare-elements.

This report uses major and trace element content to evaluate the degree of fractionation of bulk whole rock samples of fertile granites, aplites and fine-grained pegmatite zones. The molecular ratio A/CNK [Al_2O_3/(CaO + Na_2O + K_2O)] is used to indicate whether a sample is mildly peraluminous (A/CNK = 1.0 to 1.1) or strongly peraluminous (A/CNK > 1.2). The higher the A/CNK ratio, the higher the aluminum content and the greater the abundance of aluminum-rich minerals, such as garnet and muscovite. Barren granites will have a low A/CNK ratio, fertile granites will have a moderate A/CNK ratio and rare-element pegmaites will have a high A/CNK. This report also uses the CaO–Na_2O–K_2O ternary diagram to determine which alkali/alkaline element is dominant. Metasomatized mafic or ultramafic rocks have high calcium contents, aplites have high sodium contents and muscovite-rich granites and potassic pegmatites have high potassium contents.

The rare-element content in a bulk analysis of a fertile granite or pegmatite can be used to determine the degree of fractionation of the sample. The higher the rare-element contents in a bulk analysis, the higher the degree of fractionation and the higher the economic potential of the pegmatite. The following rare-elements are excellent fractionation indicators: Be, Cs, Ga, Li, Nb, Rb, Sn and Ta. The most highly fractionated samples will have high values of some or all of these elements. Average upper continental crust values for Be (3 ppm), Cs (3.7 ppm), Ga (17 ppm), Li (20 ppm), Nb (25 ppm), Rb (112 ppm), Sn (5.5 ppm) and Ta (2.2) shown in Table 1 are from Taylor and McLennan (1985).

Elemental ratios can also be used to determine the degree of fractionation and assess the economic potential of bulk samples. The following ratios are excellent fractionation indicators: K/Rb, K/Cs, Nb/Ta and Mg/Li. Ratios shown in Table 1 were derived from the upper continental crust data (Taylor and McLennan 1985) as follows: K/Rb (252), K/Cs (7630), and Nb/Ta (11.4). The K/Rb and K/Cs ratios evaluate the K–Rb and K–Cs substitution in potassium feldspar and micas within the bulk samples. The Nb/Ta ratio evaluates the Nb–Ta substitution in oxide minerals within the samples. For example, the fertile Separation Rapids pluton has an average Nb/Ta ratio of 4.3 with a range from 0.8 to 8.4 (Breaks and Tindle 1997a). According to Beus et al. (1968) and Černý (1989a), Mg/Li ratios less than 30 indicate a high degree of fractionation. Magnesium-rich rocks (i.e., mafic and ultramafic rocks) will have high Mg/Li ratios and lithium-rich rocks (i.e., spodumene pegmatites) will have very low Mg/Li ratios (e.g., Mg/Li < 1.0). Primitive fertile granites will have moderate Mg/Li ratios (e.g., Mg/Li ≈ 100). Pegmatites with the greatest economic potential will have very low K/Rb, K/Cs, Nb/Ta and Mg/Li ratios.

Using Mineral Compositions as an Exploration Tool

As a granitic melt crystallizes and fractionates, minerals become enriched in rare-elements (e.g., Li, B, Be, Rb, Cs, Nb, Ta, Mn, F). For example, potassium feldspar and muscovite become enriched in Rb and Cs; garnet becomes enriched in Mn; and apatite becomes enriched in F. Increasing fractionation also results in crystallization of (Be, B, Li, Ta and Cs)-bearing minerals, for example, beryl (Be), tourmaline (B) and lithium-rich minerals: spodumene, petalite, lepidolite, elbaite, liddicoatite and amblygonite/montebrasite. Pegmatites can be viewed as host rocks for ore deposits of rare-elements: manganotantalite, ferrotapiolite, microlite and wodginite are all ore minerals of Ta; pollucite is the ore mineral of Cs; and spodumene and petalite are used in the making of ceramics because of their high Li, low Fe content and their low expansion coefficient.

The presence of common rock-forming minerals enriched in rare-elements in fertile granites are often the first clue in exploring for blind or buried pegmatite deposits. Below is a description of some of the indicator minerals that can be used to locate and identify rare-element-enriched pegmatite bodies. Table 4 (*see* Appendix 2) contains chemical formulae and Table 5 (*see* Appendix 2) contains physical properties for common pegmatite minerals.

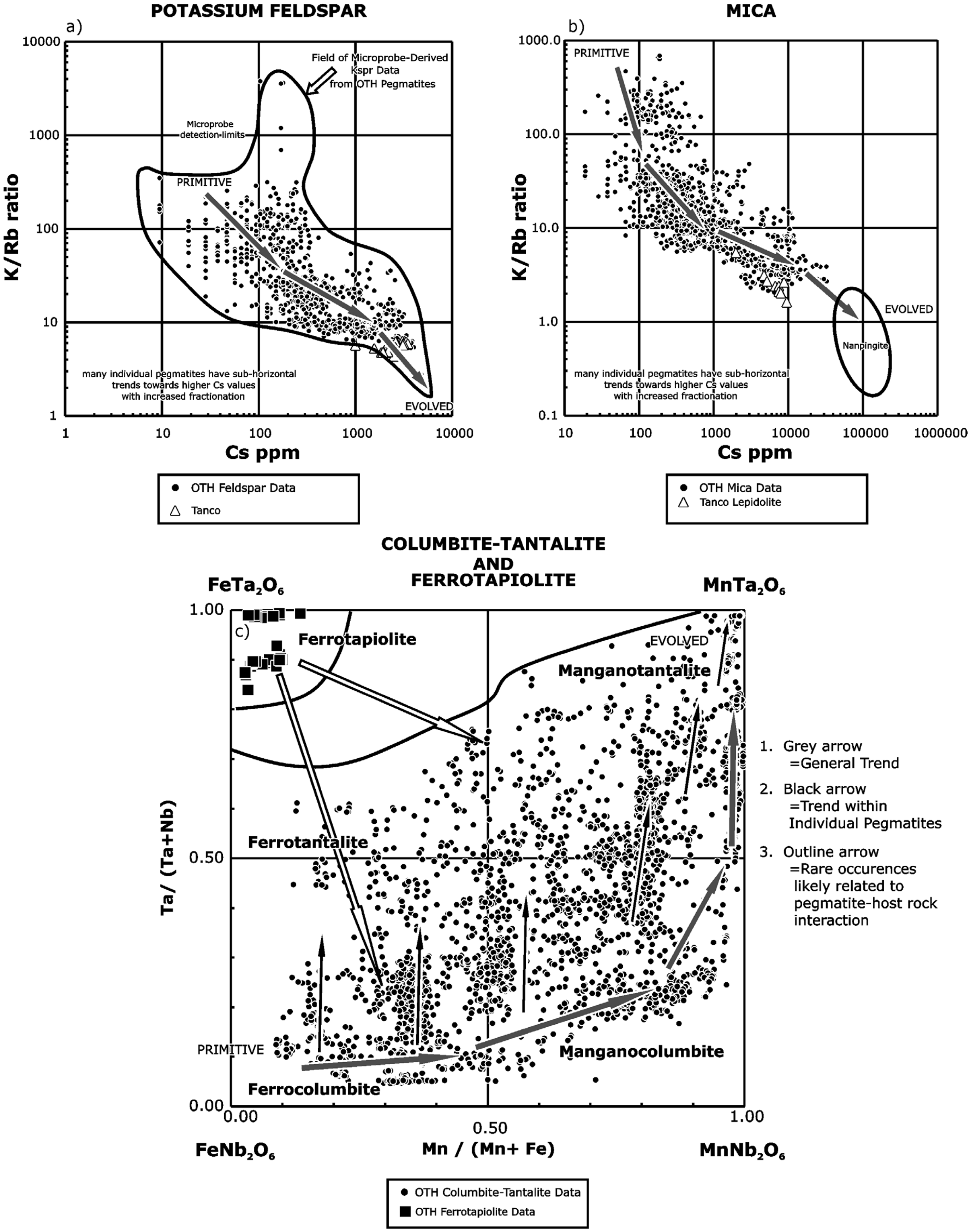


Figure 3. General fractionation trends for key pegmatite indicator minerals. All potassium feldspar, mica, columbite-tantalite and ferrotapiolite compositions measured from this study are plotted in the graphs and compositions from Tanco pegmatite are plotted for comparison. a) K/Rb versus Cs (ppm) for potassium feldspar and b) for mica. With increasing fractionation of the pegmatite-forming melt, the composition of the potassium feldspar and mica becomes more enriched in Rb and Cs. Data in (b) for the Tanco lepidolite are *from* Rinaldi, Černý and Ferguson (1972) and *from* Černý, Ercit and Vanstone (1998). c) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for columbite-tantalite and ferrotapiolite. The grey arrows represent the general fractionation trend from primitive ferrocolumbite to manganocolumbite to evolved manganotantalite. The black arrows represent the fractionation trends of increasing Ta within individual pegmatites. The outline arrows represent host rock contamination, which changes the composition of the tantalum-oxide minerals from Ta-rich ferrotapiolite to Ta-poor ferrocolumbite or manganotantalite.

POTASSIUM FELDSPAR

Potassium feldspar is abundant in barren granites, fertile granites and pegmatites. Potassium feldspar tends to be pink and medium grained in barren granites. Potassium feldspar in potassic pegmatite and rare-element pegmatites tends to be white and blocky (>5 cm in size). Graphic intergrowths of potassium feldspar and quartz are common in fertile granites and pegmatites.

Bulk analysis of blocky potassium feldspar is an excellent exploration tool because the mineral occurs in both fertile granites and rare-element pegmatites (Gordiyenko 1971; Černý et al. 1981; Černý 1989a; Morteani and Gaupp 1989). The 4 key elements in bulk analysis of potassium feldspar are K, Na, Rb and Cs. Elevated Na contents indicate albite contamination or misidentification of potassium feldspar. Elevated Rb and Cs contents indicate that the feldspar is from a highly fractionated pegmatite. The Rb contents for fertile granites is usually >1000 ppm Rb, whereas the Rb contents for rare-element pegmatites is usually >10 000 ppm Rb (based on data collected for this report). For example, the most fractionated parts of the fertile Separation Rapids pluton have potassium feldspar with >6000 ppm Rb and >150 ppm Cs (Breaks and Tindle 1997a).

The K/Rb versus Cs plot for potassium feldspar is one of the standard plots used to evaluate the degree of fractionation of a pegmatite (Figure 3a). The K/Rb ratio measures the degree of Rb for K substitution in the potassium feldspar crystal structure. Barren granites have K/Rb >100 and <10 ppm Cs, whereas rare-element pegmatites have K/Rb <10 and >100 ppm Cs (based on plots within this report). Warning: samples submitted to the lab for bulk analysis must be pure, as graphic quartz and albite from albitization can artificially lower the K, Rb and Cs contents and muscovite alteration can artificially raise the Rb and Cs contents.

Pegmatites with the highest degree of fractionation (and thus the most economic potential) contain white blocky potassium feldspar with >10 000 ppm Rb, K/Rb <10 and >100 ppm Cs.

MICAS

The colour and grain size of the muscovite changes with increasing fractionation: muscovite in barren granites tends to be silver and medium grained, whereas muscovite in fertile granites and pegmatites tends to be green and coarse grained (>2 cm across). The green muscovite usually has a composition of lithian muscovite. In highly fractionated pegmatites, green muscovite may have thin rims of lepidolite. With increasing fractionation, the composition of the mica will change from green lithian muscovite to purple lepidolite.

Bulk analysis of muscovite books is also an excellent exploration tool because it occurs in both fertile granites and rare-element pegmatites and it is an excellent indicator of tantalum mineralization (Gordiyenko 1971; Černý 1989a; Morteani and Gaupp 1989). This technique is limited as coarse muscovite books may not be present in fertile granites. The 5 key elements in bulk analysis of muscovite are Li, K, Rb, Cs and Ta. Elevated Li, Rb and Cs contents indicate that the muscovite came from a rare-element pegmatite. The Li contents for muscovite from a fertile granite is >200 ppm Li, whereas the Li contents for muscovite from a spodumene pegmatite is usually >1000 ppm Li (based on data collected for this report). The Rb contents for muscovite from fertile granites is usually >1000 ppm Rb, whereas the Rb contents for rare-element pegmatites is usually >10 000 ppm Rb (based on data collected for this report). The Cs contents for muscovite from a fertile granite is usually >10 ppm Cs, whereas the Cs contents for rare-element pegmatites is usually >50 ppm Cs (based on data collected for this report). The tantalum versus cesium plot is an excellent exploration tool, as samples with >65 ppm Ta and >50 ppm Cs have a high probability to contain Ta–Nb mineralization (Gordiyenko 1971). Tantalum-oxide minerals inclusions between muscovite sheets can produce artificially high tantalum values and, thus, they should be removed from the muscovite before submitting the sample to the lab for bulk analysis.

In addition to muscovite, some pegmatites also contain a purple mica (lepidolite) in which lithium, rubdium and cesium contents are significantly enriched. The presence of lepidolite in the innermost zones of a rare-element pegmatite indicates that the pegmatite-forming melt reached a high degree of fractionation. As it is difficult to find sufficient coarse-grained lepidolite suitable for bulk analyses and it commonly contains rubidium and cesium contents above the detection limits of bulk analytical techniques, such as X-ray fluorescence (XRF), this report uses an electron microprobe to analyze the composition of primary lepidolite and fine-grained primary muscovite. Similar to the potassium feldspars, the K/Rb versus Cs plot is an excellent plot to evaluate the degree of fractionation of a pegmatite (Figure 3b). The K/Rb ratio measures the degree of K–Rb substitution in the mica's crystal structure. Muscovite from spodumene pegmatites usually have K/Rb <20 and >100 ppm Cs (based on plots within this report). Primary lepidolite in pegmatites have much higher Rb and Cs contents, as K/Rb is usually <10 and Cs is usually >1000 ppm (based on plots within this report).

Pegmatites with the most economic potential contains coarse-grained green muscovite with >1000 ppm Li, >10 000 ppm Rb, >50 ppm Cs and >65 ppm Ta. Many potentially economic rare-element pegmatites contain primary lepidolite and are surrounded by metasomatized aureoles containing (Li, Rb, Cs)-rich "biotite" that crystallizes when pegmatite-derived fluids migrate into host rocks.

GARNET

Garnet is a mineral group in which the species have the same crystal structure, the same general formula ($A_3B_2(SiO_4)_3$) and a number of solid solution series between the end-members (e.g., almandine to spessartine). The most common garnet compositions in pegmatites are almandine (where A = Fe, B = Al) and spessartine (where A = Mn, B = Al). The composition of a garnet can be described by giving the percentage of each of the common end-member components. For example, an almandine with a composition of 66% almandine and 33% spessartine would have a formula of $(Fe_2Mn)_{\Sigma 3}Al_2(SiO_4)_3$. Common garnets in pegmatites may also have minor amounts of Mg (attributed to a pyrope component), Ca (attributed to a grossular or andradite component) or Fe^{3+} (attributed to an andradite component).

The presence of garnet in a granite indicates that the granite is peraluminous and fertile, as barren granites do not contain garnet, whereas peraluminous fertile granite do. Garnet is an excellent exploration tool because its colour and composition changes with increasing fractionation of the granitic melt: fertile granites contain red iron-rich garnet (almandine) and the innermost zone of a rare-element pegmatite may contain orange manganese-rich garnet (spessartine). Red almandine is the most common species of garnet in fertile granites and pegmatites. The Fe/Mn ratio decreases, iron content decreases and manganese content increases in garnet due to increasing fractionation of the pegmatite melt (Černý 1989a; Whitworth 1992) (Figure 4c). Baldwin and von Knorring (1983) concluded that, within an individual pegmatite, garnet with Fe > Mn occurs in the wall and contact zones, garnet with Mn ≈ Fe occurs in intermediate mineral assemblages and Mn-rich garnet (27–41 weight % MnO) occurs in the inner and replacement zones. Pure spessartine garnet is typical of replacement and quartz-rich core zones of pegmatites containing lithium minerals, such as spodumene, lepidolite, petalite and amblygonite (Baldwin and von Knorring 1983).

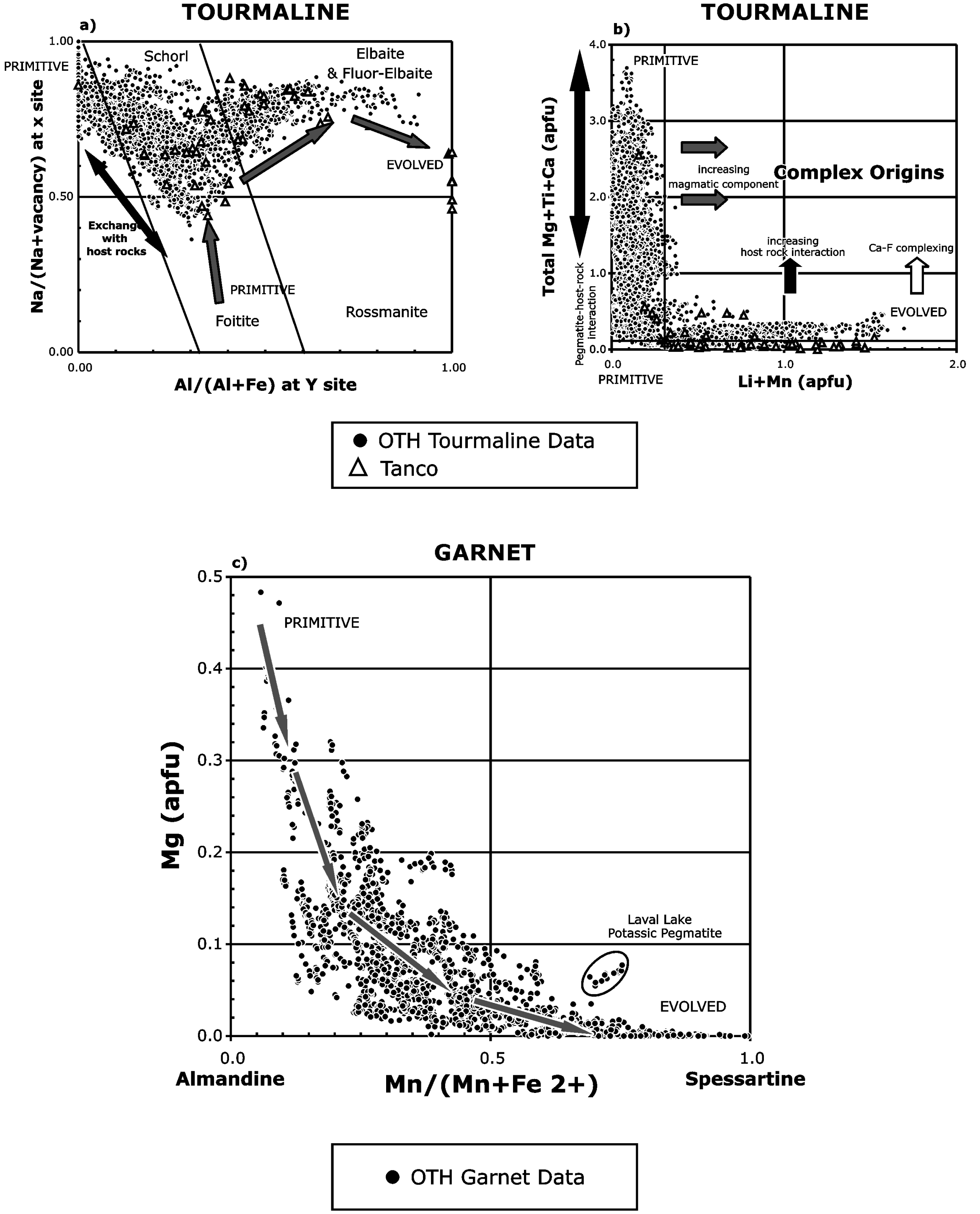


Figure 4. General fractionation trends for key pegmatite indicator minerals. All of the tourmaline and garnet compositions measured for this study are plotted on the graphs and compositions from Tanco pegmatite are added for comparison.
a) Na/(Na+vacancy) at the *X*-site versus Al/(Al+Fe) at the *Y*-site for tourmaline compositions. The black arrow indicates tourmaline compositions which are contaminated by host rocks. The grey arrows show the magmatic fractionation trend from primitive foitite to evolved elbaite. b) total Mg+Ti+Ca (*apfu*) versus Li+Mn (*apfu*) for tourmaline compositions. Tourmaline contaminated by host rocks have elevated Mg, Ti and Ca contents, whereas uncontaminated magmatic tourmaline has elevated Li and Mn contents. c) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet compositions. Garnet contaminated by host rocks have elevated Mg contents. With increasing fractionation of pegmatite-forming melt, the composition of the garnet changes from almandine to spessartine.

Elevated magnesium contents in garnet in a pegmatite likely indicates contamination of the granitic melt by hydrothermal fluids from a magnesium-rich host rock (usually mafic metavolcanic rocks) or assimilation of the host rock into the granitic melt (Černý and Hawthorne 1982) (*see* Figure 4c). Granites and outermost pegmatite zones contaminated by magnesium-rich fluids from host rocks are generally not economic, although uncontaminated inner pegmatite zones within the same body may be economic.

Garnet was used as an exploration tool for 2 fertile granites in this report: the Allison Lake batholith, east of Red Lake and the Armstrong highway area, north of Thunder Bay. The Allison Lake batholith is a 40 km long fertile granite with garnet throughout the batholith (Figure 8, see below for a more detailed discussion). The authors wanted to determine the direction in the granite-forming melt (that now forms the batholith) had fractionated, so that we could reduce the area that we needed to search for pegmatites to along this direction. The authors collected and analyzed garnet samples throughout the batholith and discovered that spessartine (manganese-rich garnet) only occurs along the western contact of this batholith. Thus, we propose that the Birch–Uchi greenstone belt west of the Allison Lake batholith is a good area to be prospected for rare-element pegmatites.

Fertile granites occur along a 45 km long stretch of the Armstrong highway between Walkinshaw and DeCourcey lakes (Figure 25, see below for a more detailed discussion). The authors wanted to determine what part of this area had the most potential for pegmatites, so the authors collected and analyzed garnet samples throughout the area. The south end of the Armstrong highway near Onion and Walkinshaw lakes contains manganese-rich garnet (>30% spessartine component), whereas the rest of the highway section contains iron-rich garnet. Thus, the authors propose that the south end of the Armstrong highway is a good prospect when searching for rare-element pegmatites.

Thus, by spatially mapping manganese distribution in garnet, it is possible to locate the most evolved part of a granite pluton which, in turn, may lead to the discovery of pegmatites and rare-element concentrations. The economic potential of the pegmatites can be partially assessed by an examination of garnet compositions, as pegmatites with the most economic potential contain orange manganese-rich garnets.

TOURMALINE

Tourmaline is a mineral group in which species have the same crystal structure, same general formula $[XY_3Z_6(BO_3)_3(Si_6O_{18})(OH)_3(OH, F)]$ and solid solution series between end-members (e.g., schorl and elbaite). End-members are ideal compositions for a species within the tourmaline group. For example, the most common tourmaline species in pegmatites are schorl ($X = Na$, $Y = Fe_3$, $Z = Al_6$) and elbaite ($X = Na$, $Y = Al_{1.5}Li_{1.5}$, $Z = Al_6$). To find a tourmaline composition that is an ideal end-member composition is rare in nature because tourmaline is often referred to as a “garbage can” mineral, as so many elements may substitute into its crystal structure. If a tourmaline composition is close to the 50:50 division between 2 end-member compositions, then both names are used, with the first name being the dominant end-member. For example, a composition of $Na(Fe_{1.4}Al_{0.8}Li_{0.8})_{\Sigma 3}Al_6(BO_3)_3(Si_6O_{18})(OH)_3(OH)$ would have the name elbaite-schorl since the elbaite component is 53% ((0.8 Al + 0.8 Li)/3×100) and the schorl component is 47% (1.4 Fe/3×100). “Fluor-elbaite” is a fluorine-rich elbaite and quotation marks are put around the name because, even though the composition is common in nature, the name has not yet been approved by the International Mineralogical Association (IMA).

The presence of tourmaline in a granite indicates that the granite is more likely to be fertile, as barren granites do not usually contain tourmaline, whereas boron-bearing peraluminous fertile granite do. Tourmaline is prismatic, and can be distinguished from hornblende by its rounded triangular cross-section and conchoidal fracture. Tourmaline is an excellent exploration indicator mineral because its colour and composition changes with increasing fractionation: fertile granites contain black iron-rich tourmaline (schorl) and the innermost zone of a rare-element pegmatite may contain pink, green or blue lithium-rich tourmaline (elbaite). Black schorl is the most common species of tourmaline in fertile granites and pegmatites. As a pegmatite-forming melt crystallizes, it becomes depleted in iron and enriched in lithium and the composition of the tourmaline changes from schorl to elbaite (London 1999) (Figures 4a and 4b). If a pegmatite-forming melt is capable of crystallizing elbaite, it is likely enriched in other rare elements, such as Rb, Cs or Ta (e.g., McCombe spodumene pegmatite, and Tanco pegmatite). Some pegmatite melts do not crystallize any tourmaline (e.g., Tebishogeshik and North Aubry spodumene pegmatites) due to the lack of boron in the melt. The use of tourmaline as a petrogenetic indicator mineral has been reviewed by Henry and Guidotti (1985), Jolliff, Papike and Shearer (1986) and London, Morgan and Wolf (1996).

The presence of pink, green or blue lithium-rich tourmaline indicates that the pegmatite has economic potential, although not all tantalum-mineralized pegmatites contain tourmaline.

Elevated calcium or magnesium contents in tourmaline in a pegmatite likely indicates contamination of the granitic melt by a calcium-magnesium-rich host rock (usually mafic metavolcanic rocks) (London, Morgan and Wolf 1996; London 1999) (*see* Figures 4a and 4b). Granites and outermost pegmatite zones contaminated with magnesium from host rocks are generally not economic, although uncontaminated inner pegmatite zones within the same body may be economic. For example, the tourmaline in the border zone of the Tanco pegmatite is black calcium-magnesium-rich schorl, but the tourmaline in the most fractionated pegmatite zones is pink elbaite (Selway et al. 2000a). The Tanco pegmatite has economic quantities of tantalum (wodginite), lithium (spodumene) and cesium (pollucite).

FLUORAPATITE

The presence of blue or green fluorapatite in a granite, pegmatite or aplite indicates crystallization from a phosphorus-fluorine-rich melt. If such a melt is allowed to fractionate, it may produce elevated manganese contents (i.e., >2.0 weight % MnO) in fluorapatite and concentrate rare-elements in the pegmatite (based on data collected for this report). For example, the fluorapatite in the North Aubry spodumene pegmatite contains up to 6.1 weight % MnO. Some pegmatites crystallize manganese-poor fluorapatite due to a lack of manganese or the preferential partition of Mn into garnet or oxide minerals over fluorapatite. For example, the McCombe spodumene pegmatite contains fluorapatite with up to 0.8 weight % MnO associated with manganese-rich garnet and oxide minerals (spessartine and manganotantalite).

The presence of blue or green manganese-rich fluorapatite indicates that the pegmatite has economic potential, although not all tantalum-mineralized pegmatites contain manganese-rich fluorapatite.

NIOBIUM-TANTALUM OXIDE MINERALS

The presence of niobium-tantalum oxide minerals (e.g., ferrocolumbite, manganotantalite, wodginite, etc.) in a pegmatite is a definite indicator of a rare-element pegmatite as these are the main ore minerals for tantalum (Foord 1982; Černý and Ercit 1989; Ercit, Černý and Hawthorne 1992b, Ercit et al. 1992a). Niobium-tantalum-oxide minerals commonly occur as tiny (1–2 mm) black metallic specks in a pegmatite and rarely form crystals up to 5 cm across. They are usually difficult to identify even with a hand lens. It is almost impossible to distinguish fine-grained niobium-rich oxide minerals (not economic in granitic pegmatites) from tantalum-rich oxide minerals (economic) by eye (*see* Table 5, Appendix 2). These minerals are also sometimes mistakenly identified as cassiterite (hard, black, ore mineral of tin) and black tourmaline. They are also confused with ilmenite and magnetite, which are the common oxide species in barren granites. The best way to distinguish them is by determining their composition using an electron microprobe. It is recommended that prospectors submit non-magnetic oxide mineral grains to analytical labs for electron microprobe analysis or have bulk analysis undertaken on rock samples rich in possible tantalum-niobium-bearing oxide minerals.

Tantalum mineralization is usually concentrated in albite-rich assemblages (aplite or cleavelandite) or in greisen-like assemblages (muscovite + quartz) or lepidolite pods (Černý 1989b). Tantalum mineralization occurs in intermediate or core-margin zones within a zoned pegmatite. Spodumene and petalite-subtype pegmatites contain a wide variety of tantalum minerals (i.e., columbite-tantalite, microlite, cassiterite and wodginite), whereas lepidolite-subtype pegmatites have microlite dominant over manganotantalite (Černý 1989b). The Swole Lake lepidolite pegmaites are an exception with Mn-rich manganocolumbite and manganotantalite dominant over microlite.

There is a solid solution series between the columbite-tantalite group minerals (Ercit, Wise and Černý 1995). The most common fractionation trend is ferrocolumbite (Fe, Nb) to manganocolumbite (Mn, Nb) to manganotantalite (Mn, Ta); sometimes this trend continues to microlite (Ca, Ta) (Figure 3c). Ferrotantalite is perhaps the most uncommon columbite-tantalite species that can form if the F content of the pegmatite-forming melt is relatively low (Tindle and Breaks 1998). In a small number of cases ferrotapiolite (Fe, Ta) crystallizes, often at the margins of a pegmatite and likely because of a degree of pegmatite–host-rock interaction (*see* Figure 3c).

Wodginite (Mn, Sn, Ta) is a wedge-shaped tantalum-oxide mineral and is the main ore mineral of tantalum at the Tanco Mine, Manitoba (Černý, Ercit and Vanstone 1996). Wodginite is uncommon in areas covered by this study, but many varieties of it were recorded in the Separation Rapids pegmatites (Tindle, Breaks and Webb 1998). Niobium-tantalum-oxide minerals may be associated with cassiterite and tantalum-rich rutile (strüverite), both of which can contain a few percent of Ta_2O_5.

BERYL

The presence of beryl in a granite indicates that the granite is fertile, as barren granites do not contain beryl, whereas beryllium-bearing peraluminous fertile granites do. Beryl is an good exploration tool because its colour and composition changes with increasing fractionation: fertile granites contain green cesium-free beryl and the innermost zone of a rare-element pegmatite may contain white or pink cesium-rich beryl. For example, the white beryl from the North Aubry spodumene pegmatite contains up to 3.2 weight % Cs_2O. Pegmatites with economic potential may contain white cesium-rich beryl.

Metasomatized Host Rocks

Bulk whole-rock analysis of metasomatically altered host rocks is a good exploration tool for finding hidden or blind pegmatites (Černý 1989a). When a rare-element pegmatite melt intrudes a country rock (e.g., mafic metavolcanic rocks or metasedimentary rocks), rare-element-enriched fluids flow into the country rock and alter the composition of it to form a dispersion halo. The chemically altered host rock surrounding a pegmatite is called the exocontact. The host rock becomes enriched in highly mobile alkali elements (i.e., Li, Rb, Cs) and volatile components (i.e., B, F) (Černý 1989a). Lithium is the most mobile exomorphic element in most rare-element mineralized systems (Trueman and Černý 1982) and can form halos many times larger than the pegmatite bodies themselves (Breaks and Tindle 1997a). The mean level of Li in mafic metavolcanic rocks from the Superior Province of Ontario, not known to contain rare-metal mineralization, is 16 ppm Li (Breaks 1989, p.314). The following elements in dispersion halos are diagnostic of tantalum-enriched pegmatites: B, Li, Sn, Cs, Be and Rb (Beus et al. 1968). For example, the dispersion halo in the mafic metavolcanic host rocks surrounding the Big Whopper pegmatite system, at Separation Rapids, has Li values that commonly exceed 80 ppm Li with a maximum of 245 ppm Li (Breaks and Tindle 1997a).

Elevated cesium contents (>1% Cs) in highly altered metavolcanic host rocks, immediately adjacent to a pegmatite, closely correlate with the presence of pollucite zones in the adjacent rare-element pegmatite system (Breaks and Tindle 1997a). For example, the metasomatized host rock surrounding Marko's pegmatite, at Separation Rapids, contains up to 1% Cs (Breaks and Tindle 1997a) and host rock in the Dryden area contains up to 1.6% Cs (Breaks 1989, p.332).

The metasomatized host rocks immediately adjacent to a rare-element pegmatite (or exocontact) will have unusual mineralogy due to the influx of rare-element fluids: holmquistite (lithium-amphibole), (Li, Rb, Cs)-rich "biotite" (more correctly phlogopite-siderophyllite or zinnwaldite) and tourmaline (London, Morgan and Wolf 1996). All 3 minerals occur in the metasomatized mafic metavolcanic host rocks surrounding the North Aubry spodumene pegmatite and the Tanco pegmatite (Morgan and London 1987; Selway et al. 2000b). Holmquistite is a lithium amphibole that has the appearance of purple/dark blue matted needles. Holmquistite is an excellent exploration tool because it only occurs in metasomatized host rocks within 10 m of a rare-element pegmatite (London 1986). The K/Rb versus Cs plot is an excellent plot to evaluate the degree of metasomatism of the biotite's host rock. Metasomatic "biotite" associated with rare-element pegmatites has elevated Rb and Cs contents, as K/Rb is usually <10 and Cs is usually >1000 ppm (based on plots within this report). The composition of metasomatic black tourmaline usually reflects the bulk composition of the host rock, for example, metasomatized mafic metavolcanic rocks will contain calcium-magnesium-rich tourmaline (i.e., dravite, uvite, feruvite). In most cases, the presence of abundant tourmaline in metasedimentary and metavolcanic rocks indicates the close proximity of a pegmatite (Beus et al. 1968; Černý 1989a).

Uchi–English River Subprovincial Boundary Zone

INTRODUCTION

Rare-element pegmatite mineralization occurs along a 350 km strike length of the Uchi–English River subprovincial boundary, from the Sandy Creek beryl pegmatite near Ear Falls to the Lilypad Lake complex-type pegmatite (Wallace 1978; Avalon Venture Ltd's web site: http://www.avalonventures.com) in the Fort Hope area. Rare-element mineralization is also known in 3 intervening areas of this zone at Jubilee Lake, Root Lake and East Pashkokogan Lake (Figure 5; and Figure 13, see below for a more detailed discussion). Fertile, peraluminous, parent granites, that potentially generated rare-element mineralization in this boundary zone, are considered to be the Wenasaga Lake batholith (Sandy Creek beryl pegmatite), the Allison Lake batholith (Jubilee Lake pegmatite group and possibly the Root Lake pegmatite group) and the Twinname Lake stock.

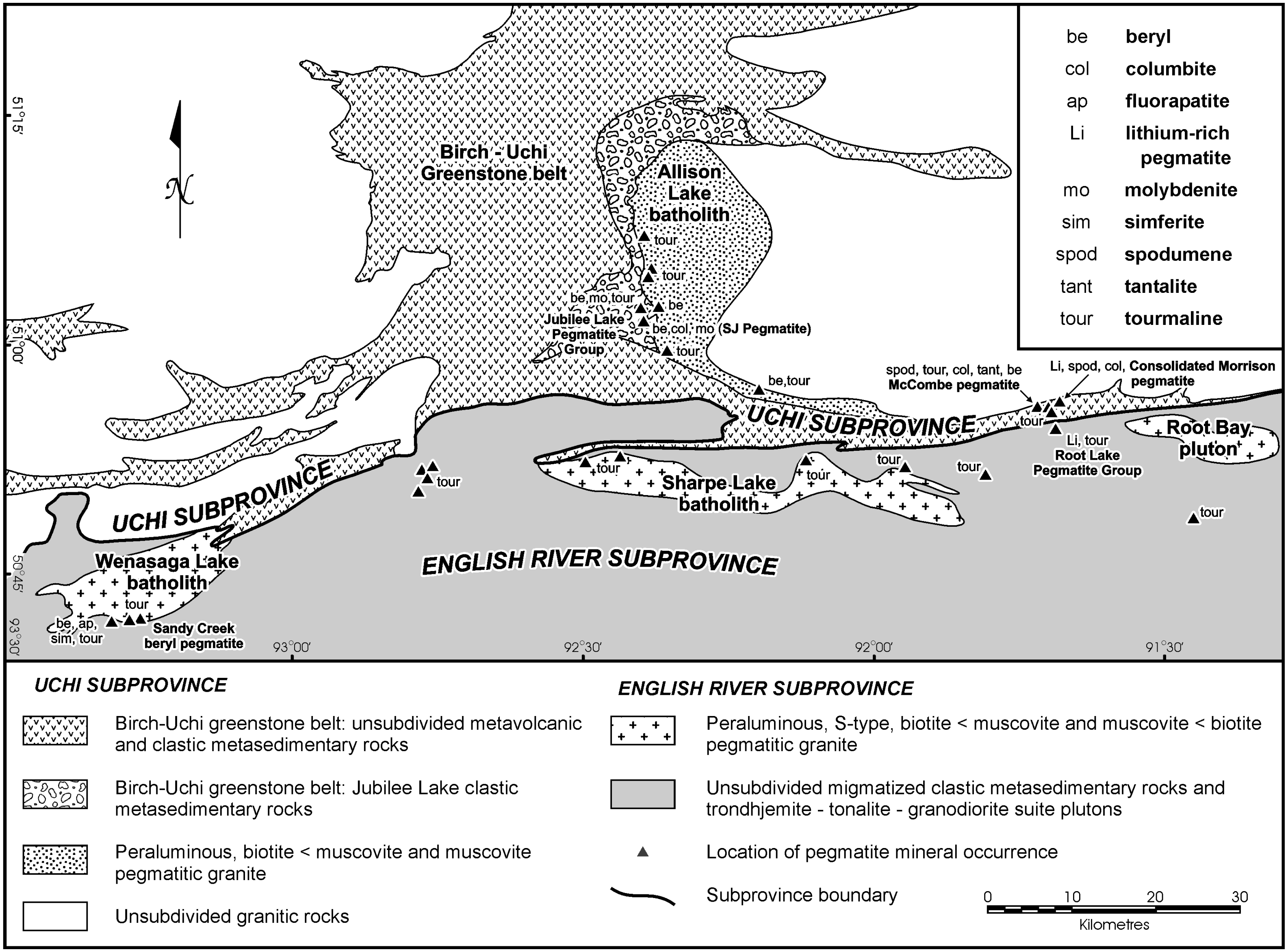


Figure 5. General geology and location of peraluminous granite masses and rare-element mineralization in the English River–Uchi subprovincial boundary zone between western Lake St. Joseph and Ear Falls (geology *compiled from* Thurston (1985a, 1985b) and Breaks and Bond (1993)).

JUBILEE LAKE AREA

Allison Lake Batholith

Previous geological work (Bateman 1939; Breaks et al. 1976, 1979; Thurston 1985a, 1985b) in the vicinity of the Allison Lake batholith (Figures 5 and 6) encompassed only small portions of this extensive, 16 by 40 km, tadpole-shaped, peraluminous, pegmatitic granite body. Breaks et al. (1976, 1979) delineated most of the southeast-striking tail of the pluton and mapped it as a "pegmatite zone". Thurston (1985a, p.60) mapped small areas of the batholith along its western contact with the Jubilee Lake metasedimentary unit in the Allison–Margaret lakes area. A reconnaissance study of the batholith during this project has indicated that the Allison Lake batholith is the largest known fertile, peraluminous, granite mass in northwestern Ontario. A regional geophysical gravity survey was conducted over the Allison Lake batholith (Gupta and Wadge 1986) and detected a significant –680 to –700 mgal Bouguer gravity low ("Allison–Sesikinaga low") which corresponds with the main mass of the batholith (Figure 7; Gupta and Wadge 1986). Gravity modelling suggests that the batholith is 8 km thick and plunges north beneath the Jubilee Lake metasedimentary rocks (Gupta and Wadge 1986).

PETROLOGY

Granitic units of the Allison Lake batholith consist of white weathered, muscovite and biotite-muscovite potassic pegmatite; pegmatitic leucogranite and fine-grained leucogranite intermittently layered with fine- to medium-grained biotite granite; biotite-muscovite granite; garnet-muscovite granite; and sodic aplite. Widespread accessory minerals include black tourmaline, garnet and fluorapatite. The pegmatitic leucogranite commonly contains plumose muscovite-quartz intergrowths (e.g., near Jubilee Lake, UTM 544160E, 5653844N, Zone 15) that are typical of fertile granite plutons (e.g., Separation Rapids pluton (Breaks and Tindle 1996, 1997a, 1997b)). Quartz-rich patches represent a minor but widespread subunit within potassic pegmatite or pegmatitic leucogranite. Such quartz-rich domains were conducive to development of coarse blocky potassium feldspar crystals that range from 30 to 100 cm in diameter. Pale green crystals of beryl (2 cm in size) occur sporadically in the quartz-rich patches as at Curie Lake (*see* Figure 6). Veins and dikes of potassic pegmatite transect the fine- to medium-grained granite.

Tourmaline is a widespread accessory mineral, however, it is most abundant in the Peg Lake area near the western contact of the batholith. Locality 01-FWB-28 (UTM 542668E, 5663342N, Zone 15) is dominated by tourmaline-muscovite potassic pegmatite that is gradational into quartz-rich patches with increased amounts of tourmaline and larger crystal sizes (up to 3 by 5 cm cross-sections and 2 by 16 cm in prismatic sections). Tourmaline-muscovite pegmatitic leucogranite at Curie Lake contains relatively abundant black tourmaline (5 volume %) that is gradational into medium- to coarse-grained biotite granite. The tourmaline also occurs in quartz-rich patches where it is associated with rare pale green beryl.

PETROCHEMISTRY

Nineteen rock bulk samples were collected from various internal units across the Allison Lake batholith (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20a). Samples were analyzed from the biotite granite, biotite muscovite granite, muscovite granite, two-mica potassic pegmatite, muscovite potassic pegmatite and fine-grained leucogranite in the batholith. These pegmatitic granite units are mildly to strongly peraluminous with mean A/CNK = 1.116 within a range of 0.969 to 1.314. Variation in the CaO–Na_2O–K_2O diagram (Figure 35a) indicates a distribution of data points that closely follows the low calcium granite trend that Breaks and Moore (1992, p.855) first defined for the peraluminous, S-type Ghost Lake batholith and later established for the Separation Rapids pluton (Breaks and Tindle 2001). Several ratios also indicate modest to locally significant fractionation that typify fertile granite plutons: K/Rb (mean 176; range 49–309), K/Cs (mean 4182; range 353–5985), Mg/Li (mean 13, range 4–56) and Nb/Ta (mean 8.9; range 3–15).

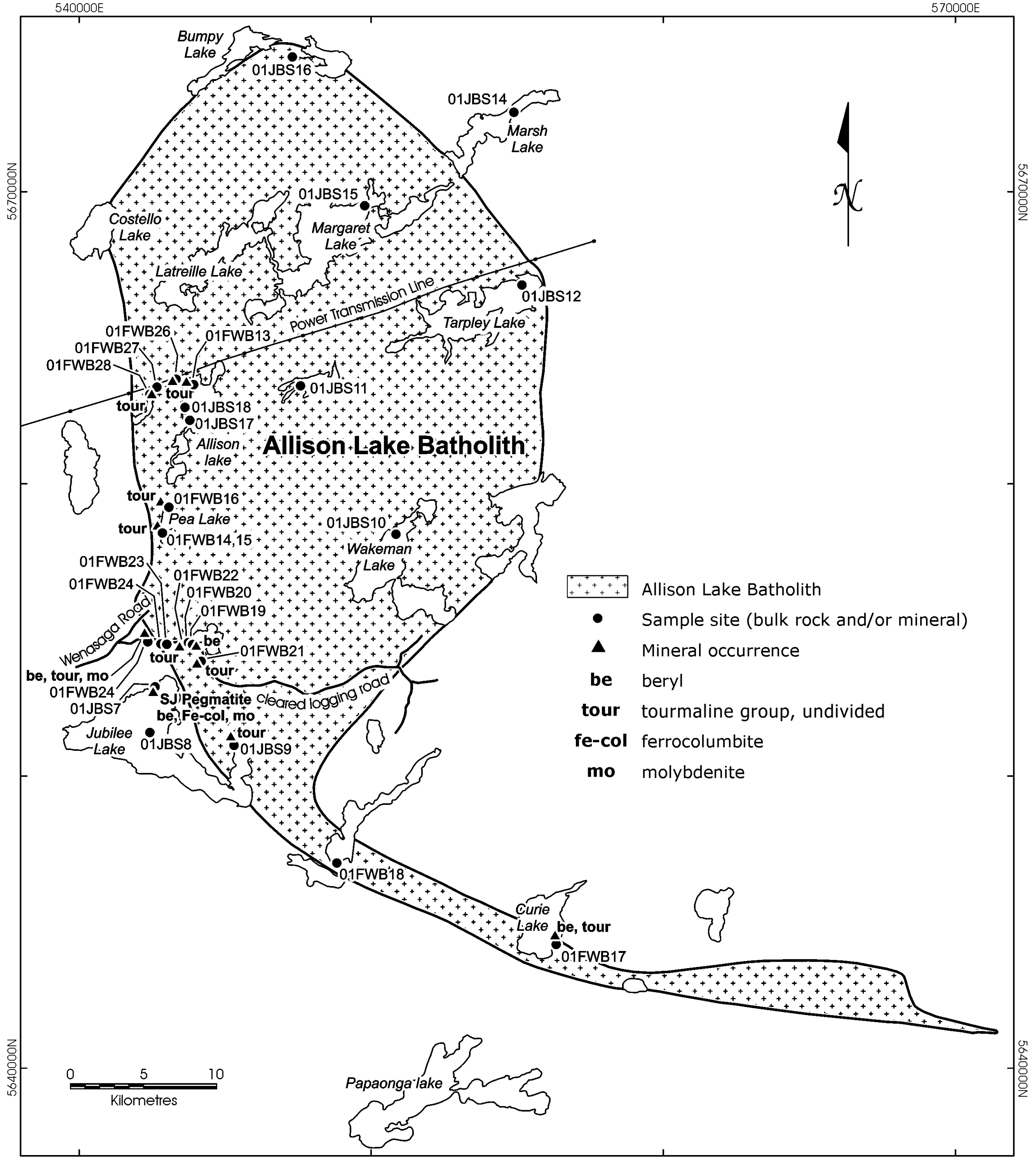


Figure 6. Sample locations within the Allison Lake batholith. Tourmaline and beryl only occurs along the western contact of the batholith and at Curie Lake.

Trace elements that have significant variation across the Allison Lake batholith include lithium and cesium. An overall mean of 78 ppm Li was measured within a range of 9 to 190 ppm Li. A significant areal distribution of lithium within the Allison Lake batholith is also obvious. The western contact zone of the pegmatitic granite, situated within 1.5 km of the Jubilee Lake metasedimentary rocks—in addition to the narrow southeastern tail—contains the highest lithium levels. These data suggest this is the most

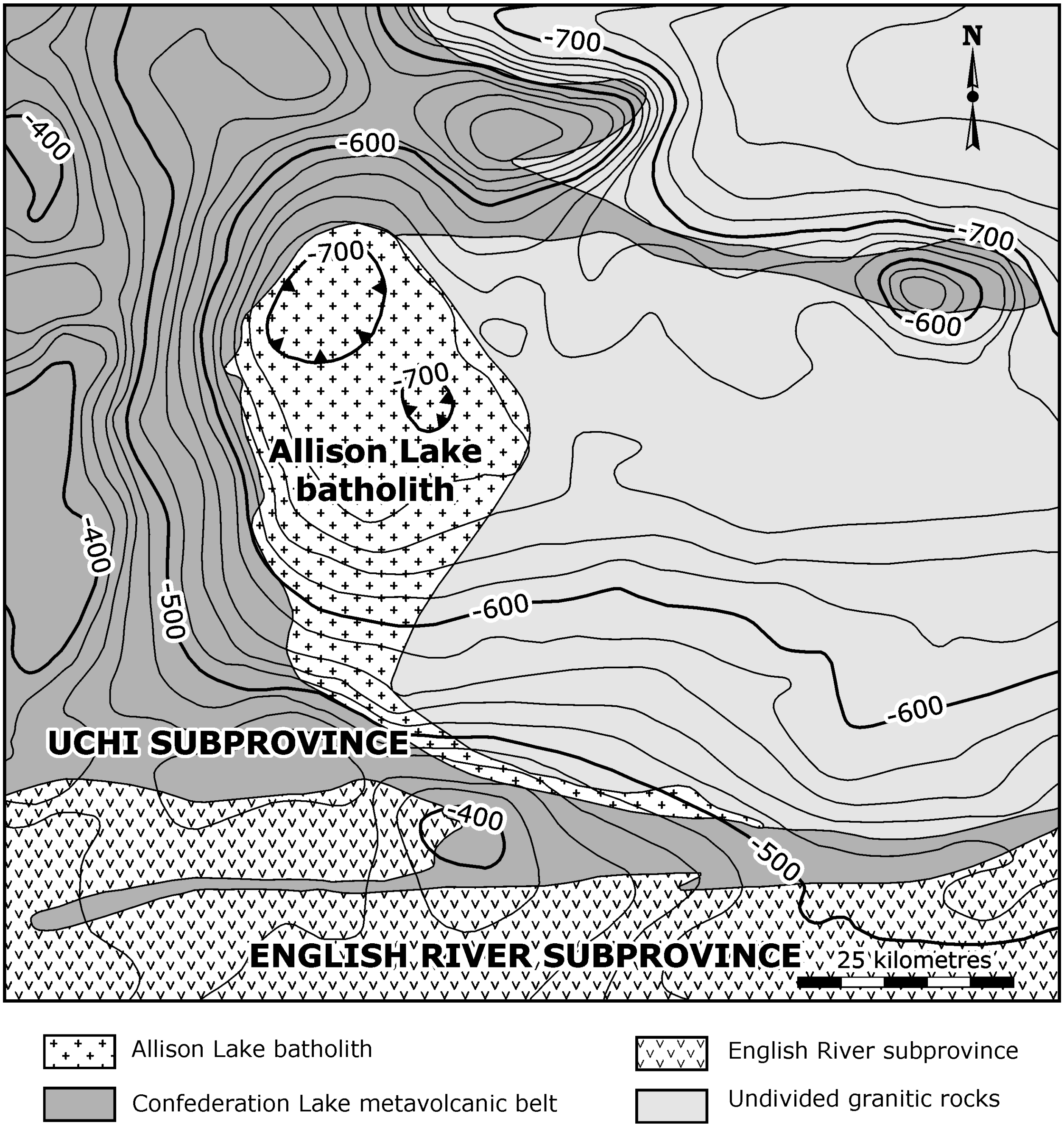


Figure 7. A regional geophysical gravity survey over the Allison Lake batholith detected a significant –680 to –700 mgal Bouguer gravity low ("Allison–Sesikinaga low"), which corresponds with the main mass of the batholith (*from* Gupta and Wadge 1986).

evolved part of the batholith and, therefore, most likely to be close to rare-element pegmatites (mean_{19} = 90 ppm Li versus a mean_{6} = 41 ppm Li for areas of the batholith outside these 2 zones). Such lithium values fall within the mean content for various internal units from fertile peraluminous granites elsewhere in the Superior Province (Černý and Meintzer 1988, p.189).

Cesium levels are also anomalous in several samples with an overall mean for the batholith of 17 ppm Cs and a range of 3 to 90 ppm Cs. Cesium exhibits an identical concentration pattern to that of lithium with highest levels occurring within 1.5 km of the western contact. The highest values occur on the powerline just west of Allison Lake where samples that contain 45 ppm and 90 ppm Cs were collected. The mean rubidium content of 226 ppm Rb reveals enrichment of twice the upper continental crust average (*see* Table 1), but locally anomalous values up to 587 ppm Rb are detected adjacent to the western contact in the Allison Lake area (locality 01-FWB-24: UTM 542761E, 5654536N, Zone 15). Most rubidium values are below 275 ppm Rb. Tantalum exhibits a restricted range of 0.5 to 12.9 ppm Ta (mean 1.9 ppm Ta), however, modest fractionation relative to niobium is observed as the Nb/Ta ratio has a mean value of 8.9 within a range of 3 to 15.

MINERAL CHEMISTRY

A total of 23 bulk potassium feldspar samples were collected from the Allison Lake batholith and related rare-element pegmatite dikes (SJ pegmatite: 01-JBS-7-12, 01-JBS-7-17 and a nearby dike at 01-JBS-8-01) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21a). The potassium feldspar in the batholith has mean rubidium and cesium contents of 820 ppm Rb (range 322–2259 ppm Rb) and 29 ppm Cs (range 8–122 ppm Cs) (Figure 35b). Samples from several localities had significant rubidium levels that exceed 1000 ppm Rb and cesium that exceed 50 ppm Cs as within the western contact zone in the Pea Lake area (01-FWB-16-05: 1654 ppm Rb and 54 ppm Cs); along the powerline west of Allison Lake (01-FWB-28: 1185 ppm Rb; 80 ppm Cs); in the vicinity of the SJ Pegmatite (01-FWB-19-02: 1861 ppm Rb; 122 ppm Cs); and at Curie Lake (01-FWB-17: 2259 ppm Rb; 38 ppm Cs).

Electron microprobe compositions of minerals from the Allison Lake batholith are published in MRD 111 (Tindle, Selway and Breaks 2002): tourmaline compositions (*see also* Table 17), garnet (*see also* Table 11), fluorapatite (*see also* Table 10) and muscovite (*see also* Table 13a).

The garnets throughout most of the Allison Lake batholith consist of red almandine (50–74% almandine, 19–50% spessartine, 0–8% pyrope, 0–3% andradite) (Figure 32a). Spessartine garnet (50–78% spessartine, 22–50% almandine) occurs along the southwest contact of the batholith in fine-grained leucogranite and potassic pegmatite at Pea Lake; in potassic pegmatite along the south shore of Jubilee Lake; in white aplite on an island in Jubilee Lake (locality 01-JBS-8: UTM 542360E, 5651532N, Zone 15); and in potassic pegmatite at Curie Lake (*see* Figures 6 and 8). Spessartine also occurs in fine-grained leucogranite at Wakeman Lake (*see* Figure 8). The most manganese-rich spessartine (56–78% spessartine, 22–43% almandine) occurs in potassic pegmatite at Curie Lake (locality 01-FWB-17-03: UTM 556180E, 5644559N, Zone 15), which contains very coarse-grained, albitized, graphic, potassium feldspar; quartz; fine-grained, orange garnet; and fine-grained, black tourmaline. The magnesium content of the garnets decreases with increasing manganese content throughout the Allison Lake batholith. Elevated manganese content in garnets is indicative of increasing fractionation of the parent melt (Černý 1989a) whereas elevated calcium and magnesium contents are indicative of contamination of the parent melt by hydrothermal fluids originating from the host rocks or assimilation of the host rock by the granitic parent melt (Černý and Hawthorne 1982).

Black tourmaline occurs along the western contact of the Allison Lake batholith along the shores of Allison, Peg, Pea, Jubilee and Curie lakes (*see* Figure 8). Most of the tourmaline is schorl with significant magnesium and minor calcium contents due to contamination of the granitic magma from the mica-rich metasedimentary host rocks (Figure 34). The tourmaline collected from a potassic pegmatite on the north shore of Allison Lake (locality 01-FWB-13-04: UTM 543868E, 5663407N, Zone 15) is relatively unaffected by contamination (*see* Figure 34). The minor black tourmaline at this location has a composition of magnesium-bearing, aluminum-rich schorl (up to 7 mm long) associated with red almandine garnet (63–65% almandine, 32–35% spessartine, 2% pyrope) in a rock composed of white potassium feldspar, quartz and coarse-grained, green muscovite. The most evolved tourmaline from the Allison Lake batholith is hosted by the potassic pegmatite at Curie Lake (locality 01-FWB-17-03: UTM 556180E, 5644559N, Zone 15) (*see* Figure 34). This is the only tourmaline in the batholith that has not interacted with the surrounding metasedimentary host rocks. This fine-grained, black tourmaline is schorl with almost no magnesium, elevated manganese content (0.3–1.4 weight % MnO) and moderate estimated lithium content (<0.4 weight % Li_2O).

Exocontact tourmaline occurs in the metasomatized metawacke host rocks along the contact with a potassic pegmatite dike north of Jubilee Lake (locality 01-FWB-25: UTM 542209E, 5654674N, Zone 15). The Jubilee Lake exocontact tourmaline occurs as 1) porphyroblastic, equant, coarse-grained, black schorl to dravite (up to 7 mm) in plagioclase; 2) fine-grained, black tourmaline (schorl, dravite, foitite) in chloritized mica layers with minor fluorapatite; and 3) fine-grained, black tourmaline (schorl, dravite) with quartz and fluorapatite in the metawacke along the contact with the potassic pegmatite (Figure 33). The tourmaline crystals in the pegmatite are oriented perpendicular to the pegmatite/host rock contact. The tourmaline crystals are zoned with 4 types of distinct zonation: a) a dravite-foitite core, dravite-schorl zone, schorl rim; b) schorl-dravite core, schorl rim; c) foitite-schorl core, dravite-schorl rim; and d) magnesium-bearing schorl core, thin schorl-dravite rim. The first 2 types of zoning are normal with decreasing magnesium and increasing iron from core to rim and the last 2 types show reverse zoning with decreasing iron and increasing magnesium from core to rim. The presence of tourmaline in metasomatized metawacke indicates close proximity to a boron-bearing pegmatite. Metasomatic tourmaline is an excellent exploration tool in the search for unexposed pegmatites.

Fine-grained green or blue fluorapatite (0.1–1.2 weight % MnO) occurs in the two-mica granite, leucogranite and potassic pegmatite within the Allison Lake batholith (Figure 37a). The potassic pegmatite, along the north shore of Allison Lake, contains white potassium feldspar, quartz, green muscovite with biotite cores, red almandine garnet and blue fluorapatite with up to 2.2 weight % MnO. The most manganese-rich fluorapatite occurs on an island in Jubilee Lake (sample 01-JBS-8-03: UTM 542360E, 5651532N, Zone 15). A sample collected from this location contains fine-grained, blue fluorapatite with up to 4.5 weight % MnO and red spessartine garnet (66–67% spessartine, 32–34% almandine) in a white aplite pod.

A pegmatitic leucogranite with a quartz pod occurs on top of a hill in the eastern part of Jubilee Lake (locality 01-JBS-9: UTM 545194E, 5651051N, Zone 15). The pegmatitic leucogranite contains blocky graphic pink potassium feldspar, and minor blue fluorapatite, red almandine to spessartine garnet (51–59% almandine, 37–47% spessartine, 1–3% pyrope), graphic black tourmaline (magnesium-rich schorl), green muscovite and biotite (*see* Figures 32 and 34). The quartz pod contains coarse-grained silver to pale green muscovite (up to 3.5 cm), blocky pink potassium feldspar and minor black tourmaline (magnesium-rich schorl, up to 1.8 cm long). A bulk analysis of the muscovite from the quartz pod contains 0.33 weight % Rb_2O, 905 ppm Li and 360 ppm Ta. The elevated tantalum contents in the muscovite is significant because greater than 60 ppm Ta in muscovite indicates tantalum mineralization in a pegmatite. The authors suspect that there are tantalum-oxide minerals within this pegmatite.

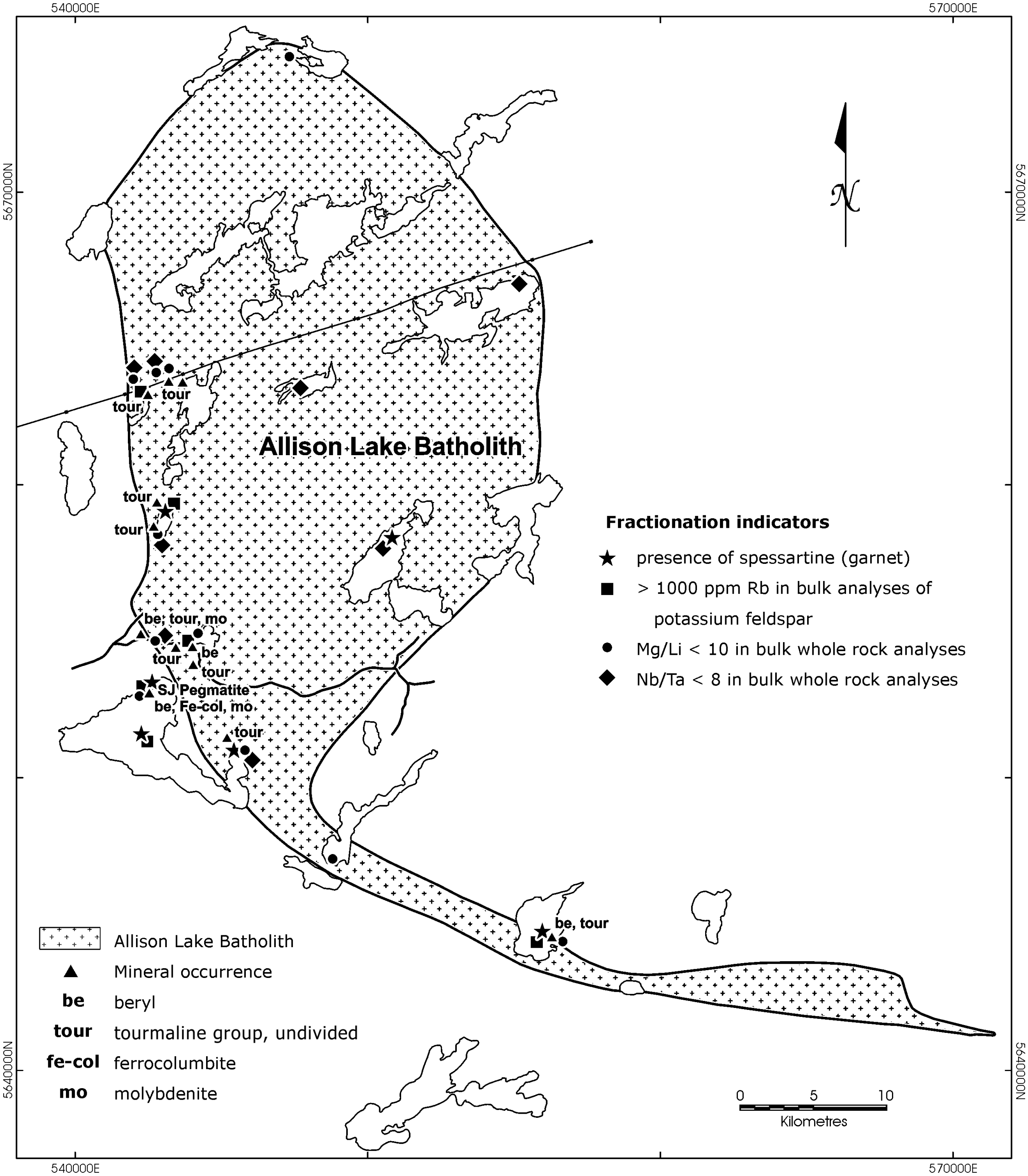


Figure 8. Key fractionation indicators plotted on the map of Allison Lake batholith: presence of spessartine content of garnet (based on microprobe data), Rb content (ppm) in the potassium feldspar bulk analyses, Mg/Li ratio and Nb/Ta ratio in the bulk whole rock analyses. The fractionation indicators suggest that the western contact of the batholith is the most fertile and the most likely to contain rare-element mineralization either within or adjacent to the batholith.

INTERPRETATION OF ALLISON LAKE BATHOLITH CHEMICAL DATA

In order to determine the direction of increasing fractionation within the Allison Lake batholith, 4 key fractionation indicators were plotted on a map of the batholith (Figure 8):

1. Mg/Li ratio in bulk whole rock analyses
2. Nb/Ta ratio in bulk whole rock analyses
3. Rb content in bulk analyses of potassium feldspar
4. presence of spessartine garnet (manganese-rich)

The western contact and southeast tail of the Allison Lake batholith is the most fractionated part of the batholith, as it has low Mg/Li ratios (<10) in bulk samples, low Nb/Ta ratios (<8) in bulk samples, elevated rubidium contents (>1000 ppm Rb) in potassium feldspar, elevated manganese contents in garnet (i.e., presence of spessartine), presence of common tourmaline, and presence of rare beryl and ferrocolumbite. The western contact zone and the southeastern tail of the pegmatitic granite, situated within 1.5 km of the Jubilee Lake metasedimentary rocks, contain the highest lithium and cesium levels in bulk granitic samples. The highest values of cesium occur on the powerline just west of Allison Lake where samples that contain 45 ppm and 90 ppm Cs were detected in granite. Locally anomalous values up to 587 ppm Rb in muscovite potassic pegmatite are detected adjacent to the western contact in the Allison Lake area. Bulk potassium feldspar samples with significant rubidium levels that exceed 1000 ppm Rb and cesium that exceed 50 ppm Cs occur within the western contact zone of the batholith in the Pea Lake area, along the powerline west of Allison Lake, and in the vicinity of the SJ pegmatite. Spessartine garnet occurs along the southwest contact of the batholith in fine-grained leucogranite and potassic pegmatite at Pea Lake; in potassic pegmatite along the south shore of Jubilee Lake; in white aplite on an island in Jubilee Lake; and in potassic pegmatite at Curie Lake.

The above chemical data indicate that the Allison Lake batholith is a large fertile granite and its rare-element contents are increasing from east to west with the highest values occurring along the western contact and southeast tail. Fertile granites are the parents of rare-element (potentially economic) pegmatites. Thus, the authors recommend that the Birch–Uchi greenstone belt west of the Allison Lake batholith be prospected for rare-element pegmatites.

Jubilee Lake Pegmatite Group

Rare-element pegmatite mineralization (in the form of beryl) was initially discovered near Jubilee Lake by prospector Stan Johnson in 1964 and the pegmatite was named the SJ pegmatite after its founder. Recently, additional beryl mineralization was discovered by prospector Sherridon Johnson a short distance to the north (locality 01-FWB-19: UTM 543685E, 5654625N, Zone 15) (*see* Figure 8). Locality 01-FWB-19 consists of a rare-element pod surrounded by a pegmatitic leucogranite. The rare-element pod consists of green beryl up to 3 by 13 cm with moderate Cs contents (average of 0.34 weight % Cs_2O), euhedral quartz (9 by 10 cm), blocky potassium feldspar (14 by 12 cm) and brown muscovite books with accessory red garnet and black tourmaline. A third beryl-bearing pegmatite dike, 12 to 95 cm thick, was identified during the present survey (locality 01-FWB-25: UTM 542209E, 5654674N, Zone 15). This cluster of 3 beryl-type pegmatites has been named the Jubilee Lake pegmatite group by the authors (*see* Figure 5). A fourth beryl occurrence was found by the authors on the east shore of Curie Lake (locality 01-FWB-17: UTM 556180E, 5644559N, Zone 15), 11.5 km southeast of Jubilee Lake. The occurrence consists of a single 5 cm diameter pale green beryl crystal in a quartz-rich patch within a tourmaline-rich pegmatitic leucogranite. The beryl from all 4 localities, except locality 01-FWB-19, is relatively primitive, as its Cs contents ranges from 0.04 to 0.13 weight % Cs_2O.

SJ PEGMATITE

The SJ pegmatite (also known as the Johnson pegmatite) (locality 01-JBS-07: UTM 542529E, 5653027N, Zone 15) represents the largest pegmatite in the Jubilee Lake group and is exposed over a minimum area of 35 by 30 m (*see* Figure 6). This pegmatite may represent an external dike to the Allison Lake batholith hosted in metasedimentary rocks, although no external intrusive contacts were observed. The pegmatite consists of apatite-garnet-muscovite-potassium feldspar-quartz-albite with local quartz-rich patches that contain pale pink blocky potassium feldspar crystals up to 30 by 50 cm. Irregular, lime green replacement masses of muscovite-albite are obvious in the largest blast pit and contain abundant platy black ferrocolumbite.

Petrochemistry

A large bulk rock sample from the SJ pegmatite (locality 01-JBS-7: UTM 542529E, 5653027N, Zone 15) contained the highest tantalum value of 173 ppm Ta thus far documented in the area and consists of a green muscovite-albite greisen-like assemblage with the highest megascopic content of tantalum-niobium oxide minerals observed at the locality (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20a). This strongly peraluminous unit (A/CNK = 1.669) also contains maximum values of Rb (1227 ppm) and Nb (462 ppm) in bulk whole rock samples for the entire area.

Mineral Chemistry

Highest rubidium contents in bulk potassium feldspar from the Allison Lake batholith were documented at the SJ pegmatite with 2 samples of potassium feldspar containing 2211 and 2207 ppm Rb. This potassium feldspar also has elevated cesium levels of 53 and 69 ppm Cs. A nearby muscovite pegmatite dike on an island in Jubilee Lake (sample 01-JBS-8-01) is likely genetically related to the SJ pegmatite by virtue of a similar rubidium content of 2339 ppm Rb and substantial cesium content of 118 ppm Cs in the potassium feldspar. White to faint green beryl crystals reach up to 6 cm diameter in the SJ pegmatite. A bulk analysis of several beryl crystals revealed 78 ppm Rb, 477 ppm Cs and 1350 ppm Li. Electron microprobe compositions of minerals from the SJ pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11), ferrocolumbite (*see also* Table 8a), fluorapatite (*see also* Table 10) and muscovite (*see also* Table 13a).

The SJ pegmatite contains manganese-rich garnet and fluorapatite and iron-rich oxide minerals. The apatite-garnet-muscovite-potassium feldspar-quartz-albite pegmatite zone of the SJ pegmatite contains fine-grained red garnet with a composition between almandine and spessartine (48–55% almandine, 43–50% spessartine, 1–2% pyrope). In the pegmatite zone, the fine-grained blue-green fluorapatite contains up to 7.6 weight % MnO and in the replacement zone, the fluorapatite contains 5.1 weight % MnO. Platy black ferrocolumbite (average of 25.2 weight % Ta_2O_5) occurs in the pegmatite zone and the muscovite-albite replacement zone. Electron microprobe analyses (140) of the tantalum-oxide minerals reveal an iron-dominated fractionation trend marked by a modest increase in Ta_2O_5.

The SJ pegmatite is more evolved than the Allison Lake batholith, as it contains tantalum-oxide minerals which so far have not been found in the batholith, and the fluorapatite is significantly more manganese-rich than that in the batholith. It also has elevated Rb and Cs contents in the potassium feldspar, and the highest Ta contents in bulk whole rock samples (as discussed above).

Rare-Element Exploration Potential

The Allison Lake batholith represents an important new exploration target for rare-element mineralization and is the largest such granite thus far documented in Ontario.

A large area is highly recommended for follow-up exploration and involves a 15 by 50 km corridor that follows the western to southwestern contact of the batholith (from Bumpy Lake in the north to Curie Lake near the southeastern termination, *see* Figures 6 and 8). This area has high potential for further discoveries of rare-element mineralization that could occur in exocontact, metasedimentary-hosted pegmatites or as internal pegmatites within the parent granite. Only beryl-type pegmatites have been discovered to date, however, in light of the common regional zonation sequence of rare-element pegmatites from beryl-rich into lithium-rich types (Černý 1991b) (albite-spodumene-type and complex-type) with increasing distance from the parent granite, this corridor is recommended for detailed exploration. The high potential for tantalum mineralization is highlighted by the economically interesting bulk rock tantalum value of 173 ppm Ta obtained by the authors from the SJ pegmatite and the presence of 306 ppm Ta in bulk muscovite from locality 01-JBS-09.

WENASAGA LAKE BATHOLITH

This peraluminous, S-type granite mass, 7 by 26 km in size, was delineated by Breaks and Bond (1993) and is elongate concordant to the Uchi–English River subprovincial boundary (*see* Figure 5). The batholith was examined for potential linkage with metasedimentary-hosted rare-element pegmatite mineralization as it was known that a beryl-type pegmatite is situated proximal to the southwestern flanks of the batholith.

The Wenasaga Lake batholith consists of a variety of pegmatitic granites that are comparable with other fertile granite plutons (Figure 9). These massive to foliated and locally cataclastic units include white weathered, medium- to coarse-grained, biotite-muscovite pegmatitic leucogranite; biotite-granite, muscovite-biotite granite, and biotite-muscovite granite. The granite units are particularly abundant in the southwestern part of the batholith and are well exposed in a blast cut along the former Griffith iron mine rail line near Detector Lake (locality 01-FWB-09: UTM 475959E, 5619076N, Zone 15). At this location, biotite-muscovite pegmatitic leucogranite grades into muscovite-biotite granite, which contains local enclaves of metasedimentary migmatite. Sparse symplectites of cordierite-quartz occur in the granite where the cordierite has largely been converted into mica-rich pseudomorphs. Such symplectites are widespread in peraluminous, S-type granites of the English River Subprovince (Breaks 1991) and also in parts of the Quetico Subprovince examined in this study. Fluorapatite is a particularly widespread accessory phase and is notably abundant in the phosphorus-rich pegmatite pods within the Sandy Creek beryl dike.

A late episode of aluminium enrichment is evident due to the presence of closely spaced, deformed veins, 1 to 2 cm in thickness, that are composed essentially of grey fibrolite, muscovite, biotite and local fluorapatite. The aluminium-rich veins are transected by undeformed veins of black tourmaline and quartz. A genetic connection of these vein-emplacement episodes with rare-element-mineralization is possible and requires a more detailed examination.

Petrochemistry

Thirteen bulk rock samples were collected from the Wenasaga Lake batholith and Sandy Creek pegmatite (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20a). Several units were analyzed from the Wenasaga Lake batholith: pegmatitic biotite granite, pegmatitic two-mica granite, pegmatitic muscovite granite and two-mica granite. The biotite albite granodiorite host rock, and two-mica potassic pegmatite, simferite zone and sodic aplite from Sandy Creek was also analyzed. Due to accessibility problems and sparcity of outcrop, sampling was confined to the southwestern part of the batholith adjacent to the Sandy Creek pegmatite (*see* Figure 9).

The Wenasaga Lake batholith is mildy to strongly peraluminous with a mean A/CNK of 1.155 and a range of 1.093 to 1.274. The Sandy Creek pegmatite is generally mildly metaluminous (mean A/CNK = 0.999; range 0.883–1.274). In the CaO–Na_2O–K_2O plot (Figure 36), data points from this granite-rare-element pegmatite system closely correspond to the low calcium granite trend of Breaks and Moore (1992). Highest Na_2O contents occur in the primary cleavelandite-rich aplite of the Sandy Creek pegmatite where 3 analyses average 9.42% Na_2O. The biotite-muscovite potassic pegmatite unit of this

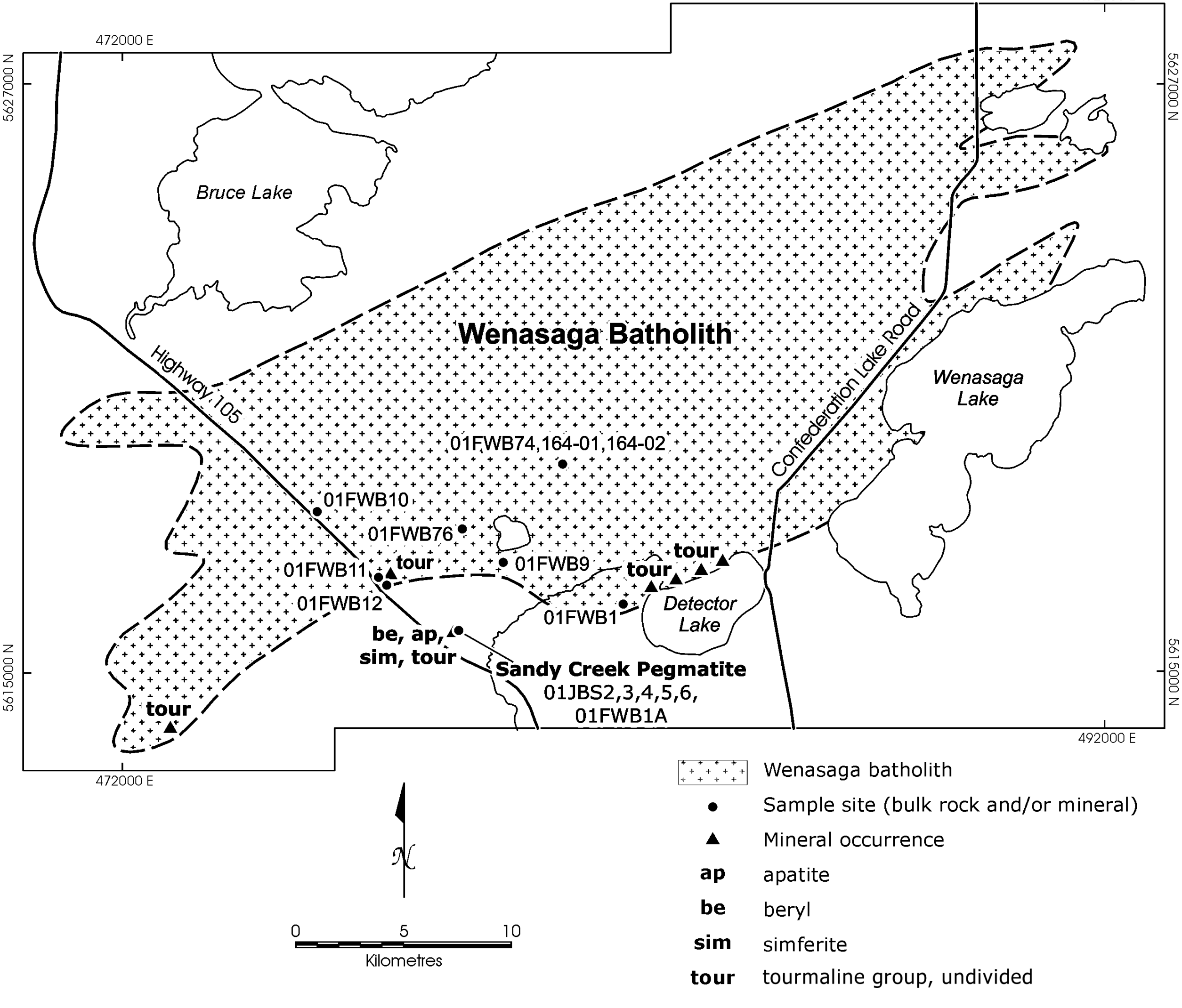


Figure 9. The location of rare-element mineral occurrences in the Wenasaga batholith and Sandy Creek pegmatite.

pegmatite contains approximately equal levels of Na_2O and K_2O and more closely resembles analyses from the Wenasaga batholith itself. In terms of K/Rb, K/Cs, Mg/Li and Nb/Ta ratios, the Sandy Creek pegmatite is more fractionated than the Wenasaga Lake batholith, although there is overlap of the respective ranges for all of these ratios.

Lithium contents in granitic rocks of the Wenasaga Lake batholith are mainly below 40 ppm Li. However, the mean value of 43 ppm Li and its range of 9 to 170 ppm are based upon a small population of 7 samples. Highest lithium level of 170 ppm was detected in biotite-muscovite granite at locality 01-FWB-164-01. The Sandy Creek beryl dike, exclusive of the phosphate-rich unit, has a similar range of lithium (28–146 ppm) to the Wenasaga batholith. The most fractionated unit in the Sandy Creek pegmatite comprises the phosphate-rich pods that contain much lower Na_2O (1.47 weight %) and considerable P_2O_5 (10.17 weight %). Maximum levels for Li (3522 ppm or 0.75 weight % Li_2O), Rb (567 ppm), Cs (47 ppm), Be (298 ppm), Nb (56 ppm) and Ta (16 ppm) for the entire area occur within this unit and represent a concentration that is unusual for beryl-type pegmatites that typically do not contain lithium-rich minerals.

Grab samples previously collected over the exposed area of the Sandy Creek pegmatite revealed less than 30 to 240 ppm Ta (Breaks and Bond 1993). The present survey documented a mean tantalum content of 7.27 ppm within a range of 1.12 to 15.62 ppm Ta in 5 channel cuts distributed across an exposed strike length of dike. Although tantalum values are low in the aplite and simferite (lithium-, iron-phosphate) zones, the Nb/Ta ratios average 3.14 and range from 1.29 to 7.6, which indicates significant fractionation between niobium and tantalum relative to the average upper continental crust ratio of 11.4 (Taylor and McLennan 1985). These data indicate that the dike should be carefully checked for tantalum-rich zones at depth in addition to the possibility of vertical internal zonation and for complex-type pegmatites in the surrounding area. The dominant cleavelandite-rich, aplite could represent a sodium-rich cupola zone that grades into lithium-rich zones at depth. Such lithium zones could contain higher levels of tantalum than those currently sampled.

Mineral Chemistry

Electron microprobe compositions of minerals from the Wenasaga Lake batholith are published in MRD 111 (Tindle, Selway and Breaks 2002): fluorapatite (*see also* Table 10), biotite (phlogopite-siderophyllite, *see also* Table 13d) and tourmaline (*see also* Table 17).

Garnet is scarce in the Wenasaga Lake batholith. Fine-grained pink almandine (71% almandine, 24% spessartine, 4% pyrope) occurs in medium-grained two-mica granite at Detector Lake (locality 01-FWB-01: UTM 497158E, 5617005N, Zone 15) (Figure 41a). A vein of coarse-grained red almandine garnet (up to 7 mm in diameter, 71–80% almandine, 8–21% spessartine, 6–11% pyrope, 1–2% grossular) with fibrolite, muscovite and accessory monazite and xenotime intrudes biotite granite along the southern contact of the batholith (locality 01-FWB-09: UTM 475959E, 5619076N, Zone 15). The "biotite" in this sample has a composition intermediate between phlogopite and siderophyllite. The presence of magnesium-enriched biotite and almandine indicates that the Detector Lake granite and associated veins are relatively primitive in composition (Černý 1989a; Whitworth 1992) and unlikely to host rare-element mineralization.

Tourmaline occurs along the southern contact of the Wenasaga Lake batholith. Prismatic black tourmaline ranges in composition from dravite to schorl with minor calcium enrichment (up to 0.5 weight % CaO) in the two-mica granite (Figure 38). In the quartz veins intruding a muscovite granite, the black tourmaline is dravite with significant iron content (6.7–7.7 weight % FeO) and minor calcium

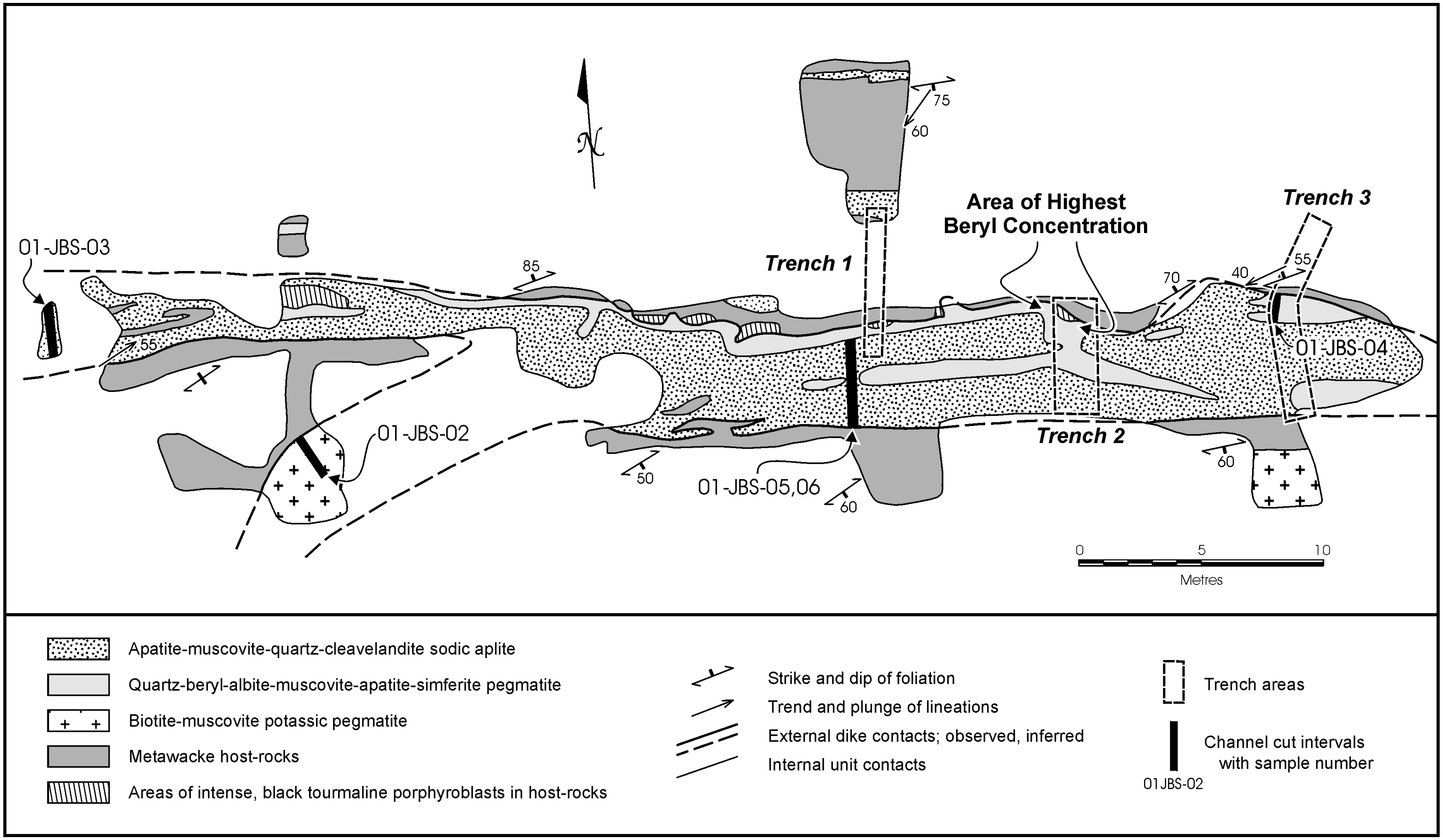


Figure 10. Detailed geology of Sandy Creek beryl dike and sample sites of this study.

content (0.5–0.6 weight % CaO). The magnesium-rich nature of the tourmaline in the batholith indicates that their compositions have been influenced by an influx of magnesium from the host rock into the granitic melt (London, Morgan and Wolf 1996; London 1999).

Fluorapatite also occurs along the southern contact of the Wenasaga Lake batholith. In the two-mica granite, most of the medium-grained blue fluorapatite contains 0.2 to 0.5 weight % MnO, except for the coarse-grained (up to 1.5 cm across) blue-green fluorapatite with 1.0 to 3.2 weight % MnO west of Detector Lake (locality 01-FWB-01) (*see* Figure 37a).

Rare-Element Mineralization: Sandy Creek

To date, rare-element mineralization spatially associated with the Wenasaga Lake batholith has only been found at the Sandy Creek beryl dike by exploration work by Madsen Red Lake Gold Mines Limited in 1963 (assessment files, Red Lake Resident Geologist's office) (Figure 10). This dike, hosted by metasedimentary rocks, is classified as beryl-type, phosphate-subtype (Černý 1991a). The mineralized system, which includes related *en échelon* smaller pegmatite dikes, occupies a minimal area of 20 by 60 m in an area of generally poor exposure. The main pegmatite dike, which strikes 090° and dips from 65 to 85° to the north, varies from 1 to 2.5 m in thickness and bifurcates near its west end (*see* Figure 10).

Most of the dike consists of a white to pale pink, quartz-megacryst-bearing, sodic aplite that is subtly foliated. Fine-grained cleavelandite is the dominant mineral and makes up about 70 to 80% of the mode. Field relations and petrographic observations indicate that the aplite is of primary origin. There is no field evidence to support late-stage, subsolidus albitization that may be responsible for the high sodium contents. Minor phases in the aplite include large books of muscovite, dark green apatite, white beryl and black tourmaline. Tantalum-oxide minerals have not been observed to date in thin section, but this could be due to the nugget effect.

MINERAL CHEMISTRY

Electron microprobe compositions of minerals from Sandy Creek pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): fluorapatite (*see also* Table 10) and tourmaline (*see also* Table 17).

The sodic aplite zone contains minor amounts of fine-grained tourmaline and fluorapatite. The black tourmaline in the sodic aplite zone is schorl with significant magnesium contents (1.9–4.1 weight % MgO) (*see* Figure 38). The green to blue manganese-rich, iron-poor fluorapatite contains 1.5–3.3 weight % MnO and 0.2–0.7 weight % FeO (*see* Figure 37a). The aplite also contains rare manganese-iron-rich chlorapatite with 4.2 weight % MnO and 3.1 weight % FeO.

Pods of phosphate-rich pegmatite occur predominantly along the northern contact of the pegmatite where spectacular masses of friable, chocolate-brown, weathered simferite (a lithium phosphate mineral) $[Li(Fe^{3+}, Mg, Mn^{2+}, Fe^{2+})_2 (PO_4)_2]$ are complexly intergrown with dark green fluorapatite and comprises about 20% of the mode. Faint green to white crystals of beryl, up to 7 cm in diameter, with 0.06 weight % Cs_2O attains is the most cesium-rich in the pegmatite unit.

Coarse-grained (up to 5 mm), dark blue, fluorapatite occurs in a greisen-like assemblage of abundant coarse-grained green muscovite (up to 5mm) and coarse-grained quartz, and minor chocolate-brown phosphate minerals. Coarse-grained (8 mm), euhedral, dark blue-green fluorapatite occurs between sheets of triangular-shaped green muscovite (10 cm long). Both types of fluorapatite are manganese-rich with 2.1 to 3.1 weight % MnO and relatively iron-poor with 0.4 to 0.6 weight % FeO (*see* Figure 37a).

Electron microprobe analysis indicates that the coarse-grained chocolate-brown phosphate minerals are mostly the iron-rich analog of simferite. The Sandy Creek simferite is different from ideal simferite, as at Sandy Creek the mineral contains Fe > Mg > Mn and ideally the mineral should contain Mg > Fe > Mn. This is the only known locality in the world for the iron-analog of simferite. The simferite has too much manganese to be ferrisicklerite [$Li(Fe^{3+},Mn)PO_4$] and too much magnesium to be triphylite [$LiFe^{2+}PO_4$] . Messelite [$Ca_2(Fe^{2+},Mn^{2+})(PO_4)_2 \cdot 2H_2O$] with Fe > Mg > Mn and chlorapatite with 0.3 to 2.6 weight % MnO, 1.7 to 6.0 weight % FeO and 0.3 to 0.7 weight % SrO are associated with simferite. The simferite is veined by chlorapatite, chalcopyrite and hematite.

Black tourmaline concentrations in domains up to 0.8 by 3 m in size occur intermittently along the northern contact of the pegmatite (*see* Figure 10), where metawacke host rocks contain 50 to 60 volume % tourmaline porphyroblasts that are randomly oriented and overprint the foliation. The metasomatized, biotite-rich, metawacke at the contact with the pegmatite contains coarse-grained (up to 2.3 cm long) black tourmaline with a composition of iron-rich dravite (*see* Figure 38). This exocontact tourmaline likely crystallized after an influx of boron-rich fluid from the pegmatite intruded the iron- and magnesium-rich biotite metawacke (London, Morgan and Wolf 1996).

RARE-ELEMENT EXPLORATION POTENTIAL

The modestly to significantly evolved range of Nb/Ta ratios in bulk analysis of channel samples collected across the exposed strike length of Sandy Creek pegmatite indicate that the Sandy Creek dike should be carefully checked for tantalum-rich zones at depth in addition to the possibility of vertical internal zonation. The dominant cleavelandite-rich aplite could represent a sodium-rich cupola zone that grades into lithium-rich pegmatite at depth. Such lithium zones could contain high levels of tantalum.

Rare-element pegmatites commonly occur in zoned swarms of many individual pegmatites, therefore, exploration in the 10 km^2 area around the Sandy Creek dike should be focussed on the potential for lithium- and tantalum-rich pegmatites of the spodumene-subtype, complex-type. Such pegmatites could be concealed by the extensive overburden of the area and, hence, may not have been detected in previous surface prospecting.

ROOT LAKE PEGMATITE GROUP

The Root Lake pegmatite group has been renamed from “Root Lake Field” of Mulligan (1965) in accordance with terminology of Černý et al. (1981). This group was discovered during the lithium claim staking rush of the 1950s (Pye 1956; Mulligan 1965) and comprises 4 spodumene pegmatites within a 3 by 4 km area that are hosted both in mafic metavolcanic rocks of the Lake St. Joseph belt (Clifford 1969) and metasedimentary rocks of the English River Subprovince (Breaks et al. 1979) (Figures 5 and 11). Genetic linkage with fertile granite plutons has not been definitely established, however, these pegmatites lie proximal to the chemically evolved southeast arm of the Allison Lake batholith (*see* Figure 5). The Root Bay pluton, a peraluminous, S-type granite is also situated near the pegmatite group (*see* Figure 5) and could represent a parental source for the lithium-rich pegmatites.

Several pegmatite dikes, hosted in mafic metavolcanic rocks of the western Lake St. Joseph belt and clastic metasedimentary rocks of the English River Subprovince, were examined during this project. At locality 01-FWB-41-03 (UTM 591763E, 5643280N, Zone 15), a 1 m thick tourmaline-bearing quartz-porphyritic aplite dike was discovered about 1 km south of the McCombe pegmatite dikes (*see* Figures 5 and 11). Two 3 to 4 m wide pegmatite dikes along the Root Lake road were also investigated (localities 01-JBS-33: UTM 593510E, 5640223N, Zone 15; and 01-JBS-34: UTM 595831E, 5640394N, Zone 15) and respective samples of tourmaline-bearing fine-grained leucogranite and biotite-muscovite potassic pegmatite were analyzed.

Root Bay Pluton

The muscovite granite of the Root Bay pluton contains tourmaline with a composition of magnesium-rich schorl (Figure 39). The potassic pegmatite contains more magnesium-rich tourmaline with a composition of dravite-schorl. The presence of magnesium-rich tourmaline indicates that the Root Bay pluton is primitive because as a granitic melt crystallizes, its composition changes from magnesium-rich to iron-rich.

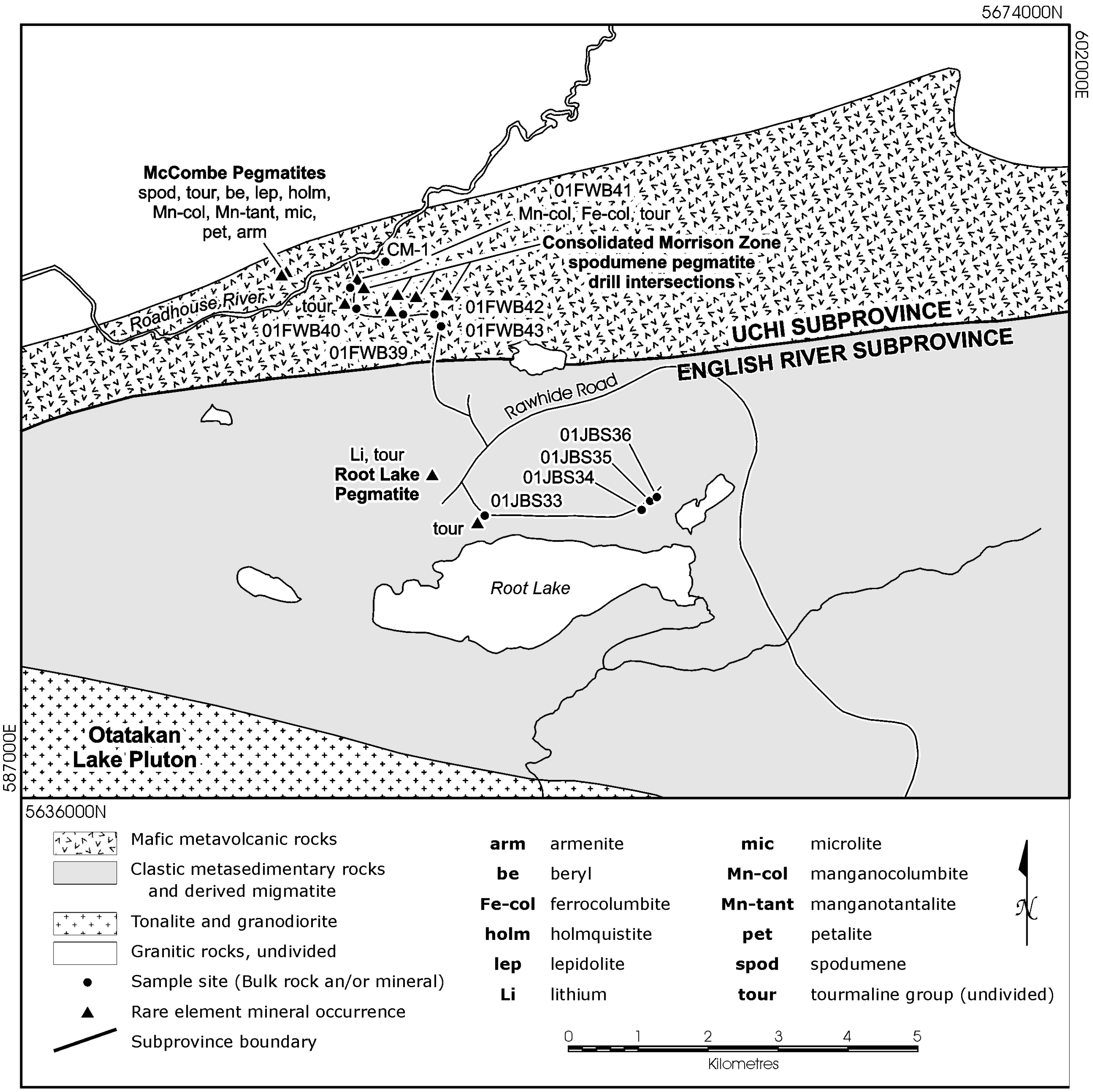


Figure 11. The location of rare-element mineral occurrences in the Root Lake area and the McCombe pegmatites.

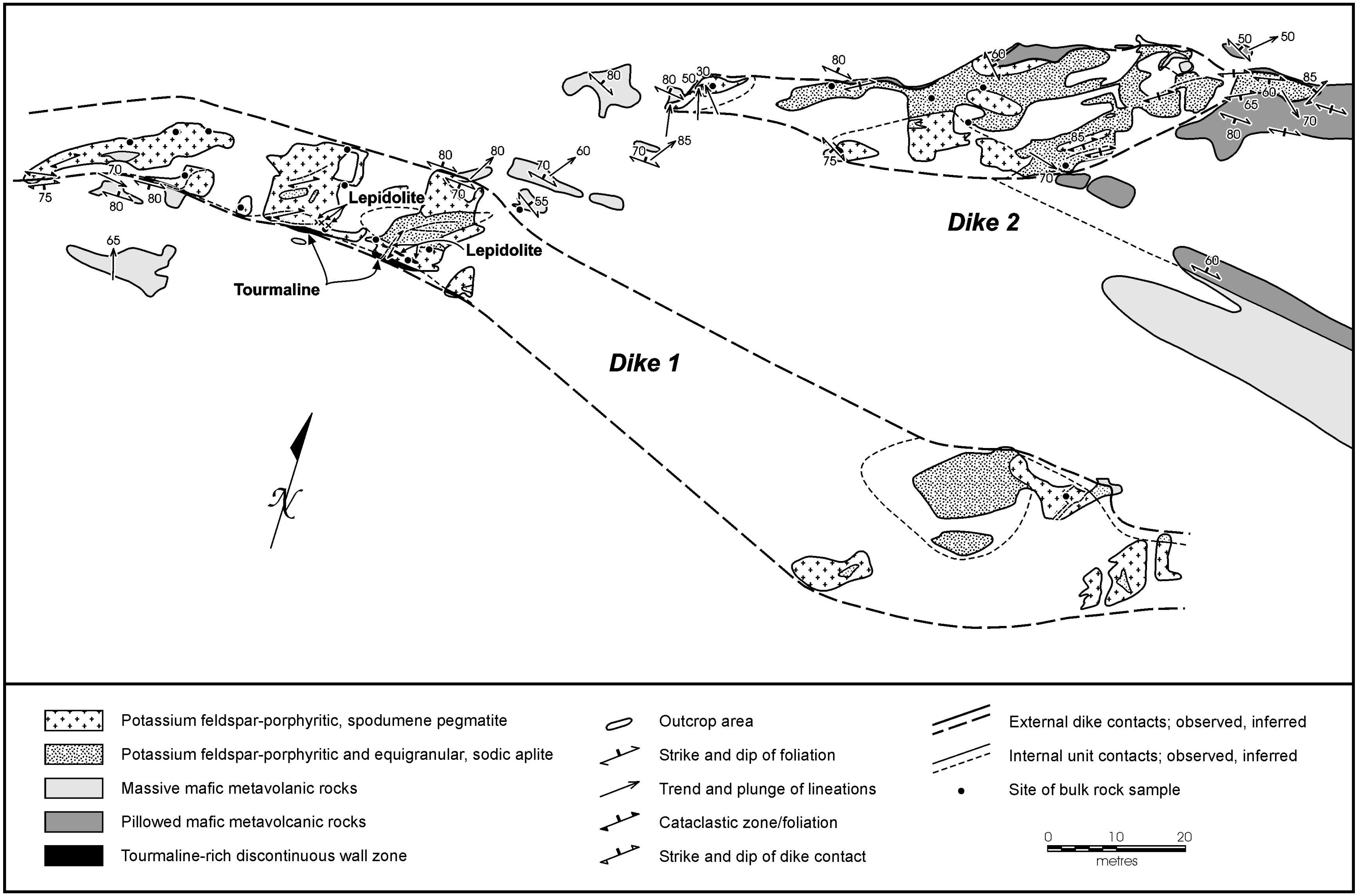


Figure 12. Detailed geology and sample sites at McCombe complex-type pegmatite Dikes 1 and 2 in the Root Lake pegmatite group.

PETROCHEMISTRY

Only 3 bulk samples of pegmatitic rock were collected during this survey due to poor access and the generally low amount of exposure south of the Roadhouse River (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20a). Two pegmatitic granite dikes hosted in clastic metasedimentary rocks from the Root Lake pegmatite group were sampled at Root Lake (localities 01-JBS-33-04 and 01-JBS-34-04) (Figure 40). These are considered to be poorly fractionated in terms of their rare-element content and of no further exploration interest.

The most fractionated sample was collected at locality 01-FWB-41-03 (UTM 591763E, 5643280N, Zone 15) near the western end of a 1 km long zone of spodumene pegmatites delineated by Consolidated Morrison Exploration in 1966 (Mulligan 1965). This aplite dike contains 104 ppm Ta, which is one of the highest value of any such discovery made during this study. The highly evolved nature of this dike is also corroborated by anomalous Li (98 ppm), Cs (111 ppm), Be (357 ppm) and Rb (617 ppm) and very low K/Rb (6.6), K/Cs (37), and Nb/Ta (0.6) ratios.

Rare-Element Mineralization

McCOMBE PEGMATITE DIKES 1 AND 2

Considerable exploration for lithium was undertaken in 1956 on these 2 dikes, which were traced on surface for a strike length of 550 m. Diamond drilling (55 holes totalling 10 442 m) established 2.297 million tons grading 1.3% Li_2O (Mulligan 1965, p.64). The best exposed part of these pegmatite dikes, situated toward the west end, have been mapped and described by Breaks and Bond (1993).

Several internal zones were observed in the 2 pegmatites (Figure 12):

- tourmalinite zone (exocontact) along dike contacts
- white feldspar-rich wall zone
- tourmaline-bearing, equigranular to porphyritic potassium feldspar, sodic aplite zone
- tourmaline-bearing, porphyritic potassium feldspar spodumene pegmatite zone
- lepidolite-rich pods and seams

Dike 1 is the largest and is intermittently exposed for a strike length of 176 m and maximum width of 15 m. Dike 2 is lens-shaped in plan and measures 19 by 87 m. Highly deformed mafic metavolcanic rocks comprise the host rocks that contain local, acicular, purple/blue holmquistite (lithium amphibole) crystals formed due to lithium-enriched fluids from the pegmatites metasomatizing the host rocks. A mafic metavolcanic rock (sample RR20) from near the southern contact of Dike 1 contains holmquistite in subhedral to euhedral grains. Armenite ($BaCa_2Al_6Si_9O_{30}{\cdot}2H_2O$) was also found in mafic metavolcanic host rocks near Dike 1 and is likely the first occurrence documented in the Superior Province of Ontario.

Twenty-four bulk rock samples selected across the 2 McCombe dikes gave a mean of 91 ppm Ta and a range of 30 to 380 ppm Ta. The highest tantalum value occurs in a tourmaline aplite pod contained within spodumene-rich pegmatite.

Mineral Chemistry

An extensive electron microprobe investigation of various minerals (1720 analyses) from the McCombe pegmatite dikes (also known as the Roadhouse pegmatites) has revealed a highly evolved rare-element system. Electron microprobe compositions from McCombe pegmatite dikes—muscovite, lepidolite, biotite (phlogopite-siderophyllite), tourmaline, garnet, columbite-tantalite and microlite—will be published in a future MRD. Mineral chemistry plots of samples from McCombe pegmatite dikes are based on unpublished data.

The pegmatites have been classified as complex-type, spodumene-subtype (classification system of Černý 1991a) on the basis of the abundance of spodumene, highly evolved potassium feldspar chemistry, coupled with the presence of local petalite, microlite, lepidolite and lithium-calcium liddicoatite. Liddicoatite is the most evolved lithium tourmaline composition found yet in the Superior Province of Ontario. Electron microprobe analyses of potassium feldspar has average Rb_2O and Cs_2O values of 1.59 weight % and 0.09 weight %, respectively.

DIKE 1

Garnet occurs in the exocontact zone within the host rock and adjacent to the pegmatite and the spodumene zone (*see* Figure 41a). Red almandine garnet (40–47% almandine, 22–34% spessartine, 24–32% grossular, 1-2% andradite, 1% pyrope) occurs in the tourmaline-rich exocontact. Exocontact sample RR10, a tourmaline-rich rock from the southern contact, contains abundant garnet with a 27.0 to 29.8% grossular component. Spessartine (59–89% spessartine, 9-40% almandine, 1–11% grossular) occurs in the spodumene zone. Fluorapatite occurs in the tourmaline-rich discontinuous wall zone and also in the spodumene zones of both dikes (Figure 42).

The tantalum-oxide minerals are mainly manganocolumbite and rarely manganotantalite in the spodumene zone (Figure 41b). Tantalum-oxide minerals in Dike 1 have a mean content of 29.32 weight % Ta_2O_5 and range of 20.12 to 69.09 weight % Ta_2O_5. The highest tantalum content is from spodumene zone sample RR15, which is zoned from a manganocolumbite core (25.38 weight % Ta_2O_5) to a manganotantalite rim (69.09 weight % Ta_2O_5). Microlite has formed primary grains (e.g., in the lepidolite pod of sample RR16 in Dike 1) or has crystallized around earlier formed columbite-tantalite, either partially replacing it, or as a tantalum-rich successor during protracted fractionation. Microlite also forms late veinlets that cut columbite-tantalite. The average Ta_2O_5 content of microlite from McCombe pegmatites is 67.99 weight %. Uranium content in the microlite is relatively high with the highest value of 4.71 weight % UO_2 obtained from spodumene zone sample RR8. Microlite from RR8 is also unusual since it contains high Sc and Ba contents (6.97 weight % Sc_2O_3 and 3.06 weight % BaO, respectively).

The composition of the exocontact tourmaline in the mafic metavolcanic rocks is controlled by the composition of the host rock. The exocontact tourmaline is mostly calcium-magnesium-rich schorl and rarely, foitite and elbaite (Figure 43a). The wall zone of the pegmatite, along the southern contact, contains 2 groups of tourmaline compositions: a) intermediate between foitite and schorl and between schorl and elbaite; and b) calcium-magnesium-rich schorl. The tourmaline grains are zoned with lithium-manganese-bearing primary magmatic cores (composition a) and calcium-magnesium-titanium-rich rims (composition b). Wall zone sample RR7 has early lithium-bearing schorl overgrown by ragged, almost poikilitic calcium-magnesium-rich schorl. The zoned tourmaline in the wall zone had a complex crystallization history. First, foitite, schorl and elbaite crystallized from a pegmatite-forming melt. This was followed by intrusion of the pegmatite-forming melt and digestion of host rocks which contaminated the melt. Calcium-magnesium-rich schorl crystallized from this contaminated melt.

The primary internal tourmaline occurs in 2 pegmatite zones: the spodumene zone and the lepidolite zone. The tourmaline in the spodumene zone has a wide range of compositions from rare foitite to common schorl to elbaite to “fluor-elbaite” (*see* Figure 43). Sample RR5 contains zoned tourmaline with a schorl core, elbaite zone and a “fluor-elbaite” rim. The most evolved tourmaline in the spodumene zone occurs in sample RR14. The tourmaline in this sample is zoned from an elbaite core to a calcium-rich manganese-bearing “fluor-elbaite” rim (up to 3.71 weight % MnO, 1.55 weight % CaO). The tourmaline in the lepidolite zone is more evolved than that in the spodumene zone. The tourmaline in the lepidolite zone ranges from elbaite to “fluor-elbaite” to liddicoatite (sample RR11) (*see* Figure 43). Liddicoatite is a calcium-lithium-fluorine-rich tourmaline phase indicating crystallization from a highly fractionated pegmatite-forming melt. Liddicoatite is rare in nature because it requires a combination of high calcium and lithium to be available. Calcium is removed early from most pegmatite melts due to crystallization of plagioclase, therefore, the melt is often already depleted in calcium when the highly fractionated lithium-rich minerals start to crystallize. With increasing fractionation, tourmaline compositions decrease in iron and increase in calcium, lithium, aluminum and fluorine, and, at an intermediate stage, contain elevated manganese contents.

Lepidolite and potassium-feldspar are rubidium- and cesium-rich, and beryl is cesium-rich in the Dike 1 pegmatite (Figure 37b). Lepidolite has 2 parageneses in Dike 1: a) as alteration rims on muscovite in the spodumene zone; and b) as massive lepidolite in the lepidolite zone. Lepidolite zone sample RR16, which is a tourmaline-rich albitite contains rubidium-cesium-rich lepidolite (average 2.72 weight % Rb_2O and average 0.82 weight % Cs_2O). Lepidolite crystallized from a highly evolved pegmatite-forming melt as the rubidium and cesium contents are comparable to that of the Tanco pegmatite (Tanco Mine, Lac du Bonnet, Manitoba), where the highest values are 3.93% Rb_2O and 0.79% Cs_2O (Rinaldi, Černý and Ferguson 1972). Sample RR16 also has the highest Rb and Cs contents in potassium-feldspar in the McCombe pegmatites (average of 2.07 weight % Rb_2O and average 0.29 weight % Cs_2O). Spodumene zone sample RR17 contains zoned beryl with a cesium-poor core with an average of 0.87 weight % Cs_2O and a cesium-rich rim with 2.31 weight % Cs_2O.

DIKE 2

Spessartine garnet (64–83% spessartine, 12–32% almandine, 2–9% grossular) only occurs in the spodumene zone of Dike 2 (*see* Figure 41a). Fluorapatite occurs in the mafic metavolcanic exocontact, spodumene zone and aplite zone (*see* Figure 42).

Wall zone sample RR22 is unique since it hosts the only ferrocolumbite from these pegmatite dikes. The data come from a single grain attached to a larger tourmaline crystal and probably represent either a relict grain or one that has recrystallized after interacting with iron-rich host rocks. In the spodumene zone, the tantalum-oxide minerals are mainly manganocolumbite and rarely manganotantalite and microlite (Figure 41b). Oxide minerals in Dike 2 have a mean Ta_2O_5 content of 37.58 weight % and a range of 22.97 to 68.51 weight % Ta_2O_5.

The exocontact tourmaline in the host rock adjacent to the plagioclase-rich wall zone of Dike 2 is fibrous calcium-magnesium-rich schorl and rare feruvite which is similar in composition to the exocontact tourmaline at Dike 1 (Figure 44a). The exocontact tourmaline also has foitite and schorl compositions with minor Ca and Mg contents similar to that in the wall zone which reflects a mixture of host rock and pegmatite fluids. The wall zone also contains primary magmatic foitite and schorl with very low Ca and Mg contents. In wall zone sample RR22, zoned tourmaline grains contain primary magmatic foitite replaced by calcium-magnesium-rich schorl with a host rock chemical signature.

The primary internal tourmaline occurs in 2 pegmatite zones: the spodumene zone and the aplite zone (Figure 44). The tourmaline in the spodumene zone ranges from schorl to elbaite. The tourmaline in the aplite is more evolved than that in the spodumene zone. The dark green prismatic tourmaline ranges in composition from rare schorl to common elbaite and “fluor-elbaite” (up to 4.06 weight % MnO, 1.53 weight % CaO). The tourmaline decreases in Fe and increases in Li, Al, Mn and F with increasing fractionation of the pegmatite-forming melt.

The highest Cs content in mica is not from a pegmatite sample at all, nor from lepidolite, but from phlogopite-siderophyllite in metasomatized mafic metavolcanic exocontact sample RR21 in which Cs contents average 1.12 weight % Cs_2O (equivalent to 10 600 ppm Cs) (*see* Figure 37b).

The presence of holmquistite, tourmaline and cesium-rich siderophyllite in the metasomatized mafic metavolcanic rocks surrounding the McCombe pegmatite indicates that lithium-boron-cesium-rich fluids migrated out of the pegmatite and altered the composition of the host rock. The presence of abundant spodumene, rubidium-cesium-rich lepidolite and rubidium-cesium-rich potassium-feldspar, minor petalite, spessartine, manganotantalite, microlite, fluorapatite, “fluor-elbaite”, liddicoatite and cesium-rich beryl indicates derivation from a highly fractionated pegmatitic melt.

CONSOLIDATED MORRISON SHOWING

The Consolidated Morrison showing occurs 2 km southeast of McCombe River Dikes 1 and 2 (*see* Figure 11). Only one grab sample (CM-1) from a large boulder of muscovite-tourmaline spodumene pegmatite was analyzed. The sample contains spessartine (69–79% spessartine, 18–26% almandine, 4–6% grossular); manganocolumbite with an average of 29.87 weight % Ta_2O_5; calcium-bearing, iron-rich elbaite and rare schorl; and muscovite with 1.42 weight % Rb_2O (*see* Figures 41 and 39). Electron microprobe compositions from Consolidated Morrison—spessartine garnet, manganocolumbite, tourmaline and muscovite—will be published in a future MRD.

Mineral Exploration Potential

The newly classified, complex-type pegmatites in the Root Lake pegmatite group indicate that the mafic metavolcanic and adjacent low- to medium-grade metasedimentary rocks of the English River Subprovince, in the Root Lake area, are areas of high potential for tantalum-rich pegmatite deposits. Exploration should focus upon lithochemical techniques, as detailed below, in order to detect blind pegmatite mineralization.

Previous exploration for lithium in the 1950s may have disregarded aplite dikes that are barren of spodumene during routine prospecting. However, such dikes constitute highly favourable targets for tantalum, therefore, the entire area should be prospected thoroughly with a focus on aplite and sodic pegmatite dikes that could host inconspicuous, but potentially economic, concentrations of tantalum-niobium-rich oxide minerals. This recommendation is enhanced significantly by the discovery, by this survey, of a highly evolved aplite dike at locality 01-FWB-41 (UTM 591763E, 5643280N, Zone 15) that contains 104 ppm tantalum (*see* Figure 11).

LITHOGEOCHEMICAL EXPLORATION

Widespread black tourmaline-quartz veins and adjacent tourmaline porphyroblasts were observed in mafic metavolcanic rocks exposed along a roughed-in logging road that crosses the mid-part of the pegmatite group and provides a 1.5 km section normal to the strike of foliation. These undeformed, tourmaline-quartz veins are typically 1 to 2 cm thick and are discordant to foliation in the host rocks.

One such quartz vein contains fine-grained black tourmaline stringers with a composition of dravite-schorl with significant calcium contents (0.84–2.29 weight % CaO) (*see* Figure 39; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 17). The calcium-magnesium-rich composition of the tourmaline suggests interaction of fluids from the pegmatite with the mafic metavolcanic host rocks. Five samples of foliated mafic metavolcanic rocks and 2 samples of tourmaline-quartz veins gave respective lithium ranges of 15 to 98 ppm Li and 47 to 328 ppm Li (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20a). A progressive increase in lithium content was also noted in a northerly direction along the road. The highest values of lithium were documented at locality 01-FWB-41 (UTM 591763E, 5643280N, Zone 15), which occurs approximately 1 km east of the McCombe pegmatite dikes. A 1 m thick tourmaline-bearing quartz-porphyritic aplite dike from this locality also contains anomalous lithium (98 ppm). Electron microprobe analysis of the prismatic fine-grained black tourmaline in the aplite dike indicate that it is calcium-bearing schorl-dravite, whereas the fine-grained black tourmaline vein within the aplite dike is more calcium- and magnesium-rich with a composition of dravite-uvite (*see* Figure 39; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 17).

It would appear from this small sample population that lithium lithogeochemistry could be an effective geochemical tool in the exploration for rare-element pegmatites hosted by mafic metavolcanic rocks in the Root Lake area. The chemistry of tourmaline-rich veins, which has not been utilized in exploration to the authors' knowledge, may potentially be useful as a guide to finding exposed or blind rare-element pegmatite deposits in the area, as tourmaline is present in the McCombe pegmatites and in veins in the surrounding mafic metavolcanic rocks.

EASTERN LAKE ST. JOSEPH AREA

This area of the Uchi–English River subprovincial boundary zone has potential for rare-element pegmatite mineralization owing to widespread peraluminous pegmatite dikes that, in part, may be related to large pegmatitic granite plutons (Twiname Lake stock and Caron Lake pluton: Kay and Stott 1985; Stott 1996). A detailed description of these rocks and a preliminary geochemical evaluation is provided by Kay and Stott (1985). The present survey undertook a brief investigation of pegmatite dikes in 2 areas: eastern Lake St. Joseph and at the East Pashkokogan Lake lithium occurrence (Figure 13).

Peraluminous Granite Plutons

The Twiname Lake stock (65 km^2 in size) and Caron Lake pluton (145 km^2 in size) represent the largest pegmatitic granite masses recognized in the eastern Lake St. Joseph area (Kay and Stott 1985). Numerous small pegmatite dikes, 6 to 70 m wide, occur in the Soules Bay–Doghole Bay area of eastern Lake St. Joseph and may be coeval with these plutons. For example, at locality 01-JBS-19 (UTM 692310E, 5668455N, Zone 15), on an island in Lake St. Joseph, an extensively sheared and boudinaged white pegmatite dike is hosted by metawacke (*see* Figure 13). This 3 to 5 m thick dike consists of coarse-grained, green muscovite-rich potassic pegmatite gradational into quartz-rich patches with blocky potassium feldspar and white aplite containing garnet.

Tourmaline within pegmatite dikes and adjacent exomorphic aureoles developed in metasedimentary and metavolcanic host rocks were noted by Kay and Stott (1985, p.33-34). A significant example occurs on a small island (locality 01-JBS-20: UTM 686483E, 5660530N, Zone 15) about 2 km west of the entrance of Ace Lake (*see* Figure 13) where a 10 m thick, pale pink dike of tourmaline-muscovite pegmatitic leucogranite is emplaced into foliated mafic metavolcanic rocks. The dike contains impressive single and radiating clusters of black tourmaline up to 2 by 23 cm in size and graphic intergrowths of quartz-potassium feldspar megacrysts up to 35 by 50 cm in size. The pegmatite contact is characterized by an 8 cm thick exomorphic aureole composed of tourmaline, biotite and muscovite.

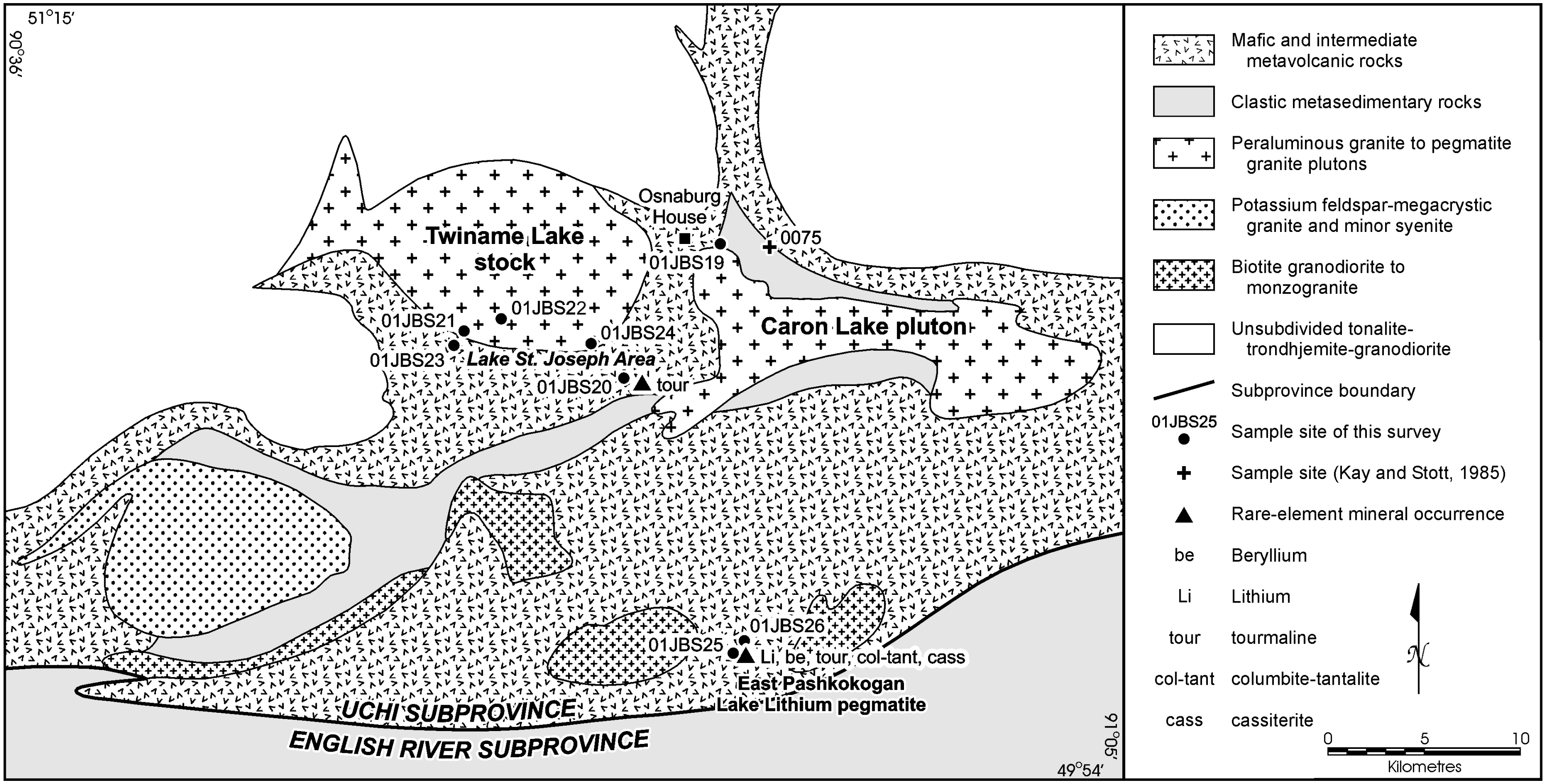


Figure 13. General geology and location of peraluminous granite masses and rare-element mineralization in the English River–Uchi subprovincial boundary zone near Lake St. Joseph and East Pashkokogan Lake.

The Twiname Lake stock is an ovoid, 9 by 15 km, pegmatitic granite mass that is dominated by biotite-muscovite and muscovite-biotite pegmatitic leucogranite. In the Twiname pegmatitic leucogranite, the coarse-grained red garnet is dominantly almandine in composition (55–71% almandine, 24–39% spessartine, 3–4% pyrope, 1–2% andradite) (Figure 45a). This unit is gradational into pockets of potassic pegmatite, quartz-rich patches and layers of garnet-biotite, fine-grained leucogranite. Slender biotite-rich blades typically developed in radiating aggregates ("crowfoot texture") were noted at locality 01-JBS-24 (UTM 687617E, 5663609N, Zone 15) on Lake St. Joseph and represents a common texture in fertile granite plutons (Černý et al. 1981). The Caron Lake pluton, in contrast, is fine- to medium-grained and contains muscovite, biotite, local garnet and tourmaline (Kay and Stott 1985).

PETROCHEMISTRY

Five bulk rock samples were collected from pegmatitic dikes in the vicinity of the peraluminous granite plutons (*see* Figure 13). Bulk compositions for Lake St. Joseph area are published in Table 20a of MRD 111 (Tindle, Selway and Breaks 2002) and include the Lake St. Joseph garnet aplite, muscovite potassic pegmatite and garnet muscovite potassic pegmatite and the East Pashkokogan spodumene pegmatite: apatite tourmaline aplite and tourmaline spodumene zone. The pegmatite dike at locality 01-JBS-19 (UTM 692310E, 5668455N, Zone 15) is possibly coeval with the Caron Lake pluton. Petrochemical data indicate modest chemical evolution for the potassic pegmatite at locality 01-JBS-19: 67 ppm Li, 973 ppm Rb, 21 ppm Cs and 65 ppm Nb. A pegmatite dike investigated by Kay and Stott (1985, p.33, sample 0075B) is situated 3 km to the east of sample location 01-JBS-19 and contains anomalous levels of most rare-elements, such as 50 ppm Cs, 36 ppm Nb, 23 ppm Ta, 15 ppm Be and 5 ppm Li. Bulk rock samples from the Twinname Lake pluton could not be obtained and, hence, mineral chemistry (potassium feldspar) serves as a proxy for fractionation interpretation.

Garnet-muscovite pegmatite dikes, encountered about 1 km south of the East Pashkokogan Lake spodumene pegmatite, were determined to have anomalous rare-element content. A sample from this locality, 01-JBS-25 (UTM 693245E, 5648182N, Zone 15), contains anomalous levels of Be (94 ppm), Rb (796 ppm), Cs (61 ppm), Sn (21 ppm), Nb (34 ppm) and Ta (14 ppm). The significantly fractionated nature of this pegmatite is also supported by low K/Rb (33), K/Cs (423) and Nb/Ta (2.3) ratios.

MINERAL CHEMISTRY

Five potassium feldpar samples were collected during a brief investigation of the eastern Lake St. Joseph area (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21a). Four of the five samples were collected from the Twinname Lake pegmatitic granite pluton (localities 01-JBS-21 and 01-JBS-24) and related exocontact dikes (localities 01-JBS-21 and 01-JBS-22). Rubidium contents of the samples revealed modest enrichment (mean 600 ppm; range 543–676 ppm) and low cesium (mean 12 ppm; range 7–17 ppm) (Figure 35b). However, the most evolved potassium feldspar came from locality 01-JBS-20 (UTM 686484E, 5660530N, Zone 15) with bulk rubidium and cesium contents of 1381 ppm Rb and 153 ppm Cs in a tourmaline pegmatite near Ace Lake. The cesium value is the highest for any potassium feldspar sampled in the Uchi–English River subprovincial boundary zone during the present study.

Electron microprobe compositions of minerals from Lake St. Joseph are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11), fluorapatite (*see also* Table 10), tourmaline (*see also* Table 17) and ferrocolumbite (*see also* Table 8a).

An island in Lake St. Joseph, contains potassic pegmatite with coarse-grained green muscovite and white aplite (locality 01-JBS-19: UTM 692310E, 5668455N, Zone 15). The muscovite potassic pegmatite contains red almandine garnet (58–64% almandine, 33–41% spessartine, 0–2% pyrope) and minor fluorapatite with 0.9 to 1.0 weight % MnO (Figures 45a and 46). The garnet and fluorapatite compositions in the aplite are similar to those in the potassic pegmatite. The aplite contains fine-grained red almandine garnet (58–62% almandine, 36–39% spessartine, 1–2% pyrope) and minor fine-grained blue fluorapatite with manganese-rich rims (0.5 weight % MnO in core; 1.2 weight % MnO in rim). The aplite also contains medium-grained black schorl with minor Mg content and platy fine-grained black ferrocolumbite (10 weight % Ta_2O_5) (Figures 47 and 45b).

A small island about 2 km west of the entrance of Ace Lake, locality 01-JBS-20, is characterized by prismatic euhedral splayed coarse-grained black schorl (*see* Figure 47). The tourmaline has quartz and green muscovite inclusions parallel to the length of the crystals. In thin section plane-polarized light, the tourmaline has a navy blue core and an almost blue-black rim. The core is slightly enriched in Al and depleted in Na and the rim is slightly enriched in Ca, Na, Mg, Fe and F. This suggests that the rims were slightly contaminated by interaction with the mafic metavolcanic host rocks. The black schorl is associated with red spessartine (52–66% spessartine, 32–45% almandine, 1–2% andradite) (*see* Figure 45a). The presence of schorl with very low Mg contents and spessartine garnet indicates that the pegmatitic leucogranite did not interact with host rocks to a significant degree and its composition likely reflects crystallization from an uncontaminated, moderately fractionated pegmatitic melt (Černý and Hawthorne 1982; London, Morgan and Wolf 1996; London 1999).

The biotite-rich mafic metavolcanic exocontact zone adjacent to the tourmaline pegmatitic leucogranite contains tourmaline with a composition of calcium-bearing schorl-dravite (*see* Figure 47). Such a composition is consistent with boron-rich fluids from the pegmatite-forming melt that invaded the host rocks and formed tourmaline early in the development of the pegmatite.

East Pashkokogan Lake

A pegmatite dike (3 to 4 m wide) occurs in the southeastern part of East Pashkokogan Lake (locality 01-JBS-25: UTM 693245E, 5648182N, Zone 15) about 1 km south of the East Pashkokogan spodumene pegmatite. The spodumene-free pegmatite dike consists of pink fine-grained potassium feldspar, plagioclase, quartz and minor green muscovite. Electron microprobe compositions of minerals from this pegmatite dike are published in MRD 111 (Tindle, Selway and Breaks 2002): potassium feldspar (*see also* Table 12), columbite-tantalite (*see also* Table 8a) and fluorapatite (*see also* Table 10). The potassium feldspar contains 0.4 to 0.6 weight % Rb_2O and 0 to 0.6 weight % Cs_2O. The pegmatite dike also contains fine-grained black ferrocolumbite (26.2–27.7 weight % Ta_2O_5), and black platy ferrocolumbite to ferrotantalite (48–56 weight % Ta_2O_5) associated with black veins of unidentified minerals (*see* Figure 45b). Most of the fluorapatite is manganese-free, although Mn contents can reach up to 0.7 weight % MnO (*see* Figure 46).

Another pegmatite dike (1 to 2 m wide) (locality 01-JBS-27: UTM 693445E, 5648332N, Zone 15) occurs 0.5 km from the East Pashkokogan spodumene pegmatite. The pegmatite dike consists of quartz, white potassium feldspar with red hematite staining and minor blue fluorapatite (1.4–1.7 weight % MnO) (*see* Figure 46). Green muscovite occurs along fractures in the pegmatite dike. Aplite and biotite muscovite granite also occur at this locality. All of these granitic bodies intrude metasedimentary host rocks.

The aplite contains black tourmaline with a composition of schorl-elbaite with almost no Mg and Ca content (*see* Figure 47; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 17). Some of the tourmaline in the aplite is zoned with elbaite cores and schorl rims. Fine-grained black tourmaline occurs along the edge of a felsic vein (1.5 cm wide) that has intruded metasedimentary host rocks. The schorl contains significant Li contents. Brown tourmaline occurs in the host rocks and has a composition of schorl-feruvite, which is more calcium-magnesium-rich than the tourmaline in the felsic vein.

East Pashkokogan Spodumene Pegmatite

The main rare-element occurrence in the eastern Lake St. Joseph area is the East Pashkokogan Lake spodumene pegmatite. Goodwin (1965, p.55) reported an average of 1.25% Li_2O from a chip sample collected across the exposed 16 m width of the pegmatite. Kay and Stott (1985, p.30, p.32-33) mapped the pegmatite in detail and delineated northeast-striking layers of spodumene pegmatite and aplite. Five grab samples, taken by these workers, gave an average of 33 ppm Ta within a range of 16 to 80 ppm Ta.

The East Pashkokogan spodumene pegmatite consists of alternating layers of spodumene and aplite zones and stringers of tourmaline. The spodumene zone contains abundant coarse-grained green and white spodumene (up to 2.5 cm in size), coarse-grained potassium-feldspar (5 to 8 cm in size), albite and quartz. The spodumene is often altered to a waxy dark green mineral. The spodumene zone also contains dark green to black tourmaline, silver and green muscovite, fine-grained zircon, tantalum-tin oxide minerals, fine-grained montebrasite, fluorapatite and rare cesium-rich beryl. The white aplite contains fine-grained dark green to black tourmaline and fluorapatite.

MINERAL CHEMISTRY

Electron microprobe compositions of minerals from East Pashkokogan spodumene pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): beryl (*see also* Table 6), cassiterite (*see also* Table 7), columbite-tantalite (*see also* Table 8a), tourmaline (*see also* Table 17), muscovite (*see also* Table 13a) and potassium feldspar (*see also* Table 12).

The presence of cesium-rich beryl (1.6–3.2 weight % Cs_2O), elbaite-schorl, platy manganocolumbite (18–51 weight % Ta_2O_5) and rare manganotantalite and tantalum-bearing cassiterite (1.4–1.6 weight % Ta_2O_5) in the spodumene layers indicate the pegmatite underwent a moderate degree of fractionation (*see* Figures 47 and 45b). The fact that the elbaite-schorl has low Mg and Ca contents indicates that the melt from which it crystallized was not contaminated by material from the host rocks. The elevated Rb and Cs contents in the muscovite and potassium feldspar is consistent with a moderate degree of fractionation (*see* Figure 37b). The green muscovite in the spodumene layer contains 0.3 to 0.6 weight % Rb_2O and 0 to 0.3 weight % Cs_2O, whereas the potassium feldspar contains 0.8 to 0.9 weight % Rb_2O and 0.1 to 0.3 weight % Cs_2O. The tourmaline in the aplite is mostly elbaite-schorl and rarely fluorine-rich elbaite-schorl, magnesium-rich schorl and dravite-schorl, which indicates some contamination of the pegmatite melt by the host rocks (*see* Figure 47).

Mineral Exploration Potential

Exploration for rare-element mineralization is warranted in the eastern Lake St. Joseph area in the vicinity of the Twiname Lake stock and Caron Lake pegmatitic granite pluton. This recommendation is based upon previous work of Kay and Stott (1985) and Stott (1996), in addition to modestly evolved pegmatites documented during the present survey. Furthermore, the area around the East Pashkokogan Lake spodumene occurrence should be scruitinized for further pegmatite dikes that could be similar to those documented at locality 01-JBS-25 (UTM 693245E, 5648182N, Zone 15).

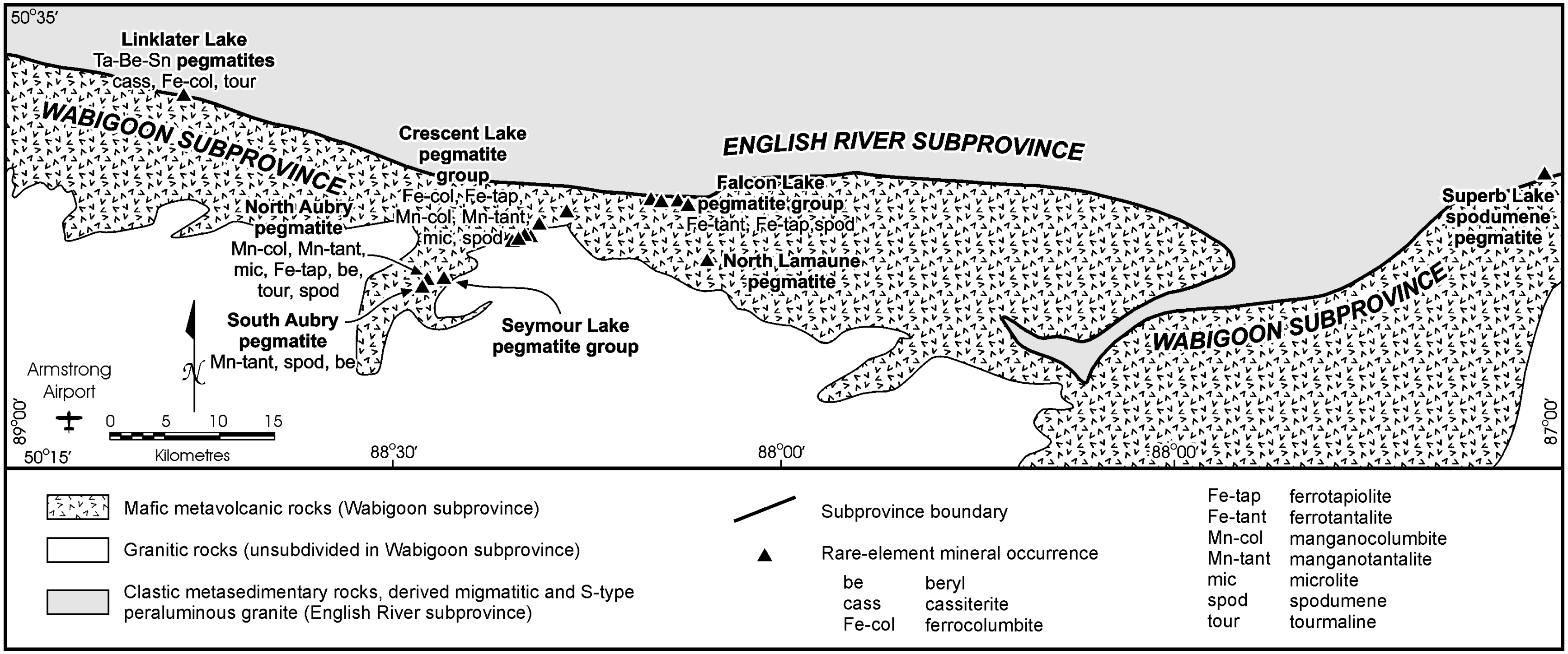


Figure 14. General geology and location of peraluminous granite masses and rare-element mineralization in the Wabigoon–English River subprovincial boundary zone between Linklater Lake and Superb Lake (geology generalized *after* Parker and Stott 1998).

Wabigoon–English River Subprovincial Boundary Zone

INTRODUCTION

This boundary zone has rare-element mineralization distributed over a 130 km strike length between Linklater Lake to Superb Lake near Nakina (Figure 14). The rare-element mineralization in this region has not been investigated in detail since the 1950s with the exception of the Superb Lake spodumene pegmatite (Stott and Parker 1997).

LINKLATER LAKE COLUMBITE-BERYL-TOURMALINE-CASSITERITE PEGMATITES

Cassiterite-bearing pegmatites were discovered near the southeastern end of Linklater Lake (*see* Figure 14) in 1941 by prospector Stan Johnson (Chisholm 1948). The 15 by 500 m area was extensively examined for tin mineralization in 1948 by San Antonio Gold Mines Limited, which reported grades up to 1.83% Sn in a channel sample across a 15 cm width (Chisholm 1948, p.3). However, the tantalum potential of the area had not been given adequate consideration until recent work by O'Reilly (2000).

An extensive swarm of pale to deep pink, tourmaline-muscovite pegmatite dikes are concordant to intensely foliated and sheared metawacke host rocks. The host rocks form part of an extensive metasedimentary unit that can be traced on surface for about 40 km, from Rove Lake east to Ratte Lake (Pye et al. 1965), and varies between 0.6 and 1 km in width. This unit was incorrectly mapped as "quartzite" by Gussow (1940). The pegmatites are 0.2 to 1 m thick, variably sheared, boudinaged and typically exhibit a protomylonite texture marked by augen of potassium feldspar and plagioclase up to 2.5 by 4 cm and lenses of grey quartz up to 1 to 2 mm by 5 cm.

Petrochemistry

Five bulk rock analyses were collected from these mildly peraluminous pegmatites (mean A/CNK = 1.111) during the present study (Figure 48; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20b). Four of the five samples were collected from the main tin-bearing zone (muscovite granite) that was investigated in 1948. The fifth sample consists of white, green muscovite-bearing potassic pegmatite that is located on the shore of Linklater Lake near an outpost cabin (locality 01-FWB-94: UTM 374585E, 5602003N, Zone 16). This 20 to 30 cm wide, relatively undeformed dike was found to be the most evolved granitic pegmatite in the area in terms of its Ta (71 ppm) content and very low Nb/Ta ratio of 0.54. Furthermore, anomalous levels of Be (110 ppm), Cs (45 ppm) and Sn (14 ppm) in this dike would appear to support a linkage with the highly deformed muscovite granite dikes that occur 100 m south of this potassic pegmatite dike.

The muscovite deep-pink granite dikes, which host the cassiterite mineralization, reveal a degree of fractionation typical of beryl-type pegmatites (Černý 1989a). This is indicated by modestly evolved K/Rb (mean 83; range 67–115), K/Cs (mean 2883; range 1750–4541) ratios and anomalous levels of Be (mean 130 ppm; range 66–250 ppm), Rb (mean 525 ppm; range 233–599 ppm), Cs (mean 17 ppm; range 12–45), Nb (mean 54 ppm; range 36–67 ppm), Ta (mean 26 ppm; range 8.5–36 ppm) and Sn (mean 50 ppm; range 14–74 ppm). Nb/Ta ratios are, however, considerably evolved (mean 2.6; range 1.7–4.2) and, thus, the area merits a thorough investigation of pegmatitic rocks that could potentially contain tantalum mineralization.

Lithium levels are mostly low (4–15 ppm) except for a value of 120 ppm Li that was detected in a 1 cm thick, biotite-rich exocontact within 1 cm of the contact of a cassiterite-bearing muscovite granite dike in the main cassiterite-bearing zone.

Mineral Chemistry

Electron microprobe compositions of minerals from Linklater Lake pegmatite dikes are published in MRD 111 (Tindle, Selway and Breaks 2002): cassiterite (*see also* Table 7), columbite-tantalite (*see also* Table 8b), garnet (*see also* Table 11), fluorapatite (*see also* Table 10), muscovite (*see also* Table 13a), biotite (phlogopite-siderophyllite, *see also* Table 13d) and tourmaline (*see also* Table 17).

Accessory phases in the pegmatite include almandine (56–70% almandine, 27–39% spessartine, 2–3% pyrope, ~1% andradite), fluorapatite (up to 2.8 weight % MnO), alluaudite [$NaCaFe^{2+}(Mn^{2+}, Fe^{2+}, Fe^{3+}, Mg)_2 (PO_4)_3$] and black tourmaline with a composition of calcium-bearing schorl-dravite (Figures 49a, 50a and 51). Cassiterite is dark brown to black, generally fine grained and inconspicuous. Contents of Ta_2O_5 in the cassiterite vary from 0.3 to 1.0 weight %, which is low when compared with cassiterite from the Separation Rapids pegmatite group (up to 11 weight % Ta_2O_5: Tindle and Breaks 2000).

A small electron microprobe data set of 37 analyses of various oxide minerals from the pegmatite confirms the presence of ferrocolumbite and ferrotantalite (Figure 49b) that exhibit a range of Ta/(Nb+Ta) ratios (0.177–0.616) and are comparable to the iron suite described by Tindle and Breaks (1998) at Separation Lake. The ferrocolumbite has an average of 44.80 weight % Ta_2O_5 and a range of 20.51 to 58.76 weight % Ta_2O_5, whereas the ferrotantalite has an average of 57.58 weight % Ta_2O_5 and a range of 55.57 to 58.76 weight % Ta_2O_5.

The biotite-rich metapelite exocontact contains almandine (66–71% almandine, 23–30% spessartine, 2–5% pyrope, ~1% andradite), fluorapatite (up to 0.2 weight % MnO) and black calcium-rich schorl-dravite (*see* Figures 49a, 50a and 51). Along the shore of Linklater Lake, there is a massive black tourmaline layer in a quartz sheet intruding the metapelite host rock. This tourmaline is the most calcium- and magnesium-rich tourmaline at Linklater Lake with a composition of dravite-uvite and dravite-schorl (*see* Figure 51). This indicates that the tourmaline layer in the quartz sheet is more primitive than the tourmaline in the pegmatites, and has a lower economic potential.

Mineral Exploration Potential

The metawacke-meta-arkose metasedimentary rocks of the Linklater Lake area are widely distributed along the English River–Wabigoon subprovincial boundary and represent the only known host rocks for the cassiterite-bearing pegmatites in the area. Geological mapping was conducted only in the western part of this unit (Sutcliffe 1988). The area east of Hollingsworth Lake has not received detailed coverage since the work of Gussow (1940). Further examination of this metasedimentary host is warranted for additional occurrences of beryl-type pegmatites that could contain tantalum- and tin-bearing oxide minerals particularly in light of the significantly anomalous tantalum value of 71 ppm detected in potassic pegmatite on the shore of Linklater Lake.

SEYMOUR LAKE PEGMATITE GROUP

This pegmatite group (*see* Figure 14), with a minimum extent of 0.8 by 1.8 km, comprises 3 known spodumene pegmatites called the North Aubry, the South Aubry and the Seymour pegmatites (Pye 1968, p.47-49). These pegmatites were previously evaluated for lithium in the 1950s by the Anaconda Company (Canada) Limited, however, their potential for tantalum has only been examined recently by Linear Resources Inc. (www.linearresources.com).

North Aubry Pegmatite

Two large pegmatite dikes of the complex-type, spodumene-subtype (P. Černý, University of Manitoba, personal communication, 2002) are situated 2.7 km west of Seymour Lake along a prominent ridge that has approximately 100 m of local relief (*see* Figure 14). Exploration for tantalum by Linear Resources Inc. in the summer of 2001 exposed the North Aubry pegmatite in 6 trenches over 210 m strike length and the South Aubry pegmatite in 4 trenches over 180 m strike length. Additional trenches were dug and examined in the summer of 2002 (*see* Breaks, Selway and Tindle 2002). Trench numbering, referred to in this report, follows that of Linear Resources Inc.

The North Aubry pegmatite varies from 15 to 75 m in width and is at least 265 m in strike length. The South Aubry pegmatite, situated 600 m to the south, is at least 120 m in strike length with a width of up to 50 m. The highest tantalum values found by Linear Resources Inc. occur in trench NA-5 of the North Aubry pegmatite where Ta values in 15 samples ranged from 0.029 to 5.7 weight % Ta_2O_5. An average of 2.39 weight % Ta_2O_5 was obtained from four 1 m long channel samples near the eastern end of trench NA-5 (Linear Resources Inc., News Release, www.linearresources.com, July 3, 2001). Further results from other trenches (Linear Resources Inc., News Release, www.linearresources.com, July 16, 2001) include 0.036 weight % Ta_2O_5 across 5.7 m in trench NA-4; 0.027 weight % Ta_2O_5 across 5.1 m in trench NA-3; 0.42 weight % Ta_2O_5 across 2 m in trench NA-4; and 0.026 weight % Ta_2O_5 across 17.6 m in trench NA-2. The South Aubry pegmatite has also been extensively channel sampled by Linear Resources Inc. who reported Ta_2O_5 contents up to 0.028% across 1 m.

The North Aubry pegmatite can be divided into several internal pegmatite zones, which, from the outermost to innermost zone, are

- thin quartz-rich border zone (~1 cm thick)
- outer sodic zone (the albite is aplite or cleavelandite), aplite dikes, aplite pods, miarolitic cavities
- quartz-muscovite zone (identified in the summer of 2002 and discussed by Breaks, Selway and Tindle (2002))
- muscovite pods
- quartz pods
- spodumene main zone: further subdivided into potassium feldspar zone, albite-spodumene zone, potassium feldspar-spodumene zone after field work in summer 2002 by Breaks, Selway and Tindle (2002))
- inner core zone: coarse tantalite, pink beryl, cleavelandite and spodumene, highly evolved zone (found only in trench NA-5)
- corona zone (found only in trench NA-5, identified in the summer of 2002 and discussed by Breaks, Selway and Tindle (2002))

The spodumene main zone comprises 90% of the North Aubry pegmatite. Work by Breaks, Selway and Tindle (2002) indicates the main zone can be futher subdivided. The main zone consists of a coarse muscovite-green spodumene-quartz-blocky potassium feldspar-cleavelandite assemblage augmented by layers and irregular masses of primary aplite, quartz-rich pods and sparse muscovite-rich, greisen-like pods. Randomly oriented, coarse green spodumene, up to 35 by 35 cm in basal sections and 20 cm by 1.6 m parallel to the long dimension, comprise 30 to 40 volume % of the main pegmatite zone.

PETROCHEMISTRY

Sixteen bulk rock samples were collected from the North Aubry and South Aubry pegmatites (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20b). Thirteen of the sixteen samples were collected from the North Aubry pegmatite. Most of the samples collected from the North Aubry pegmatite, during this study, consist of aplites, as coarse grain size problems minimized the collection of representative samples of the main spodumene pegmatite unit. However, 3 consecutive channel cuts (1 m length for each) across the spodumene pegmatite in trench NA-5 gives some data on their bulk chemical features (localities 01-FWB-90, 01-FWB-91 and 01-FWB-92: UTM 396892E, 5585124N, Zone 16). Sodium-rich aplites are a useful unit to sample when exploring for tantalum, as their oxide minerals commonly exhibit preferential concentration in sodium-rich units of a pegmatite. Furthermore, due to the fine-grain size of aplite, compositionally representative samples are readily obtainable.

Aplites from the North Aubry pegmatite reveal typical high Na_2O (mean 10.16 weight %; range 7.88–11.39 weight %) (Figure 52a). Rubidium (mean 649 ppm; range 34–2954 ppm) and cesium (mean 91 ppm; range 8–250 ppm) have variable contents that are dependant upon modal quantity of muscovite and potassium feldspar which are typically rare or absent in sodium-rich aplite. However, the highly evolved nature of the aplite is demonstrated by very low K/Rb (mean 14.5; range 9–39) and K/Cs (mean 79; range 36–162) ratios. Tantalum (mean 191 ppm; range 62–212 ppm) values indicate pronounced enrichment relative to niobium (mean 106 ppm; range 50–150 ppm), resulting in extremely low Nb/Ta ratios (mean 0.6; range 0.3–0.8). The low Nb/Ta ratio indicates that the pegmatite is highly fractionated and the elevated Ta contents indicate that the pegmatite has abundant tantalum-oxide minerals.

The spodumene pegmatite from North Aubry trench NA-5 (*see* Figure 14) represents the inner core zone that is enveloped by the outer sodic zone and is the most fractionated zone in the North Aubry pegmatite. This is revealed by the lowest K/Rb (mean 7.2; range 6.6–7.9), K/Cs (mean 18; range 6–33) and Nb/Ta (mean 0.12; range 0.05–0.2) ratios in this zone. Cesium levels are especially elevated (mean 1323 ppm; range 271–3284 ppm) and are concentrated in cesium-rich, pink beryl and potassium feldspar.

MINERAL CHEMISTRY

Analyses of 13 bulk potassium feldspar samples from the North Aubry pegmatite show pronounced enrichment in Rb (mean 10 367 ppm; range 9204–11 267 ppm) and Cs (mean 528 ppm; range 312–1125 ppm) indicating that this pegmatite is one of the most evolved pegmatites that were investigated during the current study (Figure 52b; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21b). This is corroborated by very low K/Rb (mean 10.6) and K/Cs (mean 225) ratios in the potassium feldspar. The mean rubidium data reveal a general southward increase in the fractionation sequence of the pegmatite, for example, from trench NA-4→ trench NA-3 → trench NA-1, the rubidium and cesium values in potassium feldspar show the following enrichments:

Trench NA-4:	9204 ppm Rb; 312 ppm Cs
Trench NA-3:	9960 ppm Rb; 585 ppm Cs
Trench NA-1:	10, 898 ppm Rb; 516 ppm Cs

Cesium values in potassium feldspar also generally increase southward. Although samples from trench NA-3 show a slightly higher mean cesium content than trench NA-1, the overall trend should expectedly increase southward from trench NA-4 (northernmost trench) to trench NA-5 (southernmost trench). In trench NA-5, beryl and muscovite contain high cesium values (up to 3.0 weight % Cs_2O in beryl and up to 0.4 weight % Cs_2O in muscovite), which may also be elevated in co-existing potassium feldspar.

Electron microprobe compositions of minerals from North Aubry pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): beryl (*see also* Table 6), columbite-tantalite (*see also* Table 8b), ferrotapiolite (*see also* Table 9), fluorapatite (*see also* Table 10), muscovite (*see also* Table 13a), lepidolite (*see also* Table 13b), microlite (*see also* Table 14), tourmaline (*see also* Table 17) and strüverite (*see also* Table 16).

The spodumene main zone contains abundant spodumene, potassium feldspar and quartz, and common muscovite. Accessory minerals in the spodumene main zone include pale green, white and rare pale pink beryl up to 15 by 17 cm in basal sections and containing up to 3.2 weight % Cs_2O (01AGT10-17); manganocolumbite; manganotantalite; lepidolite; fluorapatite (1.0–6.1 weight % MnO); and minor zircon (Figures 54a and 53). The potassium feldspar and mica in the spodumene main zone are enriched in Rb and Cs. Bulk analyses of blocky potassium feldpar indicate 1.0–1.2 weight % Rb_2O and 0.03–0.12 weight % Cs_2O, as discussed above (*see* Figure 52b; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21b). Coarse-grained mica (probe data from sample 01-AGT-10-07) from trench NA-1 consist of muscovite cores (to 1.3 weight % Rb_2O, 0.01 weight % Cs_2O, 1.5 weight % F, 0.6 weight % MnO) with lepidolite rims that are significantly enriched in rare-elements, Mn and F (to 2.2 weight % Rb_2O, 0.5 weight % Cs_2O, 3.7 weight % F, 1.5 weight % MnO) (Figure 53b). Tantalum versus cesium contents in muscovite are an excellent exploration tool, as samples with >65 ppm Ta and >50 ppm Cs have a high probability to contain Ta-Nb mineralization (Gordiyenko 1971). Bulk coarse-grained muscovite analyses from the spodumene main zone have values ranging from 129 to 149 ppm Ta and 526 to 561 ppm Cs (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 22).

Primary sodic aplite occurs in pods, up to 60 cm by 1 m, and in layers within the spodumene-rich zone that are up to 1 m thick and at least 6 m in length. This unit mainly consists of sugary quartz and albite with minor blue fluorapatite and muscovite (*see* Figure 53). Notable concentrations of black, manganocolumbite crystals (about 1 cm long) occur along the contact between primary aplite pods and quartz-rich masses, that envelope the aplite pods, near the eastern end of trench NA-2 (*see* Figure 54a). The apatite-muscovite aplite pods contain 62 to 185 ppm Ta.

Quartz-rich masses consist of 70 to 80% grey quartz and typically contain the coarsest blocky potassium feldspar crystals (up to 95 cm by 2.5 m). Petrographic evidence suggests the following sequence of mineral crystallization: apatite, early quartz, early oxide mineral → spodumene → potassium feldspar, albite → beryl → late oxide mineral → late quartz.

Miarolitic cavities, up to 5 by 6 cm in size, rarely occur in cleavelandite-rich aplite in trenches NA-4 and NA-5 and are mainly lined with cleavelandite crystals with minor muscovite and tourmaline, all of which are coated by a drusy film of hematite. The miarolitic cavities are located close to the contact with the mafic metavolcanic host rocks and contain coarse-grained black tourmaline (1.5 cm long), which is zoned from a foitite core, through a calcium-bearing schorl zone, to a dravite rim (*see* Figure 51). This observation suggests that the pegmatite-forming melt may have initially crystallized primary magmatic foitite in the cavities and then became contaminated with Ca and Mg from the mafic metavolcanic host rocks resulting in the crystallization of the calcium-bearing schorl zone followed by a dravite rim. A few centimetres away from the tourmaline-bearing miarolitic cavity is a cavity containing more fractionated minerals, such as tiny primary microlite inclusions in quartz, adjacent to a white cesium-rich beryl (0.5–2.3 weight % Cs_2O) and minor fluorapatite in cleavelandite (*see* Figure 53a).

A fine-grained reddish aplite dike (0.3–0.6 m thick) hosted by mafic metavolcanic rocks is located near the east end of trench NA-4. A bulk sample collected from this aplite contains elevated Ta (278 ppm Ta). The east end of North Aubry trench NA-2 has a thin fine-grained granitic border zone with accessory fluorapatite, biotite, green muscovite and manganocolumbite to manganotantalite (*see* Figures 53 and 54a).

The most spectacular manganotantalite mineralization was encountered in trench NA-5. The North Aubry pegmatite is partly exposed in this trench as erosional remnants of relatively horizontal thin sheets that strike 155° with a dip of 15° southwest. At the east end of this trench, the pegmatite is zoned, marked by an outer sodic zone that is a 60 cm thick sodic aplite unit composed of quartz, cleavelandite and sparse, platy fine-grained black oxide mineral grains, lepidolite and fluorapatite (*see* Figure 53). The aplite symmetrically envelops an inner core zone that is at least 3.5 m thick and consists of abundant spodumene blades (up to 1.6 m long), blocky potassium feldspar, quartz and minor coarse-grained manganotantalite, cleavelandite, rare cesium-rich beryl, muscovite and strüverite (1.5–8.2 weight % Ta_2O_5) (*see* Figure 54a and 53b). Several coarse crystals of pale pink cesium-rich beryl (2.7–3.0 weight % Cs_2O) occur in the inner core zone with basal sections up to 20 cm in size. Lepidolite, as narrow books up to 2 cm wide and 10 cm in length, also occur in this zone and could represent a late alteration of muscovite. In the west part of the trench, the relatively horizontal pegmatite sheets are connected by subvertical aplite dikes suggesting that a "stacked" pegmatite-aplite emplacement system is present, therefore, more horizontal pegmatite-aplite sheets could occur at depth.

Tantalum Oxides

Coarse, black, subhedral to euhedral, manganotantalite crystals, up to 3.5 by 5 cm in size, are among the largest crystals of the species observed by the authors in Ontario (*see* Figure 54a). These crystals occur within the interstices between coarse, randomly oriented blades of pale green to locally pale pink spodumene, best described as a "box-work" texture. The "box-work" texture appears as large randomly oriented spodumene blades, which may intersect to form a "box". Abundant quartz, cleavelandite and beryl, and common manganotantalite are interstitial to the spodumene blades. The manganotantalite is commonly partly or completely enveloped by white cleavelandite. The manganotantalite crystals appear to have formed during primary magmatic crystallization of the pegmatite-forming melt since no petrographic evidence of subsolidus, replacement-stage albitization could be found.

Field and chemical evidence indicate that the most chemically evolved part of the North Aubry pegmatite is situated in trench NA-5, where high Ta_2O_5 values (0.029–5.7 weight % Ta_2O_5) were obtained from channel sampling conducted by Linear Resources Inc. The range in Ta_2O_5 content in columbite-tantalite group minerals for trenches NA-1 to NA-4 (36–67 weight % Ta_2O_5), were somewhat lower than that in trench NA-5 (77–86 weight % Ta_2O_5), but still significant in terms of the potential delineation of economic tantalum mineralization. The analyses collectively reveal a strong manganese-suite trend for the North Aubry pegmatite (*see* Figure 54a).

Manganocolumbite and manganotantalite are the most common tantalum-oxide minerals in the North Aubry pegmatite (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 8b). Increasing Ta content in columbite-tantalite is due to increasing fractionation of the original pegmatite-forming melt. The Ta content of the oxide minerals increases from

1. the aplite pods (average 42 weight % Ta_2O_5) and outer sodic zone (average 51 weight % Ta_2O_5) with mostly manganocolumbite and minor manganotantalite to
2. aplite dike (average 51 weight % Ta_2O_5), granitic border zone (42–62 weight % Ta_2O_5) and spodumene main zone (36–67 weight % Ta_2O_5) with a range from manganocolumbite to manganotantalite to

3. almost end-member manganotantalite (77–86 weight % Ta_2O_5 from 170 compositions) in the fractionated inner core zone. The manganotantalite from the inner core zone is the most tantalum-rich tantalite in Ontario.

The trend of increasing Mn content in the columbite-tantalite minerals in the North Aubry pegmatite has been caused by extreme fractionation of the pegmatite-forming melt and is similar to the Ta trend (*see* Figure 54a). The Mn content in the oxide minerals increases from

1. aplite pods, aplite dike and outer sodic zone, which have manganocolumbite to manganotantalite relatively iron-enriched to
2. granitic border zone with manganocolumbite to manganotantalite to
3. spodumene main zone with manganocolumbite to manganotantalite to
4. almost end-member manganotantalite in the fractionated inner core zone.

In addition to manganocolumbite and manganotantalite, the North Aubry pegmatite also contains 2 other tantalum-rich oxide minerals: ferrotapiolite and microlite (*see* Figure 54a; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Tables 9 and 14). Ferrotapiolite occurs only in the inner core zone as rims on or along fractures in the manganotantalite. Microlite occurs close to the contact between the pegmatite and the host rock; in miarolitic cavities in a 2 m thick aplite dike in trench NA-4; and in the outer sodic zone. Microlite occurs as a replacement of manganotantalite and ferrotapiolite. Rare very fine-grained uranmicrolite occurs in the outer sodic zone 4 cm from the biotite-rich host rock. The uranmicrolite is mantled by magnetite and contains up to 5.7 weight % UO_2, 2.4 weight % Sc_2O_3 and 66.7 weight % Ta_2O_5. The crystallization of the oxide minerals probably began with primary crystallization of manganocolumbite followed by manganotantalite. Ferrotapiolite crystallized as a result of a sudden increase in iron content in the melt due to consumption of host rocks by the pegmatite-forming melt. Microlite crystallized from a late-stage, calcium-fluorine-rich, highly fractionated melt.

South Aubry Pegmatite

The South Aubry pegmatite (*see* Figure 14) (50 m in width) is similar to the North Aubry pegmatite as spodumene is the dominant lithium-bearing mineral. However, it differs from the North Aubry because muscovite is a much more abundant mineral phase and spodumene is much lower in abundance. The South Aubry pegmatite can be divided into 4 pegmatite zones:

- aplite border zone
- plumose muscovite zone in trench SA-2
- beryl-spodumene zone in trench SA-1
- coarse spodumene zonelayers

The South Aubry pegmatite largely consists of a plumose muscovite zone characterized by impressive ovoid symplectites of quartz-muscovite. These segregations, up to 1 m in diameter, contain approximately equal amounts of quartz and muscovite and are dominant in trench SA-2. Crystals of green beryl (up to 4 by 3 cm in size) and beige spodumene (30 by 2.5 cm in size) are minor mineral phases in the plumose muscovite zone. The beryl-spodumene zone of trench SA-1 is characterized by very coarse-grained green beryl crystals (up to 46 by 34 cm in size) together with white coarse-grained albite, quartz and green muscovite. A cluster of 10 coarse-grained green beryl crystals (>2 cm in size) occur at the east end of the trench.

Trench SA-3 consists of alternating layers of spodumene-rich layers and plumose muscovite layers. Green spodumene is mainly confined to layers, up to 4 m thick, that also contain faint green beryl-quartz-blocky potassium feldspar-cleavelandite (trench SA-3). The spodumene is very coarse-grained and range in size up to 56 cm in length by 6 cm thick. Beryl only occurs in the spodumene layers within trench SA-3.

PETROCHEMISTRY

Three bulk analyses were collected from the South Aubry pegmatite: 2 from the aplite border zone (trenches SA-2 and SA-3) and 1 from a spodumene aplite (trench SA-1) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20b). As at North Aubry, the coarse-grain size of the minerals within the South Aubry pegmatite precluded bulk analysis of most of the pegmatite. All 3 samples are sodium-rich (6.79–9.90 weight % Na_2O) (*see* Figure 52a). The aplites are enriched in rare-elements: 32–76 ppm Li, 12–243 ppm Be, 39–161 ppm Rb, 19–88 ppm Cs, 4–72 ppm Nb and 7–50 ppm Ta. The evolved nature of this pegmatite is also indicated by the key fractionation indicator ratios: 15–170 K/Cs, 27–34 K/Rb, 0.5–5 Rb/Cs and 0.5–1.4 Nb/Ta. The elevated Nb and Ta contents and the low Nb/Ta ratio indicates that South Aubry pegmatite has potential to contain economic tantalum mineralization.

MINERAL CHEMISTRY

Electron microprobe analyses of minerals from the South Aubry pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): muscovite (*see also* Table 13a), lepidolite (*see also* Table 13b), fluorapatite (*see also* Table 10), potassium feldspar (*see also* Table 12) and manganotantalite (*see also* Table 8b).

Mineral compositions from the aplite border zone and plumose muscovite zone indicates that these pegmatite zones are less evolved than the rest of the pegmatite. A fluorapatite-rich white aplite border zone occurs along the western contact of trenches SA-2 and SA-3. The fine-grained blue fluorapatite is relatively manganese-poor (0.2–0.4 weight % MnO) (*see* Figure 53a) indicating it crystallized early from relatively unfractionated pegmatite-forming melt. The coarse-grained green muscovite in the plumose muscovite zone is relatively rubidium- and cesium-poor (0.1–0.2 weight % Rb_2O, 0.02–0.07 weight % Cs_2O) (*see* Figure 53b).

The green mica in trench SA-1 beryl-spodumene zone is actually muscovite (0.2–0.4 weight % Rb_2O, 0.06–0.07 weight % Cs_2O) with rubidium-cesium-rich lepidolite rims (0.9–1.2 weight % Rb_2O, 0.02–0.80 weight % Cs_2O) (*see* Figure 53b). The presence of rubidium-cesium-rich lepidolite rims on muscovite indicates that the late-stage pegmatite-forming melt that crystallized the beryl-spodumene zone was rich in rubidium and cesium.

The alternating spodumene and plumose muscovite layers in trench SA-3 represent the most evolved part of the pegmatite. Microprobe analyses indicate that the potassium feldspar is enriched in Rb and Cs (1.3–1.5 weight % Rb_2O, 0.17–0.30 weight % Cs_2O). The green mica in the spodumene and plumose muscovite layers is actually lepidolite with rubidium-cesium-rich rims (0.9–1.8 weight % Rb_2O, 0.02–0.90 weight % Cs_2O) (*see* Figure 53b). Platy black crystals of manganotantalite (average 68 weight % Ta_2O_5) occur mainly as radiating aggregates up to 1 to 6 mm by 2 cm in size in the spodumene layers (Figure 54b). A late, 20 μm thick, veinlet of relatively tantalum-poor manganotantalite (average 55 weight % Ta_2O_5) cuts the largest manganotantalite grain that was examined.

North and South Aubry Metasomatized Host Rocks

The host rocks surrounding the North Aubry pegmatite have been affected by metasomatism, which produced biotite, tourmaline and holmquistite (purple/blue, lithium-rich amphibole) aureoles. The host rocks can develop a bright blue colouration due to high concentration of randomly oriented acicular, holmquistite. The host rocks also contain local calc-silicate segregations consisting of chlorite-epidote-quartz-carbonate.

Bulk compositions of metasomatized mafic metavolcanic host rocks are published in Table 20b of MRD 111 (Tindle, Selway and Breaks 2002). The holmquistite-rich mafic metavolcanic host rock is calcium- and CO_2-rich due to the abundance of calcite, whereas the biotite-rich mafic metavolcanic host rock is potassium-rich (*see* Figure 52a). Extensive metasomatism is evident in the pillowed, mafic metavolcanic host rocks near the west end of trench NA-5. Biotite metasomatism is common in the host rocks surrounding North Aubry, whereas the holmquistite metasomatism is more localized. The biotite metasomatized host rocks in trench NA-5 are very rich in rare-elements with 7519 to 8044 ppm Li, 12 447 to 18 136 ppm Rb, 10 089 to 11 661 ppm Cs, 6 to 40 ppm Nb and 4 to 74 ppm Ta, and low K/Rb (3.0–3.1) and K/Cs (3.1–5.6) ratios. The holmquistite metasomatized host rocks in trench NA-5 have lower rare-element contents with 5420 ppm Li, 1745 ppm Rb and 6047 ppm Cs and low K/Rb (6.4) and K/Cs (1.8) ratios. The decrease in rare-element contents from the biotite to the holmquistite aureoles is because biotite can substitute Rb and Cs in its crystal structure, whereas holmquistite does not.

Electron microprobe compositions from the metasomatized host rocks are published in MRD 111: biotite (*see also* Table 13c) and tourmaline (*see also* Table 17) (Tindle, Selway and Breaks 2002). In the North Aubry metasomatized host rocks, the biotite has a composition of siderophyllite-zinnwaldite and is rich in Li, Rb, Cs and F (1.9–2.6 weight % Li_2O (estimated), 1.4–2.4 weight % Rb_2O, 0.2–3.5 weight % Cs_2O, 2.6–3.4 weight % F) (*see* Figure 53b). The metasomatic tourmaline is calcium-rich dravite-schorl (*see* Figure 51).

The mafic metavolcanic host rocks surrounding the South Aubry pegmatite have been metasomatized to a biotite-rich aureole at the contact with the pegmatite. In the South Aubry metasomatized host rocks, the biotite has a composition of siderophyllite-zinnwaldite and is enriched in Li, Rb, Cs and F (2.0–2.3 weight % Li_2O (estimated), 1.4–1.5 weight % Rb_2O, 0.1–0.4 weight % Cs_2O, 2.2–2.3 weight % F) (*see* Figure 53b; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 13c).

Recommendations for Pegmatite Exploration

The elevated Nb and Ta contents and the low Nb/Ta ratios in bulk and microprobe analyses indicate that the North and South Aubry pegmatites have a high potential to contain economic tantalum mineralization.

Bulk analyses of the metasomatized host rocks surrounding these pegmatites contain elevated Li, Rb and Cs contents. Thus, lithium, rubidum and cesium may be useful elements in detecting other rare-element pegmatites by lithogeochemical sampling surveys in the area. The presence of lithium-rubidium-cesium-rich biotite, tourmaline and holmquistite in the mafic metavolcanic host rocks indicates that lithium-, rubidium-, cesium- and boron-rich fluids emanating from the pegmatite-forming system infiltrated and altered the host rocks.

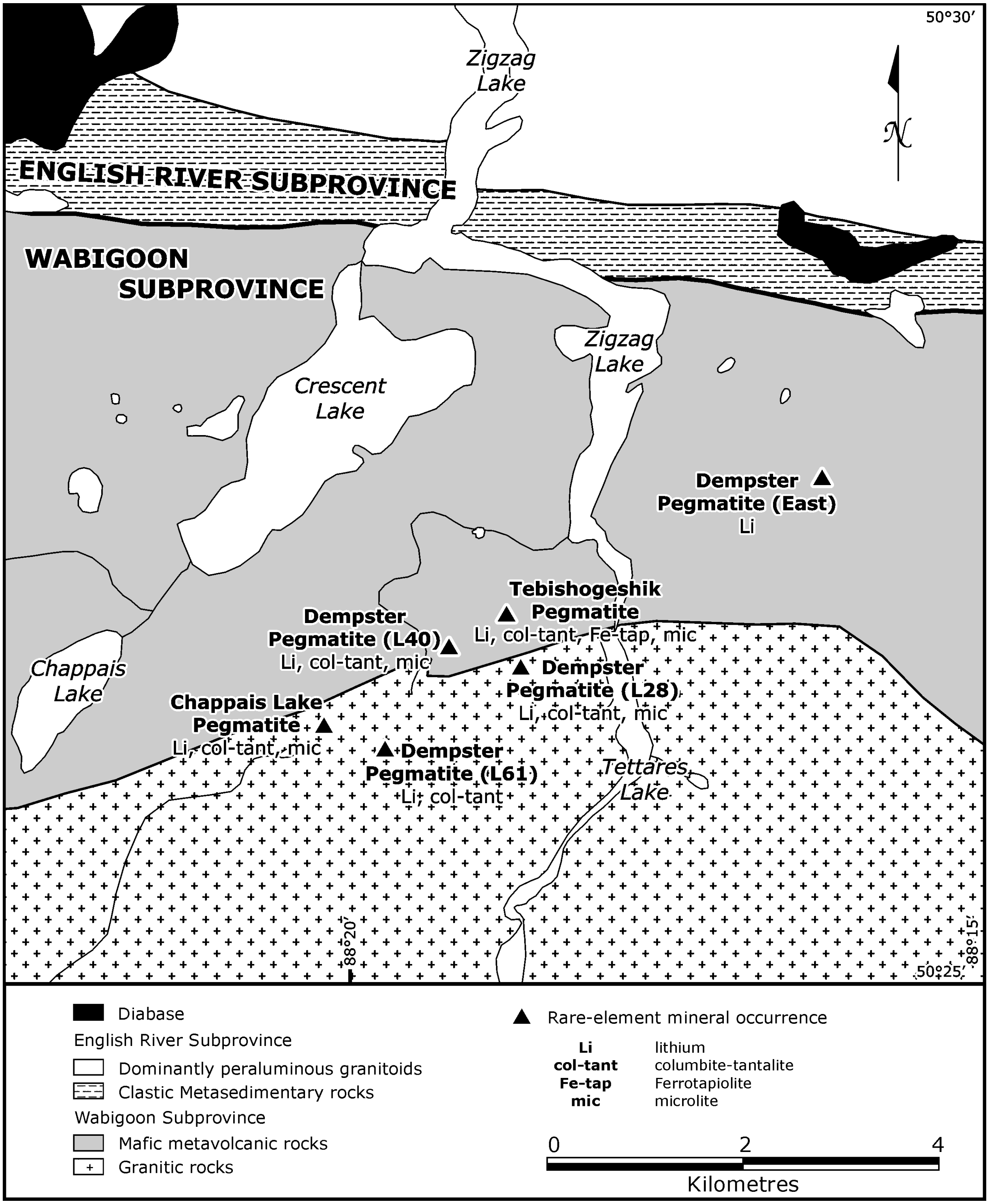


Figure 15. General geology and location of rare-element mineralization in Crescent Lake pegmatite group in the Wabigoon–English River subprovincial boundary zone (*from* Pye 1968).

CRESCENT LAKE PEGMATITE GROUP

This group consists of 8 pegmatites that are hosted in mafic metavolcanic and meta-tonalite rocks within a 1.2 by 6 km area south of Crescent and Zigzag lakes (*see* Figure 14). The pegmatites were initially described in detail by Pye (1968, p.50, p.56-59, *see also* Figure 8) and later examined briefly by Breaks (1981). Exploration for tantalum was initially undertaken by Donner (1982) in the Tebishogeshik lenses 1 to 4, where Ta_2O_5 values ranging from 0.045% Ta_2O_5 across 8.4 m to 0.37% Ta_2O_5 across 1 m were obtained from a series of continuous chip samples collected intermittently across a 700 m strike length. Platinova Resources Limited recently optioned 46 claim units that contain most of the pegmatites in the Crescent Lake group (Platinova Resources Limited, News Release, www.platinova.com, August 15, 2001).

The Crescent Lake pegmatite group consists of Tebishogeshik pegmatites (lenses 1 to 4), Dempster pegmatites (lenses 28, 40 and 61) and the Chappais pegmatite (Figure 15). Tebishogeshik lenses 1 to 4 are numbered sequentially from west to east. The pegmatites are classified as complex-type, spodumene-subtype (Černý 1989a, 1991a), and are notable for the high tantalum content of their oxide minerals (columbite-tantalite group, ferrotapiolite and microlite) coupled with evolved garnet compositions and widespread albitization. The Crescent Lake pegmatites exhibit simple internal zonation:

- border zone
- outer zone (or main body) of quartz-muscovite-cleavelandite
- central spodumene core zone
- primary sodic aplite pods in the spodumene core
- secondary, replacement albite veins and patches

The primary border zone contains an assemblage of garnet-potassium feldspar-quartz-cleavelandite and minor black and dark brown oxide minerals along the northern contact of Dempster lens 28. The border zone consists of garnet-muscovite-quartz-albite and minor black oxide minerals along the southern contacts of the Tebishogeshik lens 2 and Chappais pegmatites. The outer zone is apparently primary in origin and grades in to the central spodumene core zone, as in lenses 2 and 3 (*see* Figure 15). The green muscovite-quartz-albite outer zone contains local blocky potassium feldspar (lens 4) and minor garnet, euhedral black oxide minerals (up to 1.5 by 4 mm) and fine-grained green secondary mica. The spodumene core zone consists of an assemblage of muscovite-blocky potassium feldspar-green spodumene-quartz-albite with minor black tantalum-oxide minerals and garnet. The oxide minerals are fine-grained or coarse-grained and wedge-shaped. In lens 2, a 3 m thick quartz-rich core zone is traceable for 37 m on surface and contains between 18 to 42 volume % green spodumene megacrysts.

The Tebishogeshik–Chappais pegmatites also contain sodic aplite pods in the spodumene core. The sodic aplite pods contain minor fine-grained black tantalum-oxide minerals and blue fluorapatite with locally abundant garnet and muscovite. Aplite pods in the spodumene pegmatite also contain fine-grained black tantalum-oxide minerals. Possible secondary, replacement albite veins and patches intrude the spodumene core zone and the muscovite-quartz-albite outer zone. The albitized zones contain black oxide minerals (up to 2 by 3 mm in size) together with fine-grained green mica (muscovite?), which could be a replacement of spodumene. Blocky potassium feldspar, up to 20 cm in diameter, is variably replaced by irregular masses of albite. Thin platy to rectangular black grains of columbite-tantalite, up to 6 by 7 mm in size, are disseminated in rare quantities throughout these albitized areas.

Mineral Chemistry

An extensive electron microprobe investigation that involved 998 analyses was undertaken on the various oxide minerals, garnet, potassium feldspar and mica. Electron microprobe compositions of minerals from the Crescent Lake pegmatite group (Tebishogeshik lens 2 and 3) are published in MRD 111 (Tindle, Selway and Breaks 2002): columbite-tantalite (*see also* Table 8b), microlite (*see also* Table 14), garnet (*see also* Table 11), fluorapatite (*see also* Table 10), muscovite (*see also* Table 13a) and potassium feldspar (*see also* Table 12). Microprobe analyses (including from ferrotapiolite), from the rest of the pegmatite dikes in the Crescent Lake pegmatite group, will be published in a future MRD. Plots include both published and unpublished data. This work involved most of the pegmatites in the pegmatite group: the Tebishogeshik lenses 1, 2 and 3; the Dempster lenses 28, 40, and 61; and the Chappais Lake pegmatite (*see* Figure 15)(Pye 1965). Samples from Tebishogeshik lens 4 were not examined in this study. The Tebishogeshik and Dempster lenses are grouped together in the plots, as they are mineralogically very similar.

Oxide minerals of the columbite-tantalite group are widespread in pegmatites of the Crescent Lake group as indicated from 478 electron microprobe analyses collected from 28 samples. The tantalum-oxide minerals were formed during primary magmatic crystallization and by late-stage, albite-rich replacement. Spectacular oscillatory zoning (visible in back-scattered electron images) marked by zones of generally increasing tantalum content is a clear indication of the primary process, whereas the late enrichment is typified by irregular, patchy textures. In some cases, both processes have left signatures on individual crystals of columbite-tantalite. Late-stage albitization is also apparent in the pegmatites of this group, subtly marked by cleavelandite-rich replacement in parts of coarse blocky potassium feldspar megacrysts as in lens 1. Black oxide mineral grains, generally 1 mm in diameter or less, have been noted within these alteration zones.

A significant proportion of the electron microprobe data plot within the manganotantalite field (*see* Figure 55) and confirms the pegmatite underwent a high degree of fractionation. Manganocolumbite, ferrotantalite, microlite and ferrocolumbite compositions have also been documented. Ferrocolumbite and manganese-poor manganocolumbite represent the most primitive compositions and occur in the Chappais pegmatite (33.69 weight % Ta_2O_5), Dempster lens 61 (average 43.81 weight % Ta_2O_5), and Tebishogeshik lens 2 (average 35.42 weight % Ta_2O_5) (*see* Figure 55). With increasing pegmatite evolution, average Ta_2O_5 content in oxide minerals increases in the following order: Tebishogeshik lens 2 (46.20 weight % Ta_2O_5); Dempster lens 28 (48.04 weight % Ta_2O_5); Tebishogeshik lens 3 (51.76 weight % Ta_2O_5); Dempster lens 40 (57.98 weight % Ta_2O_5); and Tebishogeshik lens 1 (65.15 weight % Ta_2O_5). Individual analyses of manganotantalite from lenses 3 and 40 exceed 80 weight % Ta_2O_5 and are amongst the highest documented in lithium-rich pegmatites of Ontario. The pegmatites of this group have a high potential for producing an economic tantalum deposit.

At the Chappais pegmatite, the border zone has relatively primitive tantalum-oxide compositions intermediate between ferrocolumbite and manganocolumbite and associated with spessartine (58–80% spessartine, 19–38% almandine, 1–2% grossular) and muscovite (0.1–0.6 weight % Rb_2O, <0.03 weight % Cs_2O) (*see* Figures 55a, 49a and 50b). However, in the border zone of the Teshogeshik lenses, the tantalum-oxide minerals have more evolved compositions, that is, manganotantalite and uranmicrolite, and these are associated with spessartine (68–90% spessartine, 9–30% almandine, 1–2% grossular) and rubidium-rich muscovite (0.3–1.0 weight % Rb_2O and 0.01–0.09 weight % Cs_2O) (*see* Figures 55a, 49a and 50b). The Mn is preferentially partitioned into the spessartine and manganotantalite over the fluorapatite, so the fluorapatite in the border zone is relatively manganese-poor (0.3–1.3 weight % MnO) (*see* Figure 50a).

The muscovite-quartz-albite main body contains a wide range of tantalum-oxide species with ferrocolumbite, manganocolumbite, manganotantalite, ferrotantalite, ferrotapiolite, microlite and uranmicrolite all reported (Figure 55b). The spessartine garnet in the main body at Tebishogeshik also has a wide range of compositions: 38 to 96% spessartine, 3 to 60% almandine, 0 to 2% grossular, 0 to 1% andradite, 0 to 1% pyrope (*see* Figure 49a). The spessartine may be zoned, for example, sample TPL-1 from lens 1 contains a zoned garnet with manganese-rich cores (96% spessartine, 3% almandine, 1% grossular) and manganese-depleted and iron-enriched rims (59% spessartine, 38% almandine, 2% grossular, 1% andradite). In the muscovite-quartz-albite zone, fluorapatite and rubidium-cesium-rich muscovite (0.3–1.1 weight % Rb_2O, 0.00–0.23 weight % Cs_2O) are present (*see* Figure 50).

The tantalum-oxide minerals in the spodumene core zone are mostly manganocolumbite, commonly manganotantalite and rarely microlite (*see* Figure 55b). The spodumene zone also contains spessartine (61–88% spessartine, 11–38% almandine, 0–3% grossular) and rubidium-rich muscovite (0.4–0.9 weight % Rb_2O, 0.01–0.09 weight % Cs_2O) (*see* Figures 49a and 50b).

The oxide minerals in the aplite pods within the spodumene pegmatite are mostly manganocolumbite and rarely microlite, which is similar to that in the spodumene zone (*see* Figure 55a). The presence of rare tantalum-rich manganotantalite grains make the aplite pods more fractionated than the spodumene zone. The muscovite in the aplite pods within the spodumene zone contains 0.4 to 0.8 weight % Rb_2O and 0.00 to 0.11 weight % Cs_2O (*see* Figure 50b).

Most of the tantalum-oxide minerals in the sodic aplite bodies from the wall zone and blasted material are manganotantalite, but minor manganocolumbite and ferrocolumbite also occurs (*see* Figure 55a). The manganotantalite is associated with spessartine (87–91% spessartine, 8–13% almandine) and muscovite (0.6–0.7 weight % Rb_2O, 0.03–0.06 weight % Cs_2O) (*see* Figures 49a and 50b).

The albite veins and patches in the Chappais border zone contain tantalum-oxide minerals, which are mostly intermediate between manganocolumbite and manganotantalite, together with a few compositions of ferrotantalite and uranmicrolite (*see* Figure 55). These albitized patches also contain manganese-poor fluorapatite (0.3–0.4 weight % MnO) and spessartine with a wide range of compositions: 56 to 82% spessartine, 16 to 40% almandine, 0 to 2% grossular, 0 to 2% andradite (*see* Figures 50a and 49a). The spessartine may be zoned, for example, sample TPL-281 of lens 28 contains a zoned garnet crystal with manganese-rich cores (79% spessartine, 19% almandine, 2% grossular) and manganese-depleted and iron-enriched rims (69% spessartine, 29% almandine, 2% grossular). This is similar to the zoning seen in spessartine from the main body muscovite-quartz-albite zone. The rubidium-cesium-rich muscovite in these albitized patches contains 0.3 to 0.9 weight % Rb_2O and 0.0 to 0.5 weight % Cs_2O (*see* Figure 50b).

The wide range in compositions, particularly the columbite-tantalite and mica species, is likely due to primary compositions overprinted and/or replaced with secondary compositions during late albitization of the pegmatite. The presence of ferrotapiolite and iron-enriched rims on spessartine may be due to host rock contamination, which contaminated the pegmatite melt with iron.

Recommendations for Pegmatite Exploration

The majority of the tantalum-oxide minerals in the Crescent Lake pegmatite group are manganotantalite, and microlite is also common. Individual analyses of manganotantalite from Tebishogeshik lens 3 and Dempster lens 40 exceed 80 weight % Ta_2O_5 and are amongst the highest documented in lithium-rich pegmatites of Ontario. Thus, the pegmatites of this group have a high potential for economic tantalum deposits.

FALCON LAKE PEGMATITE GROUP

This 0.25 by 4.5 km cluster of 7 spodumene-subtype pegmatites is located approximately 10 km east of the Crescent Lake pegmatite group (*see* Figure 14). The pegmatites are located between Funnel and Falcon lakes within the mafic metavolcanic rocks (amphibolites) of the Wabigoon Subprovince approximately 300 m south of the subprovince boundary with the English River Subprovince. One sample from a 3 m thick spodumene pegmatite dike within a group of 3 spodumene pegmatites near Ottertail Creek (Pye 1968, "Far West deposits", p.55-56) was examined with the electron microprobe. Pye (1968) describes these 3 spodumene pegmatites as consisting of coarse-grained unaltered spodumene and blocky potassium feldspar in a groundmass of quartz, albite, muscovite and minor apatite and tourmaline. The spodumene makes up 5 to 15 volume % of the pegmatites and is up to 15 cm long (Pye 1968). This study found rare tantalum-oxide minerals with compositions of manganotantalite and ferrotapiolite (*see* Figure 54b).

Electron microprobe compositions of minerals from Falcon Lake spodumene pegmatite—columbite-tantalite, ferrotapiolite, potassium feldspar, muscovite and fluorapatite—will be published in a future MRD. Plots are based on unpublished data.

The ferrotapiolite has an average Ta_2O_5 content of 78.46 weight % with values that range from 76.88 to 80.58 weight % Ta_2O_5 from 24 microprobe analyses. These values are some of the highest reported from tantalum-rich oxides in Ontario. The fluorapatite is manganese-rich with 0.4 to 2.0 weight % MnO (*see* Figure 50a). Exceptionally high Rb_2O (average 4.5 weight %) and Cs (4653 ppm) were determined in the potassium feldspar from Falcon Lake pegmatite and are the second highest values recorded to date in potassium feldspars within Ontario. The highest rubidium contents in potassium feldspar from pegmatites in Ontario are from the Lilypad Lake pegmatite, northeastern Ontario (Teertstra, Černý and Hawthorne 1998) with Rb contents that range from 13.44 to 22.00 weight % Rb_2O in late rubicline and rubidium-rich potassium feldspar. The cesium content in potassium feldspar at Falcon Lake exceeds values reported from limited data from Lilypad Lake (up to 0.37 weight % Cs_2O) and the Tanco pegmatite (Černý, Ercit and Vanstone 1996: 0.02–0.30 weight % Cs_2O; 0.77–2.93 weight % Rb_2O). The muscovite at Falcon Lake is also rubidium- and cesium-rich (3.0–3.6 weight % Rb_2O, 0.4–0.6 weight % Cs_2O: *see* Figure 53b). Pegmatites of this group could contain pollucite (the ore mineral of cesium) mineralization, in addition to representing a good target for tantalum.

SUPERB LAKE LITHIUM PEGMATITE

The spodumene-type Superb Lake pegmatite (*see* Figure 14) was discovered in the 1950s by unknown person(s) (Mulligan 1965, p.63) and has not been examined until recently (Stott and Parker 1997; Parker and Stott 1998). The Superb Lake pegmatite was not visited during this (2001) study, but was examined the following summer 2002 (Breaks, Selway and Tindle 2002).

Sioux Lookout Domain (Wabigoon–Winnipeg River Subprovincial Boundary Zone)

INTRODUCTION

Rare-element mineralization is distributed along a 70 km strike length of the Sioux Lookout domain (Beakhouse 1988; Breaks and Moore 1992, p.836), between the Gullwing–Tot lakes pegmatite group southwest to the Temple Bay pegmatite (with Nb greater than Ta) near Eagle Lake (Figure 16). Although the rare-element pegmatites of the Dryden field have previously been described in detail (Breaks 1989; Breaks and Janes 1991; Breaks and Moore 1992), the present survey establishes a newly recognized wide distribution of metasedimentary-hosted, rare-element pegmatite mineralization within the Minnitaki–Warclub and Abram metasedimentary groups of Blackburn et al. (1991). These host rocks have likely been subjected to minimal exploration since prior work has mainly focussed upon rare-element deposits contained within mafic metavolcanic host rocks in the Mavis Lake and Gullwing Lake areas. The presence of anomalous tantalum values between 35 and 150 ppm in pegmatites from this metasedimentary context determined by the present study has established a new and extensive exploration area for tantalum.

METASEDIMENTARY-HOSTED RARE-ELEMENT PEGMATITE MINERALIZATION IN THE ABRAM, MINNITAKI, WARCLUB AND ROYAL ISLAND GROUPS

Seven rare-element pegmatite localities occur within 4 metasedimentary groups of the Sioux Lookout domain (*see* Figure 16): the Abram, Minnitaki, Warclub and Royal Island groups (Blackburn et al. 1991). These pegmatites are described below.

Drope Township Columbite-Molybdenite Pegmatite

This 2 m thick, green muscovite-rich, pegmatite dike was discovered by Breaks (1989, p.161) and is situated within the southwestern part of the Abram group (*see* Figure 16). The pegmatite is white on weathered surfaces and was emplaced concordant to foliation in andalusite-muscovite-bearing metapelitic rocks. The dike occurs as asymmetric boudins with quartz fillings at the boudin “necks”. Black tantalum-oxide minerals occur sporadically in the pegmatite as subhedral grains up to 7 by 8 mm and are associated with green muscovite, quartz, garnet and plagioclase. Molybdenite plates occurs rarely and are up to 4 mm in diameter.

The tantalum-oxide minerals are ferrocolumbite to rare ferrotantalite and contain an average Ta_2O_5 content of 34.34 weight % and range of 18.77 to 55.49 weight % Ta_2O_5. Ferrotapiolite (mean of 4 analyses = 76.23 weight % Ta_2O_5) probably crystallized early due to contamination. A strong contamination trend (Figure 72b) is marked by transition from ferrotapiolite to ferrotantalite to dominant ferrocolumbite compositions. Electron microprobe analyses of the tantalum-oxide minerals will be published in a future MRD.

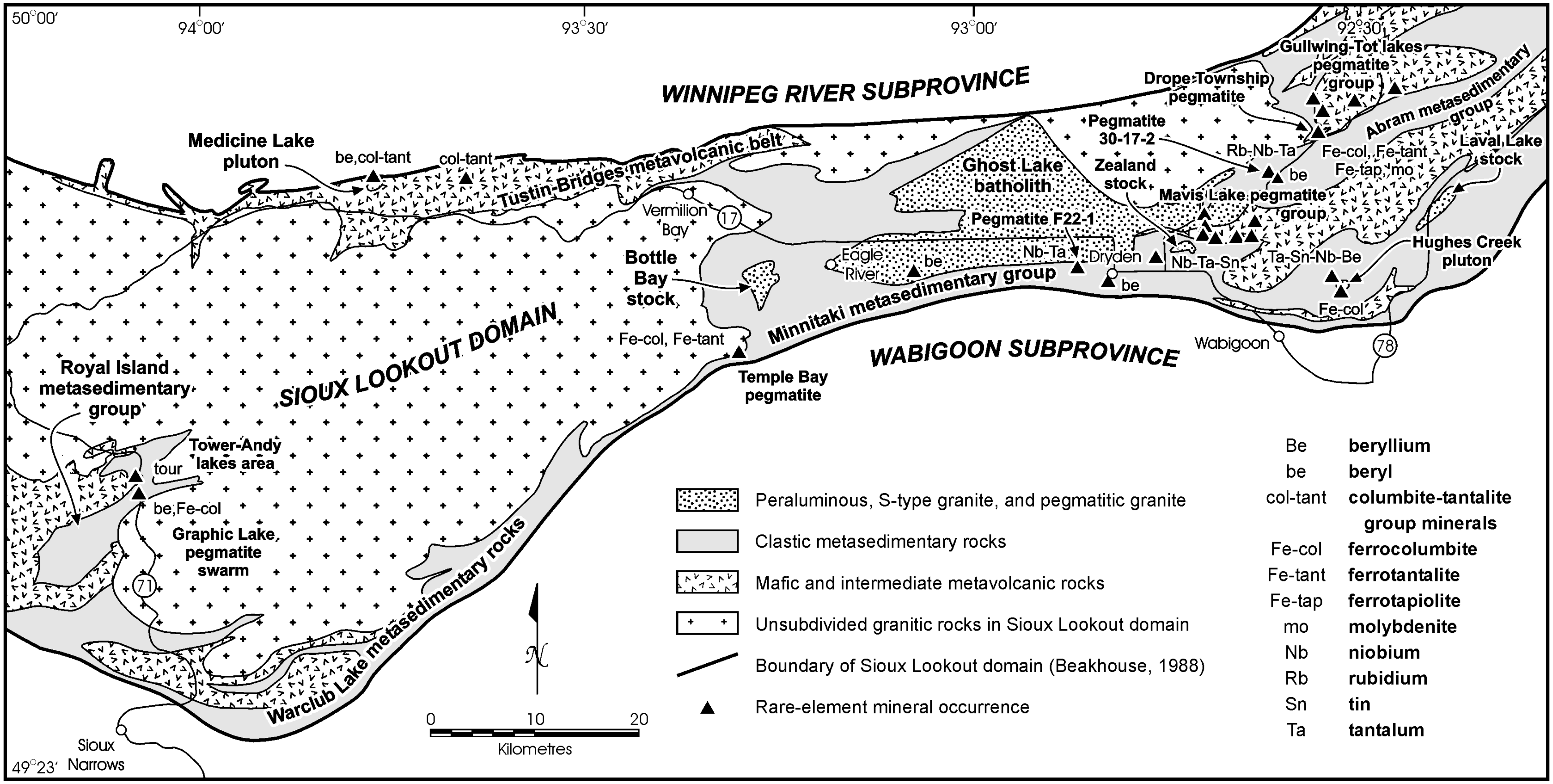


Figure 16. Rare-element mineralization and peraluminous granite masses hosted in metasedimentary rocks of the Sioux Lookout domain.

Southwestern Zealand Township Dike

A 30 cm thick, pale pink, garnet-tourmaline-muscovite pegmatite dike occurs in Concession VII, Lot 20 of southwestern Zealand Township (UTM 517330E, 5501610N, Zone 15), where it is hosted by mafic-rich metawacke interbedded with banded iron formation of the Minnitaki group. Analysis of a grab sample from one of several narrow pegmatite dikes gave the following results: 115 ppm Ta, 150 ppm Nb, 55 ppm Sn, 30 ppm Be, 20 ppm Li, 300 ppm Rb and 5 ppm Cs.

Beryl-Muscovite-Tourmaline Pegmatite Dikes, Central Brownridge Township

Numerous black tourmaline-bearing pegmatite dikes occur within a recently logged area near and along the Ghost Lake road. These dikes are hosted in metawacke and interbedded andalusite-cordierite-bearing metapelites and were recently examined by Beakhouse (2001).

Two tourmaline-rich pegmatite dikes are situated in the same area and along the Ghost Lake road about 0.5 km northeast of beryl locality 01-FWB-31 (UTM 526704E, 5221806N, Zone 15). At locality 01-FWB-33 (UTM 527277E, 5522995N, Zone 15), an 8 m thick dike is exposed and consists of interlayered tourmaline-rich, fine-grained leucogranite and muscovite-tourmaline potassic pegmatite. Both are transected by narrow discordant veins, which represent a second episode of muscovite-tourmaline potassic pegmatite formation.

PETROCHEMISTRY

Bulk rock analyses were undertaken on the 3 dikes examined in this area: tourmaline fine-grained leucogranite (localities 01-FWB-31 and 01-FWB-33) and tourmaline-muscovite sodic pegmatite (locality 01-FWB-44) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20c). The dikes are exposed in a recently logged area and, hence, were likely not previously investigated for their rare-element potential. Notable fractionation was documented for the beryl-type dike at locality 01-FWB-31 (UTM 526704E, 5221806N, Zone 15). At this locality, several green, euhedral beryl crystals, up to 4 by 6 cm in size, occur locally in a 14 m wide dike that is composed of garnet-tourmaline fine-grained leucogranite (or aplite) and apatite-garnet-muscovite-black tourmaline potassic pegmatite. The apatite-garnet-tourmaline aplite with 9.07% Na_2O was noted to be significantly evolved: Cs (84 ppm), Li (199 ppm), Ga (59 ppm), Nb (73 ppm), Ta (21 ppm) with ratios of K/Cs (38), K/Rb (32), and Nb/Ta (3.4) (Figure 73a). A nearby dike of tourmaline-garnet-muscovite potassic pegmatite at locality 01-FWB-44 (UTM 527135E, 5521542N, Zone 15) is likely part of the same swarm, as anomalous levels of Be (24 ppm), Ga (65 ppm), Rb (509 ppm), Nb (83 ppm), Ta (18 ppm) and Sn (13 ppm) were documented. Several ratios also confirm a similar degree of fractionation to locality 01-FWB-31: K/Rb = 33 and Nb/Ta = 4.8. This pegmatite represents a new rare-element occurrence in the Abram group. The third dike at locality 01-FWB-33 (UTM 527277E, 5522995N, Zone 15) is notably less enriched in the various rare-elements, but interestingly reveals the most evolved Nb/Ta ratio (2.9) in the dike swarm, although absolute levels of Nb (9.2 ppm) and Ta (3.1 ppm) are low.

At locality 30-17-2 of Breaks (1989, p.538-540), situated on the east side of the Ghost Lake road (*see* Figure 16) near locality 01-FWB-33, a 10 m thick, layered aplite-tourmaline pegmatite dike is also hosted in metasedimentary rock. One bulk rock analysis revealed significant anomalous levels of the following rare-elements: 1470 ppm Rb, 110 ppm Nb, 88 ppm Sn and 50 ppm Ta.

Additional pegmatitic granite samples (fine-grained leucogranite and potassic pegmatite) were collected in the eastern part of the Ghost Lake batholith in newly exposed outcrops along the Ghost Lake West road (locality 01-JBS-32: UTM 521843E, 5521158N, Zone 15).

MINERAL CHEMISTRY

The metasedimentary-hosted felsic dikes are tourmaline- and garnet-bearing and consist of fine-grained leucogranite, potassic pegmatite and aplite. The electron microprobe compositions of minerals from these dikes are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11), tourmaline (*see also* Table 17), muscovite (*see also* Table 13a), lepidolite (*see also* Table 13b) and manganocolumbite (*see also* Table 8c). The garnet compositions show a fractionation trend of decreasing Mg and Fe and increasing Mn from magnesium-bearing almandine (66–73% almandine, 17–31% spessartine, 2–9% pyrope, 2–3% grossular) in the leucogranite (Ghost Lake batholith), to almandine in the potassic pegmatite (Ghost Lake batholith), to spessartine (up to 66% spessartine, 32% almandine, 1% andradite) at the central Brownridge Township beryl locality (01-FWB-31) (Figure 57), situated 17 km northeast of the batholith. A similar compositional trend is shown by tourmaline with decreasing Mg and increasing Al and Li from dravite in the leucogranite (Ghost Lake batholith), to magnesium-rich schorl in the potassic pegmatite (Ghost Lake batholith), to schorl in the Ghost West aplite, to "fluor-elbaite" at the central Brownridge Township beryl locality (01-FWB-31) (Figures 58 and 59).

The beryl locality 01-FWB-31 is one of the most managanese, lithium, rubidium, cesium and beryllium-rich localities in this area. The fine-grained leucogranite or aplite contains manganese-rich garnet: spessartine (50–66% spessartine, 32–47% almandine, 1% pyrope, 1% andradite) and almandine-spessartine (49–52% almandine, 46–50% spessartine, 1% pyrope, 1% grossular) (*see* Figure 57). The tourmaline has 2 distinct compositions: magnesium-rich schorl and "fluor-elbaite", which is zoned with iron-magnesium-enriched cores and aluminum-lithium-manganese-fluorine-enriched rims (*see* Figure 59). The earlier iron-magnesium-rich tourmaline is the result of host rock contamination of the granitic melt, whereas the later aluminum-lithium-manganese-fluorine-rich tourmaline crystallized from a more evolved and relatively uncontaminated melt. The mica is rubidium-cesium-fluorine-rich lepidolite (0.6–1.0 weight % Rb_2O, 0.4–1.2 weight % Cs_2O, 3.1–4.6 weight % F) and muscovite (0.3 weight % Rb_2O, 0.0–0.1 weight % Cs_2O, 0.6–0.9 weight % F) (Figure 60a). Only one grain of manganocolumbite (6.6 weight % Ta_2O_5) was found at this locality (Figure 60b). It is also the only tantalum-oxide grain found from Ghost West road. The potassic pegmatite consists of quartz, white potassium feldspar, beryl, fine-grained red garnet and coarse-grained black tourmaline with a composition of schorl and "fluor-elbaite" (*see* Figure 59). The green beryl has an average of 0.74 weight % Cs_2O with a distinct, but discontinuous Cs-rich rim (up to 3.49 weight % Cs_2O). Cesium-rich beryl only occurs in complex-type pegmatites.

One garnet-tourmaline potassic pegmatite and an aplite dike along Ghost West road are hosted by mafic metavolcanic rocks (locality 01-FWB-30: UTM 521808E, 5518184N, Zone 15). The host rock consists of layers of black amphibolite, and a tourmaline + biotite layer. The columnar coarse-grained black tourmaline (up to 1 cm long) in the host rock is calcium-magnesium-rich schorl (*see* Figure 59). The host rock contains calc-silicate pods consisting of red garnet, green diopside, pale orange scheelite, epidote and calcic plagioclase. The host rock also contains pale purple fibrous holmquistite along the edges of the pillow basalt. The presence of holmquistite in a mafic metavolcanic rock is significant, as holmquistite is a lithium-amphibole that only occurs in close proximity to lithium-bearing pegmatite.

At locality 01-FWB-30 along Ghost West road, the potassic pegmatite consists of stringers composed of potassium feldspar, quartz, green muscovite, acicular, coarse-grained black tourmaline (schorl up to 3.6 cm long) and almandine-spessartine (50–52% almandine, 46–48% spessartine, 1% andradite) (*see* Figure 57). The aplite contains fine-grained black schorl and minor garnet (*see* Figure 59).

One bulk sample of potassium feldspar was collected from the Brownridge Township pegmatite dike swarm in the Abram group metasedimentary rocks (Figure 56b). At locality 01-FWB-33, modest Rb (950 ppm) and Cs (36 ppm) levels also indicate that this tourmaline-rich pegmatite dike is genetically related to nearby pegmatites described above.

Northwest Hartman Township Tantalum-Tin-Niobium-Beryllium Pegmatite

A 15 cm thick pegmatite dike, emplaced in garnet-bearing metawacke of the Minnitaki group, was discovered by Berger (1990, p.71), who reported analyses of 152 ppm Ta, 115 ppm Sn, 74 ppm Nb and 65 ppm Be. The low Nb/Ta ratio of 0.49 indicates strong fractionation of Ta relative to the upper continental crust ratio of 11.4 (Taylor and McLennan 1985), therefore, the area warrants exploration for additional, tantalum-mineralized pegmatite dikes.

Hughes Creek Pluton

This 1.3 km circular pluton (*see* Figure 16), which was delineated by Berger (1990), consists of tourmaline-biotite-muscovite-bearing pegmatitic granite units and related fine- to medium-grained biotite granite. The discovery of ferrocolumbite by this survey, in the southern part of the pluton at locality 01-FWB-35 (UTM 534442E, 5513244N, Zone 15), confirms this pluton as a fertile granite. The pluton is a plausible source of the northwest Hartman Township tantalum-tin-niobium-beryllium pegmatite, situated 1.3 km northwest of the pluton (Berger 1990).

PETROCHEMISTRY

Bulk compositions of biotite granite, biotite-muscovite potassic pegmatite, fine-grained muscovite leucogranite from Hughes Creek pluton are published in MRD 111 (Tindle, Selway and Breaks 2002). Four bulk rock analyses were selected from the western part of the mildly peraluminous (mean A/CNK = 1.080), pegmatitic granite Hughes Creek pluton (Figure 56a). The most fractionated rock consists of a biotite-garnet-muscovite potassic pegmatite from locality 01-FWB-35 (UTM 534427E, 5513244N, Zone 15). Modest anomalous values of Li (86 ppm), Ga (63 ppm), Rb (541 ppm), Nb (61 ppm) and Sn (16 ppm) were documented for this unit which are corroborated by evolved ratios of K/Rb (51), Rb/Sr (100) and Mg/Li (2.8). However, biotite granite at locality 01-FWB-38 (UTM 534031E, 5514096N, Zone 15) contained the highest Ta (10 ppm) and the lowest Nb/Ta ratio (4). These data confirm that this pluton is a fertile granite and worthy of further exploration.

MINERAL CHEMISTRY

One bulk potassium feldspar sample from Hughes Creek locality 01-FWB-35 has significantly elevated Rb (1787 ppm) and modest Cs (26 ppm) values (*see* Figure 56b; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21c). The elevated rubidium supports the status of this pluton as a fertile granite.

Electron microprobe compositions of minerals from Hughes Creek pluton are published in MRD 111 (Tindle, Selway and Breaks 2002): ferrocolumbite (*see also* Table 8c), garnet (*see also* Table 11), fluorapatite (*see also* Table 10) and tourmaline (*see also* Table 17). Electron microprobe analysis of a 3 by 5 mm ferrocolumbite grain indicates modest fractionation along an iron-rich trend (*see* Figure 60b). An average Ta_2O_5 content of 15.29 weight % within a range of 9.20 to 30.43 weight % Ta_2O_5 was determined from 28 electron microprobe analyses.

Garnet (almandine) occurs in the potassic pegmatite and aplite. The almandine in the potassic pegmatite (55–74% almandine, 24–42% spessartine, 1–2% pyrope, 1–2% andradite) is more manganese-rich than in the aplite (66–68% almandine, 30% spessartine, 1% pyrope, 1% andradite) (Figure 61b). One garnet grain from a muscovite potassic pegmatite (sample 01-FWB-36-04) is zoned with an almandine zone (55% almandine, 42% spessartine, 2% pyrope, 2% andradite) and a spessartine zone (58% spessartine, 39% almandine, 2% pyrope, 1% andradite). The potassic pegmatite also contains zoned fluorapatite with manganese-rich cores (1.1–1.4 weight % MnO) and manganese-depleted rims (0.3–0.6 weight % MnO) (Figure 62a).

Tourmaline does not occur within the Hughes Creek pluton, but does occur along the contact between the Hughes Creek pluton and the metasedimentary host rocks. This indicates that aluminium-boron-rich fluids from the pegmatite-forming melt may have leached elements (iron, magnesium and calcium) from the host rocks. Black, calcium-magnesium-bearing schorl occurs as veins within the granite near the contact and along the contact (Figure 64).

Temple Bay (Eagle Lake) Tantalum-Niobium Pegmatite

A 75 by 600 m, tantalum-niobium-bearing pegmatite, hosted in metawacke of the Minnitaki group, was discovered by F. Plomp in 1997 (Plomp 1998) (*see* Figure 16). Grab samples collected by F. Plomp returned up to 182 ppm Ta and 553 ppm Rb. At locality 01-FWB-118 (UTM 477953E, 5507219N, Zone 15), a 20 m wide section of the pegmatite was observed to be concordant with foliation in the host metawacke. Most of the dike comprises garnet-muscovite potassic pegmatite (with minor biotite), which locally grades into medium-grained, garnet-muscovite granite and quartz-rich patches in contact with blocky potassium feldspar (up to 20 by 25 cm). Local plumose aggregates of muscovite-quartz, up to 5 by 10 cm, occur in the potassic pegmatite. Black, fine-grained, tantalum-oxide minerals occur locally in muscovite potassic pegmatite pods contained in the medium-grained garnet-muscovite granite.

PETROCHEMISTRY

Three different units from one part of this large pegmatite dike were analyzed (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20c):

1. garnet-muscovite granite
2. biotite-muscovite potassic pegmatite
3. muscovite-biotite pegmatitic leucogranite

The analyses indicate mildly to strongly peraluminous compositions (A/CNK 1.021–1.224) that are modestly evolved on the basis of K/Rb (mean 99; range 75–126), Rb/Sr (mean 47; range 42–52) and Nb/Ta (mean 7.8; range 7.4–8.5) ratios (*see* Figure 56a). Maximum values for Li (73 ppm), Cs (32 ppm), Rb (578 ppm), Nb (22.5 ppm) and Ta (3 ppm) also indicate a modestly fractionated rare-element pegmatite system and likely of the beryl-type (Černý and Meintzer 1988).

Four bulk rock analyses of samples submitted to the authors by F. Plomp contained 8 to 93 ppm Ta, 33 to 130 ppm Nb, 130 to 1297 Rb, 11 to 65 ppm Cs and 22 to 68 ppm Li. Nb/Ta ratios vary from 1.38 to 4.14 and indicate significant fractionation between tantalum and niobium relative to the average upper continental crust ratio of 11.4 (Taylor and McLennan 1985). These samples are significantly more fractionated than those selected by the authors and may have originated from a different part of the pegmatite dike.

MINERAL CHEMISTRY

One bulk potassium feldspar sample was obtained from muscovite-biotite pegmatitic leucogranite at Temple Bay locality 01-FWB-118 and contains elevated Rb (1262 ppm) that is typical of beryl-type pegmatites (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21c) (Černý 1989a). Electron microprobe compositions of minerals from Temple Bay pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): columbite-tantalite (*see also* Table 8c), garnet (*see also* Table 11), fluorapatite (*see also* Table 10) and muscovite (*see also* Table 13a). Electron microprobe analysis of tantalum-oxide mineral grains (46 analyses) in the biotite-muscovite potassic pegmatite has confirmed the presence of ferrocolumbite and ferrotantalite with compositions that define a strong, iron-suite, fractionation trend (Figure 61a). This trend is marked by a range of Ta_2O_5 contents between 10.21 to 59.23 weight % and a mean content of 21.52 weight % Ta_2O_5. The garnet in the same sample is also iron-rich with a composition of almandine (68–74% almandine, 24–31% spessartine, 1% pyrope, 1% andradite) (*see* Figure 61b). Most of the manganese is preferentially partitioned into almandine, so the fluorapatite is manganese-poor (0.1–0.2 weight % MnO) (*see* Figure 62a). Potassium feldspar and muscovite have very low Rb and Cs contents (<0.2 weight % Rb_2O and <0.04 weight % Cs_2O) (Figure 68b).

Graphic–Tower Lakes Area

Rare-element mineralization was first discovered in this area (Figure 17) by Trowell, Logothetis and Caldwell (1982) who documented beryl-bearing, muscovite pegmatites near Graphic Lake. Trowell (1986) noted a particular abundance of tourmaline-quartz-rich veins in the Dogtooth and Gibi metavolcanic sequence, especially in the Tower Lake area (*see* Figure 17). Such veins were examined for gold (Trowell 1986), which was found to be negligible, however, the possibility of a genetic connection with rare-element-bearing, peraluminous granite masses was not previously considered.

The beryl-bearing pegmatites are hosted in the Royal Island group metasedimentary rocks that are possibly correlative with nearby Warclub group metasedimentary rocks (*see* Figure 17) (Blackburn et al. 1991). The pegmatites comprise a swarm with a breadth of least 300 m as delineated northward along Highway 71 from Graphic Lake (*see* Figure 17). The strike length of the swarm has not been determined, although mapping by Trowell (1986) suggests at least a 5.5 km strike length. At Graphic Lake, dikes between 20 cm and 8 m in width, are mainly controlled by the foliation of host rocks (metawacke of medium metamorphic grade). These dikes are massive, garnet-muscovite white potassic pegmatite with subordinate sodic aplite and medium-grained garnet-muscovite granite. Muscovite is quite common and is typically lime green. Beryl appears as sparse, faint green crystals up to 2 by 4 cm.

PETROCHEMISTRY

Four bulk rock samples of the biotite- and tourmaline-rich metasomatic assemblage (termed “glimmerite”), that occur adjacent to the quartz-tourmaline veins at Graphic Lake, were submitted for bulk analysis (Figure 63; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20c). In addition, an ultramafic rock (locality 01-JBS-75-06: UTM 420405E5498694N, Zone 15) with black tourmaline porphyroblasts developed by a metasomatic overprint from a nearby quartz-tourmaline vein was included in the sample collection from this section of the Gibi Lake metavolcanic rocks. All 5 analyses reveal pronounced increase of K_2O, which ranges from 2.03 to 7.12 weight % K_2O, in rocks that undoubtedly initially contained very low levels of this element (Taylor and McLennan 1985, p.181, 0.3 weight % K_2O) (*see* Figure 63). Elements that proxy for potassium are also enriched in the metasomatic assemblages: Cs (mean 13 ppm; range 5–15 ppm) and Rb (mean 108 ppm; range 74–173 ppm) and both show notable enrichment above levels that are typical for mafic metavolcanic and ultramafic rocks (Taylor and

McLennan 1985, p.181, Cs <1 ppm and 10 ppm Rb). Furthermore, lithium is anomalous for rocks that were initially mafic to ultramafic in composition (Taylor and McLennan 1985, p.92, 11 ppm Li) exhibiting a mean Li content of 52 ppm within a range of 44 to 62 ppm. The enrichment trend for K_2O and the rare-elements Cs, Rb and Li gives credence to an infiltration event of metasomatizing fluids derived from a rare-element pegmatite system situated at depth or along strike.

The pegmatite dikes hosted in clastic metasedimentary rocks near Graphic Lake were sampled at 3 different sites along Highway 71 (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20c). These beryl-type pegmatites are mildly to stongly peraluminous (A/CNK = 1.092-1.598), depending upon

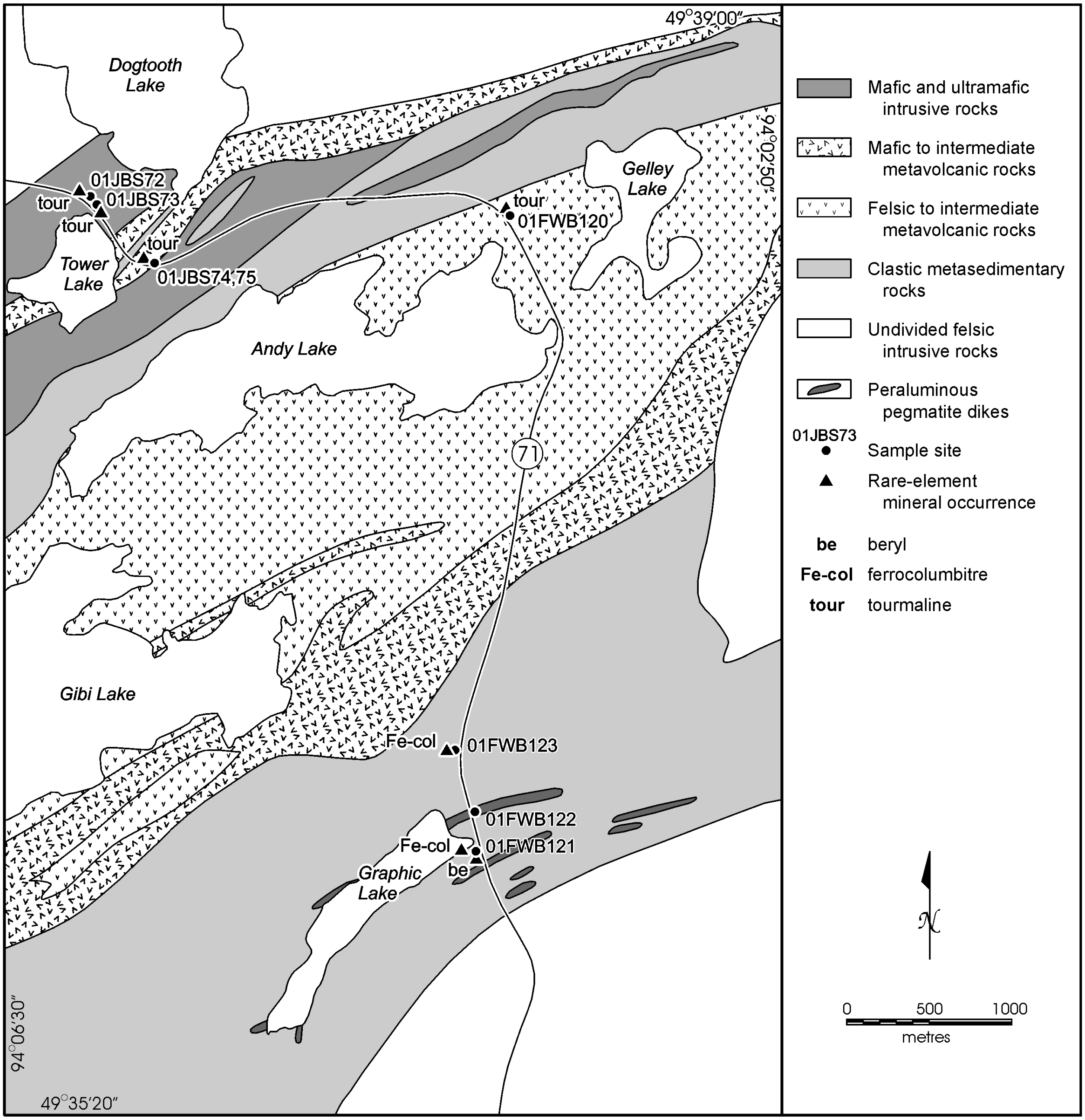


Figure 17. General geology and location of rare-element mineralization in the Graphic and Tower lakes area in the Sioux Lookout domain (Trowell et al. 1987).

the abundance of green muscovite (*see* Figure 63). A significant degree of fractionation is evident in the low K/Rb (mean 44; range 32–52), K/Cs (mean 1488; range 754–2412) and Nb/Ta (mean 4.3; range 2.4–6.9) ratios derived from bulk samples. Anomalous levels of all the rare-elements were detected: Rb (mean 763 ppm; range 672–991 ppm), Be (mean 21 ppm; 4–50 ppm), Cs (mean 27 ppm; range 14–42 ppm), Ga (mean 60 ppm; range 54–64 ppm), Sn (mean 32 ppm; 10–69 ppm), Nb (mean 89 ppm; range 66–109 ppm) and Ta (mean 23 ppm; range 16–28 ppm).

MINERAL CHEMISTRY

Bulk analysis of 4 potassium feldspar samples from the potassic pegmatite dikes situated at Graphic Lake indicate levels of Rb (mean 1707 ppm; range 1695–2002 ppm) and Cs (mean 38; range 35–42 ppm) that are typical for beryl-type rare-element pegmatites (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21c). Electron microprobe compositions of minerals from Graphic Lake area are published in MRD 111 (Tindle, Selway and Breaks 2002): columbite-tantalite (*see also* Table 8c), garnet (*see also* Table 11), muscovite (*see also* Table 13a), potassium feldspar (*see also* Table 12), beryl (*see also* Table 6) and tourmaline (*see also* Table 17).

Local black grains of ferrocolumbite were documented in garnet-muscovite leucogranite in the mid-part of the largest dike (on Graphic Lake), and specifically within a quartz-rich pod that also contains blue-grey, blocky potassium feldspar crystals up to 25 cm in diameter. An average of 9.56 weight % Ta_2O_5 was determined from 20 electron microprobe analyses of the ferrocolumbite grains (Figure 62b). The ferrocolumbite is associated with iron-rich garnet with a composition of almandine (60–66% almandine, 31–36% spessartine, 2–3% pyrope) (*see* Figure 61b). The muscovite contains only minor Rb and Cs (*see* Figure 60a).

Ferrocolumbite (12–19 weight % Ta_2O_5) also occurs in the centre of a muscovite potassic pegmatite dike hosted by Gibi metasedimentary sequence rocks at Graphic Lake on Highway 71 (*see* Figure 62b) (locality 01-FWB-123: UTM 422185E, 5495553N, Zone 15). This sample is more evolved than the garnet-muscovite leucogranite, as the garnet is more manganese-rich and the muscovite is more rubidium-rich. The spessartine-almandine has a composition of 49 to 53% spessartine, 47 to 50% almandine, 1% andradite (*see* Figure 61b). The muscovite contains 0.3 to 0.8 weight % Rb_2O and 0.0 to 0.1 weight % Cs_2O, whereas the biotite (siderophyllite) does not contain Rb or Cs above the detection limits (*see* Figure 60a). Additionally, potassium feldspar has elevated Rb contents (0.4–0.6 weight % Rb_2O, no Cs_2O detected), and beryl has a slightly elevated Cs content (0.2–0.6 weight % Cs_2O).

Prismatic, coarse-grained, black schorl (up to 1.1 cm long) and green muscovite occurs in pink sugary aplite at Graphic Lake (Figure 66). Black tourmaline-quartz-rich veins, 1 to 5 cm in thickness, are widespread in the Gibi and Dogtooth metavolcanic sequences and in intercalated ultramafic rocks of unknown origin. These veins are exposed over a 5 km interval along Highway 71 between Tower and Andy lakes (*see* Figure 17). The tourmaline veins possibly developed as a late, boron-silica fluid phase that was related to grey, massive, medium- to coarse-grained, leucocratic granitic dikes, 10 cm to 3 m in width. Vein contacts are commonly characterized by biotite-rich metasomatic mineral assemblages. The veins are relatively late and, locally, transect the granite, where attendant bleached zones, possibly due to albitization are evident. Schistose fine- to medium-grained meta-ultramafic rocks proximal to these veins also contain a relatively high abundance of biotite and lesser tourmaline porphyroblasts. Along Highway 71 near Tower Lake, the most magnesium-rich tourmaline (calcium-rich dravite) occurs as medium-grained, black, acicular, porphyroblasts with biotite in a chlorite-rich, fine-grained, mafic metavolcanic rock (*see* Figure 64) (locality 01-JBS-75: UTM 420405E, 5498694N, Zone 15). Massive, fine-grained, black tourmaline in the mafic metavolcanic rocks and massive, fine-grained, black tourmaline in felsic veins intruding the metavolcanic rocks are also calcium-rich dravite which is slightly more iron-rich than the tourmaline in the mafic metavolcanic rocks (*see* Figure 64).

The quartz diorite near Tower Lake contains green epidote, hornblende, black tourmaline, quartz, pink potassium feldspar, grey plagioclase, local biotite and minor pyrite and calcite (*see* Figure 17) (locality 01-JBS-73: UTM 420105E, 5498967N, Zone 15). Massive tourmaline and pyrite veins transect the quartz diorite. The tourmaline in the quartz diorite and the tourmaline + pyrite veins has a wide range of compositions from abundant calcium-rich dravite to common calcium-rich schorl to rare schorl-feruvite (*see* Figure 64). The coarse-grained black schorl-feruvite needles (up to 1 cm long) occur as brown alteration along fractures in the gneissic biotite quartz diorite.

MISCELLANEOUS PEGMATITE DIKES IN MINNITAKI GROUP METASEDIMENTARY ROCKS

Laval Lake Pluton

This 1.5 by 8 km pluton (*see* Figure 16) was mapped by Berger (1990). A mixture of pale pink (weathered surface) garnet-biotite pegmatitic leucogranite, medium-grained biotite granite and white weathering, muscovite-bearing pegmatitic granite were observed by the authors. The latter consist of fine-grained muscovite leucogranite intruded by garnet-muscovite potassic pegmatite.

PETROCHEMISTRY

Five bulk rock samples were selected in the vicinity of Highway 78 that obliquely transects this pluton. Bulk analyses of biotite granite, muscovite potassic pegmatite and fine-grained leucogranite from Laval Lake pluton are published in Table 20c of MRD 111 (Tindle, Selway and Breaks 2002). The analyses indicate mildly peraluminous compositions (mean A/CNK = 1.047) (*see* Figure 56a). Rubidium levels (mean 443 ppm; range 328–659 ppm) and the K/Rb ratios (mean 102; range 65–168) indicate modest fractionation. Tantalum contents are mostly low (<5.5 ppm) although an anomalous value of 20 ppm was detected in garnet-muscovite-potassic pegmatite (sample 01-JBS-30-02). Nb/Ta ratios (mean 7.8; range 3.4–9.7) also indicate modest enrichment of Ta over Nb relative to the average upper continental crust ratio of 11.4. The muscovite potassic pegmatite units reveal slightly anomalous lithium (32–58 ppm) as at locality 01-FWB-45 on Highway 78 (UTM 541959E, 5520249N, Zone 15). The pale pink biotite granite and garnet-biotite pegmatitic leucogranite units generally contain lower lithium contents (24–39 ppm), but overlap with the lithium range for muscovite-bearing, pegmatitic granite units. The above data substantiate the Laval Lake pluton as a fertile granite.

MINERAL CHEMISTRY

One bulk potassium feldspar sample was collected from the garnet-muscovite potassic pegmatite unit at locality 01-JBS-28 (UTM 542642E, 5520916N, Zone 15) contains 1181 ppm Rb, which further supports the fertile granite status of the Laval Lake pluton (*see* Figure 56b).

Electron microprobe compositions for minerals from Laval Lake pluton are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11) and tourmaline (*see also* Table 17).

The garnet in the biotite granite is almandine (54–55% almandine, 40–42% spessartine, 2% pyrope, 2% andradite) (*see* Figure 61b). Rare tourmaline in the biotite potassic pegmatite has a composition of magnesium-rich schorl (*see* Figure 66). The garnet in the potassic pegmatite varies in composition from almandine (52–64% almandine, 30–44% spessartine, 1–4% pyrope, 1% andradite) to spessartine (50–69% spessartine, 30–47% almandine, 1–2%pyrope, 1–2% andradite) (*see* Figure 61b).

Locality 01-JBS-29 (UTM 542465E, 5519919N, Zone 15) has fine-grained dark orange calcium-yttrium-rich spessartine with a composition of 63 to 68% spessartine, 21 to 27% almandine, 6 to 7% andradite, 2% pyrope and 0.8 to 2.5 weight % Y_2O_3 (Figure 65). The albitized biotite potassic pegmatite at locality 01-JBS-30 (UTM 542018E, 5519905N, Zone 15) has fine-grained, red, yttrium-rich spessartine with a composition of 56 to 57% spessartine, 38 to 39% almandine, 2% andradite, 2% pyrope and 0.5 to 1.7 weight % Y_2O_3. The spessartine in the biotite potassic pegmatite in the Laval Lake pluton is unusual because it contains elevated Y contents. This is the only locality, visited during this project, in which yttrium-rich spessartine has been found. Yttrium-rich garnet is an indicator mineral for NYF rare-earth-rich pegmatites (NYF: enrichment in Nb, Y and F). The rest of the pegmatites examined during this project are LCT pegmatites (LCT: enrichment in Li, Cs and Ta) (Černý 1991a).

Ghost Lake Batholith and Zealand Stock

The Ghost Lake batholith consists mostly of coarse-grained biotite and cordierite-biotite granite (GLB-1) (Breaks and Janes 1991) (Figure 18). Pegmatitic segregations occur throughout this unit and commonly consist of biotite and cordierite-biotite pegmatitic leucogranite with blocky megacrysts of graphic potassium feldspar. The eastern lobe of the Ghost Lake batholith is composed of several pegmatitic granite units: pegmatitic leucogranite (GLB-4), fine-grained leucogranite (GLB-5) and potassic pegmatite (GLB-6, 7 and 8) interlayered with sodic aplite according to the classification of Černý and Meintzer (1988) (Breaks and Janes 1991). The eastern lobe (GLB-4 to GLB-8) differ from the main mass (GLB-1) by the abundance of tourmaline and books of primary muscovite; rarity of biotite; and the appearance of minerals enriched in rare-elements such as beryl, muscovite and potassium feldspar. The enrichment of Rb and Cs in muscovite and potassium feldspar indicates that these rocks are fertile granites.

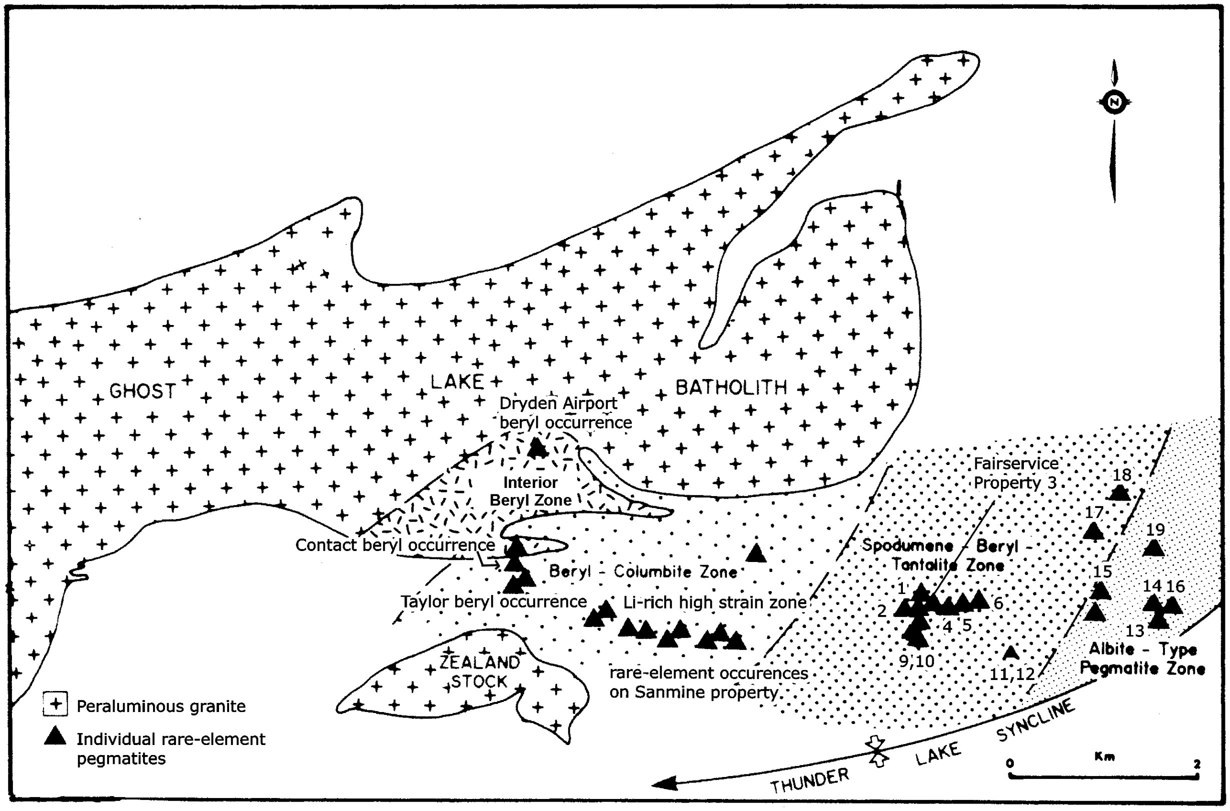


Figure 18. Geology and distribution of zones of rare-element pegmatites in the Mavis Lake pegmatite group (*from* Breaks and Janes 1991). The pegmatites increase in fractionation from west to east.

The Zealand stock is a 0.8 by 2.7 km ovoid pluton, first mapped by Satterly (1941) and contains intrusive units similar to GLB-5 to GLB-8. Thus, it is interpreted as an apophysis of the nearby fertile granites of the Ghost Lake batholith (Breaks 1989; Breaks and Moore 1992).

PETROCHEMISTRY

Modestly evolved, tourmaline-muscovite pegmatite dikes occur in clastic metasedimentary rocks proximal to the Zealand stock and the southern contact of the Ghost Lake batholith (*see* Figure 18). Potassium feldspar compositions (*see also* Breaks 1989, Figure 38 and p.553 that contain localities F22-1, F22-2, F24-3, F26-4 and F30-1) reveal anomalous levels of Rb (1370–1890 ppm) and Cs (50–84 ppm). Analyses of muscovite from the same area (*see also* Breaks 1989, Figure 38 and p.576) indicate anomalous Li (up to 1080 ppm), Rb (1370–2450 ppm) and Ta (30–60 ppm). Petrochemical data from pegmatite F22-1 reveal anomalous Li (255 ppm), Cs (120 ppm), Rb (450 ppm), Ta (35 ppm), Nb (35 ppm) and Sn (33 ppm). Such pegmatite dikes should be explored for rare elements.

A detailed examination of the petrochemistry of the Ghost Lake batholith and related rare-element pegmatites has been given by Breaks and Moore (1992) who demonstrated that the eastern part of the batholith had evolved into a fertile granite (*see* Figure 18). The present survey added 3 new bulk rock samples selected from this significant, fertile, peraluminous, S-type granite body in the vicinity of Dryden airport (locality 01-JBS-31: UTM 519317E, 5519401N, Zone 15) and on the Ghost West Road (locality 01-JBS-32: UTM 521843E, 5521158N, Zone 15) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20c). Two samples of fine-grained leucogranite from the Dryden airport outcrop are mildly peraluminous (A/CNK 1.088–1.122) with modest fractionation indicated by elevated Li (48–85 ppm) and Rb/Sr (21–56) and low K/Cs (2070–3058) and K/Rb (97–100) ratios (*see* Figure 56a). Nb/Ta ratios are quite varied at 1.2 and 8.3 due to the leucogranite's modest degree of fractionation. Sample 01-JBS-32-09, a tourmaline-garnet-muscovite potassic pegmatite, occurs in an outcrop not previously examined by the authors and is strongly peraluminous (A/CNK = 1.277), but is mildly fractionated, as shown by K/Rb (142), Nb/Ta (9.3), K/Cs (2730) and Rb/Sr (19) ratios (*see* Figure 56a). Low concentrations of tantalum (2 ppm) and niobium (19 ppm) were measured.

MINERAL CHEMISTRY

Garnet- and tourmaline-bearing fine-grained leucogranite, potassic pegmatite and aplite from the Ghost Lake batholith and Zealand stock were examined near Dryden (*see* Figure 18). Electron microprobe compositions for minerals from the Ghost Lake batholith and Zealand stock are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11), tourmaline (*see also* Table 17) and fluorapatite (*see also* Table 10).

The almandine in these 3 rock types have similar compositions: 63 to 78% almandine, 20 to 35% spessartine, 1 to 2% pyrope, 1% andradite (*see* Figure 57). The almandine from the fine-grained leucogranite at the Dryden airport locality (01-JBS-31: UTM 519317E, 5519401N, Zone 15) has 2 distinct compositions: the first is magnesium-rich (74–78% almandine, 13–19% pyrope, 4–6% spessartine, 1–2% andradite, 1% grossular), whereas the second composition is relatively magnesium-poor (80–81% almandine, 16% spessartine, 2% pyrope, 1% andradite). The tourmaline in these rocks has a range in composition from foitite to magnesium-bearing schorl (*see* Figure 58). At the Dryden airport locality, the tourmaline in the potassic pegmatite is columnar and very-coarse grained (up to 20 cm long). The tourmaline is zoned from foitite cores to magnesium-bearing schorl rims indicating decreasing aluminum and increasing magnesium and iron availability during crystallization. The Ghost Lake batholith potassic pegmatite also contains fluorapatite (*see* Figure 62a).

RECOMMENDATIONS FOR PEGMATITE EXPLORATION

Rare-element pegmatites of the beryl-type that contain interesting tantalum levels (30–150 ppm), are widely distributed in metasedimentary rocks of the Abram, Minnitaki, Warclub and Royal Island groups within the Sioux Lookout domain. Areas such as Graphic Lake require careful exploration to determine if there is a regional zonation toward lithium-rich (spodumene, petalite or even lepidolite) pegmatite subtypes. The pegmatite dike swarm in the Graphic Lake area should be examined along strike to the northeast and southwest. This recommendation is enhanced by the significant anomalous bulk chemistry of the beryl-type pegmatites sampled along Highway 71 near Graphic Lake, coupled with rare-element enrichment detected in the tourmaline-bearing, metasomatized mafic and ultramafic metavolcanic rocks of the Gibi Lake assemblage. The extensive metasomatic assemblage (Trowell 1986) implies the presence of a large rare-element-mineralized system.

Exploration is also warranted across the Minnitaki group in the Eagle Lake–Dryden–Hartman townships area since economically interesting tantalum levels occur in pegmatite dikes. Exploration should initially focus in the exocontact zones around fertile, peraluminous, parent granite masses, such as the Hughes Creek pluton, Zealand stock and Laval Lake pluton and east to northeast of the Ghost Lake batholith. The significantly fractionated pegmatite dike swarm in Brownridge Township warrants particular attention. Exploration on strike with the Temple Bay pegmatite and to the southwest into the correlative Warclub metasedimentary group is also recommended.

METAVOLCANIC-HOSTED RARE-ELEMENT MINERALIZATION IN THE SIOUX LOOKOUT DOMAIN

Dryden Pegmatite Field

Rare-element pegmatite mineralization and related peraluminous granite masses in the Dryden area have been examined in detail by Breaks (1989), Breaks and Janes (1991) and Breaks and Moore (1992) (*see* Figure 18). The Dryden pegmatite field consists of 2 pegmatite groups located about 10 km apart: Mavis Lake and Gullwing Lake–Tot Lake. Samples in the OGS archives from the Dryden pegmatites that contain tantalum-oxide minerals were extensively analyzed by electron microprobe as part of this project and the descriptions below mainly focus upon the observed variation in chemistry of columbite-tantalite group minerals, as these are the dominant tantalum-bearing species. Note that references to “stop(s)” in the following text are from a field trip guidebook written by F.W. Breaks and D.A. Janes for the Geological Association of Canada–Mineralogical Association of Canada–Society of Economic Geologists joint annual meeting in Toronto in 1991. The stop(s) are labelled on Figure 19.

MAVIS LAKE PEGMATITE GROUP

The pegmatites within the Mavis Lake pegmatite group are genetically related to their parent: the Ghost Lake batholith (described above) (*see* Figure 18) (Breaks 1989; Breaks and Janes 1991; Breaks and Moore 1992). The Mavis Lake pegmatite group consists of a 0.8 to 1.5 by 8 km, east-trending concentration of pegmatites and related metasomatic zones. It exhibits a classic regional zonation of pegmatite types with increasing distance from the parent Ghost Lake batholith, as defined by systematic changes in mineralogy, chemical association and extent of post-magmatic replacement. The following regional zones have been delinated: interior beryl zone, beryl-columbite zone, spodumene-beryl-tantalite zone and albite-type pegmatites (Breaks 1989).

The interior beryl zone occupies a 1.5 by 3.5 km area of pegmatitic granites within the Ghost Lake batholith and is defined by sporadic green primary beryl in potassic pegmatite dikes and masses (unit GLB-7) (*see* Figure 18; stop 10 in Figure 19) (Breaks and Janes 1991).

In the adjacent mafic metavolcanic country rocks, the beryl-columbite zone constitutes the first grouping in the exocontact (Breaks and Janes 1991). This rare-element mineralization is contained in muscovite-tourmaline potassic pegmatites, as at Taylor No. 1 and No. 2 pegmatites, or in locally albitic

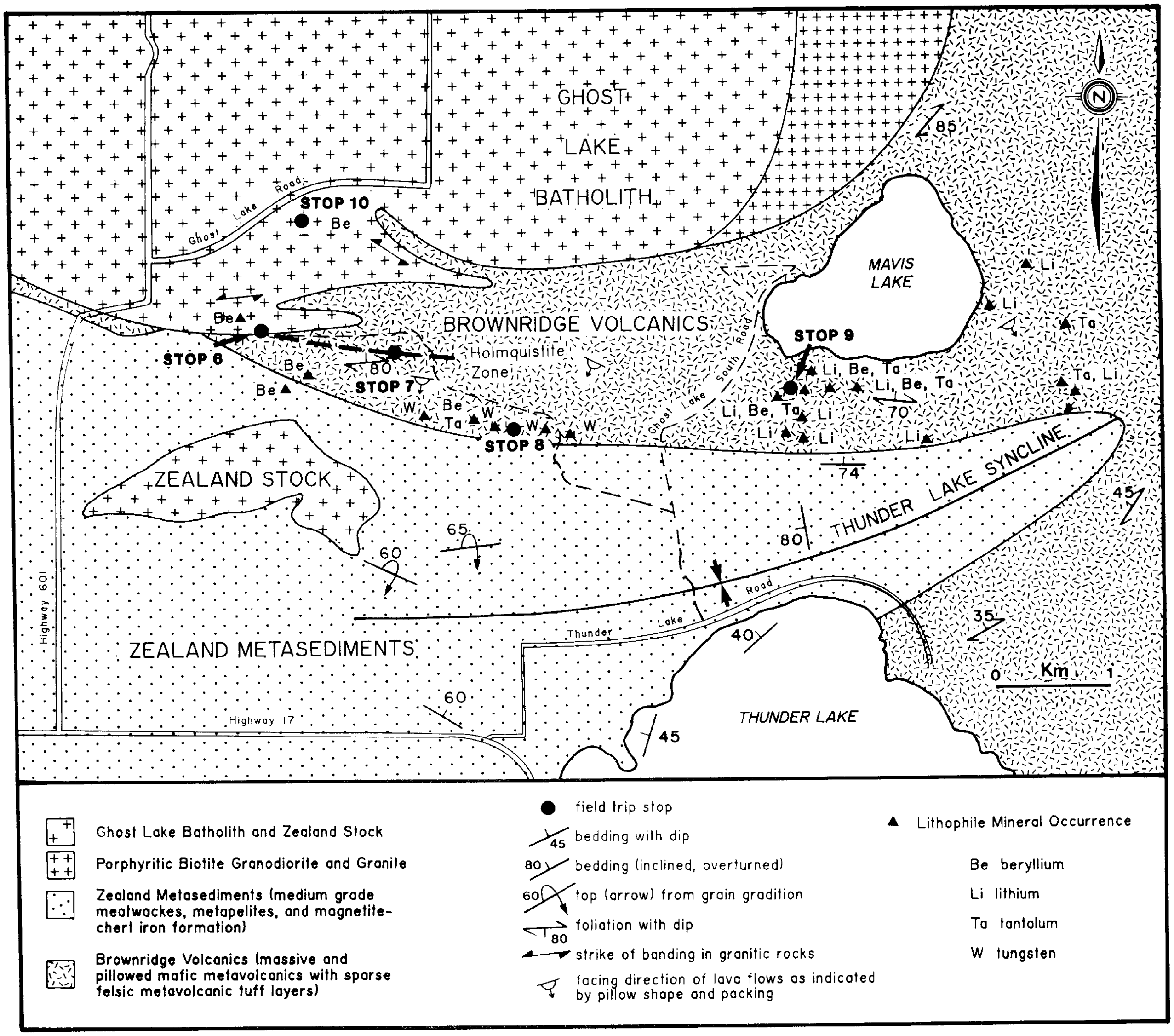


Figure 19. Detailed geology of Mavis Lake pegmatite group (*from* Breaks and Janes 1991). Stop 6: contact zone of fertile pegmatitic granites of Ghost West batholith with mafic metavolcanic host. Stop 7: lithium-enriched high strain zone. Stop 8: scheelite mineralization in tourmalinite, Sanmine property. Stop 9: Fairservice spodumene-beryl-tantalite pegmatites. Stop 10: internal parts of the Ghost Lake batholith. Stop 10 is from the interior beryl zone, stops 6 to 8 are from the beryl-columbite zone and stop 9 is the spodumene-beryl-tantalite zone of the Mavis Lake pegmatite group (*see* Figure 18).

units at the Contact Beryl occurrence (stop 6 in Figure 19). Interspersed throughout the beryl-columbite zone are low concentrations of scheelite (<0.1 weight % WO_3) in tourmalinite sheets, calc-silicate skarns and pillow selvages (Samine property, stop 8 in Figure 19).

The spodumene-beryl-tantalite zone is defined by the initial appearance of spodumene in pegmatites of the albite-spodumene type (Černý 1991a), about 3.5 km from the batholith contact with the Brownridge volcanics (Breaks and Janes 1991). Swarms of tabular pegmatite dikes, up to 10 m in thickness and 280 m in length, generally strike parallel to the foliation in the host. Internal zoning is indistinct to absent and is best exemplified at Fairservice No. 1 pegmatite (Breaks 1989) (stop 9 in Figure 19), which contains 3 gradational zones of increasing content of quartz: a) potassic pegmatite with minor interstitial spodumene and quartz; b) spodumene-quartz-rich pegmatite; and c) a discontinuous quartz-rich core zone with minor spodumene, blocky microcline and beryl.

The distal zone of the Mavis Lake pegmatite group is composed of extensively replaced, albite-rich pegmatites considered to be representative of the albite-type of Černý (1991a) (Breaks and Janes 1991). These pegmatites form thin (<1 m) sheets rich in albite. They contain sporadic fine-grained aggregates of green muscovite and albite (interpreted as secondary replacement after spodumene), tantalite, white beryl and rare green tourmaline.

Two stages of contact metasomatism have affected the mafic metavolcanic host rocks situated adjacent to the chemically most fractionated pegmatitic granite units (Breaks and Janes 1991). The synmagmatic exocontact metasomatism affected the amphibolitic host rocks along the contact with the Ghost Lake batholith. Rare-element-enriched (Li, Rb, B, F, Cs, Sn) pegmatitic fluids entered the host rocks and produced dravite (magnesium-rich tourmaline), phlogopite (magnesium-rich biotite) and actinolite. A characteristic feature of this metasomatic zone is the ubiquity of holmquistite (lithium-amphibole), which occurs within 20 m of a lithium-rich pegmatite (London 1986).

The second stage of contact metasomatism is post-magmatic endomorphism (late-stage alteration of the pegmatite) and exocontact metasomatism (Breaks and Janes 1991). The primary units of the eastern lobe of the Ghost Lake batholith (GLB-5, GLB-6 and GLB-7) are affected by albitization and minor greisenization, which is best revealed by the Contact Beryl occurrence (*see* Figure 18).

Contact Beryl Occurrence

Tourmaline-biotite-actinolite metasomatic rock occurs near the contact of the Ghost Lake batholith at stop 6 (Breaks and Janes 1991) (*see* Figure 19). Electron microprobe compositions for minerals from the Contact Beryl occurrence—tourmaline, biotite (phlogopite-siderophyllite), cassiterite and strüverite—will be published in a future MRD.

The tourmaline is dravite-uvite, the biotite is phlogopite-siderophyllite with low Rb and Cs contents (0.3 weight % Rb_2O, 0.1 weight % Cs_2O) (*see* Figures 66 and 60a). The synmagmatic alteration aureoles in the amphibolite host rock from the Ghost Lake batholith contact according to the dominant mineral are dravite, phlogopite, actinolite and holmquistite aureoles. Accessory rutile is tantalum-free, as the Ta preferentially partitioned in the strüverite over the rutile. The tantalum-oxide minerals at the Contact Beryl occurrence are cassiterite and strüverite [$(Ti,Ta,Fe)O_2$] rather than columbite-tantalite, which are common at other Ontario localities examined during this study. The abundance of tantalum-bearing cassiterite and strüverite is likely due to the abundance of Sn and Ti relative to Ta possibly due to differences in the source regions of the pegmatites.

Dark brown, tantalum-bearing, cassiterite (5 by 6 mm, 0.6–1.9 weight % Ta_2O_5) occurs in a beryl-albite-green muscovite "greisen" zone. Tantalum-poor cassiterite (<0.2 weight % Ta_2O_5) and tantalum-rich strüverite (5–11 weight % Ta_2O_5) occur in a black tourmaline-quartz-albite dike (30 cm wide) that transects the holmquistite-bearing (lithium-amphibole) metavolcanic host rocks (sample 88-36). Cassiterite and tantalum-rich strüverite (4–12 weight % Ta_2O_5) also occur in a beryl-plagioclase dike (10 cm thick) at locality B of stop 6 (Breaks and Janes 1991) (*see* Figure 19) (sample 88-40). An albite-rich dike near this locality contains dark brown, elongate, tantalum-rich strüverite (6–13 weight % Ta_2O_5). The tourmaline in samples 88-36 and 88-40 is magnesium-rich schorl (*see* Figure 66).

Taylor Beryl Pegmatite

The Taylor Beryl pegmatites are unzoned dikes enriched in boron and beryllium that intrude metamorphosed ultramafic rocks close to the Ghost Lake batholith (Breaks and Moore 1992). The host rock has been metasomatized to produce a phlogopite-tourmaline-holmquistite (lithium-amphibole) aureole within 30 cm of the southeast dike contact. The Taylor Beryl pegmatite dikes are characterized by local emerald, which formed intermediately adjacent to phlogopite-rich selvages in contact with meta-ultramafic host rocks (Breaks and Janes 1991). The primary mineral assemblage of the dikes is beryl-muscovite-potassium feldspar-quartz-tourmaline-albite and the accessory minerals are oxide minerals, garnet and apatite. The dikes contain sporadic local zones (4 by 10 cm) of albite replacement.

Electron microprobe compositions of minerals from Taylor Beryl pegmatites and ultramafic host rock—tourmaline, fluorapatite, columbite-tantalite, garnet and muscovite—will be published in a future MRD.

The holmquistite-bearing ultramafic rocks contain black tourmaline (calcium-rich dravite), fluorapatite and veins and pods of sugary quartz (Figures 67a and 62a). The border zone of the pegmatite dikes, next to the host rock, contains abundant tourmaline (calcium-bearing dravite), green manganese-rich fluorapatite (1.1–2.0 weight % MnO), minor ferrocolumbite to ferrotantalite (48–58 weight %Ta_2O_5) and quartz (*see* Figures 67 and 62). The presence of calcium-bearing dravite in the border zone suggests that this zone has been contaminated by calcium-magnesium-bearing, ultramafic, host rocks.

Dike #1 consists of an aplite with abundant fine-grained tourmaline and minor blue fluorapatite and garnet: almandine (56–60% almandine, 38–42% spessartine, 1% grossular, 1% pyrope) (*see* Figures 67, 62a and 68a). The schorl from the aplite is the tourmaline that is the least affected by host rock contamination at the Taylor Beryl locality. The fluorapatite only occurs near the south contact with the schistose ultramafic and amphibolite host rocks.

Dike #2 consists of sodic pegmatite with an assemblage of apatite-beryl-muscovite-tourmaline-quartz-albite, local blocky potassium feldspar, minor tantalum-oxide minerals and garnet. This is Ontario's only emerald occurrence (Breaks and Janes 1991). The tourmaline is zoned with magnesium-rich schorl cores and dravite-schorl rims (*see* Figure 67). The oxide minerals range in composition from ferrocolumbite to manganocolumbite (6–17 weight % Ta_2O_5) (*see* Figure 62b). The garnet is zoned with magnesium-bearing almandine cores (52–55% almandine, 41–45% spessartine, 3% pyrope, 1% grossular) and spessartine rims (54–68% spessartine, 30–43% almandine, 1–2% pyrope, 1% grossular) (*see* Figure 68a). Manganese is preferentially partitioned into the oxide minerals and garnet instead of the fluorapatite, therefore, the fluorapatite has very low manganese contents (0.1–0.4 weight % MnO) (*see* Figure 62a). The muscovite in this dike also has very low Rb contents (0.1–0.3 weight % Rb_2O) (*see* Figure 60a). The sodic pegmatite is relatively primitive, as the tourmaline is magnesium-rich, the oxide minerals are tantalum-poor and the muscovite is rubidium-poor. The only fractionation indicator that contradicts its primitive nature is the presence of spessartine (manganese-rich garnet).

Lithium-rich High-Strain Zone

The lithium-rich high-strain zone occurs in the centre of the beryl-columbite zone of the Mavis Lake pegmatite group (stop 7 on Figure 19, *see* Figure 18) (Breaks and Janes 1991). The lithium-rich high-strain zone so far appears to be devoid of rare-element pegmatites and yet it contains rare-element minerals (beryl and holmquistite) and anomalous concentrations of Li, Cs and Rb. This 4 to 6 m wide mineralized shear zone represents the on-strike continuation of similar metasomatic rocks 0.7 km to the west of the Contact Beryl occurrence (stop 6). This rusted shear zone is hosted within the amphibolitic mafic metavolcanic rocks and exhibits abundant calc-silicate segregations.

The shear zone consists of several units: 1) fine-grained saccharoidal albitite, 2) tourmaline-layered albitite, 3) pyrite-quartz schist, 4) pyrite-tourmaline-sericite schist, 5) tourmalinite, 6) holmquistite-bearing metasomatic rock and 7) porphyroblastic rock with sericite psuedomorphs after cordierite (Breaks and Janes 1991). These units are individually narrow (0.35–3 m thick) and are oriented parallel to the shear zone boundaries. A chemical analysis of the deformed holmquistite unit reveals 1820 ppm Li, 460 ppm F and 429 ppm Rb and 332 ppm Cs (Breaks and Janes 1991).

A sample (88-22) of talc-brown tourmaline- and biotite-rich rock was examined by electron microprobe and the analyses will be published in a future MRD. The exocontact brown tourmaline is mostly calcium-rich dravite, but in the bronze-coloured biotite-rich masses, the tourmaline is zoned with fluorine-rich uvite cores (calcium-rich), dravite zones and “fluor-dravite” rims (calcium-poor) (*see* Figure 66). The biotite is phlogopite-siderophyllite with low Rb and Cs contents (0.2 weight % Rb_2O, 0.1 weight % Cs_2O) and it is associated with fluorapatite (Figure 70b).

This rock was originally calcium- and magnesium-rich and it was metasomatized by an influx of fluorine-, rubidium- and cesium-rich fluids, likely from the Ghost Lake batholith. The presence of fluorine-rich tourmaline in a mafic metavolcanic rock probably indicates the close proximity of rare-element pegmatites.

Sanmine Property

Low modal abundances of scheelite ($CaWO_4$) are distributed throughout the beryl-columbite zone of the Mavis Lake pegmatite group (*see* stop 8 in Figure 19) (Breaks and Janes 1991). At the Sanmine property, the scheelite occurs in tourmaline-rich sheets that chemically and mineralogically link it with the rare-element mineralization of the Mavis Lake pegmatite group.

Tourmalinite occurs as a) flat-lying, undulating 0.3 m thick sheets which dip 10 to 20º to the south, b) as ancillary, steeply dipping (70–85ºW) fracture fillings, and c) lastly along 0.7 to 5 cm thick pillow selvages (Breaks and Janes 1991). The sheets and fracture fillings variably transect the foliation of the host pillowed mafic metavolcanic rocks. Minerals accompanying the 80 to 90 volume % black tourmaline rocks include biotite, actinolite, plagioclase, magnesium-hornblende, holmquistite (Li-amphibole) and scheelite. The scheelite predominantly occurs as predominantly anhedral, poikilitic, honey-brown grains up to 5 by 7.5 cm. Holmquistite occurs as rare mauve rosettes (up to 1 cm diameter) of fine-grained needles on the surface of thin quartz sheets and within plagioclase-dominant veins.

Chemically, the tourmalinite exhibits affinities with rare-element mineralization. A 3.5 m channel sample taken within and parallel to the dip direction of the flat-lying tourmalinite sheet, which has the highest scheelite content, contains the following element concentrations: 9600 ppm F, 950 ppm W, 246 ppm Li, 193 ppm Sn, 45 ppm Be and 40 ppm Cs (Breaks and Janes 1991). The analysis of a tourmaline-rich pillow selvage selected a few metres east of the tourmalinite sheet reveals greater enrichment in Li (1240 ppm Li) and Cs (90 ppm Cs), and lower F (1010 ppm), Sn (3.7 ppm) and Be (3 ppm).

About 30 m east and downslope from the scheelite-bearing tourmalinite sheet is a flat-lying, fine-grained garnet-tourmaline leucogranite dike, 15 to 45 cm thick, and locally grading into a metre-size zone of quartz-rich material (Breaks and Janes 1991). The quartz-rich zone also contains blocky potassium feldspar, partially to completely replaced by albite, and lesser euhedral green beryl. This dike has a tourmaline-rich halo and could have, in part, been responsible for influx of boron along adjacent pillow selvages.

The Sanmine outcrop at locality 01-FWB-34 (UTM 521191E, 5517333N, Zone 15) consists mostly of pillow metabasalts with thin felsic sheets/veins of quartz and feldspar almost completely altered to sericite and epidote. The metabasalts contain hornblende grains aligned parallel to each other with quartz, minor biotite and epidote.

MINERAL CHEMISTRY

Electron microprobe compositions of minerals from the Sanmine property are published in MRD 111 (Tindle, Selway and Breaks 2002): columbite-tantalite (*see also* Table 8c), tourmaline (*see also* Table 17), garnet (*see also* Table 11), fluorapatite (*see also* Table 10), biotite (phlogopite-siderophyllite, *see also* Table 13d) and muscovite (*see also* Table 13a).

At the Sanmine property, the columbite-tantalite has an overall average Ta_2O_5 content of 32.23 weight % within a range of 12.33 to 68.33 weight % based upon 84 electron microprobe analyses (*see* Figure 62b). Appreciable ranges in Mn/(Mn+Fe) (0.230–0.868) and Ta/(Ta+Nb) (0.101–0.753) are notable.

The mafic metavolcanic rocks contain local abundant needles of coarse-grained black tourmaline (up to 1.4 cm long) aligned parallel to hornblende (magnesio-hornblende and ferro-ferrian tschermakite) grains. The tourmaline has a composition of dravite-uvite (Figure 69). Black tourmaline porphyroblasts developed in crenulated ultramafic schist. The tourmaline prisms are randomly oriented and overprint the crenulation fold axis. The tourmaline porphyroblasts are also dravite-uvite, but more magnesium-rich (*see* Figure 66). In the mafic metavolcanic rocks, garnet inclusions in tourmaline are calcium-rich almandine (69–76% almandine, 5–15% grossular, 11–14% spessartine, 2% pyrope, 0–2% andradite) (*see* Figure 65b). Fluorapatite and phlogopite-siderophyllite (0.0–0.2 weight % Rb_2O, 0.1–0.3 weight % Cs_2O) also occur in the tourmaline-rich metasomatized host rock (*see* Figure 60a). The tourmaline in the felsic sheets has a wide range in composition (mostly dravite-uvite, common schorl-dravite and rare feruvite and uvite, calcium-rich “fluor-dravite” and fluorine-rich feruvite) and it occurs as coarse-grained radiating prisms (up to 2 cm long) (*see* Figure 69).

The presence of tourmaline in a mafic metavolcanic rock indicates that the rock has been altered by boron-rich fluids to produce the tourmaline. The tourmaline in the mafic metavolcanic rocks are magnesium- and calcium-rich because these elements are abundant in the mafic metavolcanic rocks. The tourmaline in the felsic sheets are fluorine-rich, which indicates rare-element mineralization. Fluorine is common in evolved rare-element pegmatites, but is much less abundant in granites and rare in mafic metavolcanic rocks.

The metavolcanic rocks are intruded by an albite-rich dike consisting of albitized potassic pegmatite (black tourmaline-muscovite-quartz-pink feldspar) and fluorapatite-bearing aplite. The tourmaline-rich border zone along the contact with the host rock is 5 cm thick. The tourmaline in the border zone is magnesium-rich with a composition of schorl-dravite (*see* Figure 69). The tantalum-bearing oxide minerals are ferrocolumbite and ferrotantalite (35–53 weight % Ta_2O_5) and they are associated with fluorapatite (*see* Figure 62). The biotite is rubidium-rich phlopogite-siderophyllite with 0.8 to 0.9 weight % Rb_2O and 0.1 to 0.2 weight % Cs_2O (*see* Figure 60a).

In the albitized potassic pegmatite, the tourmaline is magnesium-rich schorl and the tantalum-bearing oxide mineral is ferrocolumbite (12–33 weight % Ta_2O_5) (*see* Figures 69 and 62b). The muscovite has low Rb contents (0.3 weight % Rb_2O) and no detected Cs (*see* Figure 60a). Mineral compositions in the aplite are more evolved than those in the albitized potassic pegmatite. The tourmaline in the aplite is zoned with schorl cores and magnesium-rich schorl rims (*see* Figure 69). The oxide minerals in the aplite ranges in composition from rare ferrocolumbite, to rare manganocolumbite, to common manganotantalite (21–68 weight % Ta_2O_5) (*see* Figure 62b). The garnet is calcium-rich spessartine (52–61% spessartine, 28–33% almandine, 8–12% grossular, 2% andradite) (*see* Figure 68a). Blue-green fluorapatite is manganese-enriched (0.5–1.0 weight % MnO) (*see* Figure 62a).

Fairservice Spodumene Pegmatites

In the spodumene-beryl-tantalite zone of the Mavis Lake pegmatite group (*see* Figure 18), there are 12 spodumene pegmatites that vary in size from 3 by 25 m to 15 by 280 m (Breaks 1989). Most of these lensoidal bodies strike parallel to the host mafic metavolcanic foliation, however, dips vary in direction and amount (40–75°N to 50–80°S). The Fairservice spodumene pegmatites occur in the northwestern extremity of the spodumene-beryl-tantalite zone (*see* stop 9 in Figure 19). The north zone of the Fairservice property, directly south of Mavis Lake, contains pegmatites #1 to #6 from west to east (*see* stop 9 in Figure 19). The south zone of the Fairservice Property, within the Brownridge volcanics close to the contact with the Zealand metasediment rocks, contains pegmatites #9 to #12. The east zone of the Fairservice Property, east of Mavis Lake, contains pegmatites #13, #14, #15 and #16. The northeastern zone comprises pegmatites #17, #18 and #19. The spodumene pegmatites from these zones are very similar in mineralogy and the geology of Fairservice pegmatites #1 and #2 will be discussed as examples (Breaks 1989 and Breaks and Janes 1991). Most of the spodumene pegmatites contain 3 internal pegmatite zones: spodumene, albitized and aplite zones.

FAIRSERVICE SPODUMENE PEGMATITE #1

This 12 by 76 m pegmatite occurs in foliated and gneissic mafic metavolcanic rocks and subordinate, fine-grained laminated metawacke (Breaks and Janes 1991). It exhibits a vague internal zonation that is lacking in most spodumene pegmatites of the Mavis Lake pegmatite group with 1) quartz-rich core, 2) spodumene-rich, albite-quartz zone, and 3) spodumene-bearing potassic pegmatite.

Quartz-rich Core

This zone occurs from the dike centre to the north wall. It forms irregular pods, up to 2 by 9 m, and contains aggregates and single crystals of blocky microcline (potassium feldspar) individually up to 33 by 41 cm, green primary spodumene, yellow-green muscovite, albite, black tourmaline and lesser white and light blue beryl, together with blue apatite and orange garnet (Breaks and Janes 1991). These irregular pods are immersed within a matrix of 70 to 80 volume % light grey massive quartz. A characteristic texture occurring solely in the core zone is that of spodumene megacrysts, up to 4 by 8 cm, partially to completely rimmed by fine-grained albite, minor muscovite and rare tantalite. This texture may have been created by albitization of earlier formed phases. Euhedral primary beryl up to 3 by 7 by 2 cm occurs disseminated in low quantities throughout. It contrasts to secondary white subhedral beryl associated with albite-rich replacement zones near the south wall.

Spodumene-rich, Albite-Quartz Zone

This zone, which envelops the quartz-rich core zone, contains the highest quantity (49 volume %) and largest size (9–12 cm by 1 m) of spodumene observed in the Mavis Lake pegmatite group (Breaks and

Janes 1991). High quantities of quartz are also characteristic (37–47 volume %) as is rare total feldspar content (7–14 volume %). Pods of sodic aplite up to 1 by 3 m occur sparsely throughout the zone and are interpreted as primary as no replacement textures are discernible. The aplite pods are distinguished from the replacement albite by blue fluorapatite and triphylite (Li, Fe-phosphate).

Spodumene-bearing Potassic Pegmatite

The final primary internal zone to crystallize is a potassic pegmatite with minor spodumene (7 volume %) (Breaks and Janes 1991). It has patchy distribution, but is mainly found near the southeastern part of pegmatite #1. The zone is distinguished by coarse aggregates of light pink to white microcline (potassium feldspar) which comprises 55 volume %. Also notable is the pronounced depletion of spodumene in comparison with the adjacent spodumene-quartz zone. The spodumene is interstitial to the much coarser potassium feldspar and here the spodumene commonly forms an intergrowth with quartz.

Albite-rich Replacement Zones

Irregular albite-rich replacement zones are typical of all spodumene pegmatites of the Mavis Lake pegmatite group and are well represented in Fairservice pegmatite #1 (Breaks and Janes 1991). The intensely albitized rocks are composed of an assemblage of white beryl-green muscovite-quartz-albite and may contain accessory garnet and tantalite. In other pegmatites in the spodumene-beryl-tantalite zone, lensoidal pseudomorphs of aphanitic green mica and albite after spodumene are evident in the albitic replacement zones. Tantalite in Fairservice pegmatite #1 is clearly associated with replacement stage processes, as it occurs in albitized rims on spodumene and along cleavages in blocky microcline (potassium feldspar) (Breaks and Janes 1991).

FAIRSERVICE PEGMATITE #2

Fairservice pegmatite #2 is 268 m long and mostly consists of a spodumene-bearing potassic pegmatite zone, similar to that in Fairservice pegmatite #1 (Breaks and Janes 1991). It is distinguished by conspicuous megacrysts of green spodumene, which are complexly intergrown with quartz. Slender spodumene crystals, up to 12–20 cm by 1 m, are oriented approximately normal to the upper, shallowly south-dipping pegmatite contact. These megacrysts contain abundant, much finer grained equigranular quartz compising about 30 volume % of the intergrowth. This spodumene and quartz intergrowth is surrounded by a mixture, 4 to 5 cm thick, of quartz, green muscovite and albite and is typically enveloped by coarse microcline.

Pegmatite #2 also exhibits a locally developed quartz-rich core zone accompanied by blocky microcline (potassium feldspar), white euhedral beryl and spodumene (Breaks and Janes 1991). Pods of sodic aplite with minor apatite and triphylite (a lithium-, iron-phosphate) are also present in pegmatite #2 similar to that in pegmatite #1.

Tantalite, although sparse in quantity, is more uniformly disseminated relative to the other spodumene pegmatites in the Mavis Lake pegmatite group (Breaks and Janes 1991). Maximum concentrations of Ta (380 ppm Ta) and Nb (310 ppm Nb) for pegmatites of the spodumene-beryl-tantalite zone were found in channel samples from Fairservice pegmatite #2.

The mafic metavolcanic host rock of pegmatite #2 has been affected by metasomatism. Dark purple needles of holmquistite (lithium-amphibole) up to 4 cm randomly transect the foliation and hornblende lineation. Other exomorphic minerals are bronze biotite and black tourmaline. Host rocks containing high lithium concentrations (up to 1.48 weight % Li_2O) generally form the widest exocontact aureole around the Mavis Lake pegmatites group pegmatites (Breaks and Janes 1991).

MINERAL CHEMISTRY

Electron microprobe compositions of the minerals from Fairservice spodumene pegmatites—columbite-tantalite, wodginite, strüverite, cassiterite, tourmaline, fluorapatite and muscovite—will be published in a future MRD. Mineral chemistry plots are based on unpublished data.

At the Fairservice property (*see* Figure 18, and stop 9 in Figure 19), average Ta_2O_5 contents of columbite-tantalite from most of the rare-element pegmatite dikes (total of 221 electron microprobe analyses) are listed below (locations and numbering after Breaks 1989):

• pegmatite #1:	51.99 weight %
• pegmatite #6:	57.77 weight %
• pegmatite #9:	25.01 weight %
• pegmatite #11:	40.38 weight %
• pegmatite #15:	67.00 weight %
• pegmatite #16:	60.48 weight %
• pegmatite #18:	20.38 weight %
• pegmatite between #14 and #18:	46.95 weight %

Wodginite ($MnSnTa_2O_8$) was also discovered in pegmatites #1, #6 and #19, the latter situated in the northeastern zone about 620 m southeast of pegmatite #18 (*see* Figure 18). Hence, the Fairservice property becomes the third rare-element pegmatite area of Ontario to host this mineral (following Separation Rapids and Pakeagama Lake: Tindle, Breaks and Webb 1998; Breaks, Tindle and Smith 1999).

The mafic metavolcanic host rocks surrounding the Fairservice spodumene pegmatites have been metasomatized and a black tourmaline aureole occurs up to 3 m from the north contact of pegmatite #2 in the north zone. The presence of tourmaline in a mafic metavolcanic rock indicates an influx of boron-rich fluids, likely from a pegmatitic melt. The exocontact tourmaline is mostly calcium-rich dravite and rarely uvite and is associated with fluorapatite (*see* Figures 66 and 70b). The presence of fluorapatite in mafic metavolcanic rocks indicate an influx of fluorine-rich fluids.

For this study, the spodumene-rich, albite-quartz zone and spodumene-bearing potassic pegmatite zone from all of the Fairservice pegmatites are grouped together and labelled the spodumene zone. A fine-grained black tourmaline layer occurs in the spodumene zone. The tourmaline is iron-rich with a composition of schorl-foitite (Figure 71). The tantalum-oxide minerals are manganese-rich and range in composition from manganocolumbite to manganotantalite and rare wodginite (Figure 70a), dark brown strüverite [$(Ti,Ta, Fe)O_2$] (18–37 weight % Ta_2O_5) and tantalum-rich cassiterite (6.0 weight % Ta_2O_5). The most tantalum-rich oxide mineral in the Fairservice pegmatites is an euhedral 5 by 10 mm crystal from the spodumene zone in pegmatite #6 with a composition of manganotantalite (82 weight % Ta_2O_5). The fluorapatite is manganese-rich with 0.4 to 4.4 weight % MnO (*see* Figure 70b). The green muscovite is rubidium-rich with 0.6 to 1.3 weight % Rb_2O and up to 0.1 weight % Cs_2O (*see* Figure 60a).

The albite-rich replacement zones (or albitized zones) are altered spodumene zones. Fine-grained yellow-green muscovite and albite patches replace spodumene and blocky potassium feldspar. Black tantalum-oxides are associated with the muscovite-albite replacement patches. Some parts of the pegmatites are extensively albitized. The oxide minerals range in composition from manganocolumbite to manganotantalite (*see* Figure 70a). The muscovite is rubidium-rich with 1.2 to 2.5 weight % Rb_2O and 0.1 to 0.3 weight % Cs_2O.

Aplite has several black oxide specks, green tourmaline, blue fluorapatite and muscovite. The green tourmaline is mostly elbaite and rarely schorl (*see* Figure 71). The tantalum-oxide minerals range in composition from ferrocolumbite to manganocolumbite to rare manganotantalite, and rare wodginite and

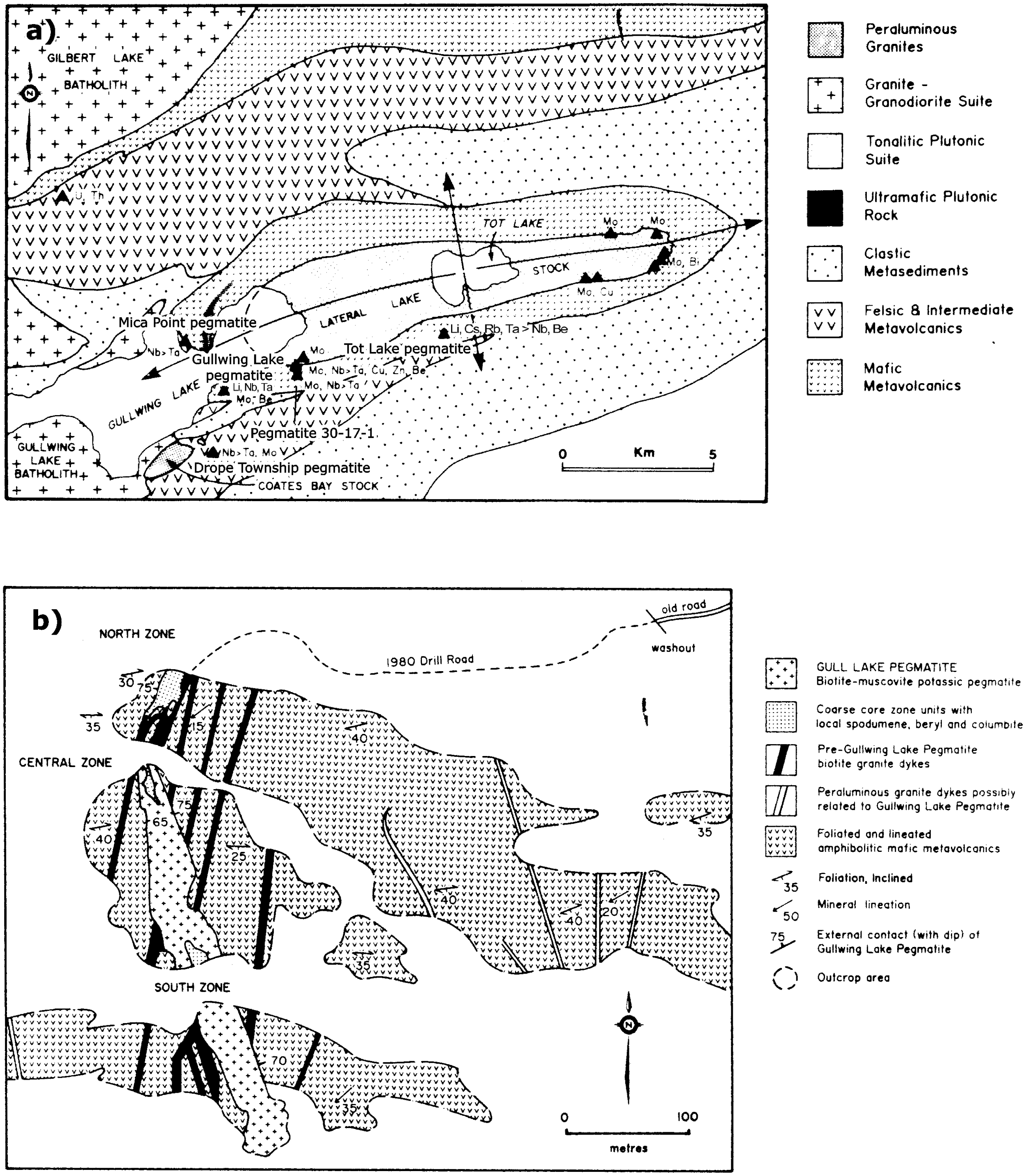


Figure 20. a) Geology and distribution of rare-element and molybdenite pegmatites of the Gullwing Lake–Tot Lake pegmatite group (*from* Breaks and Janes 1991). b) Geology in vicinity of the Gullwing Lake pegmatitic granite dike showing locations of the North, Central and South Zones (*from* Breaks and Janes 1991).

brown tantalum-bearing cassiterite (0.6–4.0 weight % Ta_2O_5) are also present (*see* Figure 70a). The fluorapatite is manganese-rich with 1.9 to 5.9 weight % MnO (*see* Figure 70b). The muscovite is rubidium-rich with 2.7 to 2.9 weight % Rb_2O and 0.3 to 0.4 weight % Cs_2O (*see* Figure 60a).

GULLWING LAKE–TOT LAKE PEGMATITE GROUP

Pegmatites in the Gullwing Lake–Tot Lake pegmatite group define an elongate, 0.8 to 2.2 by 15 km, east-northeast-trending cluster (Figure 20a) (Breaks and Janes 1991). Host rocks are predominantly highly deformed, amphibolitic mafic metavolcanic rocks which envelop the Lateral Lake stock (*see* Figure 20a). To a lesser extent, the host rocks consist of clastic metasedimentary rocks of the Northern Sedimentary Belt (<2698±4 Ma: Davis, Sutcliffe and Trowell 1988) and tonalites of the Lateral Lake stock.

According to Breaks and Janes (1991), the Gullwing Lake–Tot Lake pegmatite group differs from the Mavis Lake pegmatite group in several aspects:

1. absence of a well defined regional zonation of pegmatite types
2. a greater diversity in metal association, ranging from Mo-Bi-Cu to Li-Cs-Rb-Be-F-Ta>Nb
3. presence of a complex pegmatite of the spodumene subtype (Černý 1989b) associated with pollucite
4. absence of extensive, boron-rich exomorphism and associated scheelite
5. absence of a clearly defined parent granite

Two rare-element pegmatites in the Gullwing–Tot lakes pegmatite group are especially important: the Gullwing Lake spodumene-columbite-beryl-molybdenite pegmatite and the Tot Lake spoduemene-pollucite-beryl-tantalite pegmatite (Breaks and Janes 1991). The eastern extremity of the Gullwing Lake–Tot Lake pegmatite group, situated about 5 km east of the Tot Lake pegmatite is marked by a cluster of molybdenite-rich potassic pegmatites. A genetic relationship is inferred between the primitive molybdenite pegmatites and the spodumene pegmatites as accessory molybdenite occurs in most of the rare-element types and, conversely, rare-element minerals, such as beryl and yttro-betafite (REE-Nb-Ta oxide mineral), sporadically occurs in some of the molybdenite-rich pegmatites.

This pegmatite group also reveals a trend toward very highly evolved columbite-tantalite group compositions, but even more extreme than the Mavis Lake group. Columbite-tantalite compositions from the Gullwing–Tot lakes pegmatite group will be published in a future MRD. Of importance are the extreme manganotantalite compositions (Figure 72a) detected in the Tot Lake pegmatite that were examined by several exploration companies including Tantalum Mining Corporation (Tanco), Champion Bear Resources and Platinova Resources Limited. An average of 62.23 weight % Ta_2O_5 and a range of 23.02 to 82.35 weight % Ta_2O_5 was established from 142 electron microprobe analyses of oxide minerals from Tot Lake. Notable is the trend toward extreme Mn/(Mn+Fe) ratios (range 0.625–0.990). Other pegmatites, such as the Gullwing Lake spodumene dike (average Ta_2O_5 = 14.20 weight %) and the Mica Point (Gullwing Lake) columbite dike (average Ta_2O_5 = 9.09 weight %), generally have more primitive compositions mainly in the ferrocolumbite field (*see* Figures 20a and 72b). However, late-stage albitization at Gullwing Lake has resulted in more evolved compositions into the manganocolumbite and manganotantalite fields with appreciably more Ta (average Ta_2O_5 = 61.00 weight %) and extremely high Mn/(Mn+Fe) ratios (0.990–0.998) (*see* Figure 72b). Albitization is late-stage sodium-rich fluids that crystallize veinlets of albite and rarely tantalum-oxides within and near potassium feldspar crystals.

Tot Lake Pegmatite

The Tot Lake pegmatite is the mineralogically and chemically most diverse pegmatite in the Dryden pegmatite field (Breaks and Janes 1991) (*see* Figure 20a). The northwest-striking, 1 to 6 by >48 m, dike lies sharply discordant to the foliation (070°/50–70°) of its low-grade host mafic metavolcanic and meta-ultramafic rocks. The dike comprises 5 primary and 5 replacement zones, and the replacement zones collectively comprise about 70 volume % of the pegmatite.

The complex Tot Lake pegmatite represents one of the most chemically evolved granitoid rocks in the Superior Province of Ontario and its the fractionation indices closely approach the Tanco pegmatite, Manitoba (Černý et al. 1981; Breaks 1989). Tot Lake pegmatite also contains pollucite, which is a mineralogical indicator of extreme fractionation (Černý and Meintzer 1988). The K/Rb values (7.9–10.3) and Cs contents (660–2410 ppm) in blocky microcline (potassium feldspar) ($Or_{78}Ab_{22}$) are the most chemically fractionated of any in the Dryden pegmatite field and compare closely with other highly evolved rare-element pegmatites, such as Tanco pegmatite (Černý et al. 1981).

The primary zones are situated in 2 parts of the dike: adjacent to the small pod at the southeastern end and toward the dike centre near the northeastern end (Breaks and Janes 1991). The 5 primary zones are

1. spodumene-microcline-albite-quartz zone with randomly oriented bladed pink spodumene crystals
2. spodumene-rich zone: spodumene-green muscovite-microcline-(quartz-albite) zone with subhorizontally aligned pink spodumene in layers oriented parallel to dike contacts
3. spodumene-albite-green muscovite-(quartz) zone with medium-grained pink spodumene, poor layers grading into zone (2)
4. orange potassium feldspar zone: microcline-quartz ±beryl ±spodumene potassic pegmatite zone
5. pollucite zone: pollucite-spodumene-microcline-quartz-albite (green muscovite-fluorapatite-tantalite) zone

Spodumene zone (2) is distinguished from zone (3) by its coarser grain size and locally much higher content of pink spodumene (up to 78 volume %) relative to zone (3) (Breaks and Janes 1991). The pollucite in the pollucite zone occurs as coarse, anhedral to rarely subhedral, opaquely white single crystals and more common crystal aggregates filling the interstices between a box-work of spodumene blades. Recognition of pollucite is facilitated by the distinctive polygonal texture produced by net-veining of fine-grained green and faintly purple possible lithian muscovite and calcite—a typical alteration texture.

Replacement zones (Breaks and Janes 1991)

1. incipiently to moderately albitized spodumene zone (1) with
   secondary albite + green muscovite + lepidolite ±cookeite (Li-chlorite)
2. pervasively albitized spodumene zone (1) with
   secondary albite + green muscovite + alkali beryl
3. columbite zone: quartz-albitized potassium feldspar-spodumene
   (albitic + green muscovite alteration)-alkali beryl-columbite-spessartine
4. sodic aplite pods: albite-quartz-tourmaline-green muscovite-apatite
5. holmquistite veins in mafic metavolcanic and meta-ultramafic host rocks
6. quartz veins: quartz ±spodumene ±potassium feldspar ±tourmaline

Replacement zones were produced by post-magmatic stage metasomatism in 2 stages: 1) small pods of fine-grained aplite (zone 9) and 2) more extensive alteration related to fracture-controlled metasomatism (zones 6, 7 and 8) (Breaks and Janes 1991). Holmquistite-rich veins (Li-amphibole) (zone 10) represent an exomorphic consequence of the second alteration stage. The columbite zone is a quartz-rich zone with the highest abundance of columbite-tantalite group minerals within the Tot Lake pegmatite. The columbite crystals are steely black, euhedral (up to 1 by 2 cm) and associated with the albitized blocky microcline (potassium feldspar).

MINERAL CHEMISTRY

Electron microprobe compositions of minerals from Tot Lake pegmatite—columbite-tantalite, cassiterite, garnet, tourmaline and muscovite—will be published in a future MRD. Mineral chemistry plots are based on unpublished data.

The spodumene zone contains large pink spodumene crystals and rubidium-cesium-rich muscovite (2.0–2.3 weight % Rb_2O and 0.4–0.7 weight % Cs_2O) (*see* Figure 68b). In addition to the aplite pods, tantalum-oxide minerals occur in the spodumene zone, albitized spodumene zone, quartz pods and pollucite zone. The tantalum-oxide minerals are mostly manganese-rich manganotantalite with minor manganocolumbite (*see* Figure 72a). The most tantalum-rich manganotantalite (47–82 weight % Ta_2O_5) occurs in the pollucite zone with marginal replacement of pollucite by albite (*see* Figure 72a). The tantalum-oxide minerals from a quartz-potassium feldspar-albite unit (TL90-6) are more iron-rich and more primitive than that from sample TL90-1 that came from a highly fractionated, spessartine-muscovite-elbaite pod situated approximately 1 m from the pollucite zone. The oxide minerals are mostly manganocolumbite with rare manganotantalite (23–52 weight % Ta_2O_5) and tantalum-rich cassiterite (0.2–4.0 weight % Ta_2O_5) (*see* Figure 72a).

Pervasively albitized spodumene pegmatite with spodumene laths almost completely converted into fine-grained secondary muscovite occurs in the northeast part of the dike. The albitized spodumene zone also contains very coarse-grained pale pink beryl (2 cm in diameter) and minor black oxide minerals, wedge-shaped tantalum-bearing cassiterite (<0.3 weight % Ta_2O_5) and garnet. The garnet is manganese-rich spessartine (80–99% spessartine, 0–13% almandine, 1–6% grossular) (*see* Figure 68a).

Muscovite-tourmaline sodic aplite pods contain fine-grained black oxide minerals, blue tourmaline, orange garnet and fluorapatite. The tantalum-oxide minerals and the garnet are manganese-rich with compositions of manganocolumbite (29–33 weight % Ta_2O_5) and spessartine (70–94% spessartine, 4–26% almandine, 2–4% grossular), respectively (*see* Figures 72a and 68a). The tourmaline ("fluor-elbaite") also has an evolved composition as it is enriched in Li and F and depleted in Mg and Ca (*see* Figure 71). The muscovite is rubidium-rich with 1.6 to 1.7 weight % Rb_2O and 0.2 weight % Cs_2O (*see* Figure 68b).

Pegmatite 30-17-1 and Mica Point Pegmatite

Pegmatite 30-17-1 comprises 2 transecting, 3 to 4 m thick, garnet-muscovite potassic pegmatite dikes hosted in mafic metavolcanic rocks just south of the Coates beryl-molybdenite pegmatite (*see* Figure 20a). These dikes contain abundant muscovite and blocky potassium feldspar, and sparse molybdenite, apatite and garnet. Coarse-grained ferrocolumbite (13–14 weight % Ta_2O_5), up to 3 cm (*see* Figure 72a) occurs in albite-replacement veins along the margins of coarse blocky potassium feldspar crystals in Pegmatite 30-17-1.

The Mica Point pegmatitic granite, Drope Township, is a biotite-muscovite potassic pegmatite with minor molybdenite and V-shaped, coarse-grained ferrocolumbite (8–10 weight % Ta_2O_5) up to 1.1 cm (*see* Figure 72b). The muscovite in the Mica Point pegmatite has low Rb (0.01–0.08 weight % Rb_2O) and an undetectable Cs content (*see* Figure 68b). Electron microprobe compositions of ferrocolumbite from Pegmatite 3-17-1 and Mica Point will be published in a future MRD.

Gullwing Lake Pegmatite

The following is a summarized description of the geology of the Gullwing Lake pegmatite from Breaks and Janes (1991, stop 11). The Gullwing Lake pegmatite is a zoned 25 to 80 by 412 m dike intruding amphibolitic mafic metavolcanic rocks. This pegmatite is of critical importance in that it establishes a genetic linkage between the pegmatitic granite facies and primary spodumene in the area (Breaks and Janes 1991). It also exhibits the metal association Li-Nb±Ta-Be-Mo, which, coupled with local REE (rare-earth element) enrichment, renders this pegmatite unique to the Dryden pegmatite field.

Most of the Gullwing Lake pegmatite consists of two-mica potassic pegmatite with lesser fine-grained leucogranite (Breaks and Janes 1991). This pegmatite complex is zoned by virtue of interspersed, much coarser grained central core zones composed of muscovite-albite-blocky microcline-quartz and locally containing spodumene, beryl and columbite. The Gullwing pegmatite has 3 rare-element mineralized areas: the South, Central and North zones (Figure 20b). The pegmatite also has 3 replacement zones: Albitization I, II and III.

The South zone comprises a beryl-columbite mineralized, 5 to 12 by >25 m, discrete core zone of muscovite-blocky microcline-quartz potassic pegmatite with pink perthitic blocky microcline (up to 1 m in diameter), massive milky quartz and books of white muscovite (Breaks and Janes 1991). Columbite crystals up to 1 by 2 cm occur in weakly albitized parts of the core zone perphery. The core zone is enveloped by two-mica potassic pegmatite and muscovite-biotite fine-grained leucogranite zones. The two-mica potassic pegmatite has bladed aggregates of muscovite and lithian siderophyllite (biotite) (estimated to contain 1.0–1.5 weight % Li_2O) up to 1 m in length, sporadic euhedral green beryl and black tourmaline. A 1.5 to 4.0 m wide albite-muscovite-quartz zone (Albitization Zone I) occurs on the margin of the core zone and has a gradual contact with the two-mica potassic pegmatite zone.

The Central zone contains a 7 to 20 by >35 m core zone of blocky microcline-quartz-muscovite-albite enveloped by a two-mica potassic pegmatite and a two-mica fine-grained leucogranite (Breaks and Janes 1991). The pegmatitic granite zones are very similar to those of the South Zone, with the exception of sporadic columbite contained within the two-mica potassic pegmatite zone.

The South zone contains 2 stages of albitization: I and II (Breaks and Janes 1991). Albitization zone I occurs along the margin of the core zone similar to that in the South zone. Small pockets of fine-grained green mica-albite pseudomorphs after spodumene occur mid-way along the core zone. These pockets, within which these pseudomorphs project into the dominant smoky quartz, are prevasively replaced by a second albitization stage (Albitization II) consisting of white to light blue masses of radiating cleavelandite, green muscovite, orange garnet and rare, faint green beryl and fine-grained platy columbite.

The North zone is a 25 by 30 m pegmatite mass that lies isolated 50 m from the remainder of the Gullwing Lake dike (Breaks and Janes 1991). Continuity at depth between the North and Central zones is suggested by the shallow, south-dipping upper pegmatite contact. This observation, coupled with the absence of pegmatitic granite zones similar to those which envelop the Central zone core, infers that the lower elevation North zone represents an expansion of the spodumene-muscovite-albite-blocky microcline-quartz core with increasing depth.

Most of the North zone is composed of a coarse-grained potassic pegmatite dominated by quartz and light orange blocky microcline (Breaks and Janes 1991). Irregular masses of quartz (up to 6 by 9 m) lie interstitially between the coalesced masses of potassium feldspar. The second primary pegmatite zone in the North zone consists of 3 spodumene-bearing pods (up to 3 by 8 m), which comprise about 10 volume % of the North zone and contain spodumene-blocky microcline-quartz-albite-muscovite. The largest pod contains faint green randomly oriented spodumene crystals up to 4 by 40 by 100 cm intergrown with blocky microcline, quartz, grey muscovite and albite. Much of the spodumene is altered and is partially to completely overgrown by mauve lithian muscovite or by an fine-grained aggregate of albite and green mica.

Approximately 30% of the primary pegmatites at the North zone have been subjected to post-magmatic processes here described as Albitization I and II (Breaks and Janes 1991). The more extensive Albitization I zone is dominated by relatively coarse, equigranular albite, which progressively replaces the potassic pegmatite. This replacement stage was responsible for intense metasomatism of adjacent metavolcanic host rocks and xenoliths. Metasomatic exocontact, 10 to 100 cm thick, occur continuously in the host rocks along the contact with the pegmatite. Mafic metavolcanic host rocks exhibit relatively narrow biotite-plagioclase-quartz aureoles, typically less than 15 cm, whereas intermediate metavolcanic host rocks contain abundant biotite (50–90 volume %) and comparatively less felsic minerals, to produce aureoles up to 100 cm wide.

Albitization II zones represent a later stage of alteration, specifically confined to the 3 spodumene pods (Breaks and Janes 1991). It is dominated by radiating clusters of white to pale blue cleavelandite and co-exists with minor orange garnet, green muscovite, mauve to purple lithian muscovite and rare faint green beryl. This secondary zone replaces all primary minerals including blocky microcline, spodumene and quartz.

Rarely do the Albitization I and II zones come in contact, however, near the lowermost spodumene pod, a cleavelandite-rich vein (Albitization II) clearly crosscuts a mass of the coarser, equigranular albite-dominant type (Albitization I) (Breaks and Janes 1991). Fine-grained aggregates of purple lithian muscovite (3.0–3.4 weight % Li_2O) and lesser cleavelandite and sporadic 1 to 5 mm crystals of brown green microlite occur at the base of the outcrop (Albitization zone III).

MINERAL CHEMISTRY

Electron microprobe compositions of minerals from the Gullwing Lake pegmatite—columbite-tantalite, microlite, fluorapatite, garnet, muscovite and lepidolite—will be published in a future MRD. Mineral chemistry plots are based on unpublished data.

Albitization zone I has euhedral albite megacrysts, fine-grained green muscovite, localized common biotite aggregates, coarse-grained tantalum-oxide minerals (up to 2.5 cm), and sparse molybdenite. The oxide minerals range in composition from ferrocolumbite to rare tantalum-poor manganocolumbite (6–14 weight % Ta_2O_5) (*see* Figure 72b).

Albitization zone II has cleavelandite replacement of blocky potassium feldspar, lepidolite rims on coarse muscovite (up to 4.5 cm), quartz, minor garnet, fluorapatite (0.2 weight % MnO) (*see* Figure 70b) and tantalum-oxide minerals, and rare black zircon, xenotime and thorium-rich monazite. The oxide minerals range in composition from ferrocolumbite to manganocolumbite (24–34 weight % Ta_2O_5) (*see* Figure 72b). The spessartine is zoned with iron-rich rims (56% spessartine, 42% almandine, 1% andradite, 1% pyrope) and a manganese-rich core (67% spessartine, 31% almandine, 2% grossular) (*see* Figure 68a). The Rb and Cs contents are significantly higher in the lepidolite rims (2.4–2.7 weight % Rb_2O, 0.4–1.1 weight % Cs_2O) than the muscovite cores (0.5–1.3 weight % Rb_2O and up to 0.1 weight % Cs_2O) (*see* Figure 68b).

Albitization zone III is a quartz-lepidolite-cleavelandite replacement zone that locally replaces parts of the spodumene core zone. Albitization zone III has minor coarse-grained orange garnet (up to 1.5 cm), fluorapatite (0.6 weight % MnO), columbite-tantalite, uranmicrolite and coarse-grained sphalerite (zinc sulfide) (up to 1.2 cm). This zone has the most evolved mineral compositions at Gullwing pegmatite. The tantalum-oxide minerals are enclosed in cleavelandite very near the contact of altered spodumene megacryst. The tantalum-oxide minerals are manganese-rich and range in composition from manganocolumbite (36–38 weight % Ta_2O_5) to manganotantalite (54–68 weight % Ta_2O_5) (*see* Figure 72b). The lepidolite (1.9–2.7 weight % Rb_2O and 0.4–1.1 weight % Cs_2O) is significantly more rubidium-cesium-rich than the muscovite (0.8–1.5 weight % Rb_2O and 0.1–0.4 weight % Cs_2O) (*see* Figure 68b). The rare uranmicrolite has 3 to 4 %UO_2 and 65 to 70 weight % Ta_2O_5 occurring in the same sample (83-420, sample collected previously by F.W. Breaks) as manganotantalite with 60 to 62 weight % Ta_2O_5 (*see* Figure 72b).

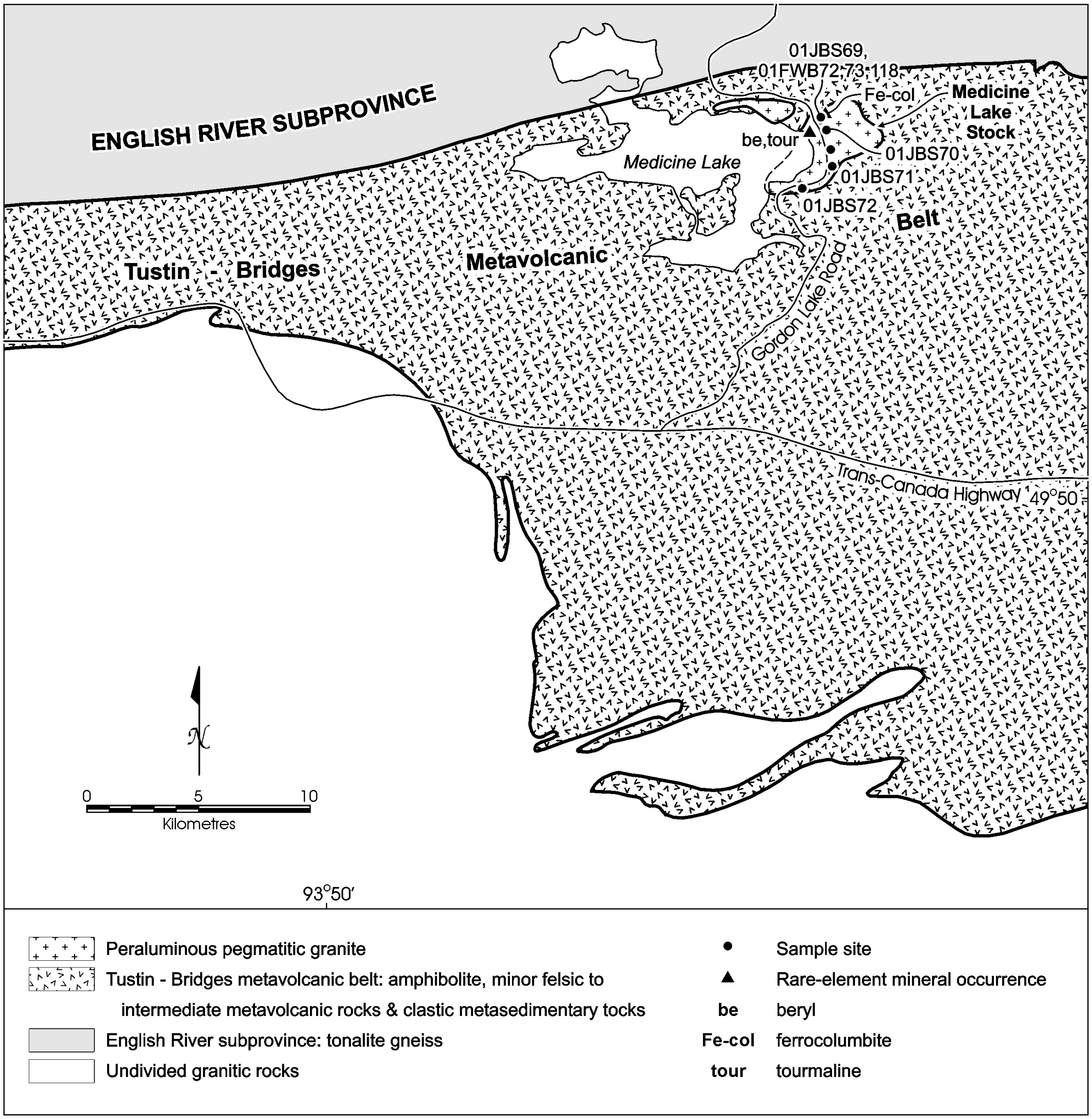


Figure 21. Geology and distribution of zones of rare-element pegmatites in the Medicine Lake area.

Medicine Lake Pluton

This 0.5 by 1.5 km ovoid mass is situated near the English River–Wabigoon subprovincial boundary zone (Figure 21, *see* Figure 16) and was first delineated by Pryslak (1976). The pluton consists of an array of internal pegmatitic granite units that are characteristic of most fertile granite plutons in the Superior Province (*see* Table 1). These include biotite-muscovite potassic pegmatite, pegmatitic leucogranite, garnet-muscovite fine-grained leucogranite, and quartz-rich patches with coarse black tourmaline (up to 5 cm) and rare pale green beryl.

Beryl was initially discovered in the Medicine Lake pluton by E. Sobiski in 1949 and the property was subsequently explored as a beryllium prospect (Pryslak 1976, p.40). Columbite-tantalite was first recognized by Chisholm (1950) near the northern contact of the pluton and immediately east of the Gordon Lake road. Pryslak (1976, p.41) reported further occurrences of columbite-tantalite in the pluton.

PETROCHEMISTRY

Bulk compositions of several units from the Medicine Lake pluton are published in Table 20c of MRD 111 (Tindle, Selway and Breaks 2002): muscovite-biotite pegmatitic leucogranite, muscovite-biotite potassic pegmatite, biotite-muscovite fine-grained leucogranite, biotite-muscovite granite, aplite and albitized potassic pegmatite. Seven bulk rock samples from the Medicine Lake stock were selected along the Gordon Lake road (*see* Figure 21). The analyses revealed mostly mildly peraluminous compositions (mean A/CNK = 1.057; range 0.996–1.146) with a wide range in K_2O (1.2–5.62 weight %) and Na_2O (4.39–9.05 weight %) contents (*see* Figure 73a).

Several of the rare-elements are notably enriched in the pluton, further substantiating its status as a fertile granite. Lithium (mean 42 ppm; range 20–71 ppm Li) is locally anomalous in the fine-grained leucogranite unit. In most units, rubidium exhibits significant enrichment (relative to the mean upper continental crustal abundance of 112 ppm) with a mean content of 523 ppm and a range of 103 to 851 ppm. K/Rb ratios vary from 32 to 97 and also reflect noteworthy fractionation because of their low values.

Tantalum contents are mostly very low, but with a maximum value of 15 ppm well above the range of the remaining analyses (<0.3 to 3 ppm). The highest concentration of Ta and Nb occurs in the albite replacement patches described above. Niobium is considerably more enriched than tantalum with a mean content of 30 ppm and a range of 8.2 to 96 ppm. However, 2 distinct groupings of Nb/Ta ratios are obvious. The first group (granite, potassic pegmatite and pegmatitic leucogranite) have relatively evolved Nb/Ta ratios of 6 to 8, whereas a second population (fine-grained leucogranite and albitized potassic pegmatite) reflects pronounced tantalum depletion with a Nb/Ta ratio range of 19 to 49.

MINERAL CHEMISTRY

Bulk analyses of 9 potassium feldspar samples from the Medicine Lake pluton indicate significant chemical fractionation that is comparable to the northern part of the Separation Rapids pluton (Breaks and Tindle 1997a) (5 samples from this study and unpublished data from 4 potassium feldspar samples previously collected by the authors): Cs (mean 33 ppm; range 12–61 ppm); Li (mean 33 ppm; range 12–49 ppm) and Rb (mean 1780 ppm; range 950–2197 ppm: *see* Figure 56b) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21c). K/Rb ratios (mean 58, range 43–79) are comparable to the northern part of the Separation Rapids pluton (Breaks and Tindle 2001). The anomalous lithium in potassium feldspar also suggests the potential for lithium minerals in more fractionated derivatives of the pluton that perhaps reside in exocontact pegmatite swarms.

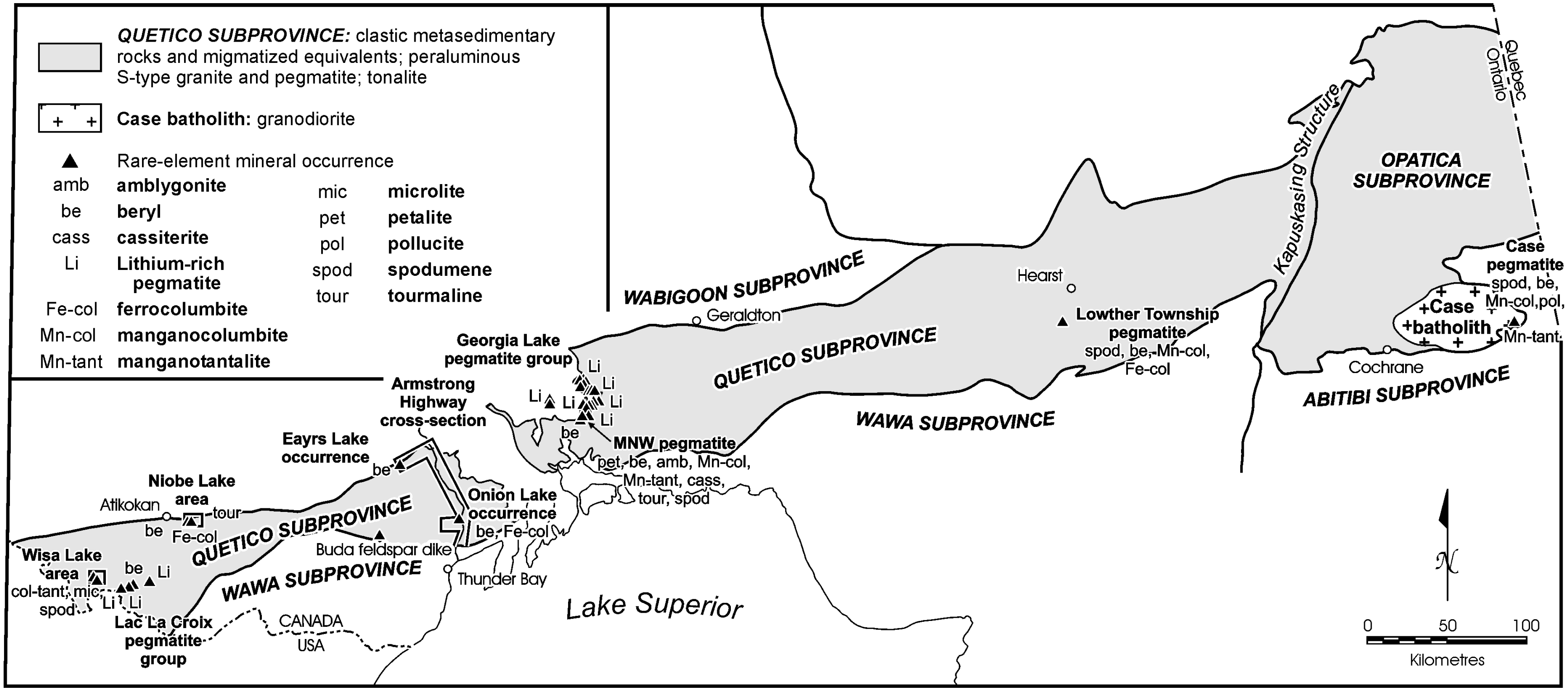


Figure 22. Location of metasedimentary-hosted rare-element mineralization associated with the Quetico and Opatica subprovinces. The Case pegmatite contains all 4 columbite-tantalite species.

Electron microprobe compositions from garnet, tourmaline and ferrocolumbite are published in Tables 11, 17 and 8c, respectively, of MRD 111 (Tindle, Selway and Breaks 2002). In the fine-grained leucogranite and potassic pegmatite, the garnet is almandine (72–84% almandine, 11–25% spessartine, 1–6% pyrope, 1% andradite) (*see* Figure 61b). The quartz-rich patches contain coarse black tourmaline (schorl) (*see* Figure 71).

Black tantalum-oxide minerals, recognized by the authors, are specifically associated with areas of albite-rich replacement patches and veins hosted by large blocky potassium feldspar crystals up to 35 by 55 cm in size. The albitized potassium feldspar megacrysts, which contain 1 to 3 volume % black ferrocolumbite (average 14.79 weight % Ta_2O_5 based on 28 analyses), specifically occur within and proximal to large quartz-rich patches (Figure 73b). The ferrocolumbite grains are commonly less than 5 mm in diameter, however, a coarse, euhedral crystal (5 by 20 mm in size) was noted to be completely isolated in the quartz-rich patch.

MINERAL EXPLORATION POTENTIAL

The bulk rock and mineral chemistry undertaken by this study establishes the Medicine Lake pluton as a fertile granite. The occurrence of ferrocolumbite associated with albite-rich replacement features within the Medicine Lake pluton indicates that pegmatitic granites of this pluton, and possibly those in the Tustin–Bridges greenstone belt, should be explored for chemically more evolved pegmatite dike derivatives spatially related to this fertile granite. More extensive albite-rich replacement within such pegmatitic granites or derivative exocontact pegmatite dikes could harbour more evolved and economically interesting tantalum oxide mineralization. Furthermore, pegmatite swarms potentially derived from pegmatitic granite plutons, such as at Medicine Lake, should be examined for lithium-rich mineralization that could have been overlooked due to the presence of easily mistaken petalite or white spodumene.

Quetico Subprovince

INTRODUCTION

Rare-element pegmatites exhibit widespread distribution in the Quetico Subprovince covering at least a 540 km strike length from the Wisa Lake area east to the Lowther Township pegmatite near Hearst (Figure 22). Furthermore, the restriction of rare-element pegmatites to boundary zones with adjacent subprovinces is not applicable to the Quetico Subprovince. It is apparent from the compilation in Figure 22 that rare-element mineralization is distributed across the Quetico Subprovince and a large percentage of rare-element pegmatites are concentrated within the centre of the subprovince as, for example, at Georgia Lake (Pye 1965).

WISA LAKE PEGMATITE GROUP

Two spodumene pegmatites discovered in the 1950s, and hosted in medium-grade metasedimentary rocks, are located in the central Quetico Subprovince of the Lac La Croix area (*see* Figure 22). The area was explored for lithium in 1956 by Lexindin Gold Mines Limited (Mulligan 1965, p.66) with attention directed to the largest pegmatite near Wisa Lake (locality 01-JBS-94: UTM 557141E, 5363473N, Zone 15) and which was traced on surface for a strike of 335 m with widths from 6 to 12 m. This pegmatite is flat lying, but may also dip 20° to the north, and consists of a mildly deformed, green muscovite-potassium feldspar-spodumene-quartz-albite zone layered with blue apatite-garnet-muscovite aplite. Minor beryl occurs in the spodumene zone and black tantalum-oxide grains were noted in both pegmatite zones.

Petrochemistry

One bulk sample was collected from each of the following 3 localities: 1) apatite-garnet-muscovite aplite from Wisa Lake spodumene pegmatite (01-JBS-94: UTM 557118E, 5363462N, Zone 15); 2) muscovite-quartz aplite (01-JBS-95) and 3) pink potassium feldspar-muscovite potassic pegmatite (01-JBS-96) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d). Samples from localities 01-JBS-95 and 01-JBS-96 are from 2 granitic pegmatitic dikes situated on the Lac La Croix road. The blue apatite-garnet-muscovite aplite from the spodumene pegmatite dike contains low tantalum (4.7 ppm) and Nb (31 ppm), however, the Nb/Ta ratio (1.5) infers the aplite-forming melt underwent significant fractionation. Further investigation of the Wisa Lake spodumene dike swarm is needed.

The apatite-muscovite sodic pegmatite dike of locality 01-JBS-95 (UTM 557456E, 5362364N, Zone 15) is the most fractionated rock encountered to date in this area. A bulk sample that comprised the entire 22 cm width of the dike, revealed anomalous Be (219 ppm), Rb (617 ppm), Cs (37 ppm), Ga (53 ppm), Sn (43 ppm), Nb (17 ppm) and Ta (10 ppm). These data infer the presence of a beryl-type pegmatite, although beryl was not encountered in the initial field examination. That the dike (or its source melt) experienced significant fractionation is confirmed by low K/Rb (41), K/Cs (693), and Nb/Ta (1.7) ratios.

Dikes of strongly peraluminous (A/CNK = 1.204), potassic pegmatite were also noted sporadically along the Lac La Croix road as at locality 01-JBS-96 (UTM 544854E, 5365952N, Zone 15) (Figure 74a). Here, a 4 m thick dike revealed slightly elevated Li (70 ppm), Be (6 ppm), Ga (49 ppm), Rb (323 ppm), Sn (19 ppm), Nb (31 ppm) and Ta (7 ppm). The moderate K/Rb (44), K/Cs (2593) and Nb/Ta (4.3) ratios also confirm the presence of an evolved pegmatite.

Mineral Chemistry

Two bulk potassium feldspar samples were analyzed from the spodumene pegmatite (locality 01-JBS-94) and the pink potassic pegmatite dike (locality 01-JBS-96) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 21d). The potassium feldspar from the spodumene pegmatite has elevated Rb and Cs contents (3967 ppm Rb and 198 ppm Cs), whereas the potassium feldspar from the potassic pegmatite dike resembles a fertile granite with 1822 ppm Rb and 20 ppm Cs (Figure 74b).

Electron microprobe compositions of minerals from the Wisa Lake pegmatite group are published in MRD 111 (Tindle, Selway and Breaks 2002): columbite-tantalite (*see also* Table 8d), microlite (*see also* Table 14), garnet (*see also* Table 11), muscovite (*see also* Table 13a) and fluorapatite (*see also* Table 10).

The aplite in the spodumene pegmatite contains manganese-rich oxide minerals and garnet. The tantalum-oxide minerals range in composition from manganocolumbite to manganotantalite (24–74 weight % Ta_2O_5) and rare microlite is also present (73 weight % Ta_2O_5) (Figure 75a). The garnet is spessartine (65–66% spessartine, 31–34% almandine, 1% andradite, 0–1% pyrope) (Figure 75b). The muscovite contains moderate Rb and Cs contents (0.3–0.8 weight % Rb_2O, up to 0.2 weight % Cs_2O) (Figure 76a).

Dikes of apatite-muscovite sodic pegmatite and muscovite-rich potassic pegmatite, between 35 cm and 4 m in thickness, occur sporadically on the nearby Lac La Croix road (e.g., locality 01-JBS-95: UTM 557456E, 5362364N, Zone 15). The 35 cm thick aplite dike at locality 01-JBS-95 contains muscovite, quartz and minor tantalum-oxide minerals, apatite and garnet. The tantalum-oxide minerals are ferrocolumbite (38–51 weight % Ta_2O_5) and the muscovite has moderate Rb contents (0.1–0.5 weight % Rb_2O) with up to 0.1 weight % Cs_2O (*see* Figures 75a and 76a).

A potassic pegmatite dike at locality 01-JBS-96 (UTM 544854E, 5365952N, Zone 15) contains blocky pink potassium feldspar (23 by 20 cm), coarse-grained green muscovite (0.1–0.2 weight % Rb_2O), quartz, minor ferrocolumbite (23–29 weight % Ta_2O_5) and fluorapatite (0.4–1.5 weight % MnO, with one analysis of 1.1 weight % Cl) (*see* Figures 76 and 75a).

Recommendations For Pegmatite Exploration

The presence of a rare-element pegmatite dike swarm near Wisa Lake (which contains spodumene pegmatite and nearby a suite of newly discovered beryl-type pegmatite dikes with very interesting Nb/Ta ratios) and the confirmed presence of manganocolumbite and manganotantalite, indicate that more exploration for rare-element mineralization is advised for the general area.

NIOBE–NYM LAKES AREA

Muscovite-bearing pegmatite dikes and small pegmatitic granite masses are widely exposed along Highway 11 at least between the Nym Lake road junction and west to Niobe Lake (McIlwaine and Larsen 1981a, 1981b). The area (Figure 23, *see* Figure 22) was briefly investigated by the present survey owing to anomalous rare-element levels (lithium, rubidium, gallium, cesium and tin) being detected in a lake sediment survey within the general area (Jackson 2001). Previous petrochemical investigation in the area indicated the presence of modestly evolved muscovite-garnet-biotite-albite granites in the Crystal Lake area as indicated by 199 to 338 ppm Rb and a range in K/Rb ratios of 80 to 211 (Smith and Williams 1980).

Petrochemistry

This area was cursorily investigated with 16 bulk rock analyses taken along a short section of Highway 11 between the intersection with the Nym Lake road east to Niobe Lake (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d). The bulk analyses covered the granitic rocks in the area: muscovite-biotite granite, muscovite granite, two-mica potassic pegmatite, muscovite potassic pegmatite and aplite. Most of the pegmatitic rocks are mildly peraluminous with a mean A/CNK ratio of 1.099 and a range of 0.936 to 1.15 (*see* Figure 74a). All of the granitic rocks are calcium-poor with approximately Na_2O and K_2O contents.

The most striking feature of the bulk rock chemistry is the significant number of anomalous lithium values. Lithium ranges from 11 to 164 ppm with a mean content of 72 ppm, however, 25% and 60% of the data, respectively, exceed 100 ppm and 50 ppm. Taylor (1964) states that lithium values exceeding 100 ppm indicate extreme fractionation.

For the rare alkali metals, cesium is significantly enriched 7 to 25 times above its mean crustal abundance for 80% of the data population and varies from 3.9 to 80 ppm. Many values exceed 15 ppm, a level considered by Černý and Meintzer (1988) to indicate significant fractionation in granitic systems. Rubidium has a range of 5 to 534 ppm and mean content of 270 ppm. Local anomalies occur at localities 01-JBS-78 and 01-JBS-80.

Anomalous tin occurs in 10 samples, where it varies from 8 to 177 ppm. Tantalum has a range of 0.81 to 20 ppm and a mean content of 3 ppm and does not appear significantly concentrated except for sample 01-JBS-78-07 where 20 ppm was documented. Gallium (mean 44 ppm; range 27–81 ppm) is enriched at about 2 times its mean crustal abundance for the area. Gallium is an uncommon rare-element and is generally in low abundance in rocks (Taylor and McLennan 1985).

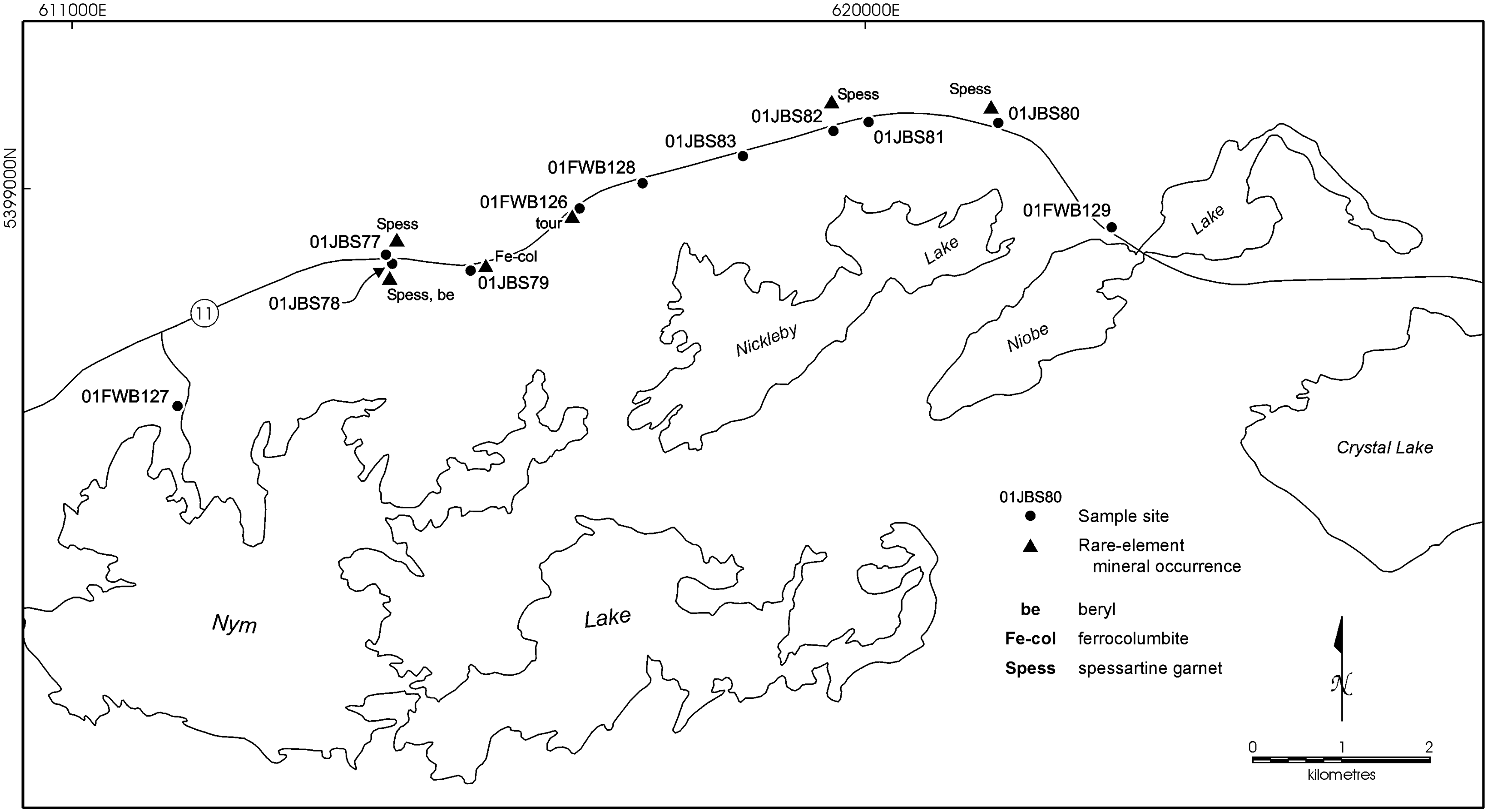


Figure 23. Location of rare-element mineralization and sample sites in the Nym–Niobe Lake area.

Several ratios also confirm the significant degree of rare-element fractionation in the area. Most striking are the low K/Cs (mean 1888; range 238–3095), K/Rb (mean 120; range 36–531) and Mg/Li (mean 5.6; range 2–9) ratios. Nb/Ta ratios reveal a modest fractionation of tantalum relative to niobium with a mean value of 5.6 and range of 2.1 to 9.4 for the area sampled.

The garnet-muscovite potassic pegmatite, sample 01-JBS-78-07 (UTM 614652E, 5398381N, Zone 15) is the most evolved pegmatitic rock encountered by the survey. This beryl-type pegmatite contains maximum levels in this area for most rare-elements: Be (18 ppm), Cs (80 ppm), Li (99 ppm), Rb (524 ppm), Sn (177 ppm), Ta (20 ppm), Nb (42 ppm) and Ga (81 ppm).

Mineral Chemistry

Electron microprobe compositions of minerals from the Niobe–Nym lakes area are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11), ferrocolumbite (*see also* Table 8d), muscovite (*see also* Table 13a), fluorapatite (*see also* Table 10) and tourmaline (*see also* Table 17).

Rare-element mineralization was discovered by the present survey at locality 01-JBS-78 within a pegmatite-aplite dike system 0.3 to 4 m thick. Sporadic, yellow-green beryl crystals, up to 2 cm in diameter, occur in a muscovite-potassium feldspar-quartz-rich pegmatite core rimmed by garnet-muscovite aplite. Black grains of gahnite ($ZnAl_2O_4$) and pyrite with hematite along fractures, up to 1 to 6 mm by 10 mm, occur in several parts of the pegmatite and aplite units. The white to pink aplite contains abundant fine-grained dark orange garnets with spessartine cores (51–54% spessartine, 44–48% almandine, 1% andradite, 1% pyrope) and almandine rims (50–55% almandine, 41–49% spessartine, 1–2% pyrope, 1% andradite) (*see* Figure 75b). One zoned garnet grain had exceptionally high Mn content in the spessartine cores (68–72% spessartine, 27–31% almandine, 0.3 weight % P_2O_5). The fluorapatite in the aplite is manganese-rich (4.2–4.8 weight % MnO), whereas the fluorapatite in the potassic pegmatite is relatively manganese-poor (0.6–1.7 weight % MnO) (Figure 76b).

Tantalum-oxide minerals were only found at locality 01-JBS-79 (UTM 615436E, 5398378N, Zone 15). This locality consists of a 20 cm thick layered aplite-potassic pegmatite. The ferrocolumbite to ferrotantalite (46–57 weight % Ta_2O_5) occurs as inclusions within muscovite in the apatite-garnet-muscovite pegmatite (Figure 77a). The white aplite contains abundant medium-grained dark orange almandine (66–70% almandine, 27–31% spessartine, 2% pyrope, 1% andradite, <0.2 weight % P_2O_5) and radiating fine-grained green muscovite (*see* Figure 75b).

Tourmaline (magnesium-bearing schorl) was only found in garnet-biotite-muscovite potassic pegmatite at locality 01-FWB-126 (UTM 616775E, 5398791N, Zone 15) (Figure 79). The pegmatite dikes (10 cm to 1 m thick) contain quartz-rich patches with blocky potassium feldspar up to 30 cm in diameter. Silvery muscovite books are up to 2 cm thick and slender biotite blades are up to 20 cm long and 1 to 2 mm thick. Bulk coarse-grained muscovite (up to 5 cm across) in the quartz-rich patch contains 1179 ppm Li, 2065 ppm Rb and 170 ppm Ta. The elevated Ta content is significant because muscovite samples with >65 ppm Ta have a high probability to contain Ta-Nb mineralization (Gordiyenko 1971). Pegmatite dikes intrude grey fine- to medium-grained muscovite-biotite granite.

Elevated rare-element contents were also found in bulk coarse-grained green muscovite (up to 3 cm across) from the potassic pegmatite at locality 01-JBS-81-02 (UTM 619907E, 5399952N, Zone 15). The muscovite contains 194 ppm Li, 2720 ppm Rb, 202 ppm Cs, 138 ppm Ta and 303 ppm Nb.

Numerous pegmatite dikes occur along Highway 11. The garnet in the potassic pegmatite is mostly almandine (50–72% almandine, 25–49% spessartine, 1–3% pyrope, 1% andradite), except for locality

01-JBS-77, which has fine-grained brown spessartine (53–65% spessartine, 33-45% almandine, 1% andradite, 1% pyrope, <0.4 weight % P_2O_5) and coarse-grained dark blue fluorapatite (<0.6 weight % MnO) (up to 1 cm) in coarse-grained green muscovite potassic pegmatite (*see* Figures 75b and 76b). The garnet in the aplite has a wide range in composition from almandine to spessartine (27–70% almandine, 26–72% spessartine, 0–3% pyrope, 0–1% andradite) (*see* Figure 75b).

Recommendations For Future Exploration

The anomalous Li, Rb, Cs, Sn and Ga documented in the bedrock by this survey corroborate the earlier lake sediment geochemistry work of Jackson (2001). Exploration for rare-element mineralization in the area should therefore focus on the numerous lake sediment anomalies for these metals in the general area as there is a close correlation with bedrock chemical data at least in the Nym–Niobe lakes area. The discovery of columbite-tantalite group minerals and beryl by this survey gives strong indications that, with careful prospecting, further rare-element minerals may be discovered. The presence of elevated Ta contents in bulk muscovite at localities 01-FWB-126 and 01-JBS-81 suggests that they should be investigated futher for possible tantalum mineralization.

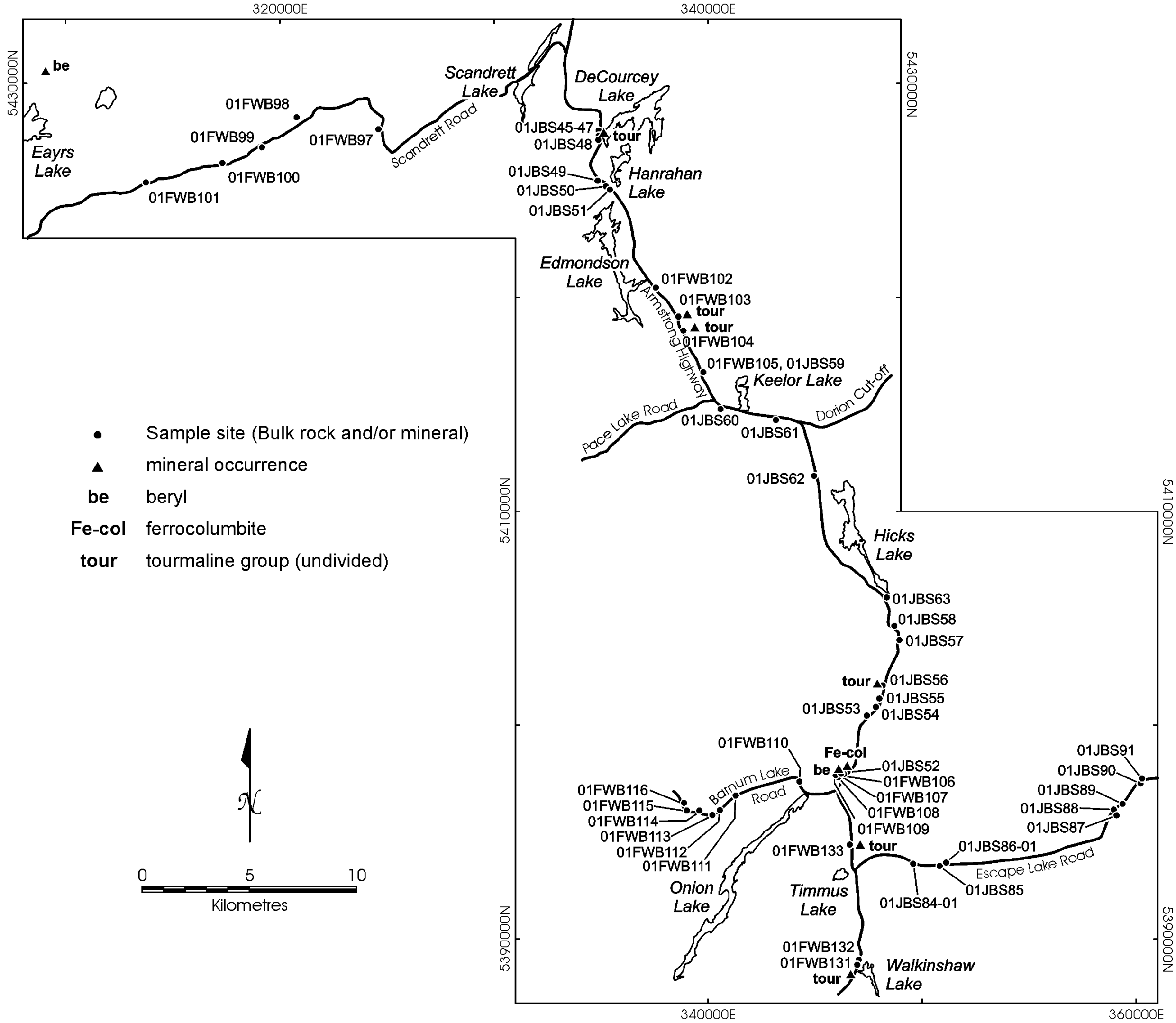


Figure 24. Location of rare-element mineralization and sample sites along the Armstrong highway.

ARMSTRONG HIGHWAY CROSS-SECTION

Strongly peraluminous, muscovite, cordierite and garnet-bearing pegmatitic granite dikes, with local black tourmaline, were found to occur widely in the Quetico Subprovince along the Armstrong highway between Walkinshaw Lake north to DeCourcey Lake (Figure 24). Detailed rock sampling was undertaken along this highway and adjacent area—including the DeCourcey–Eayrs lakes area—along the Quetico–Wabigoon subprovincial boundary zone, where beryl was reported by Jollife (1933) about 1.8 km northeast of Eayrs Lake. Although granites and pegmatites that contain garnet, tourmaline and muscovite were previously mapped within this area (Kaye 1969), no mineralogical or petrochemical work had been conducted.

Rare-element mineralization was discovered by the current survey within an extensive swarm of pegmatitic granite dikes at Onion Lake near Thunder Bay (*see* Figure 24). The lens-shaped dikes of this swarm, as seen in the area near the junction of Highway 527 and the Barnett Lake road, occur as northeast-striking, “whale-back” glacial erosional remnants that achieve a maximum size of 100 by 300 m. The internal units comprise

- muscovite-rich potassic pegmatite
- quartz-rich patches with blocky potassium feldspar, coarse muscovite books and sparse beryl
- fine-to medium-grained, garnet-biotite-muscovite granite
- garnet-biotite-muscovite pegmatitic leucogranite
- garnet and muscovite-garnet aplite

The quartz-rich patches locally contain pale green beryl up to 1 by 16 cm, as at locality 01-FWB-107 at Onion Lake (UTM 346199E, 5397916N, Zone 16). Black, tantalum-oxide minerals (ferrocolumbite: 27–31 weight % Ta_2O_5), up to 3 by 3 by 5 mm, were discovered at locality 01-JBS-52 (UTM 346512E, 5398007N, Zone 16) and apparently associated with local albitization of potassium feldspar megacrysts (*see* Figure 77a). Blocky potassium feldspar megacrysts up to 50 cm in diameter and muscovite books up to 10 cm in thickness were noted in the potassic pegmatite and enclosed quartz-rich patches.

Dikes and foliation-concordant peraluminous granites and pegmatites were emplaced into Quetico Subprovince metasedimentary rocks during at least 3 intrusive episodes characterized by the following rock types:

- grey, garnet-biotite granite, fine- to medium-grained
- cordierite and garnet-cordierite granite
- sheets of pegmatitic leucogranite and associated quartz-rich patches

Pegmatite sheets, at least 5 m thick, are evident on the Armstrong highway as at locality 01-FWB-105 near Keelor Lake (UTM 339218E, 5416563N, Zone 16). These sheets consist of coarse-grained garnet-muscovite-cordierite granite that contain 15 to 20% cordierite crystals pervasively altered to soft, dark green-black pseudomorphs. The coarse granite is gradational into muscovite-rich, miarolitic cavity-bearing, pegmatite patches (blocky potassium feldspar, muscovite, cleavelandite, quartz, brown black pyroxene and green fluorapatite).

Petrochemistry

Regional-scale, bulk rock sampling was undertaken across the Quetico Subprovince along and proximal to Highway 527, known as the Armstrong highway (Figures 24 and 25). This sampling was conducted because there is little lithogeochemical data available to assess rare-element enrichment trends associated with the abundant peraluminous, S-type granites in the subprovince. A total of 44 bulk rock samples of peraluminous granites, potassic pegmatites and aplites were collected (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d) and augmented by analyses of critical minerals such as potassium feldspar, muscovite, tourmaline and garnet. Overall, the data plotted on a CNK diagram is quite similar to the low-calcium granite trend of the Allison Lake batholith (Figure 78). The discussion of the bulk rock data is divided into 3 zones of the Quetico Subprovince (cf. Figure 25):

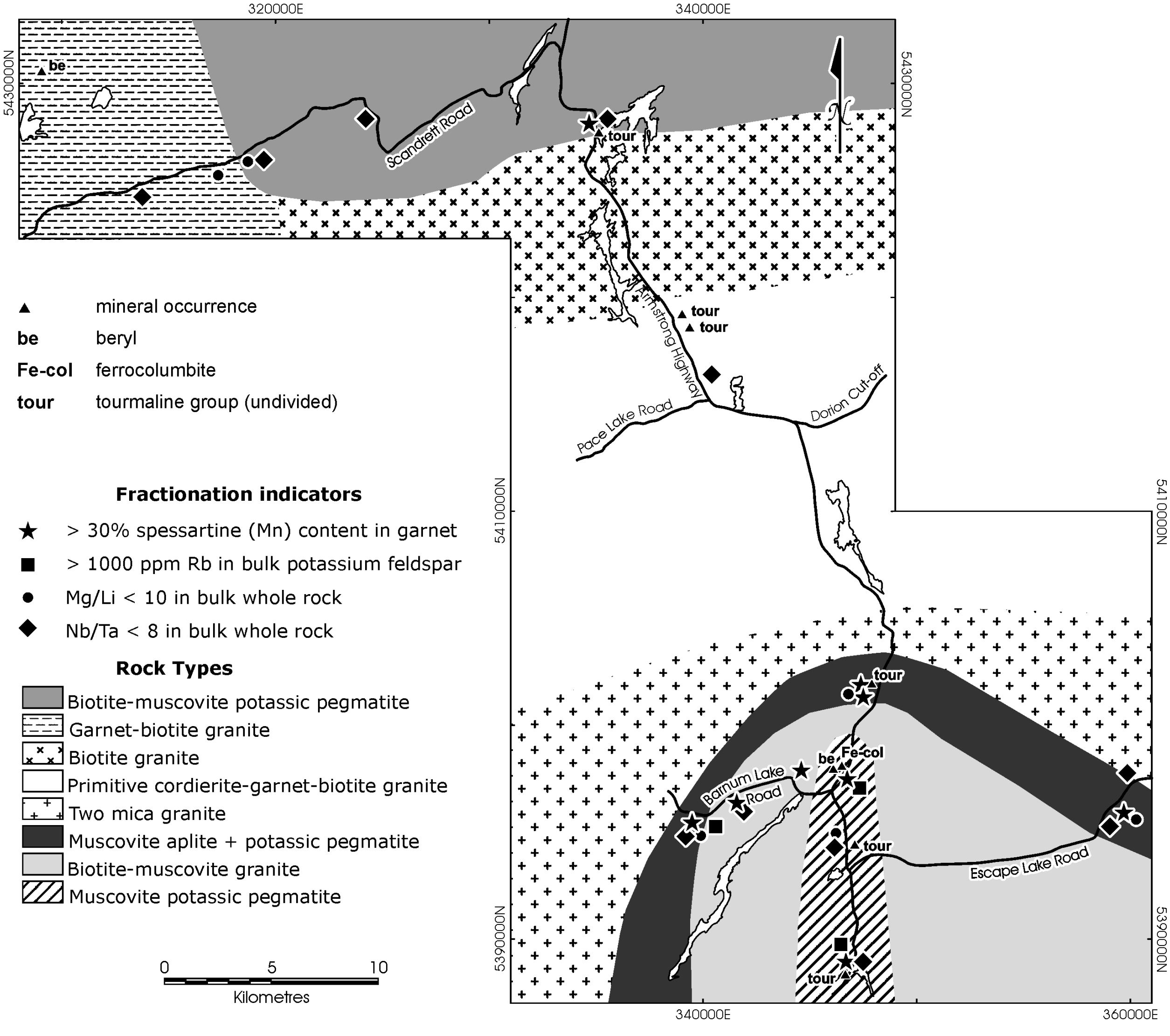


Figure 25. Key fractionation indicators plotted on the map of Allison Lake batholith: spessartine content of garnet based on microprobe data, Rb content (ppm) in potassium feldspar bulk analyses, Mg/Li ratio and Nb/Ta ratio in bulk whole rock analyses. The fractionation indicators indicate that the most fractionated pegmatitic granites occur along Scandrett, Barnum Lake and Escape Lake roads.

1. north subprovince boundary zone area: a 10 km wide zone from DeCourcey Lake west to the Eayrs Lake area and north to contact with metavolcanic-dominant rocks of the Wabigoon Subprovince
2. central Quetico Subprovince: Edmundson Lake south to Hicks Lake, a 20 km distance along the Armstrong highway;
3. south Quetico Subprovince boundary zone: a 15 by 20 km wide area from Onion Lake west to Basher Lake and south to the contact with the Wawa Subprovince

North Subprovince Boundary Zone

Ten bulk samples were collected over a 10 by 30 km area (*see* Figure 25) and comprise mildly to strongly peraluminous granites and potassic pegmatite (A/CNK: mean 1.147; range 1.059–1.526) (*see* Figure 78a) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d). Several pegmatites reveal significant fractionation and establish the area as worthy of follow-up prospecting for rare-element mineralization.

Sample 01-FWB-97-01 (UTM 324075E, 5428185N, Zone 16), a biotite-muscovite potassic pegmatite situated on the Scandrett Road, is the most highly evolved pegmatite found in this area (*see* Figure 24). This is evidenced by anomalous Be (11 ppm), Rb (554 ppm), Sn (29 ppm), Cs (27 ppm), Ta (13 ppm) and Nb (46 ppm). This strongly peraluminous rock (A/CNK = 1.526) also has significantly low K/Rb (57), K/Cs (1183) and Nb/Ta (3.6) ratios compared to the average crustal values (Table 1). A second sample (locality 01-FWB-101, UTM 313279E, 5425697N, Zone 16) of a garnet-muscovite granite, although less fractionated on the basis of K/Rb ratio (316), has a highly evolved Nb/Ta ratio of 0.176 indicating significant concentration of Ta (10.31 ppm) relative to Nb (1.81 ppm).

In general, lithium contents are not anomalous with a mean of 20 ppm and a range of 14 to 29 ppm. Nevertheless, it is recommended that lithium continue to be used as a chemical guide to evolved pegmatite systems in this area and others in the Quetico Subprovince. The mean tantalum content for nine samples of 3.5 ppm is similar to the crustal average although a significant range of 0.36 to 12.64 is notable. Rubidium has a range of 80 to 554 ppm and a mean value of 219 ppm, similar to pegmatitic rocks analyzed in the southern Quetico Subprovince boundary zone (see below).

Central Quetico Subprovince

The lithogeochemistry of the most extensive part of the Quetico Subprovince cross-section was evaluated with 13 bulk rock samples of granite and potassic pegmatite, selected mostly along the Armstrong highway (*see* Figure 25) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d). The rocks are mostly weakly peraluminous with 70% below A/CNK of 1.09 (*see* Figure 78a). However, pronounced aluminum-enrichment of 16.63 and 22.98 weight % was documented at Keelor Lake locality 01-FWB-105 with A/CNK ratios of 1.443 and 2.245, owing to abundance of peraluminous minerals such as muscovite and cordierite.

Most localities revealed no significant enrichment in the various rare elements. Lithium values of 41 ppm were documented in both the cordierite granite and miarolitic pegmatite patches at Keelor Lake locality 01-FWB-105 (UTM 339218E, 5416563N, Zone 16) indicate modest fractionation of the element at about twice the upper continental crust average (Taylor and McLennan 1985). Anomalous beryllium of 21 ppm was noted in the cordierite granite unit. Rubidium levels are considerably lower than those found in the northern and southern boundary zone areas of this Quetico section. Rubidium has a mean content of 158 ppm within a range of 52 to 283 ppm. Cesium levels are largely similar to the average crustal abundance and range from 1 to 10 ppm. Tantalum is also mostly depleted relative to its mean crustal abundance of 2.2 ppm. Its range of data is 0.37 to 13.63 with a mean value of 2.1 ppm. Nb/Ta ratios are also largely quite primitive with a mean of 14.7 in a wide range of 1.1 to 32.8. Two analyses with evolved Nb/Ta ratios (1.11 and 3.74) occur at locality 01-FWB-105. Except for locality 01-FWB-105, the granitic rocks of the Central Quetico Subprovince are primitive and have very little potential for rare-element mineralization.

South Quetico Boundary Zone

Lithogeochemistry was undertaken in this 15 by 20 km area centred around the north end of Onion Lake with 21 bulk rock samples of granite, potassic pegmatite and aplite selected (*see* Figure 25) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d). One sample from the Buda feldspar dike (Scott 1981), situated about 55 km to the west in Goldie Township near Conmee, was included in the tabulation of chemical data owing to similarities with dikes prolifically developed in the Onion Lake area.

The pegmatitic rocks are mildly peraluminous (A/CNK mean 1.106; range 0.983–1.203) and show a wide range of fractionation based upon critical trace element levels and ratios (*see* Figure 78b). Lithium is typically low, with a mean of 29 ppm and a range of 4 to 128 ppm. However, 2 samples exhibited anomalous lithium contents of 82 and 128 ppm (samples 01-JBS-86-01: UTM 351162E, 5393835N, Zone 16, and 01-JBS-91-01: UTM 360951E, 5397440N, Zone 16, respectively). Rubidium varies between 159 and 514 ppm with a mean value of 283 ppm. The highest value of 514 ppm Rb is associated with a 20 to 30 cm wide dike of potassic pegmatite rich in green muscovite situated near Walkinshaw Lake (sample 01-FWB-132-01: UTM 347063E, 5388857N, Zone 16) that also contained anomalous Ta (33 ppm), Be (27 ppm) and Sn (11 ppm) coupled with an evolved Nb/Ta ratio of 2.07. Anomalous beryllium was measured in samples from 4 pegmatites (samples 01-FWB-132-01, 01-FWB-133, 01-JBS-88-01 and 01-JBS-89-01) ranging from 20 to 29 ppm, which is about 7 to 10 times the average crustal abundance. Tin is anomalous in 4 samples (01-FWB-132-01, 01-FWB-109, 01-JBS-88-01 and 01-JBS-89-01) with levels between 8 and 16 ppm. Tantalum contents have a significant range of 1.32 to 61.7 ppm with 3 samples exceeding 10 ppm and the most interesting value by far, documented in a garnet-muscovite aplite at locality 01-JBS-88-01 (UTM 359038E, 5395880N, Zone 16) on the Escape Lake road (*see* Figure 25).

Various ratios also reveal a great range in fractionation for the pegmatitic granite rocks: Nb/Ta (mean 9.5; range 0.77–25.2), K/Rb (mean 131; range 43–402), K/Cs (mean 6690; range 657–20 598), and Mg/Li (mean 37; range 6–115). The most evolved of these ratios coincide with the samples that contains the highest Ta, Be and Cs.

Mineral Chemistry

Garnets occur throughout the entire Armstrong highway section (Figures 25 and 26; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 11). They are excellent fractionation indicators because of their abundance and the common manganese for iron substitution can be used to indicate the degree of fractionation of a granitic body (Baldwin and von Knorring 1983; Černý 1989a; Whitworth 1992). Based on the mineralogy, garnet composition and bulk analyses, samples from the Armstrong highway section were probably derived from granitic-forming melts that underwent variable degrees of fractionation (from primitive compositions all the way through to highly fractionated compositions).

Electron microprobe compositions of minerals from the Armstrong highway are published in MRD 111 (Tindle, Selway and Breaks 2002): garnet (*see also* Table 11), tourmaline (*see also* Table 17), fluorapatite (*see also* Table 10) and ferrocolumbite (*see also* Table 8d).

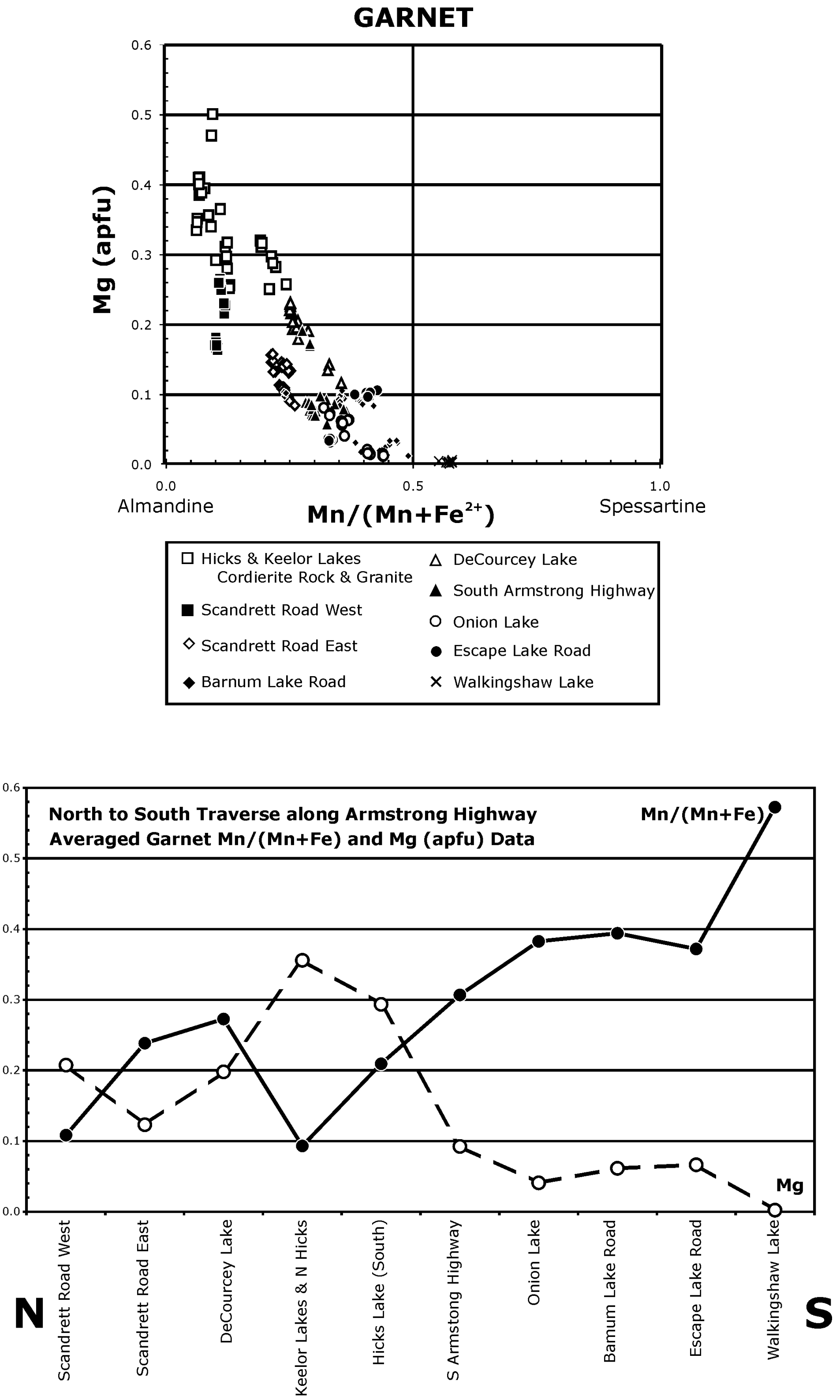


Figure 26. a) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet from the Armstrong highway. b) A north to south traverse of the average Mg (*apfu*) and Mn/(Mn+Fe) values from garnet for each lake and road along the Armstrong highway section. The most primitive garnet compositions occur at Keelor and North Hicks lakes; and the most fractionated garnet compositions occur at Walkinshaw Lake.

CENTRAL QUETICO SUBPROVINCE (*see* Figures 24 and 25)

1. Cordierite-garnet-biotite granite (Keelor Lake to Hicks Lake):
   This is the most primitive rock in the Armstrong highway section. The garnet is magnesium-rich almandine (67–81% almandine, 8–17% pyrope, 5–23% spessartine, 1–2% andradite) (*see* Figure 26a). Medium-grained black tourmaline (schorl-dravite) occurs interstitial to white potassium feldspar and euhedral grey quartz at locality 01-FWB-103 (UTM 338005E, 5418879N, Zone 16) (*see* Figure 79). Quartz-lined miarolitic cavities occur within the cordierite rock at locality 01-JBS-59 (UTM 339302E, 5416570N, Zone 16). These cavities contain abundant fine-grained yellow and silvery muscovite, euhedral quartz, and minor fluorapatite, albite, spherical fine-grained black magnesium-rich almandine, biotite and black pyroxene. Fluorapatite occurs as manganese-poor (0.0–0.1 weight % MnO) inclusions in sericitic muscovite and as coarse-grained green-blue manganese-rich isolated grains (0.0–1.8 weight % MnO, up to 1 cm) (*see* Figure 76b). The magnesium-rich almandine (74–78% almandine, 9–17% pyrope, 8–12% spessartine, 1–2% andradite), biotite and pyroxene (iron-rich diopside core, iron-rich enstatite rim) are likely remnants from the host cordierite granite (*see* Figure 26a), as the garnet, biotite, pyroxene and cordierite are all magnesium-rich and magnesium-rich pyroxene usually does not occur in granitic rocks.

NORTH QUETICO SUBPROVINCE (*see* Figures 24 and 25)

2. Biotite granite and two-mica granite (DeCourcey Lake):
   The garnet is almandine with a composition of 60 to 68% almandine, 24 to 34% spessartine, 4 to 7% pyrope and 1% andradite (*see* Figure 26a). The garnet is zoned with iron-enriched cores and manganese-enriched rims. The composition of the garnet at DeCourcey Lake is similar to that at Scandrett road east. Prismatic medium-grained black tourmaline (magnesium-rich schorl), fine-grained red almandine and green fluorapatite (3.1–3.3 weight % MnO) occurs in a 27.5 m wide dike at locality 01-JBS-47 (UTM 334434E 5427964N, Zone 16) (*see* Figures 79, 26a and 76b).

3. Biotite-garnet granite, biotite-muscovite potassic pegmatite and aplite (Scandrett road east):
   The garnet in the potassic pegmatite and aplite have the same composition: almandine (67–74% almandine, 20–29% spessartine, 2–5% pyrope, 1–2% andradite, 0.0–0.7 weight % Y_2O_3) (*see* Figure 26a). The garnet from Scandrett road east is more manganese-rich and magnesium-poor than the garnet from Scandrett road west. Locality 01-FWB-98 (UTM 320184E, 5428791N, Zone 16) has coarse-grained silver muscovite (up to 2.5 cm across) in a quartz pod. The bulk composition of this muscovite is enriched in Li (141 ppm), Rb (1683 ppm), Cs (108 ppm), Nb (444 ppm) and Ta (70 ppm). Rocks with bulk muscovite with >65 ppm Ta and >50 ppm Cs have a high potential for Nb-Ta mineralization (Gordiyenko 1971).

4. Biotite-garnet granite and muscovite potassic pegmatite (Scandrett road west):
   Medium-grained red to black garnet occurs in green muscovite potassic pegmatite. The garnet is magnesium-rich almandine (80–83% almandine, 10–11% spessartine, 7–9% pyrope, 1% andradite, 0.1–0.5 weight % Y_2O_3) (*see* Figure 26a).

SOUTH QUETICO SUBPROVINCE (*see* Figures 24 and 25)

5. Muscovite granite, potassic pegmatite and aplite (south Armstrong highway):
   The garnet is almandine with a composition of 60 to 68% almandine, 26 to 36% spessartine, 2 to 6% pyrope and 1% andradite in all 3 rock types (*see* Figure 26a). Medium-grained blue fluorapatite (0.4–1.3 weight % MnO) occurs in the two-mica granite (*see* Figure 76b). Coarse-grained black tourmaline (up to 8 cm long) occurs in muscovite potassic pegmatite at locality 01-JBS-56 (UTM 347957E, 5401412N, Zone 16). The tourmaline has a composition of calcium-rich dravite and magnesium-rich schorl and it is associated with coarse-grained, zoned mica with biotite cores and muscovite rims (*see* Figure 79).

6. Two-mica granite, muscovite potassic pegmatite and aplite (Barnum Lake road and Onion Lake):
   The garnet occurs in all 3 rock types and is more manganese-rich than in the above localities. The garnet is manganese-rich almandine with a composition of 49 to 62% almandine, 34 to 50% spessartine, 1 to 4% pyrope and 1 to 2% andradite (*see* Figure 26a). The Onion Lake (locality 01-JBS-52: UTM 346512E, 5398007N, Zone 16) outcrop on Armstrong highway has potassic pegmatite with blocky white potassium feldspar (up to 50 cm long), muscovite + quartz intergrowths, coarse black tantalum-oxide minerals (ferrocolumbite with 28–31 weight % Ta_2O_5) and green beryl (*see* Figure 77a). This is the only locality along the Armstrong highway that tantalum-oxide minerals were found. Coarse muscovite books (up to 7 cm wide by 4 cm thick) occur next to quartz pods. Locality 01-FWB-113 (UTM 340126E, 5395643N, Zone 16) on Barnum Lake road has coarse-grained silver to brown muscovite (up to 3.5 cm) in potassic pegmatite. The bulk composition of this muscovite has elevated Li (861 ppm), Rb (2871 ppm), Cs (90 ppm), Nb (480 ppm) and Ta (67 ppm).

7. Muscovite potassic pegmatite and aplite (Escape Lake road):
   The green muscovite is coarse-grained and is up to 2 cm wide. The garnet is almandine with a composition of 53 to 65% almandine, 33 to 41% spessartine, 1 to 3% pyrope, 1% andradite and <0.4 weight % P_2O_5 (*see* Figure 26a).

8. Green muscovite potassic pegmatite (Walkinshaw Lake):
   This is the only locality along the Armstrong highway section that contains spessartine garnet (55–59% spessartine, 40–44% almandine, 1% andradite, <0.3 weight % Y_2O_3) (locality 01-FWB-132: UTM 347063E, 5388857N, Zone 16) (*see* Figure 26a). The potassic pegmatite contains blocky white potassium feldspar, quartz and coarse-grained green muscovite (up to 2 cm across). Prismatic coarse-grained black tourmaline (up to 1.6 cm long) comprises 5 volume % of the potassic pegmatite at locality 01-FWB-131 (UTM 346750E, 5388084N, Zone 16). The tourmaline is schorl-foitite with minimal Mg due to contamination (*see* Figure 79). This potassic pegmatite also has lenticular miarolitic cavities (up to 7 cm long by 1 cm wide) lined with clear quartz and amethyst. The coarse-grained yellow-green muscovite (5.5 cm across) at locality 01-FWB-131 has elevated Li (28 ppm), Rb (6958 ppm), Nb (146 ppm) and Ta (117). Rocks with bulk muscovite with >65 ppm Ta have a high potential for Nb-Ta mineralization (Gordiyenko 1971).

Interpretation of Chemical Data

Key mineral fractionation indicators were plotted on a map of the Armstrong highway (*see* Figure 25) to identify the most evolved rocks and the areas with the highest potential for rare-element mineralization. The key fractionation indicators are absent in Central Quetico indicating that this area has a low potential for rare-element mineralization. The only exception in the Central Quetico is the presence of tourmaline and Nb/Ta <8 in bulk samples at Keelor Lake. The Scandrett Road and Hanrahan Lake, north Quetico Subprovince have Mg/Li ratio <10 and Nb/Ta ratio <8 in bulk whole rock samples and tourmaline and Mn-rich garnet occur only at Hanrahan Lake. This indicates that the area has moderate potential for rare-element mineralization.

South Quetico Subprovince (Barnum Lake road, Onion Lake, Escape Lake road and Walkinshaw Lake) has a high potential for rare-element mineralization (*see* Figure 25), as the Mg/Li ratio <10 and Nb/Ta ratio <8 occur in bulk whole rock samples and Rb >1000 ppm in bulk potassium feldspar samples. Key mineral indicators also occur in this area: manganese-rich garnet occurs throughout this area, tourmaline occurs along the Armstrong highway and beryl and ferrocolumbite occurs at Onion Lake.

Garnet is an excellent fractionation indicator mineral as iron-rich garnet indicates the rocks are primitive and manganese-garnet indicates the rock is evolved (Baldwin and von Knorring 1983; Černý 1989a; Whitworth 1992). Garnets were analyzed along the Armstrong highway and their compositions are plotted in Figure 26b. This plot shows that the garnet in South Quetico Subprovince (i.e., Onion Lake, Barnum Lake road, Escape Lake road and Walkinshaw Lake) are the most Mn-rich and Mg-poor and, hence, have the highest potential for rare-element mineralization.

Bulk analysis of potassium feldspar is also an excellent fractionation indicator mineral as elevated Rb and Cs contents and low K/Rb ratios indicate that the potassium feldspar is evolved (Gordiyenko 1971; Černý et al. 1981; Černý 1989a; Morteani and Gaupp 1989). Potassium feldspars were analyzed along the Armstrong highway and their compositions are plotted in Figure 80a. This plot shows that potassium feldspar from south Quetico Subprovince (Onion Lake, Barnum Lake road and Walkinshaw Lake), a sample from Edmunson Lake and a sample from Scandrett road have low K/Rb ratios and elevated Cs contents, which suggest that they have the highest potential for rare-element mineralization within the Armstrong highway cross-section of the Quetico Subprovince. Bulk muscovite from Scandrett road east, Barnum Lake road and Walkinshaw Lake have >65 ppm Ta and thus have a high potential for tantalum mineralization (Gordiyenko 1971).

Recommendations for Pegmatite Exploration

The reconnaissance work done by this survey indicates that chemically evolved pegmatitic rocks occur along the northern and southern subprovince boundary zones of the Quetico Subprovince, especially at Onion Lake and Walkinshaw Lake. To date, the field data coupled with the bulk and mineralogical data indicate that these zones are favourable thus far for beryl-type, rare-element class pegmatites. Further work is needed to establish if such beryl-type pegmatites exhibit regional zonation into Li-Cs-Ta-rich pegmatite types. The Onion and Walkinshaw lakes area is one area worthy of follow-up exploration for such pegmatites (*see* Figure 24).

BUDA FELDSPAR DIKE

The Buda feldspar dike has been previously investigated by Scott (1981) who undertook detailed geological mapping and a limited amount of bulk rock analysis. The occurrence was not examined in the field by this study and the data below pertain to 7 samples obtained by the authors. The samples consist of coarse-grained green muscovite and potassium feldspar with minor niobium-oxides (ferrocolumbite, 6–8 weight % Ta_2O_5) and orange garnet (Figure 81a). The coarse-grained muscovite contains 1 mm inclusions of garnet almost completely replaced by biotite. The garnet is zoned with spessartine cores (49–56% spessartine, 42–48% almandine, 1% pyrope, 1% andradite) and almandine rims (49–52% almandine, 46–49% spessartine, 1% pyrope, 1% andradite) (Figure 82a). The electron microprobe compositions of ferrocolumbite and garnet from Buda feldspar dike will be published in a future MRD.

HELEN LAKE

Helen Lake is located north of Nipigon along Highway 11. Helen Lake has a biotite potassic pegmatite that grades into a medium-grained biotite granite. The biotite potassic pegmatite contains coarse euhedral potassium feldspar, quartz, prismatic medium- to coarse-grained black tourmaline (schorl-dravite) and fine-grained green and blue fluorapatite (0.3–0.9 weight % MnO) (*see* Figures 79 and 76b) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Tables 17 and 10). A biotite-rich metasomatic contact occurs between the biotite granite and host diabase. Graphic coarse-grained cordierite (up to 2 cm) and tourmaline occur in the granite near the contact with the diabase.

MNW PEGMATITE, GEORGIA LAKE PEGMATITE FIELD

The MNW complex-type, petalite-subtype pegmatite, west of Cosgrave Lake, is enclosed within a medium-grained biotite-muscovite granite of the MNW stock, which is presumed to be the parent of the pegmatite (Pye 1965). Bulk analysis of the parent granite 1 m from the contact contains 490 ppm Li, 940 ppm F, 370 ppm Rb, 32 ppm Sn and 10 ppm Be. The MNW pegmatite is named from the initials of the 3 men, John Moschuk, T. Neborac and Murray Wilson, who discovered and staked it in May 1955 (Pye 1965).

The MNW pegmatite is made up of 5 distinct pegmatite zones: tourmaline-rich border zone, muscovite-quartz-feldspar wall zone with aplite pods, cleavelandite-rich intermediate zone, feldspar-muscovite-quartz intermediate zone, quartz-spodumene core (Pye 1965). The outermost pegmatite zone in the MNW pegmatite is a muscovite-plagioclase-green tourmaline-quartz wall zone near the contact with the granite. Yellow green muscovite books are up to 1 cm thick in this wall zone. Close to the squi (spodumene + quartz intergrowth) at the core boundary is a cleavelandite-rich replacement zone, which consists of albite, faint green muscovite books, coarse-grained tantalum-oxide minerals (up to 3 cm) and localized phosphate-rich masses (possibly purpurite). The MNW pegmatite is a complex-type, petalite-subtype pegmatite because of the abundance of petalite and squi, which is a spodumene + quartz intergrowth formed due to the breakdown of petalite during cooling. The core zone has a pink and white blocky potassium feldspar-petalite-quartz assemblage.

Mineral Chemistry

Electron microprobe compositions of minerals from MNW pegmatite—tourmaline, columbite-tantalite, fluorapatite, muscovite and lepidolite—will be published in a future MRD. Mineral chemistry plots are based on unpublished data.

Tourmaline (magnesium-rich schorl) occurs in the border zone along the contact between the pegmatite and granite (*see* Figure 79). The wall zone contains tantalum-oxide minerals intermediate between ferrocolumbite and manganocolumbite in composition (26 weight % Ta_2O_5) (*see* Figure 81a). The wall zone also contains iron-rich tourmaline and manganese-rich fluorapatite. The green tourmaline ranges in composition from magnesium-bearing schorl to iron-rich elbaite (*see* Figure 79). The fluorapatite is manganese-rich (2.8–4.5 weight % MnO) (Figure 81b).

The tourmaline-quartz-rich zone has patches of sugary aplite with tourmaline (iron-rich elbaite and magnesium-bearing schorl) in pockets (*see* Figure 79). The fluorapatite is manganese-rich (1.5–3.5 weight % MnO) (*see* Figure 81b). Both muscovite (0.1–0.4 weight % Rb_2O, <0.1 weight % Cs_2O) and rubidium-cesium-rich lepidolite (1.1–1.3 weight % Rb_2O, 1.0–1.3 weight % Cs_2O) occur in the tourmaline-quartz zone (*see* Figure 76a).

The coarse-grained tantalum-oxide minerals in the cleavelandite-rich replacement zone are mostly manganocolumbite (35–36 weight % Ta_2O_5) and manganotantalite (55–56 weight % Ta_2O_5) with one composition of ferrocolumbite (36 weight % Ta_2O_5) (*see* Figure 81a). The tantalum-oxide minerals in the petalite core zone are intermediate between ferrocolumbite and manganocolumbite in composition (31–32 weight % Ta_2O_5) (*see* Figure 81a).

LOWTHER TOWNSHIP PEGMATITE

This pegmatite, situated in the mid-part of the Quetico Subprovince near Hearst (Bennett et al. 1967), was discovered in 1939 by A. Villeneuve. It has been intermittently examined for its rare-element mineralization, but has not been previously evaluated for tantalum potential.

The Lowther pegmatite is classified as a lepidolite- to spodumene-subtype pegmatite that is significantly albitized. The main pegmatite occurs as a 1 to 2 m by 30 m mass oriented at 310°, which is approximately subperpendicular to the contact of its host rock, a northeast-striking, 45 m wide dike of muscovite-biotite pegmatitic granite. The pegmatitic granite dike is, in turn, hosted in a hornblende-biotite tonalite mass of unknown extent. The occurrence of a smaller pegmatite within the same pegmatitic granite dike and having a similar strike orientation suggests a “ladder vein” structure for the rare-element pegmatites.

The primary mineralogy comprises faint green spodumene, coarse muscovite books up to 5 cm in diameter, blocky potassium feldspar and faint green beryl. Irregular zones of orange garnet (presumably spessartine-rich)-green muscovite-cleavelandite-rich replacement masses are significantly present. Platy black tantalum-oxide minerals, mostly fine to medium grained, have mostly been found in the cleavelandite-rich replacement masses. The geology of the Lowther Township pegmatite is discussed in more detail by Breaks, Selway and Tindle (2002), as this study covers a limited number of Lowther samples collected several years ago.

Mineral Chemistry

Bulk analysis of coarse muscovite books gave values of 54 ppm Ta, 375 ppm Nb, 247 ppm Cs, 1155 ppm Li, and 5515 ppm Rb. The green muscovite in the cleavelandite-rich replacement masses contains 0.1 to 0.7 weight % Rb_2O and <0.2 weight % Cs_2O (*see* Figure 76a). Three analyses of blocky potassium feldspar revealed 82 to 305 ppm Cs and 971 to 3725 ppm Rb. Beryl contains 330 ppm Rb, 1728 ppm Li, 1.6 weight % Na_2O and an exceptionally high Cs_2O content of 2.6 weight %. Such a cesium level is considered to indicate crystallization from a highly evolved pegmatite-forming melt and closely compares with Cs_2O contents in beryl from the Tanco pegmatite (2.47–3.27 weight % Cs_2O: Černý et al. 1981, p.114). The Lowther pegmatite and surrounding area require exploration for similar rare-element pegmatite bodies.

Electron microprobe compositions of minerals from Lowther Township pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): muscovite (*see also* Table 13a), columbite-tantalite (*see also* Table 8d), microlite (*see also* Table 14), strüverite (*see also* Table 16) and cassiterite (*see also* Table 7).

Electron microprobe investigation of the black tantalum-oxide minerals (84 analyses) indicates that they are mostly manganocolumbite (Figure 77b) with an average Ta_2O_5 content of 26.85 weight % and a range of 11.92 to 39.45 weight % Ta_2O_5 and rarely ferrocolumbite. The manganocolumbite, however, reveals a manganese-suite trend to highly evolved compositions in terms of the Mn/(Mn+Fe) ratio that varies between 0.661 and 0.965. Microlite occurs as patch-like domains within manganocolumbite and is interpreted to have developed during late albitization of the pegmatite. Strüverite [$(Ti, Ta, Fe)O_2$] (with 11–12 weight % Ta_2O_5) has exsolved ferrocolumbite, manganocolumbite (9–12 weight % Ta_2O_5) and tantalum-bearing cassiterite (0.2–0.6 weight % Ta_2O_5) inclusions. Euhedral pyrite cubes have been replaced along their rims by hematite.

Opatica Subprovince

Rare-element mineralization in the Opatica Subprovince is currently known only at the Case pegmatite in the Lake Abitibi area (*see* Figure 22). Nevertheless, this spodumene-subtype pegmatite comprises the fifth largest lithium-rich pegmatite in the Superior Province of Ontario.

CASE PEGMATITE

This swarm of 3 pegmatites has witnessed intermittent exploration interest since its discovery in 1959 (Lumbers 1962, p.29). A previous investigation generally characterized the mineralogy that included columbite-tantalite and pollucite (Nickel 1963). A bulk sample of pollucite-bearing material contained 5.79 weight % Cs_2O (Nickel 1963). Recent work (Horne 2000) involved extensive stripping over most of the exposed strike length of 290 m was followed by channel sampling and total field magnetic and magnetic gradient ground geophysical surveys. Platinova Resources (Platinova Resources, News Release, www.platinova.com, August 8, 2001) optioned the property in order to assess the tantalum potential of the Case pegmatite system. An average content of 0.024 weight % Ta_2O_5, with a range of 0.003 to 0.068 weight %, was calculated from 16 grab samples selected by Horne (2000). Recent results from channel sampling and a limited diamond drill program established an average of 0.024 weight % Ta_2O_5 across 8 m in the Central Dike and a range of 0.011 weight % (over 1 m) to 0.032 weight % Ta_2O_5 (over 7.7 m) for the North Dike (Platinova Resources, News Release, www.platinova.com, October 4, 2001).

The Case pegmatite system is hosted in the southeastern part of the Case batholith, an extensive 50 by 85 km, ovoid granitic complex that is apparently part of the Opatica Subprovince (Jackson and Fyon 1991). The immediate host rocks of the pegmatite dikes consist of massive to subtly foliated, biotite granodiorite that is characterized by biotite-rich orbicules ranging in diameter from 1 to 7 cm. Such entities are classified as proto-orbicules (Leveson 1966) and commonly exhibit a linear alignment that is parallel to the weak foliation of its granodiorite host.

The pegmatite swarm, which strikes at 060 to 070° and dips 40 to 60° north, consists of 3 *en échelon* dikes exposed within a 260 by 350 m area situated immediately east of the contact between the Case batholith and Scapa metasedimentary rocks (Lumbers 1962):

North Dike	(12 m thickness; 100 m minimum strike length)
Central Dike	(39 m thickness; 350 m minimum strike length)
South Dike	(10 m thickness; 250 m minimum strike length)

The Central Dike progressively widens from 10 to 39 m in a west to east direction and thus remains open to the east beyond the limits of visible outcrop. The main exposure, within the eastern part of the dike (UTM 578287E, 5431689N, Zone 17), reveals a subtly zoned pegmatite that consists of the following units:

- sodic aplite border zone, 5 to 20 cm thick
- spodumene-rich zone (muscovite-potassium feldspar-quartz-green spodumene-albite)
- central quartz-rich core zone
- lime green muscovite-rich patches
- late dikes of spodumene pegmatite

The sodic aplite border zone occurs along both the north and south contacts as a sugary texture, fine-grained white to pale pink friable rock. Minor phases include red garnet and sparse black specks of tantalum-niobium oxide minerals. Toward the centre of the dike, a spodumene-rich zone assumes dominance that subsequently grades into a 5 to 10 m by 90 m quartz-rich core zone. This zone consists of 70 to 80 volume % massive white quartz and contains the coarsest blocky potassium feldspar (82 by 95 cm) and spodumene megacrysts (5 by 70 cm) in the entire pegmatite system. The spodumene in the coarse spodumene zone has 2 habits: very coarse-grained blades of beige and green spodumene (from 5 by 8 cm to 60 cm by 1.3 m) with brown manganese-oxide staining, and coarse-grained needles of white spodumene (1 cm long by 1 mm wide) often in quartz. Beryl is subtly present as white to faint blue crystals up to 5 cm diameter and mostly occur within the spodumene-rich zone. One grain of medium-grained brown euhedral zircon was found in the spodumene zone in the Central Dike. Small, blob-like masses, rich in lime green muscovite (80 volume %) and augmented by orange garnet, albite and spodumene, occur sparsely in the core zone. Rust-stained cavities characterize spodumene megacrysts within and proximal to these muscovite-rich domains. The cavities are due to inclusions of weathered sphalerite. Late dikes of spodumene pegmatite transect the aplite border zone and progress into the granodiorite host rocks, thus indicating a relatively early crystallization for the aplite that could have resulted in a rapid, pressure quench crystallization (Jahns 1982). Rare blue molybdenite pods (up to 2 cm) occur in the North Dike.

The western parts of the Central Dike, however, reveal a striking contrast in the greater abundance of sodic aplite layered with coarse-grained spodumene granite, quartz-ballpeen-texture dark mica-albite pods and muscovite albitite zones. There are also small patches of quartz-rich core zone material, which entirely disappear at the western exposure of the Central Dike.

Petrochemistry

Bulk analyses of the garnet aplite border zone, garnet-muscovite pod, dark mica-quartz-albite zone and 4 analyses of the biotite host rock were collected from the Case pegmatite (*see* Figure 80a; *see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 20d). The garnet aplite border zone is sodium-rich (10.31 weight % Na_2O) (*see* Figure 80a) and contains slightly elevated Nb (22 ppm) and Ta (25 ppm) contents. The garnet-muscovite pod from the Central Dike is potassium-rich (9.90 weight % K_2O) and has elevated Li (1074 ppm), Ga (421 ppm), Rb (10 524 ppm), Cs (1344 ppm), Nb (102 ppm), Sn (206 ppm) and Ta (160 ppm). The dark mica-quartz-albite zone in the western part of the Central Dike contains 20% massive fine- to coarse-grained rubidium-bearing muscovite (0.8–0.9 weight % Rb_2O, 0.1–0.2 weight % Cs_2O). Bulk analysis of this zone contains 3342 ppm Li, 4349 ppm Rb, 727 ppm Cs, 262 ppm Nb and 87 ppm Ta. The elevated rare-element contents indicate that it crystallized from a highly evolved pegmatite-forming melt.

The bulk samples of the biotite tonalite were collected with increasing distance from the pegmatite-host rock contact:

- 01-FWB-78 biotite tonalite, 0 to 3 cm from pegmatite contact
- 01-FWB-79 biotite tonalite, 23 to 25 cm from pegmatite contact
- 01-FWB-80 biotite tonalite, 80 to 82 cm from pegmatite contact
- 01-FWB-81 biotite tonalite, 130 to 135 cm from pegmatite contact

The biotite tonalite host rock is sodium-rich with 6.03 to 6.52 weight % Na_2O (*see* Figure 80a). Some of the rare-element contents of the biotite tonalite decrease with increasing distance from the contact with the pegmatite:

- 809 ppm Rb in 01-FWB-78 to 52 ppm Rb in 01-FWB-81
- 110 ppm Cs in 01-FWB-78 to 5 ppm Cs in 01-FWB-81
- 46 ppm Ga in 01-FWB-78 to 40 ppm Ga in 01-FWB-81
- 13 ppm Nb in 01-FWB-78 to 5 ppm Nb in 01-FWB-81

The lithium and tantalum contents are unusual, as the maximum lithium (428 ppm Li) and tantalum (6 ppm) contents in the biotite tonalite occurs in locality 01-FWB-80 at 80 to 82 cm from the pegmatite contact. The strontium and barium contents increase with increasing distance from the pegmatite contact:

- 548 ppm Sr in 01-FWB-78 to 770 ppm Sr in 01-FWB-81
- 510 ppm Ba in 01-FWB-78 to 907 ppm Ba in 01-FWB-81

The variation in the rare-element contents in the biotite tonalite host rock indicates that Rb-, Cs-, Ga- and Nb-bearing fluids travelled from the pegmatite into the host rock. The composition of the feldspars in the host rock was likely enriched in Rb and Cs and depleted in Sr and Ba by the pegmatitic fluids. With increasing distance from the pegmatite contact the degree of alteration of the host rock decreases.

Mineral Chemistry

Electron microprobe compositions of minerals from the Case pegmatite are published in MRD 111 (Tindle, Selway and Breaks 2002): columbite-tantalite (*see also* Table 8d), microlite (*see also* Table 14), garnet (*see also* Table 11), muscovite (*see also* Table 13a) and fluorapatite (*see also* Table 10).

Black tantalum-oxide minerals containing tantalum and niobium were identified in a variety of paragenesis within the Case pegmatite system:

1. aplite border zone
2. muscovite-potassium feldspar-quartz-green spodumene-albite pegmatite
3. spodumene granite near western end of the Central Dike
4. muscovite albitite layer (western limit of exposure)
5. spodumene-albite-quartz pegmatite patches in quartz-ballpeen texture dark mica-albite rock (western limit of exposure of Central Dike).

Oxide minerals were analyzed from the aplite border zone and the quartz-rich core zone of the main part of the Central Dike (Figure 82b). The fine-grained oxide minerals in the garnet-muscovite-fluorapatite aplite border zone are ferrocolumbite with an average of 16.36 weight % Ta_2O_5. These are the most primitive oxide compositions in the Case pegmatite, whereas the oxide minerals in the quartz-rich core zone have the most fractionated compositions in the pegmatite: manganocolumbite (38.73 weight % Ta_2O_5), manganotantalite patches (average 62.79 weight % Ta_2O_5) and microlite (average 69.0 weight % Ta_2O_5).

Oxide minerals were also analyzed from the aplite border zone and the spodumene granite zone of the western part of the Central Dike (*see* Figure 82b). The fine-grained oxide minerals in the garnet aplite border zone are mostly ferrocolumbite with a thin manganocolumbite rim (average 28.26 weight % Ta_2O_5). Microlite with 70.0 weight % Ta_2O_5 is also present in the aplite border zone. Oxide minerals (2 by 4 mm) in layered garnet-muscovite aplite plots in the centre of the columbite-tantalite quadrilateral and is complexly zoned with iron and tantalum-enriched rims. The composition ranges from manganotantalite core, manganocolumbite, ferrocolumbite and ferrotantalite rims with an overall average of 53.08 weight % Ta_2O_5. Most of the oxide minerals in the spodumene granite ranges in composition from ferrocolumbite to manganocolumbite with minor uranoan microlite. In sample 01-JBS-159-01, the platy oxide minerals in medium- to coarse-grained spodumene granite are zoned with tantalum-poor relict cores (ferrocolumbite to manganocolumbite, average of 24.44 weight % Ta_2O_5) and tantalum-rich rims (ferrotantalite, average 49.70 weight % Ta_2O_5).

Orange manganese-rich garnet (spessartine) occurs throughout the North Dike, Central Dike and western part of the Central Dike of the Case pegmatite (*see* Figure 82a). Orange garnet often occurs as inclusions in bladed spodumene. The composition of the garnet is 53 to 69% spessartine, 27 to 44% almandine, 1 to 10% grossular, 0 to 2% andradite, 1% pyrope. Coarse-grained orange garnet (up to 2 cm) occurs in a medium-grained green muscovite-rich pod 27 cm in diameter. The garnet is zoned spessartine with manganese-rich cores (86% spessartine, 12% almandine, 2% andradite) and iron-enriched rims (65–66% spessartine, 31–32% almandine, 2% andradite, 1% grossular).

The sodic aplite border zone contains fluorapatite and zoned muscovite. The green to blue fluorapatite is manganese-rich (0.7–1.8 weight % MnO) (*see* Figure 81b). The muscovite has cesium-poor cores and cesium-rich rims and uniform Rb content (<0.1 weight % Cs_2O in the core and 0.5 weight % Cs_2O in the rim, 0.5–0.8 weight % Rb_2O) (*see* Figure 76a).

Summary and Conclusions

INTRODUCTION

The Superior Province of northwestern to northeastern Ontario represents a vast terrain that contains widely distributed rare-element pegmatite mineralization (*see* Figure 1). This study constitutes an initial step in providing a modern comprehensive field, mineralogical and geochemical database for the Superior Province that will stimulate mineral exploration for various metalliferous commodities, such as tantalum, cesium, rubidium, and mineral products, such as petalite, low-iron spodumene, lepidolite, and high-purity sodium and potassium feldspars.

FERTILE GRANITES

Rare-element pegmatite deposits are commonly spatially associated with peraluminous, fertile, S-type granite plutons, as discussed in detail in the section on fertile granites above (Černý 1989a; Breaks and Moore 1992; Breaks and Tindle 2001) and hence the area of focus for possible rare-element-enriched pegmatitic derivatives from highly fractionated parent granites can be significantly reduced if recognition of such granites can be documented. This study has documented fertile granites in 9 new localities with the most significant discovery represented by the Allison Lake batholith, which now represents the largest fertile peraluminous granite known in Ontario.

The present study has established several important exploration target areas for rare-element mineralization in the Superior Province of northwestern Ontario:

Uchi–English River subprovincial boundary zone

- Allison Lake batholith
- Wenasaga Lake batholith
- Twinname Lake stock

Sioux Lookout domain

- Medicine Lake stock
- Laval Lake stock
- Hughes Creek stock

Quetico Subprovince

Note, the fertile granite body has not yet been identified for

- Nym–Niobe lakes area
- Onion Lake area
- DeCourcey–Eayrs lakes area

Furthermore, there are several important new areas of rare-element mineralization in which the associated fertile granite is currently not identified owing to the need for more field investigation:

- **English River–Wabigoon subprovincial boundary zone**: Onaman–Tashota metavolcanic belt between Armstrong and Superb Lake. This 10 by 200 km part of the belt contains several lithium-rich pegmatite groups that contain oxide minerals with amongst the highest Ta_2O_5 contents of any area in Ontario.
- **central Quetico Subprovince**: Wisa Lake area and the area around Hearst proximal to Lowther Township lepidolite-spodumene-subtype pegmatite are both areas with potential for additional rare-element pegmatites to be found.

COMPARATIVE MINERAL CHEMISTRY

Currently, the Tanco pegmatite, southeastern Manitoba, close to the border with Ontario, is the only operating pegmatite mine in North America, except for the gem mines in California and Maine. The pegmatite has numerous commodities: Ta (tantalite, wodginite), Cs (pollucite), ceramic-grade spodumene, Sn (cassiterite), Rb (lepidolite) and potassium feldspar. The petalite-rich Separation Rapids pegmatites (Breaks and Tindle 2001) occur within the easternmost extension of the Bird River metavolcanic-metasedimentary belt that hosts the famous Tanco pegmatite. A comparison of averaged Ta_2O_5 contents in columbite-tantalite from localities visited during this study, the Tanco pegmatite, Separation Rapids pegmatites and Pakeagama pegmatites (selected zones) is shown in Figure 27 (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 18a). The manganotantalite (average 82 weight % Ta_2O_5, maximum 85.6 weight % Ta_2O_5) from the inner core zone at the North Aubry pegmatite is the most tantalum-rich oxide mineral known to date in Ontario. Manganotantalite from several spodumene-rich pegmatites: Falcon Lake, South Aubry, Fairservice #16 and #17, Tebishogeshik and Tot Lake have average Ta_2O_5 contents higher than that found at Tanco. This indicates that tantalum-rich oxide minerals can occur in spodumene-subtype pegmatites in addition to petalite-subtype pegmatites (i.e., Tanco, Separation Rapids, Pakeagama pegmatites).

Tantalum-oxide minerals also occur in association with highly evolved rubidium-cesium-rich potassium feldspar and mica. Potassium feldspar (4.5 weight % Rb_2O, 0.5 weight % Cs_2O) from Falcon Lake spodumene-rich pegmatite is the second feldspar to date with average Rb_2O and Cs_2O contents higher than that found at Tanco (based on 1 sample that likely came from Falcon Lake) (Figures 28 and 29) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 18c). The potassium feldspar (4.4 weight % Rb_2O) from Pegmatite #7, one of the eastern petalite pegmatites at Separation Rapids, also has average Rb_2O contents higher than that found at Tanco.

To date, the only mica with average Rb_2O contents higher than that found at Tanco is muscovite (4.5 weight % Rb_2O) also from Pegmatite #7, Separation Rapids (Figures 30 and 31) (*see also* Tindle, Selway and Breaks 2002 (MRD 111): Table 18b). The highest average Cs_2O contents in mica, to date, occurs in lepidolite (1.8 weight % Cs_2O) from Marko's pegmatite, Separation Rapids (Breaks and Tindle 2001). Several localities in Ontario have mica with Cs_2O contents higher than that at Tanco: siderophyllite-zinnwaldite from North Aubry metasomatized metavolcanic host rock, phlogopite-siderophyllite from McCombe selvage (exocontact), lepidolite from the MNW pegmatite, lepidolite from the lepidolite zone of McCombe pegmatite, lepidolite from Ghost West road beryl locality, lepidolite from Gullwing Lake. The presence of cesium-rich "biotite" in the metasomatized host rocks at North Aubry and McCombe indicates that cesium-rich pegmatitic fluids migrated out of the pegmatites and altered the composition of the host rocks.

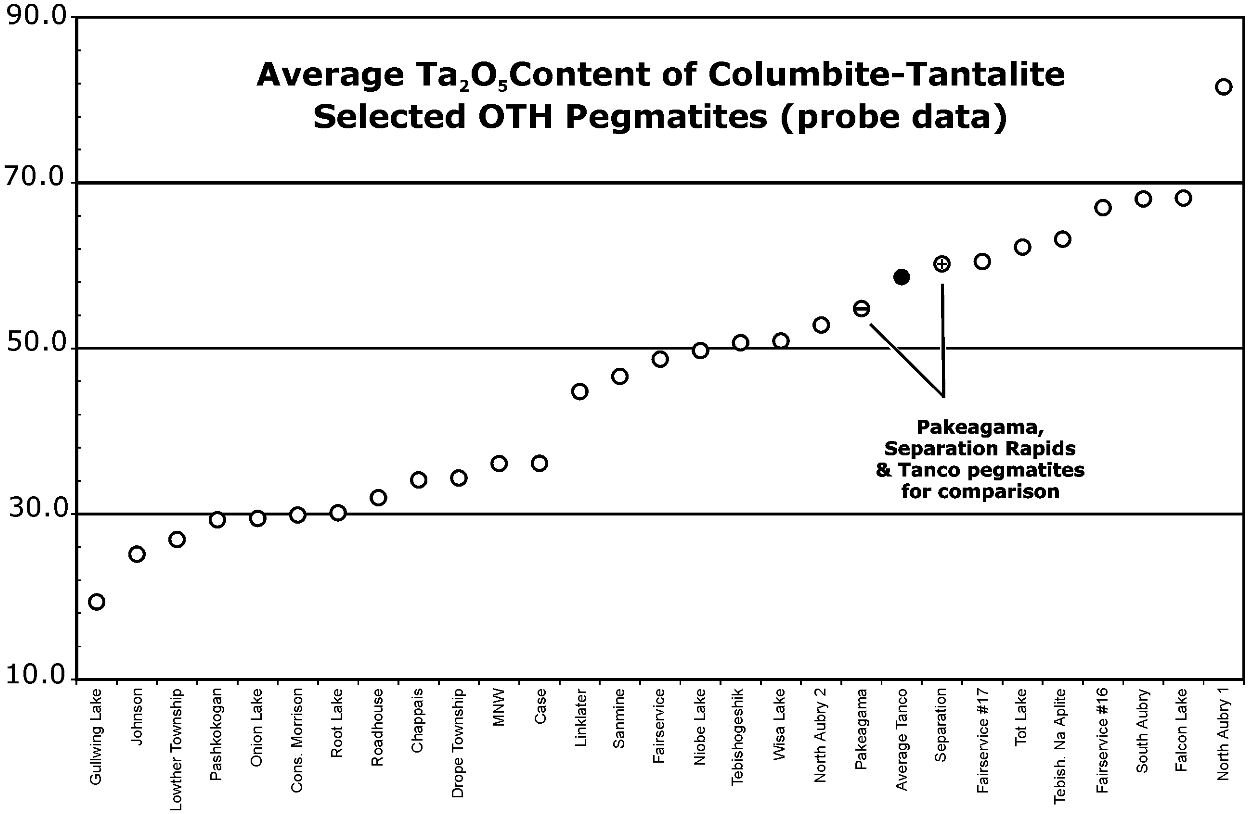


Figure 27. Average weight % Ta_2O_5 content in columbite-tantalite minerals from selected Ontario pegmatites (O). Localities with data taken from literature: ● : Tanco pegmatite, Manitoba; ⊖ : Pakeagama pegmatite, Ontario; ⊕ : Separation Rapids pegmatites (Černý, Ercit and Vanstone 1998; Breaks, Tindle and Smith 1999; Tindle and Breaks 2000; and unpublished data of authors).

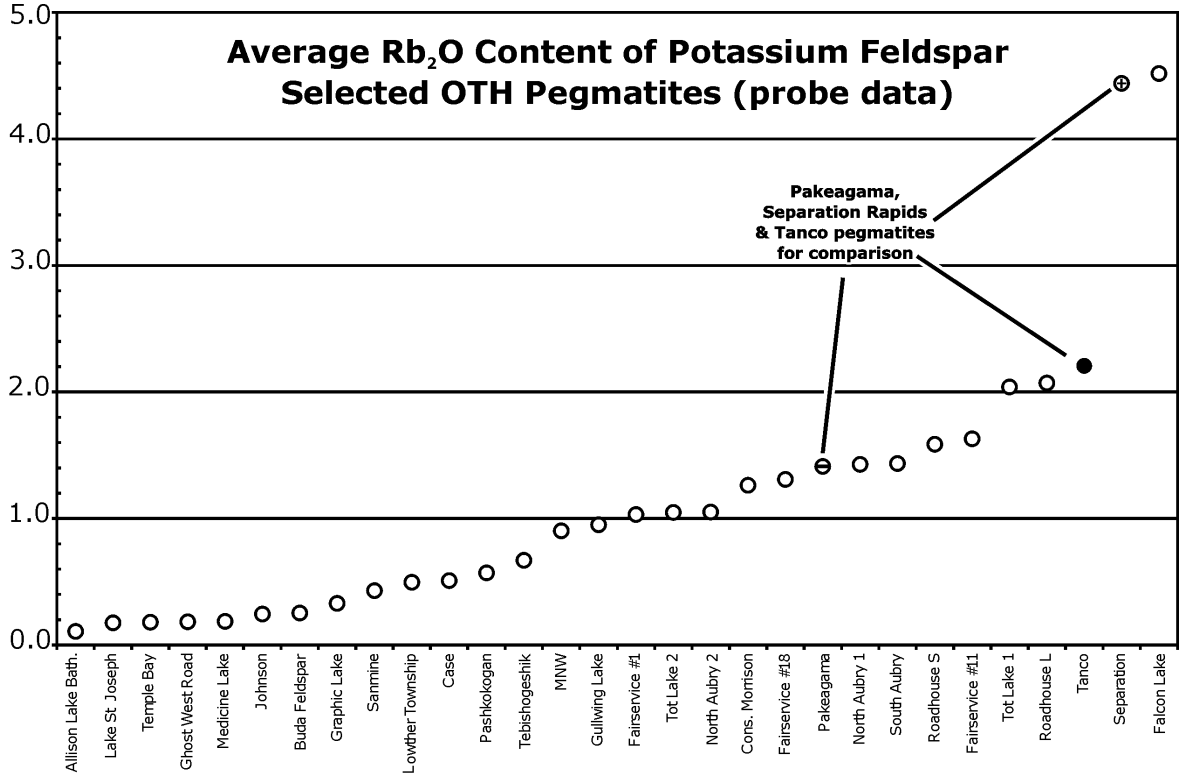


Figure 28. Average weight % Rb_2O content in potassium feldspar from selected Ontario pegmatites (O). Localities with data taken from literature: ● : Tanco pegmatite, Manitoba; ⊖ : Pakeagama pegmatite, Ontario; ⊕ : Separation Rapids pegmatites (Černý, Ercit and Vanstone 1998; Breaks, Tindle and Smith 1999; Tindle and Breaks 2000; and unpublished data of authors).

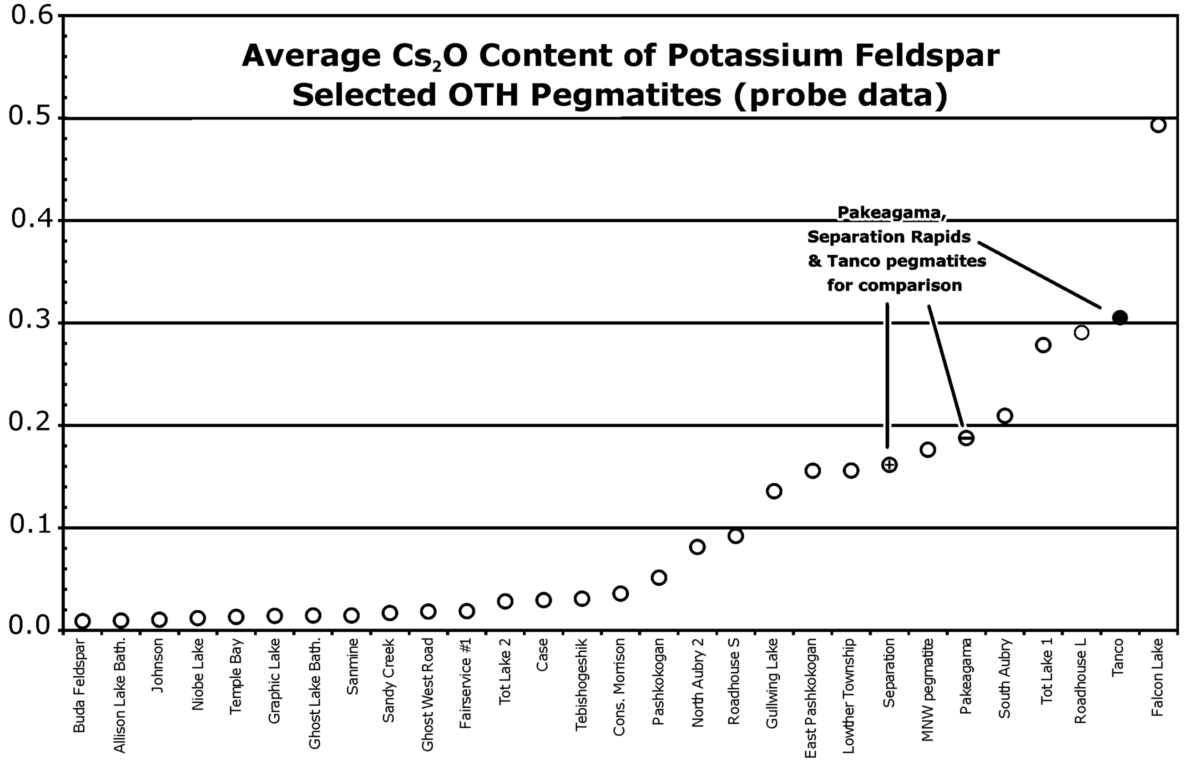


Figure 29. Average weight % Cs_2O content in potassium feldspar from selected Ontario pegmatites (O). Localities with data taken from literature: ● : Tanco pegmatite, Manitoba; ⊖ : Pakeagama pegmatite, Ontario; ⊕ : Separation Rapids pegmatites (Černý, Ercit and Vanstone 1998; Breaks, Tindle and Smith 1999; Tindle and Breaks 2000; and unpublished data of authors).

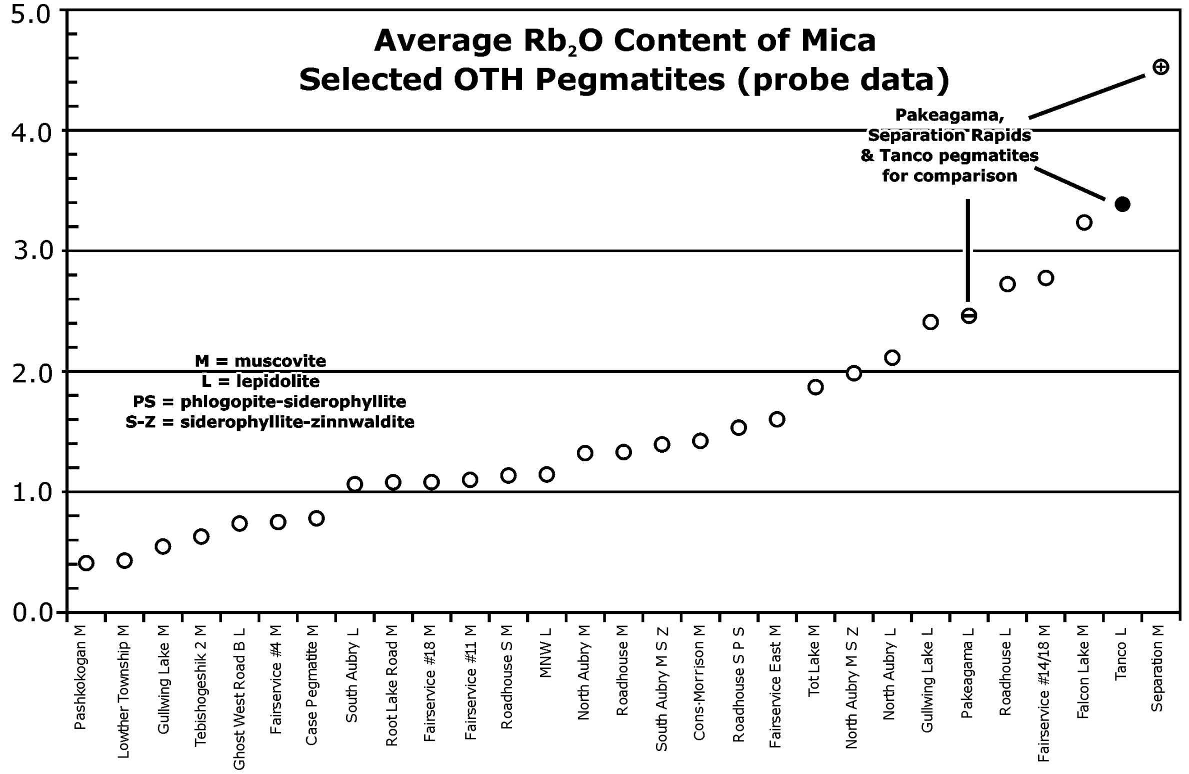


Figure 30. Average weight % Rb_2O content in mica from selected Ontario pegmatites (O). Localities with data taken from literature: ● : Tanco pegmatite, Manitoba; ⊖ : Pakeagama pegmatite, Ontario; ⊕ : Separation Rapids pegmatites (Černý, Ercit and Vanstone 1998; Breaks, Tindle and Smith 1999; Tindle and Breaks 2000; and unpublished data of authors).

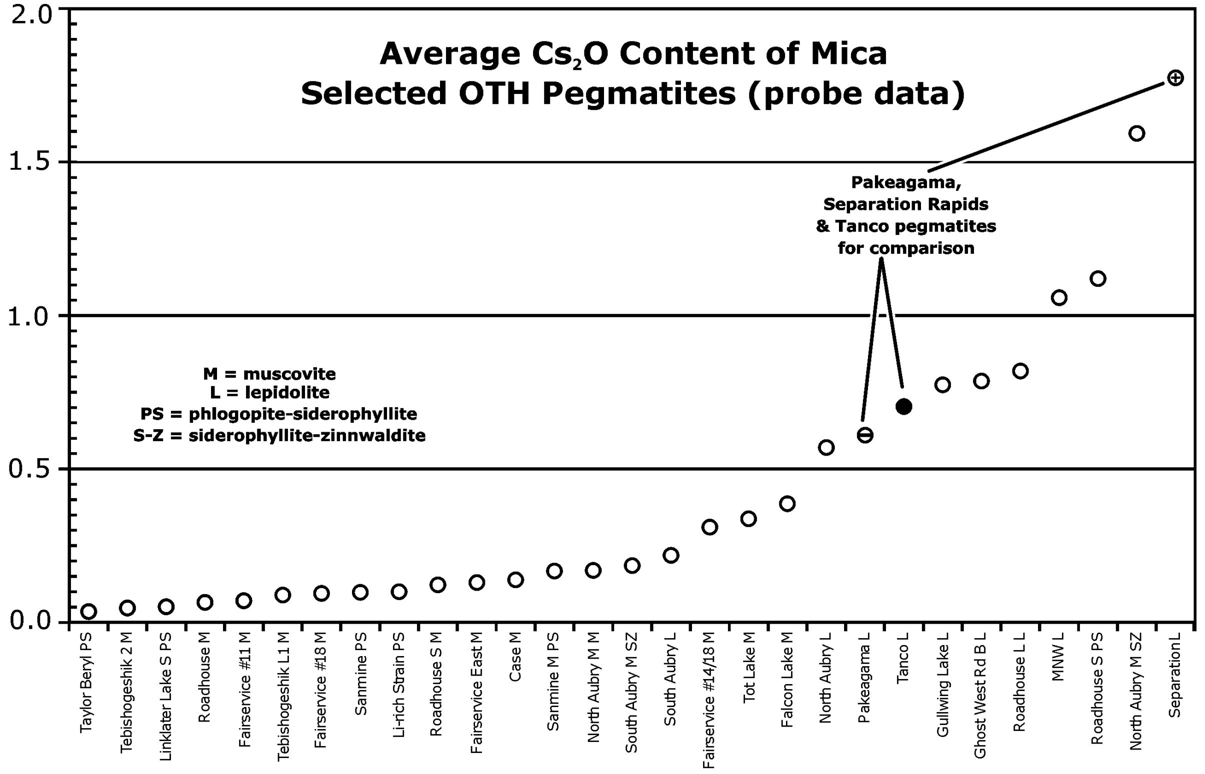


Figure 31. Average weight % Cs_2O content in mica from selected Ontario pegmatites (O). Localities with data taken from literature: ● : Tanco pegmatite, Manitoba; ⊖ : Pakeagama pegmatite, Ontario; ⊕ : Separation Rapids pegmatites (Černý, Ercit and Vanstone 1998; Breaks, Tindle and Smith 1999; Tindle and Breaks 2000; and unpublished data of authors).

RECOMMENDATIONS FOR EXPLORATION

Follow-up exploration is highly recommended in the following specific areas and more focussed targets:

- **Allison Lake batholith**; a 15 by 50 km area within the Confederation Lake metavolcanic-metasedimentary belt from Bumpy Lake south and southeast to Curie Lake. This batholith has a well-defined genetic connection with internal and exocontact rare-element mineralization in the Jubilee Lake area (SJ pegmatite). The Root Lake pegmatite group may possibly be related to the highly fractionated southeastern tail of the Allison Lake batholith. This pegmatite group contains highly evolved, complex-type, spodumene-subtype pegmatites and is an excellent area for follow-up exploration. The highest bulk tantalum content of all the newly discovered pegmatite dikes examined in this survey was detected in this pegmatite group (104 ppm).
- **Wenasaga batholith**: 5 by 10 km area of clastic metasedimentary rocks adjacent to the southwestern part of batholith in the vicinity of the Sandy Creek beryl-type pegmatite. This batholith is the probable parent granite to an unusual beryl-type, phosphate-subtype pegmatite that has significantly evolved Nb/Ta ratios and local concentrations of lithium that are unusual for beryl-type pegmatites.
- **Twinname Lake stock and area around East Pashkokogan Lake spodumene pegmatite**: The newly recognized Twinname Lake stock is a fertile peraluminous granite that is currently the most easterly known in the Uchi–English River subprovince boundary zone. The pluton is the likely parental source of a profusion of peraluminous pegmatitic granite dikes in the general area outlined by Kay and Stott (1985). New niobium-tantalum-bearing pegmatite dikes were discovered by the present survey near the East Pashkokogan Lake spodumene pegmatite occurrence.
- **Sioux Lookout domain**: exploration is warranted in this 5 to 20 by 160 km area for metasedimentary-hosted, tantalum-niobium-bearing pegmatites. Areas of particular focus include those around the Hughes Creek, Laval Lake, and Zealand stocks and the Eagle Lake area in the vicinity of the Temple Township Nb-Ta pegmatite, southwest to Warclub Lake, and adjacent to Zealand stock.
- In the metavolcanic belts within the Sioux Lookout domain, the immediate area around the Medicine Lake stock could harbour modestly to highly fractionated rare-element pegmatite swarms. The remainder of the Tustin–Bridges metavolcanic belt is also suggested for exploration for presently unrecognized fertile granites and chemically evolved pegmatite dikes.
- The Graphic Lake area, with a mixed metavolcanic-metasedimentary setting for rare-element mineralization, is recommmended for exploration as a large boron-enriched metasomatic system is quite possibly genetically connected to a swarm of peraluminous, pegmatitic granite dikes that have at least evolved into beryl-type.
- **Quetico Subprovince:** the entire subprovince is now recommended for exploration of clastic metasedimentary-hosted, rare-element pegmatite mineralization. In this subprovince, the distribution of rare-element pegmatites as linear arrays guided by subprovince boundary zones as documented elsewhere in northwestern Ontario by Breaks and Osmani (1989) is not valid. Most rare-element pegmatites occur within the central parts of the Quetico Subprovince as currently defined in the Georgia Lake, Lac La Croix and Hearst areas. Nevertheless, this study has newly documented that the northern and southern subprovince boundary zones, at least in vicinity of the Armstrong highway and in the Atikokan area, also harbour fertile granites and rare-element mineralization as discovered by this survey.

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Appendix 1

Plots of Mineral Compositions

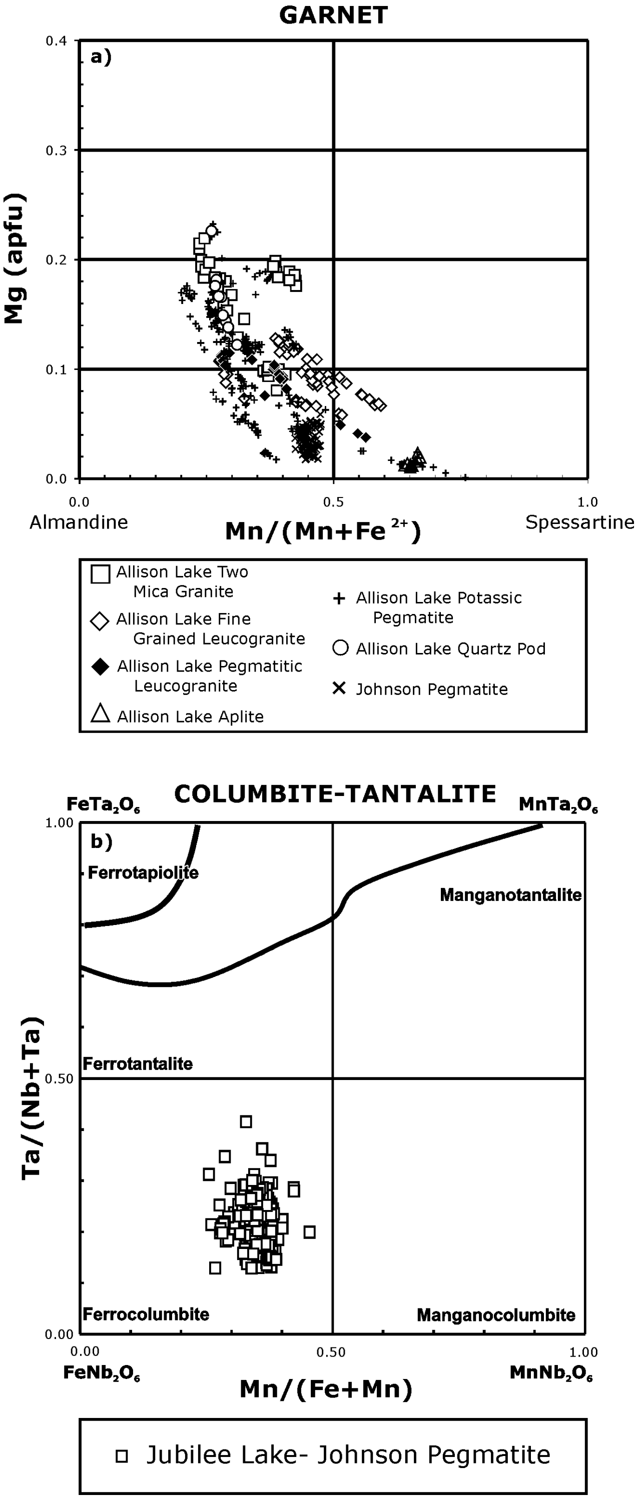


Figure 32. a) Mg (*apfu*) versus Mn/(Mn+Fe) for garnets (almandine and spessartine) from Allison Lake batholith. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for ferrocolumbite from Johnson pegmatite.

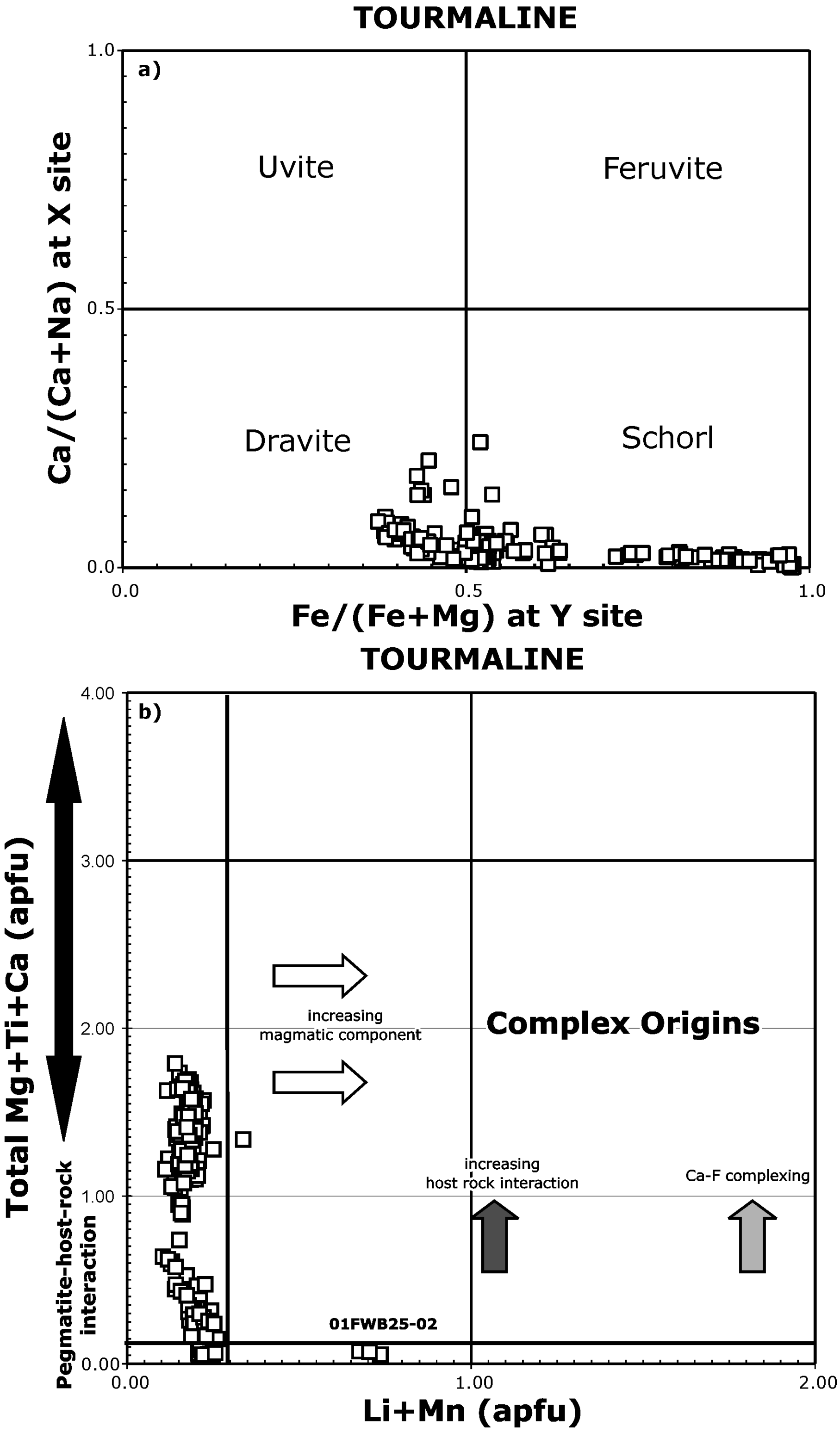


Figure 33. Allison Lake metasedimentary exocontact tourmaline (dravite and schorl). a) Ca/(Ca+Na) at X-site versus Fe/(Fe+Mg) at the Y-site, b) (total Mg+Ti+Ca) versus Li+Mn.

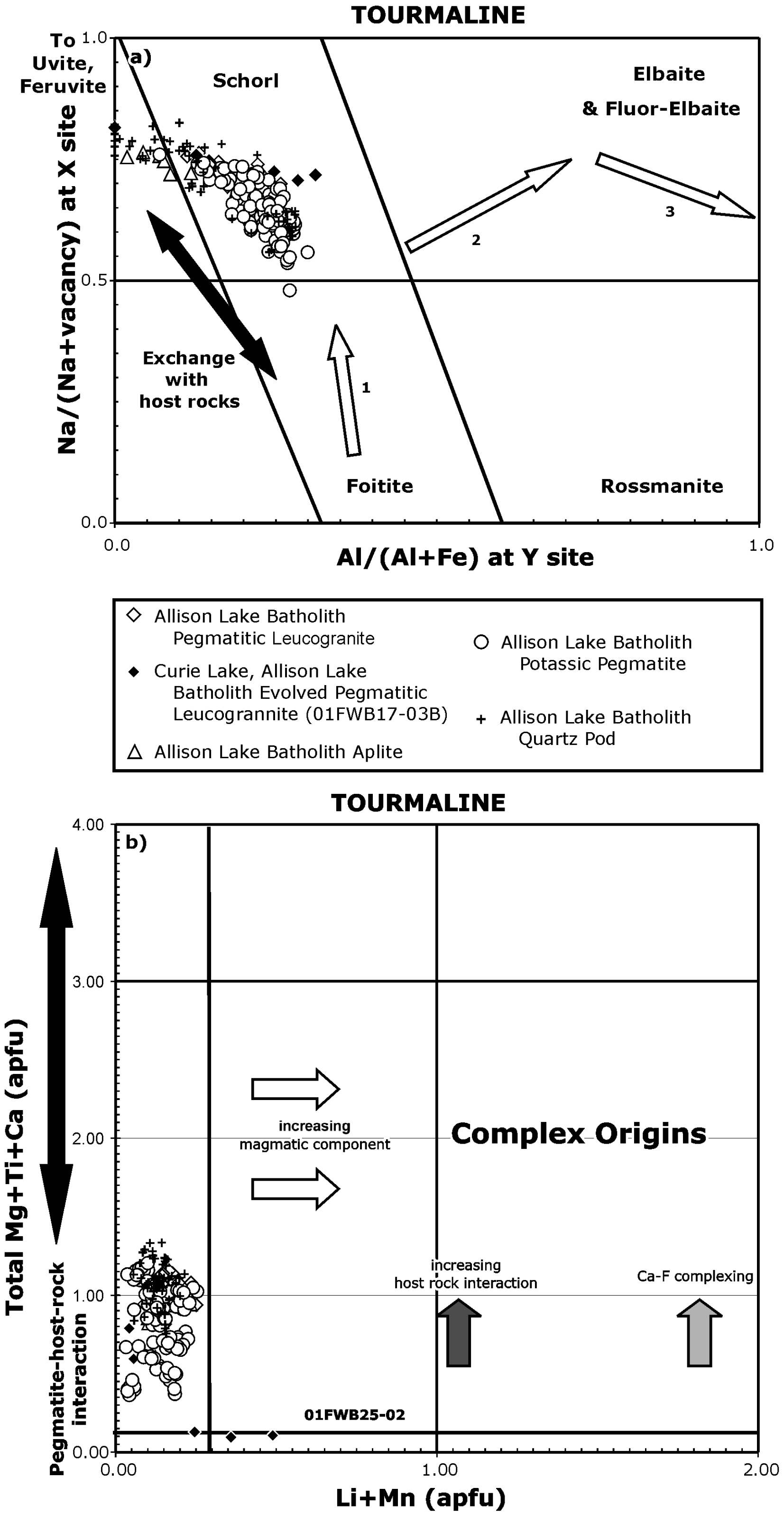


Figure 34. Allison Lake batholith tourmaline (mostly schorl). a) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, b) (total Mg+Ti+Ca) versus Li+Mn.

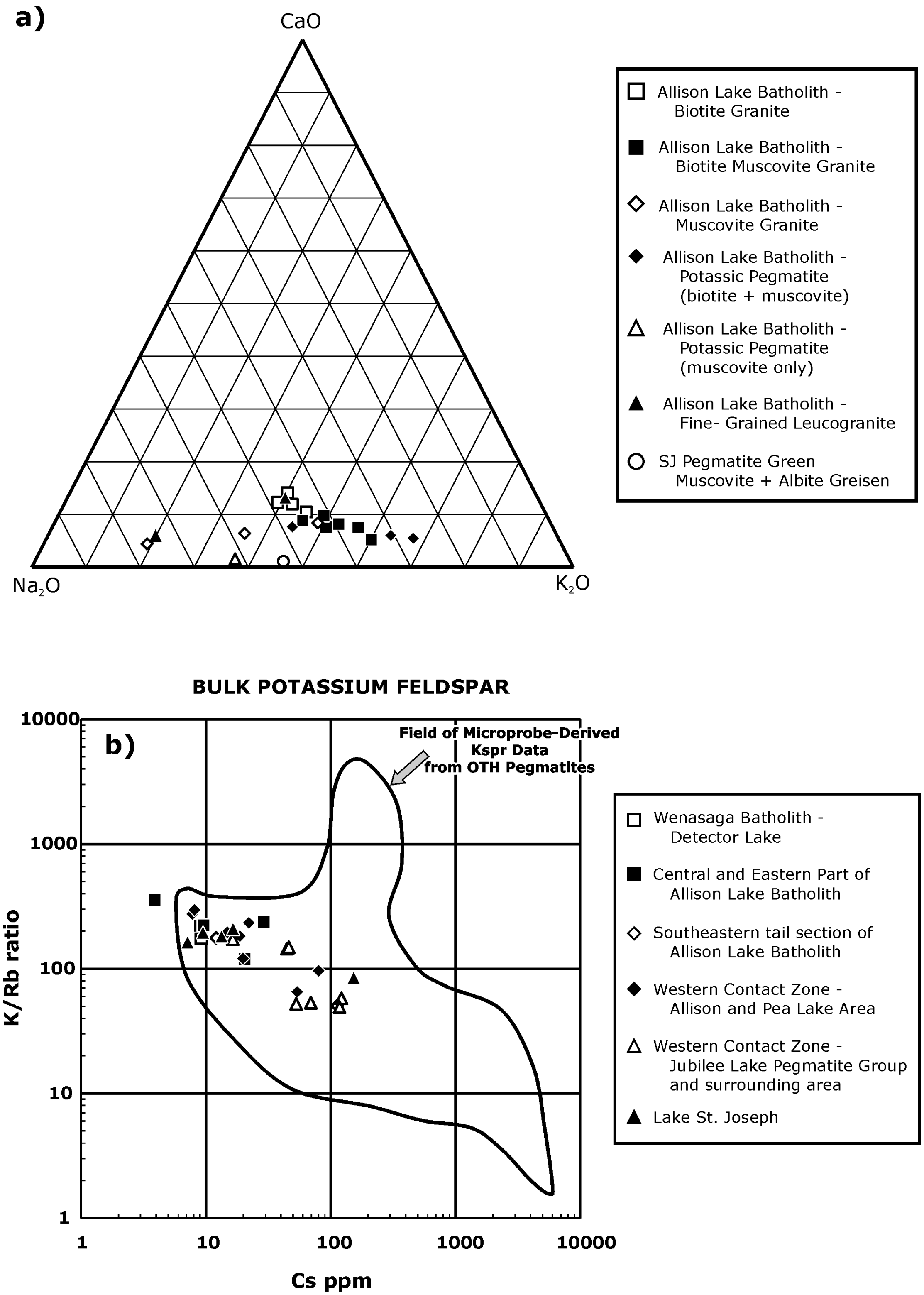


Figure 35. a) CaO–Na_2O–K_2O diagram for whole rock data from Allison Lake batholith indicating that the batholith is sodium- and potassium-rich and calcium-poor. b) K/Rb ratio versus Cs (ppm) for bulk potassium feldspar from Allison Lake batholith indicating that the central and eastern part of the batholith is more primitive than the western and tail section of the batholith.

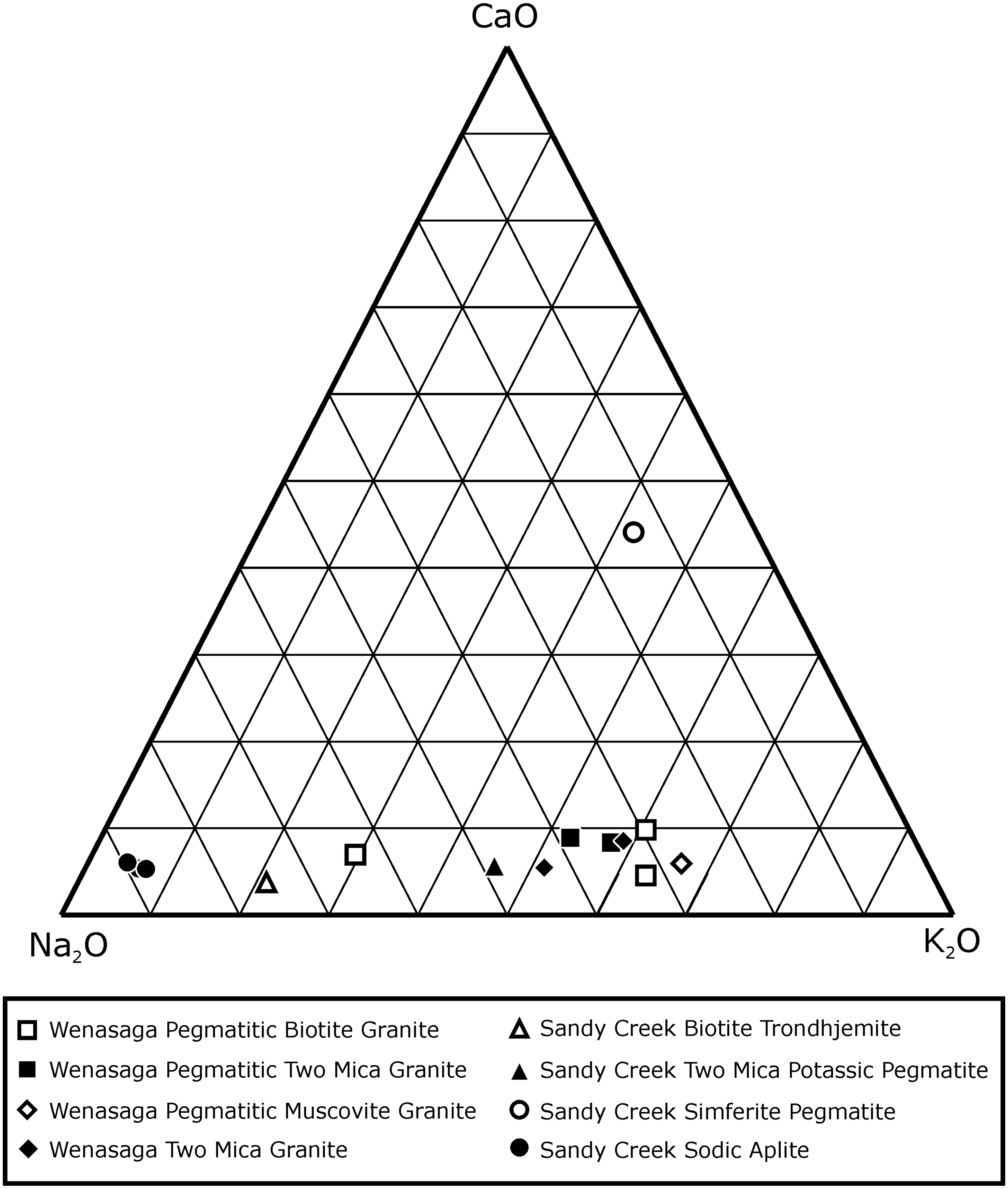


Figure 36. $CaO–Na_2O–K_2O$ diagram for whole rock data from Wenasaga batholith and Sandy Creek pegmatite.

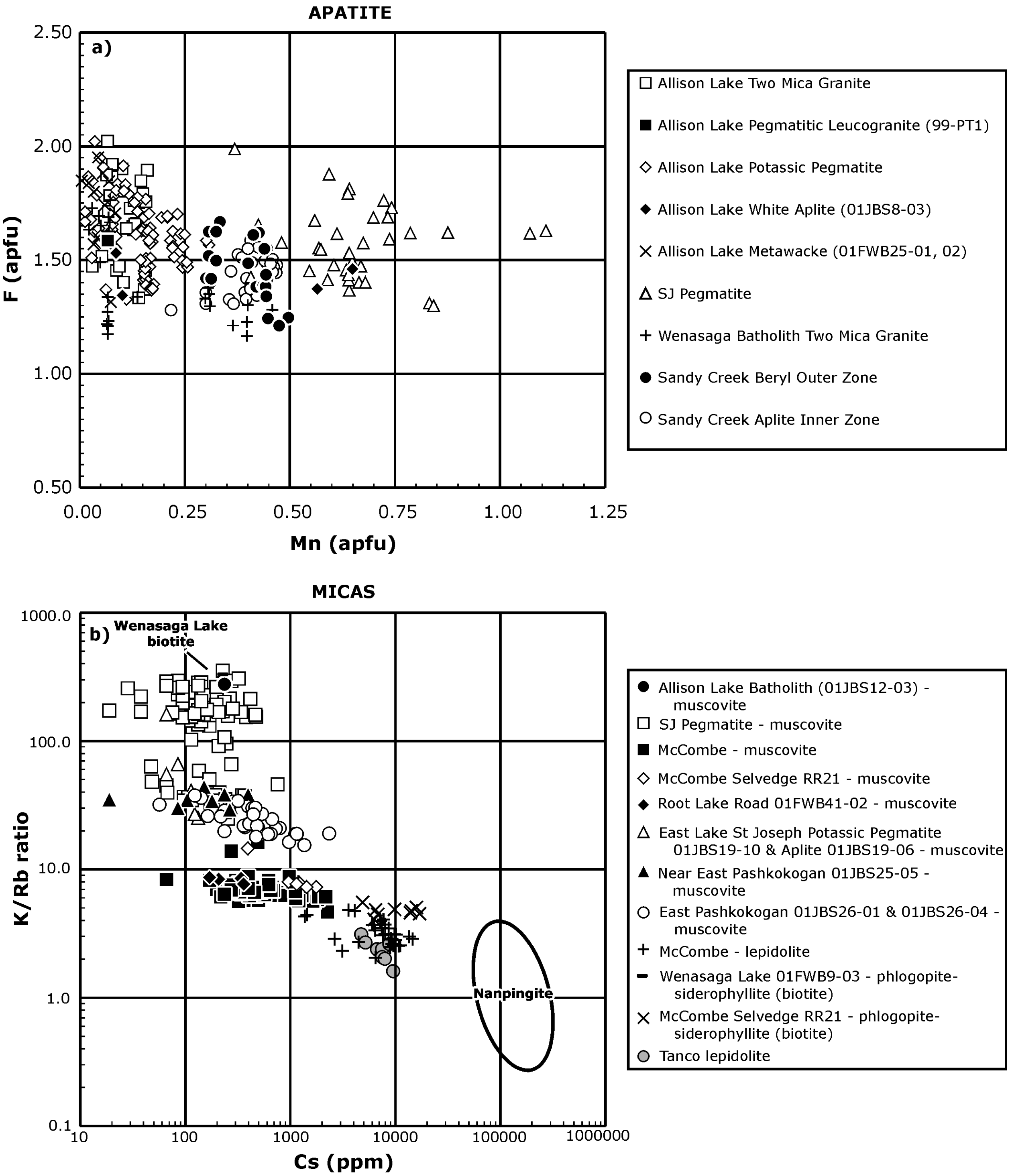


Figure 37. a) F versus Mn (*apfu*) for fluorapatite compositions from Allison Lake batholith, SJ pegmatite, Wenasaga batholith and Sandy Creek pegmatite. The fluorapatite from the SJ pegmatite is the most evolved, as it contains the most Mn.
b) K/Rb ratio versus Cs (ppm) for microprobed mica (muscovite, lepidolite and phlogopite-siderophyllite) from several localities in the Uchi–English River subprovince boundary zone. Lepidolite and phlogopite-sideropyllite from McCombe pegmatites are the most evolved as they have high Cs contents and low K/Rb ratios.

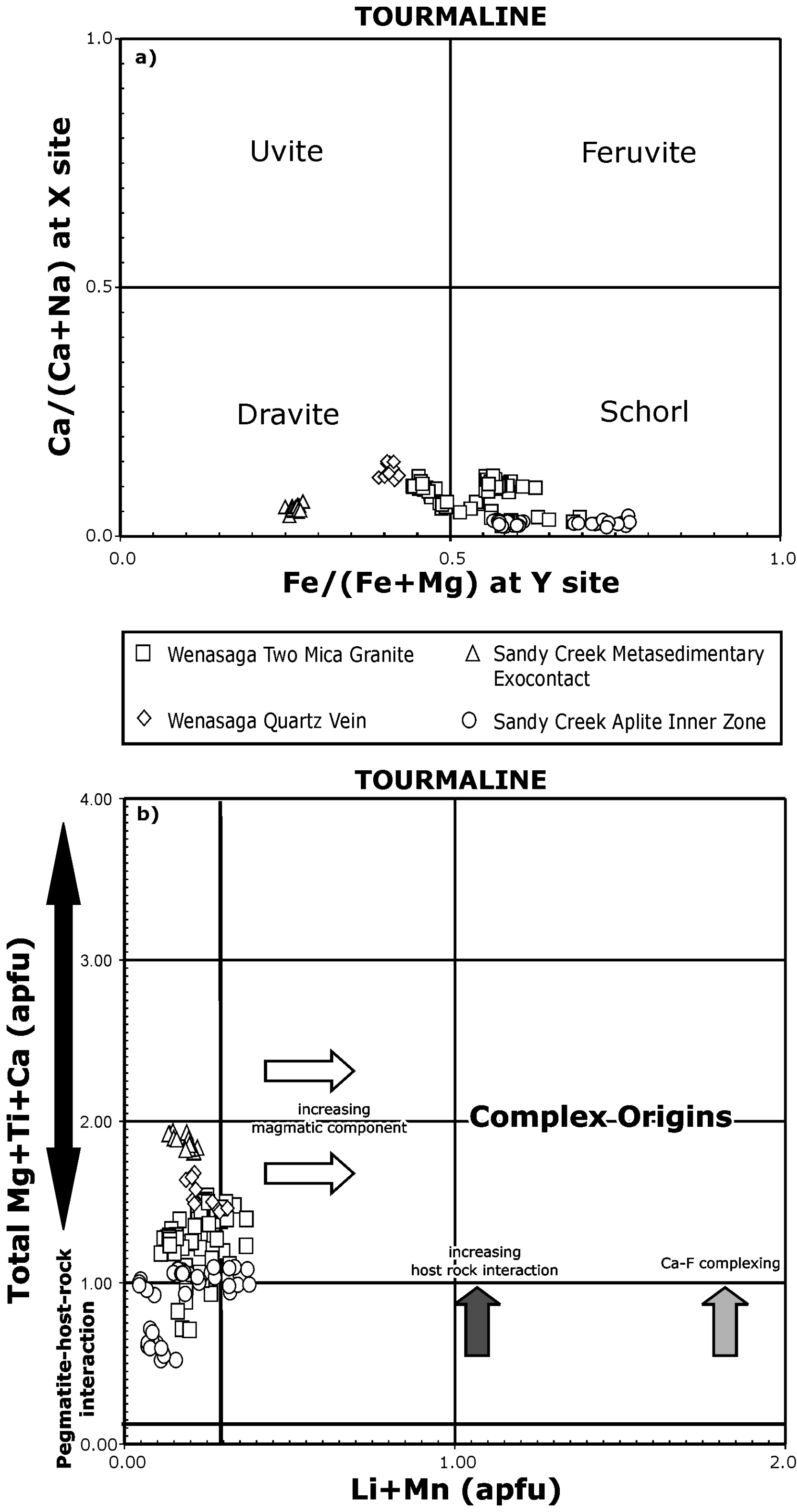


Figure 38. Tourmaline (dravite and schorl) from Wenasaga batholith and Sandy Creek pegmatite. a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

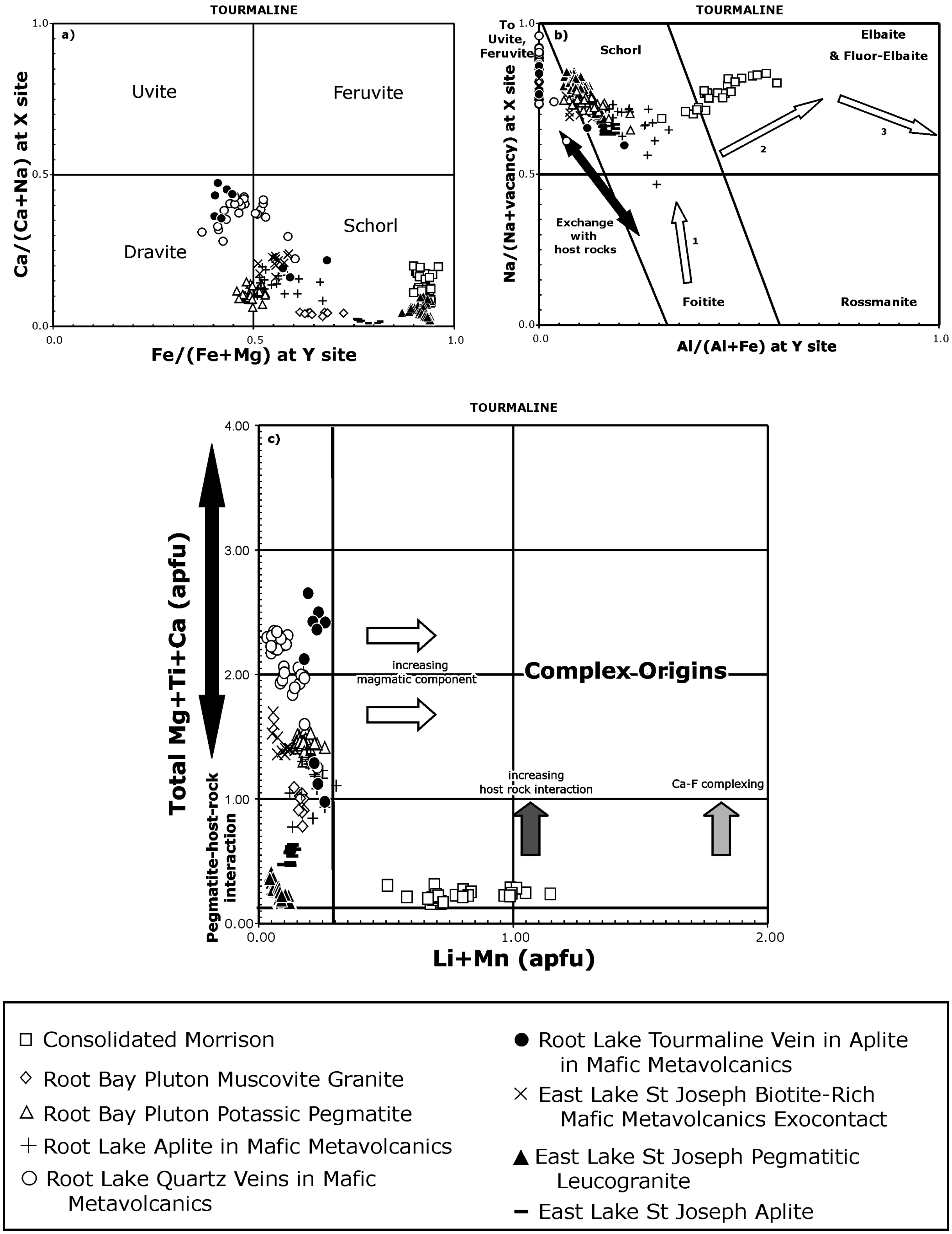


Figure 39. Tourmaline compositions from Root Lake area and East Lake St. Joseph: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, c) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

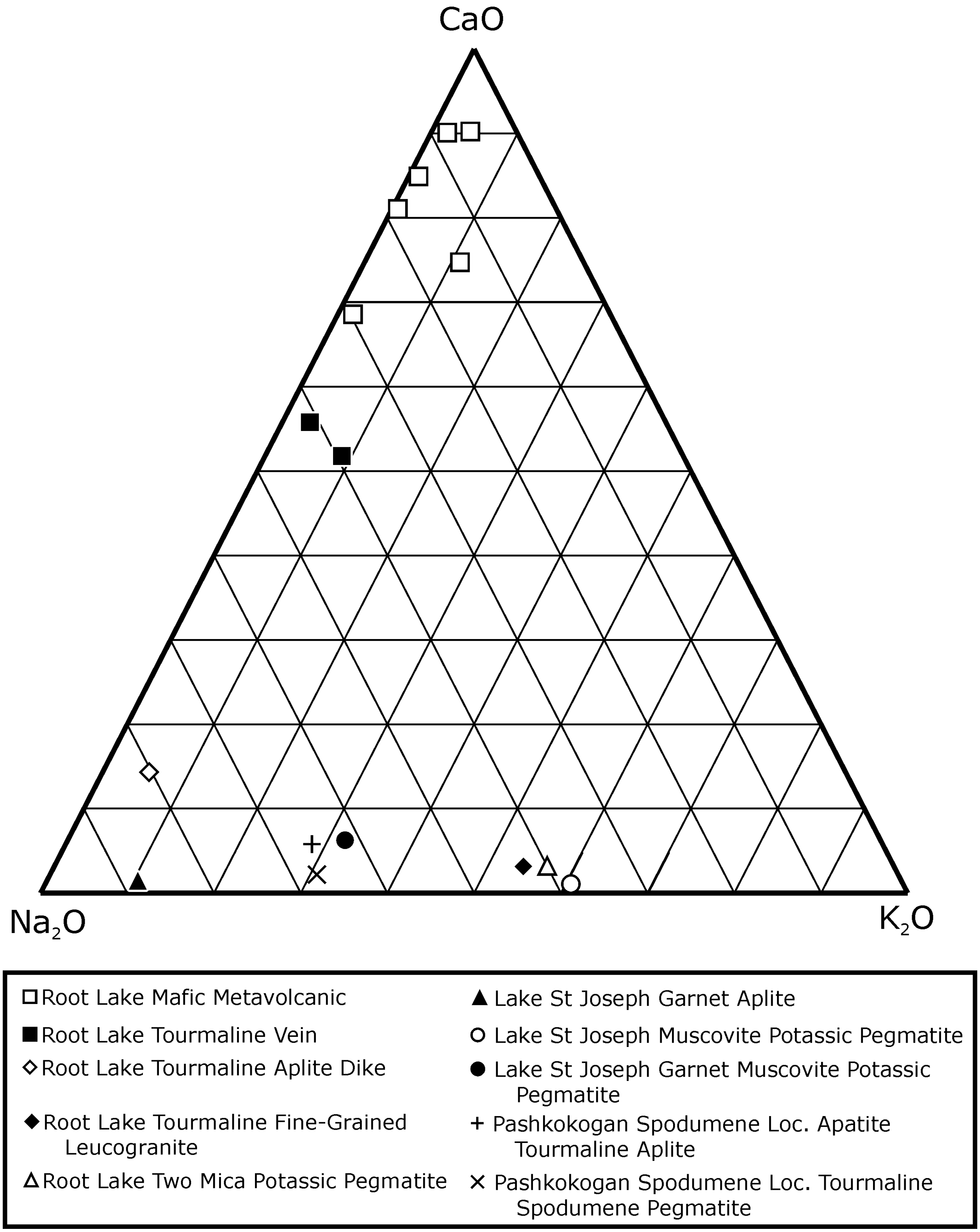


Figure 40. $CaO–Na_2O–K_2O$ diagram for whole rock data from Root Lake area, Lake St. Joseph and Pashkokogan spodumene pegmatite.

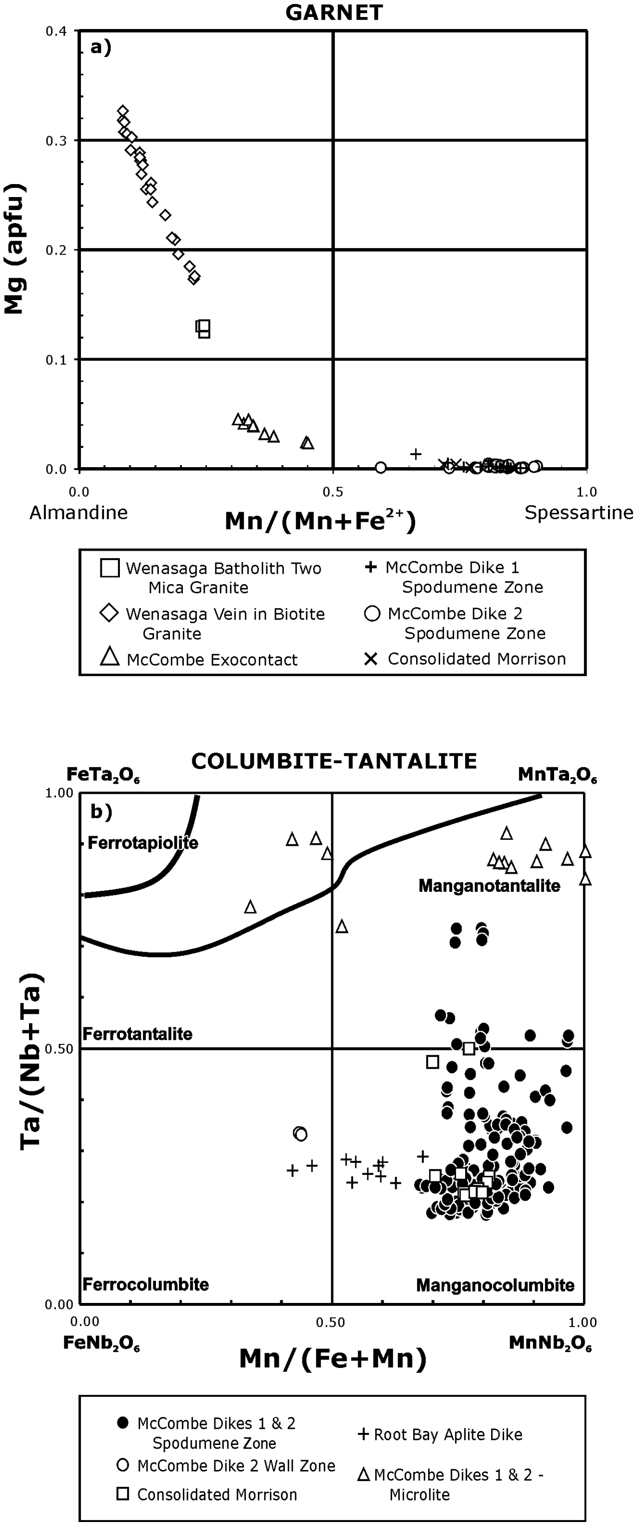


Figure 41. a) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet (almandine and spessartine) from the Wenasaga batholith, McCombe pegmatite dikes and the Consolidated Morrison pegmatite. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly manganocolumbite) from Root Bay, McCombe pegmatite dikes and Consolidated Morrison.

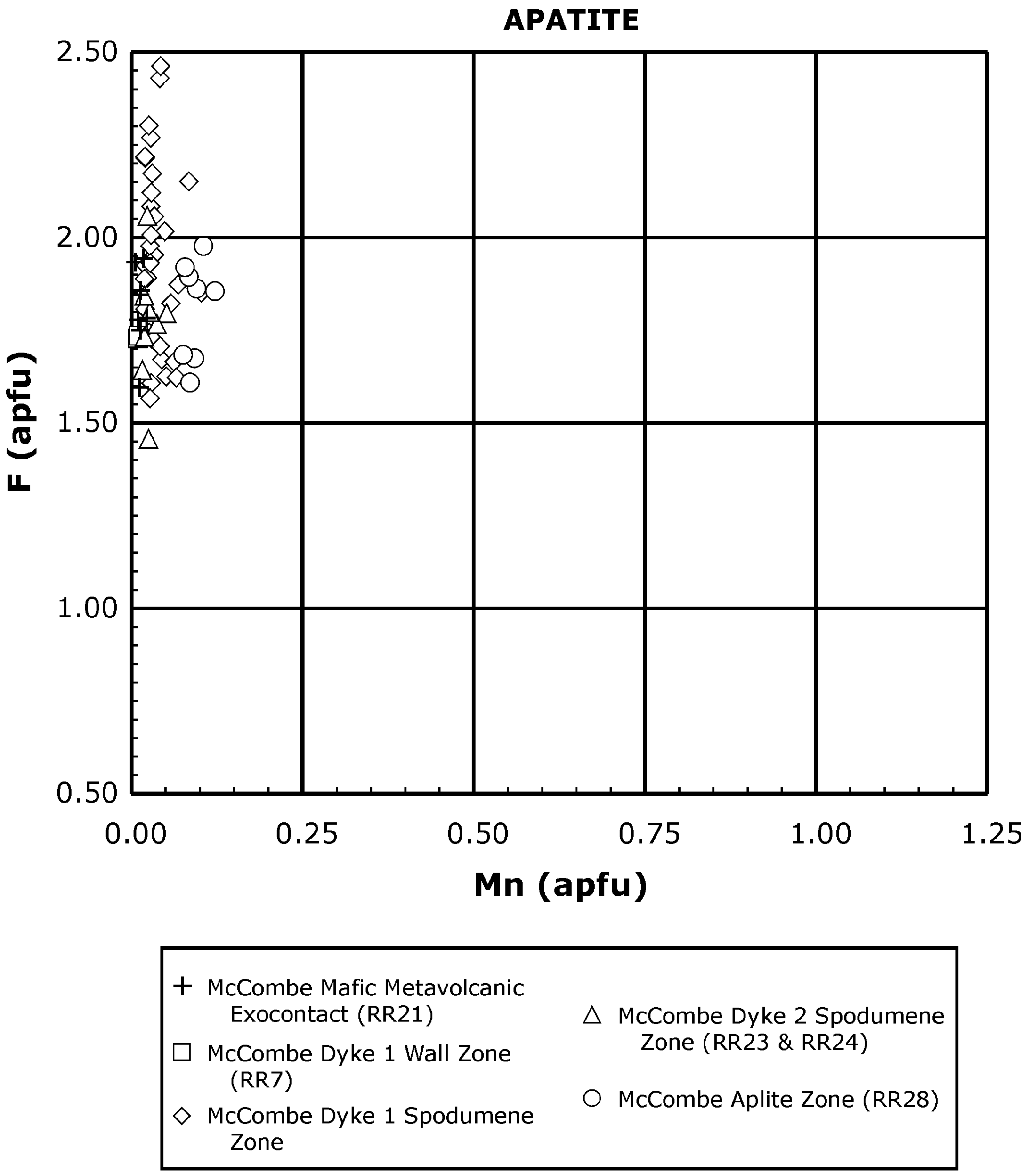


Figure 42. F versus Mn (*apfu*) for fluorapatite from McCombe pegmatite dikes.

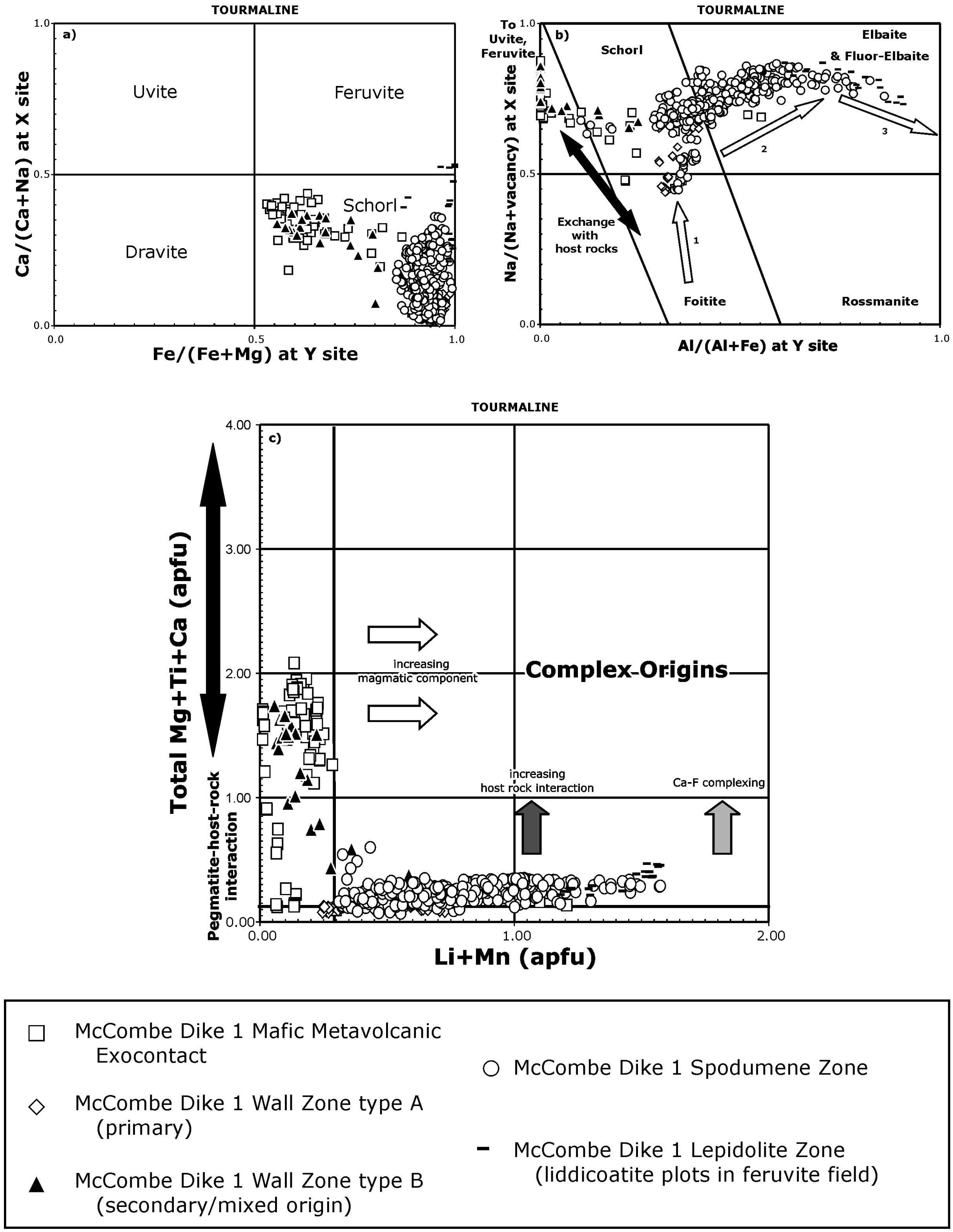


Figure 43. Tourmaline compositions from McCombe pegmatite Dike 1: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, c) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

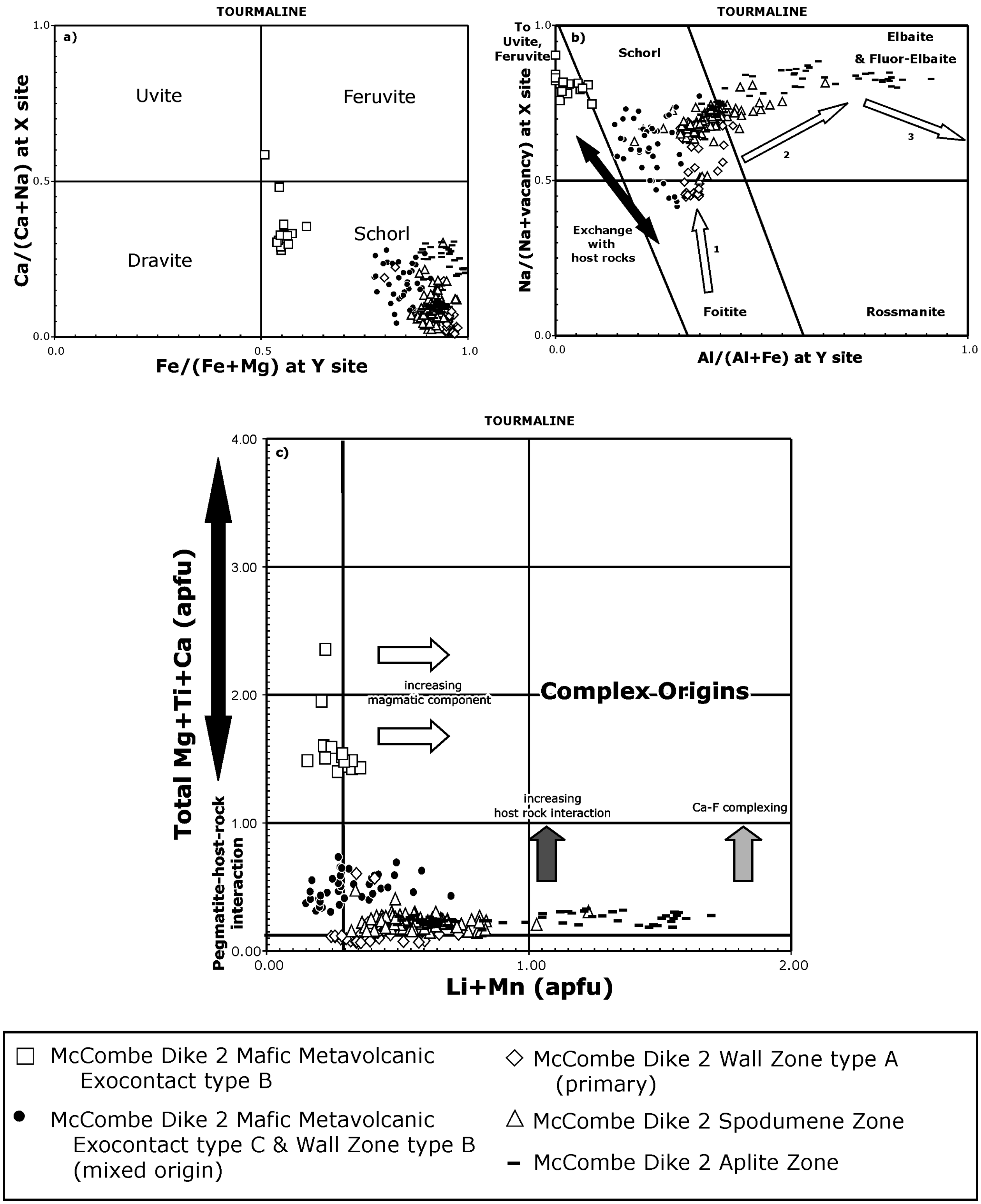
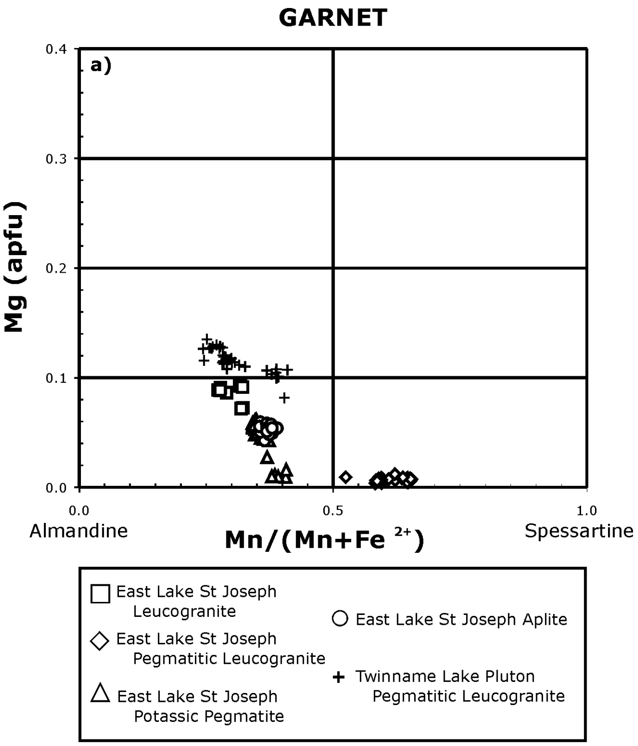


Figure 44. Tourmaline compositions from McCombe pegmatite Dike 2: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, c) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).



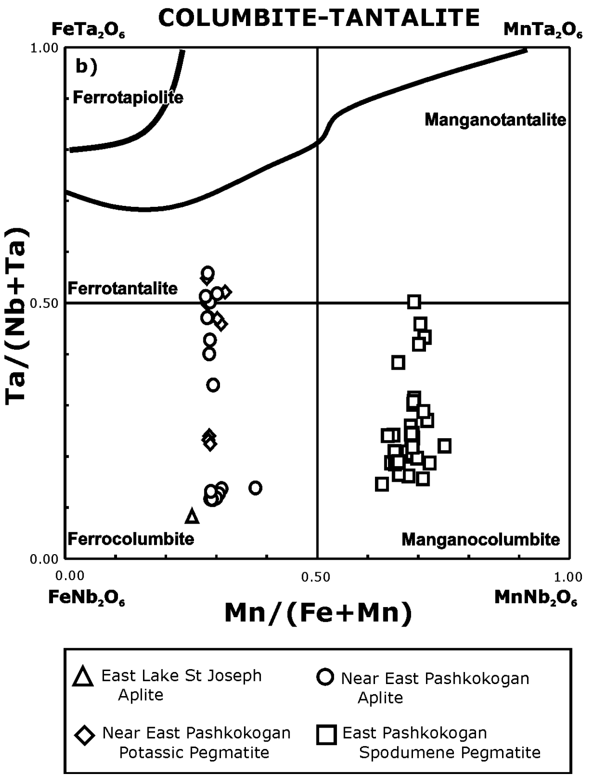


Figure 45. a) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet from East Lake St. Joseph area. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite and manganocolumbite) for East Lake St. Joseph area.

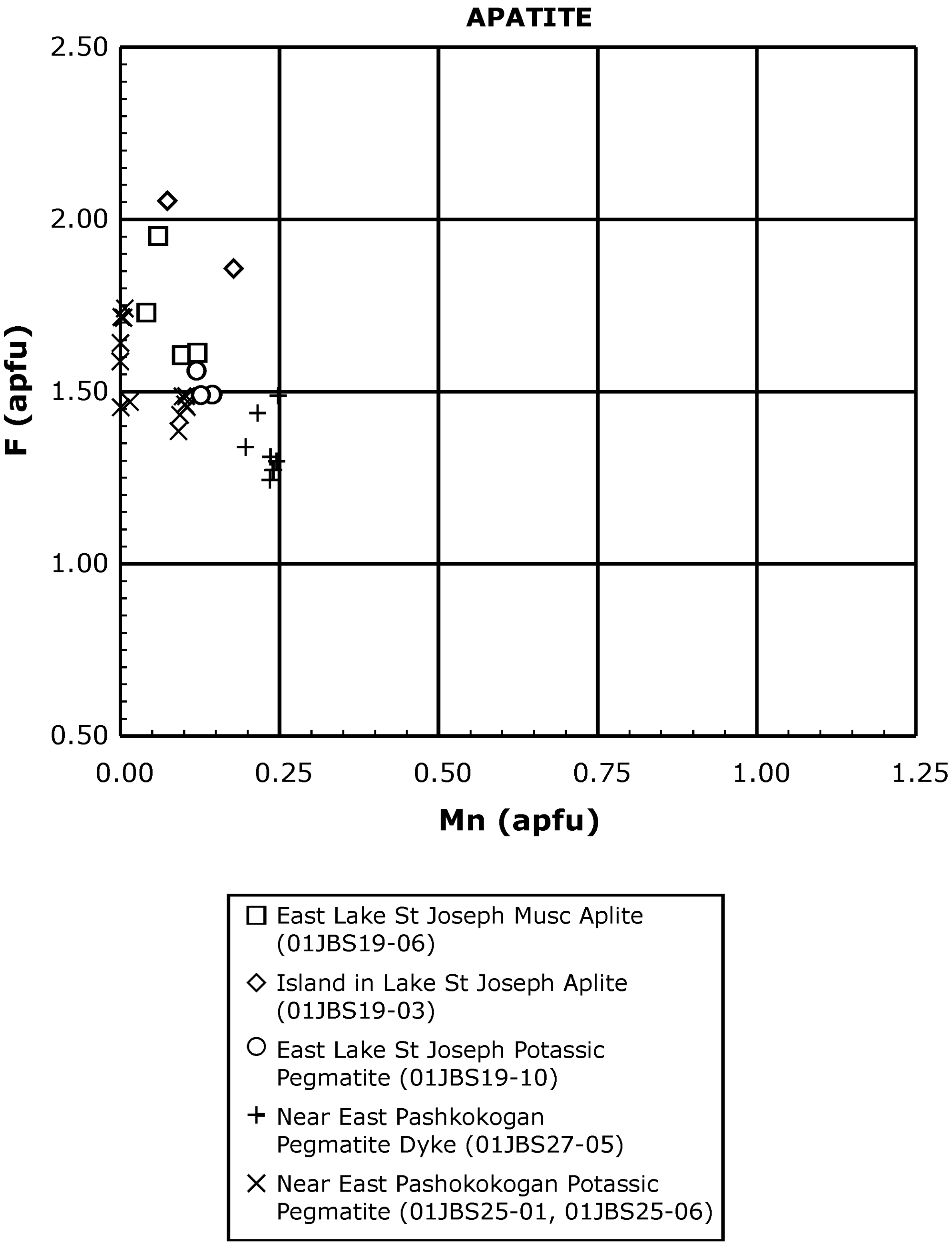


Figure 46. F versus Mn (*apfu*) for fluorapatite from East Lake St. Joseph area.

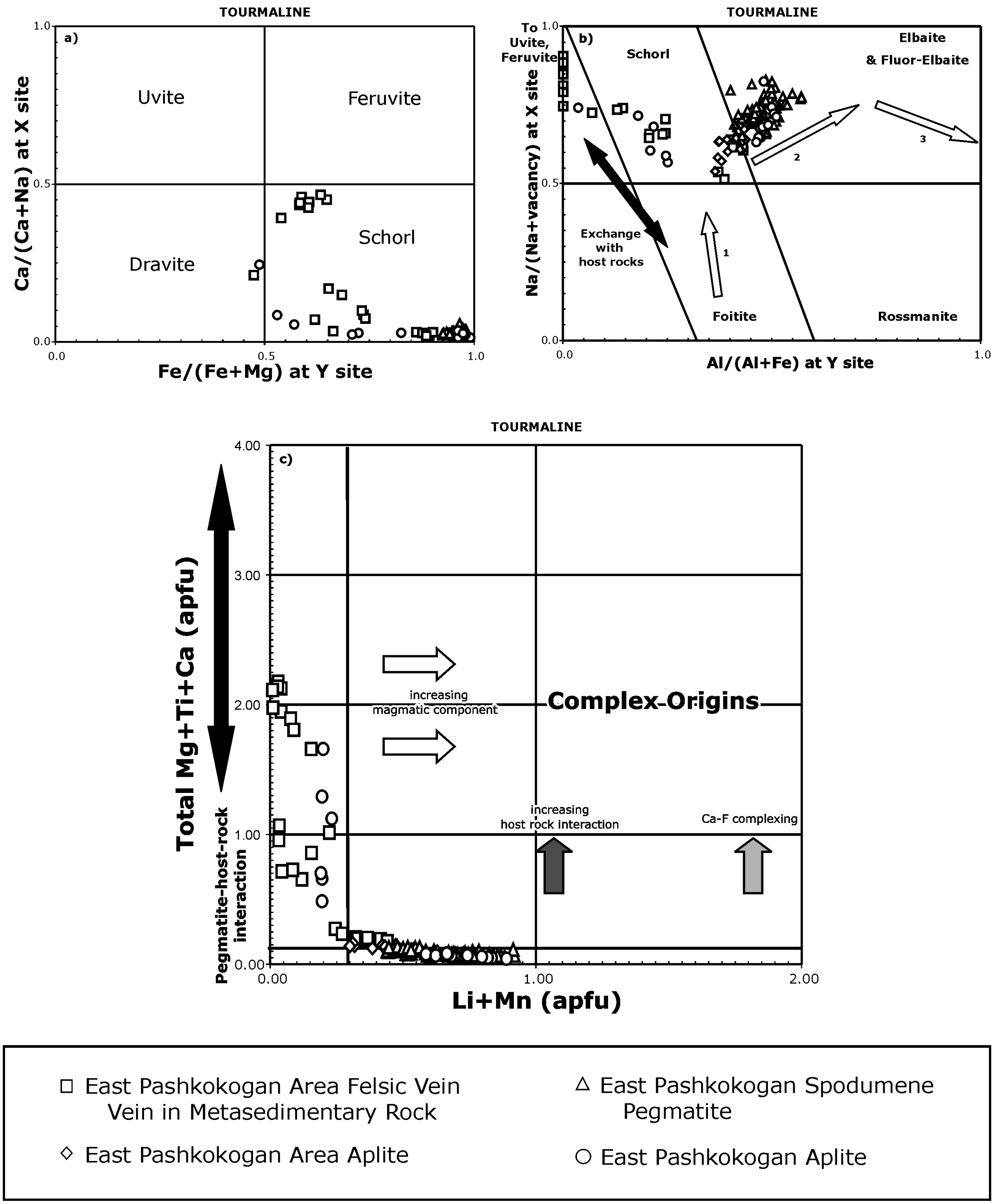


Figure 47. Tourmaline from East Lake St. Joseph area: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, c) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

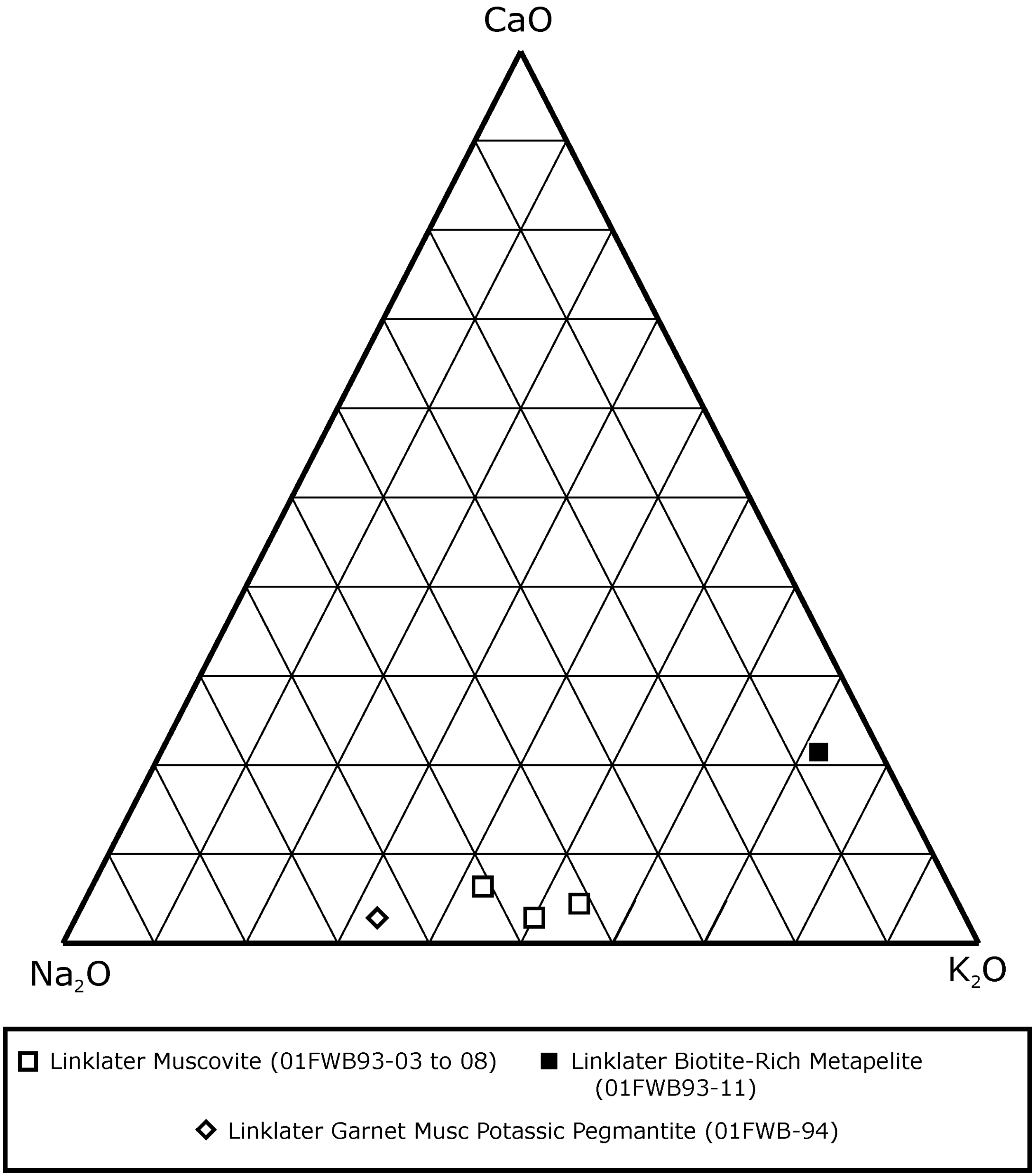


Figure 48. CaO–Na_2O–K_2O diagram for whole rock data from Linklater pegmatites.

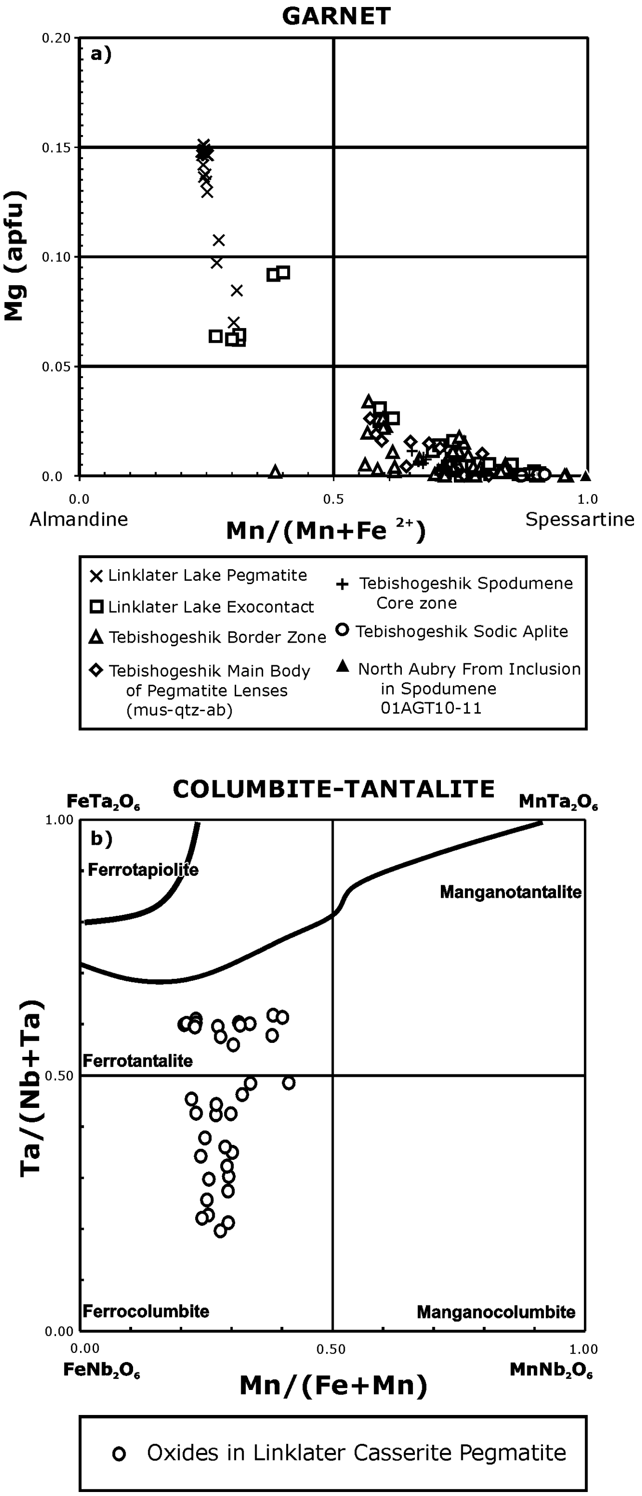


Figure 49. a) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet compositions (almandine and spessartine) from Linklater, Tebishogeshik and North Aubry pegmatites. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (ferrocolumbite and ferrotantalite) from Linklater cassiterite pegmatite.

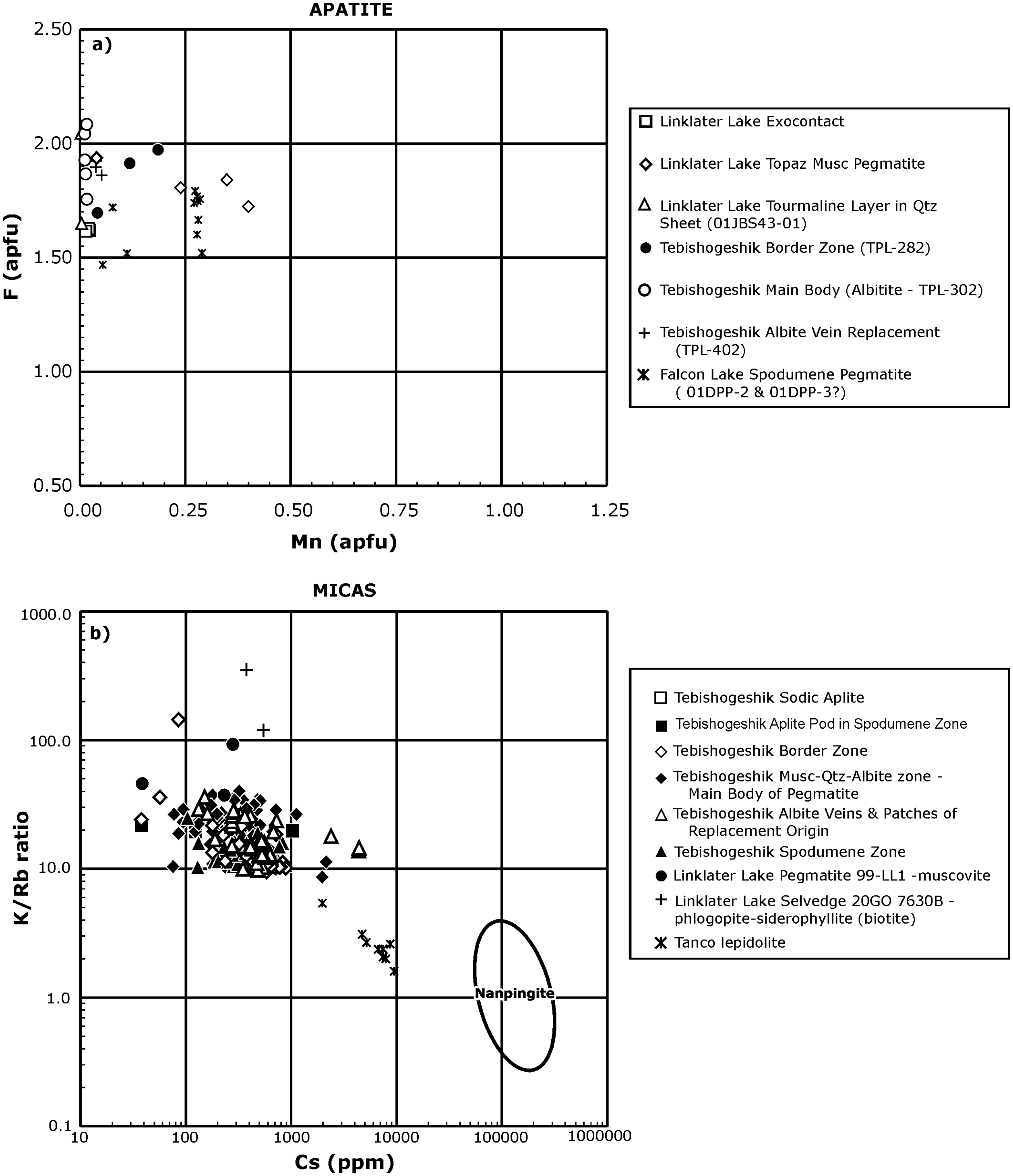


Figure 50. a) F versus Mn (*apfu*) for fluorapatite from Linklater, Tebishogeshik and Falcon Lake pegmatites. b) K/Rb ratio versus Cs (ppm) for microprobed mica (muscovite, lepidolite and phlogopite-siderophyllite) from Tebishogeshik and Linklater pegmatites.

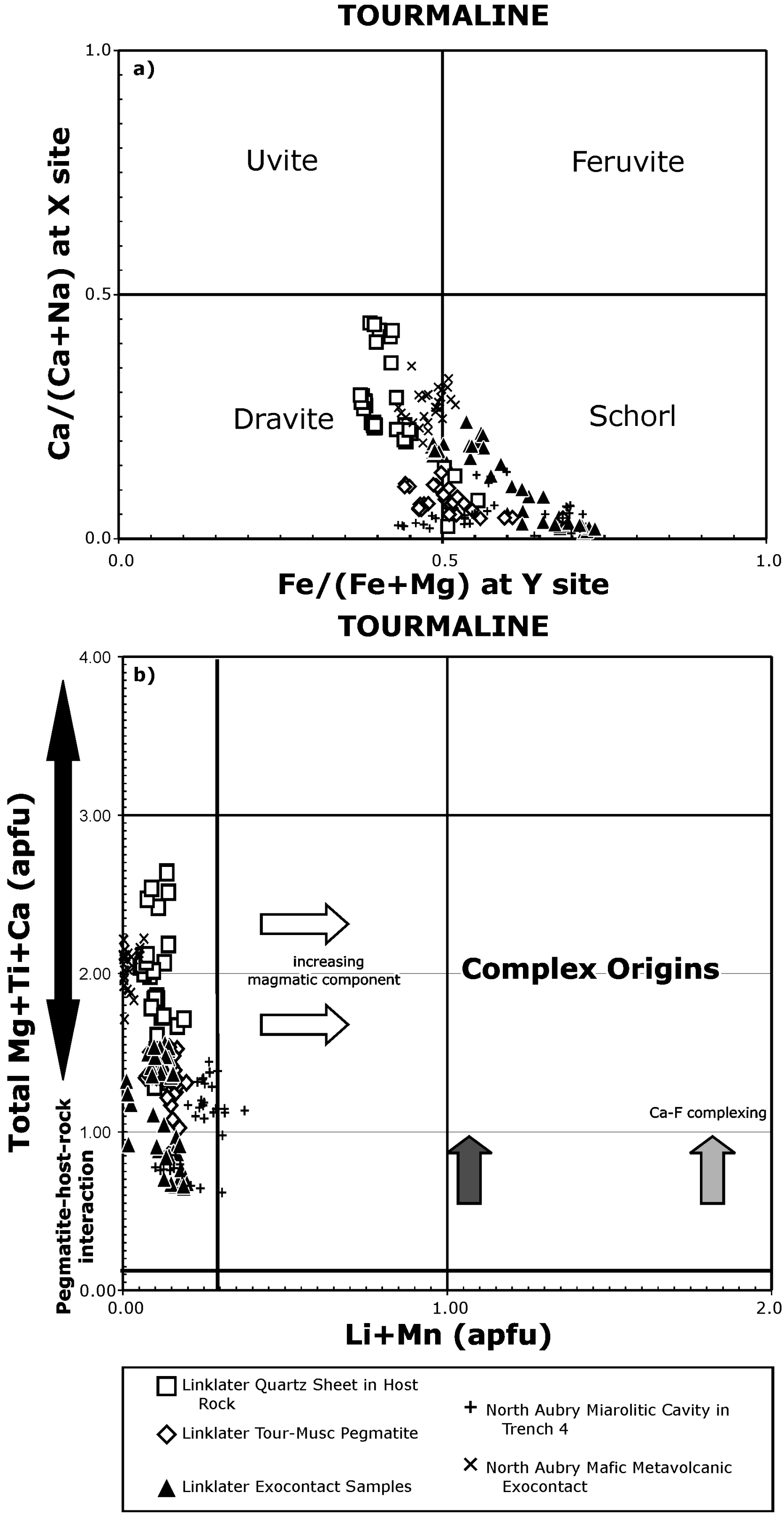


Figure 51. Tourmaline compositions from Linklater and North Aubry pegmatites: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site and b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

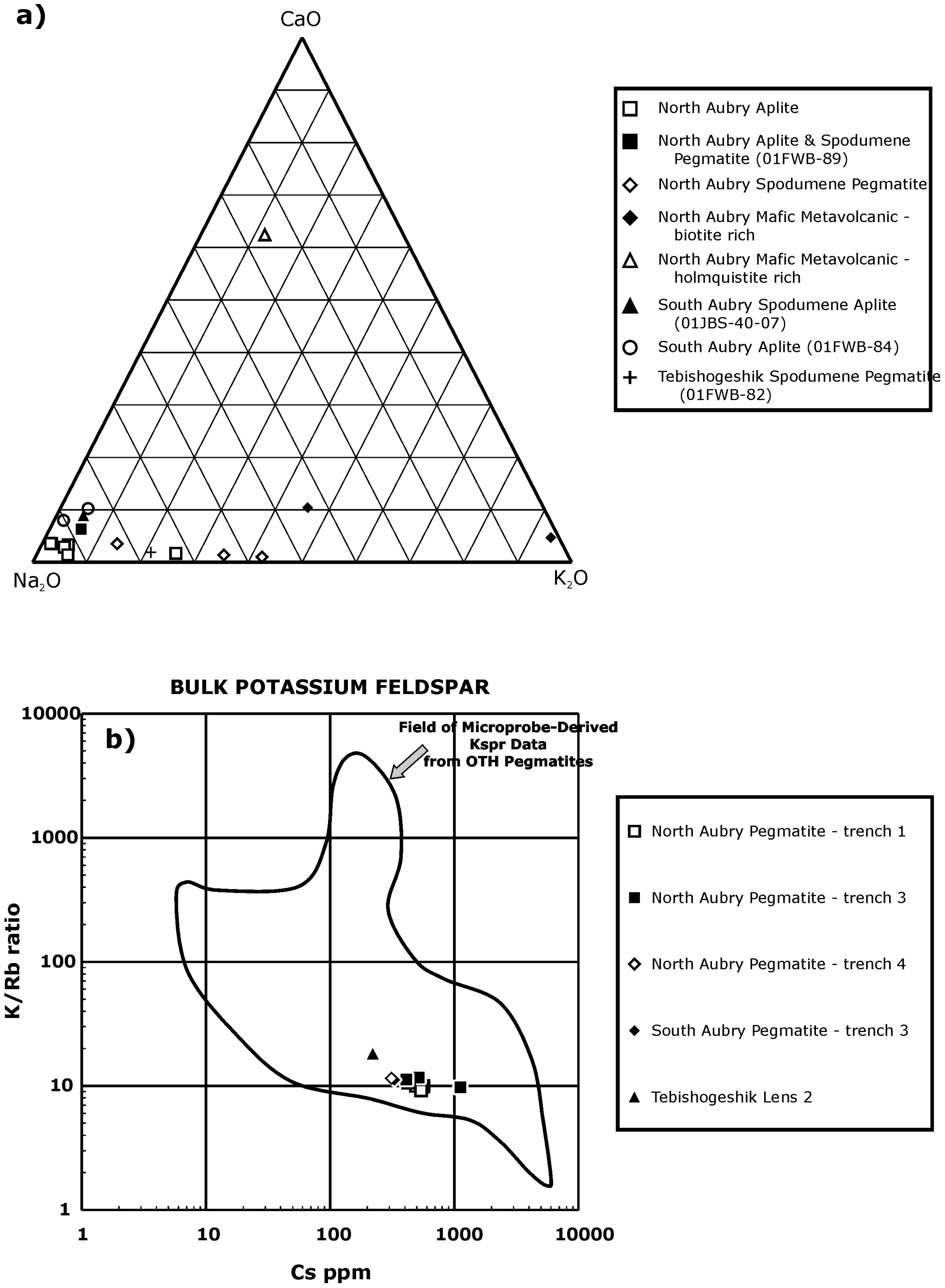


Figure 52. a) CaO–Na$_2$O–K$_2$O diagram for whole rock data from North Aubry, South Aubry and Tebishogeshik pegmatites. b) K/Rb versus Cs (ppm) for bulk potassium feldspar from North Aubry, South Aubry and Tebishogeshik pegmatites.

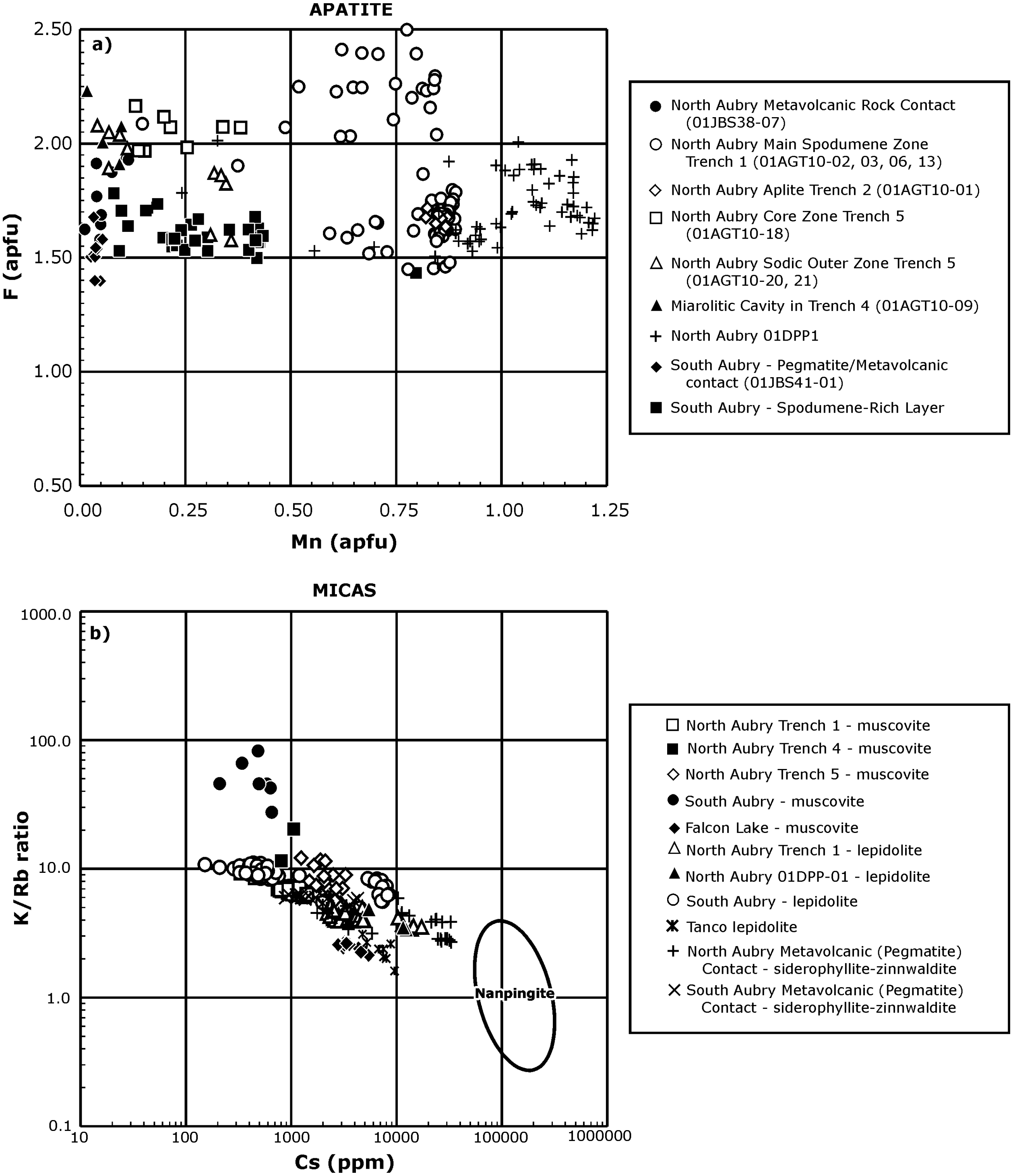


Figure 53. a) F versus Mn (*apfu*) for fluorapatite from North Aubry and South Aubry pegmatites. b) K/Rb versus Cs (ppm) for micas from North Aubry, South Aubry and Falcon Lake pegmatites.

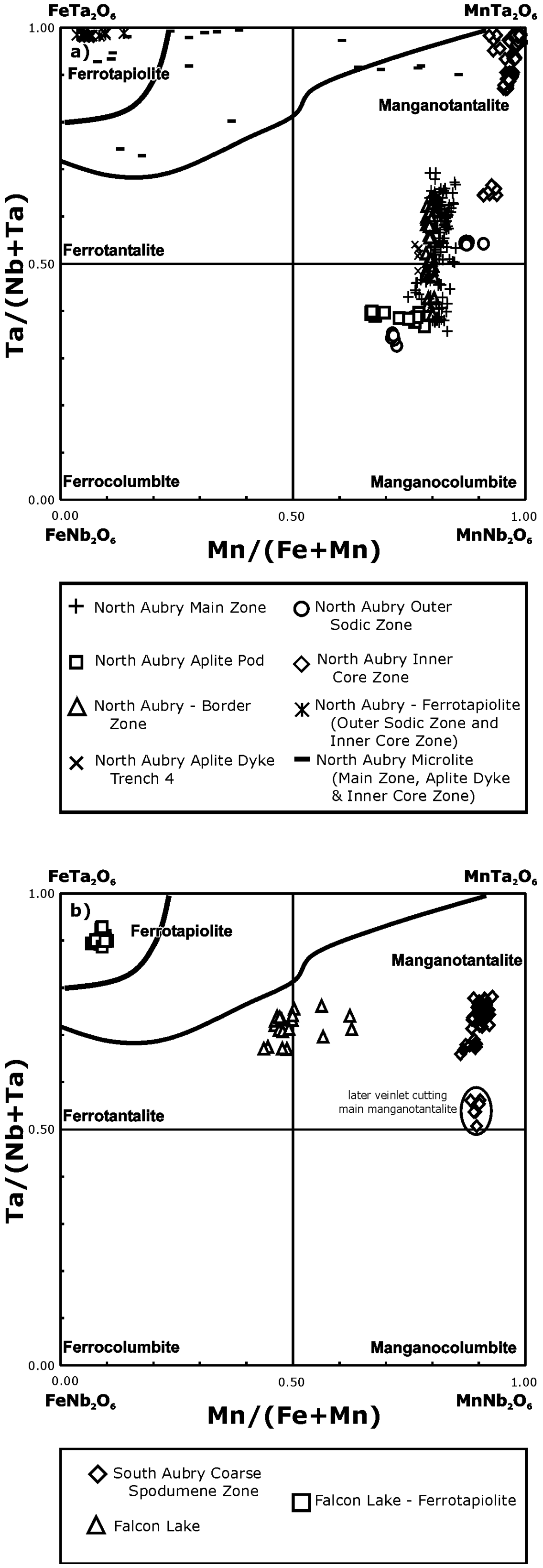


Figure 54. Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide mineral (manganocolumbite, manganotantalite, ferrotapiolite and microlite) compositions from: a) North Aubry pegmatite and b) South Aubry and Falcon Lake pegmatites.

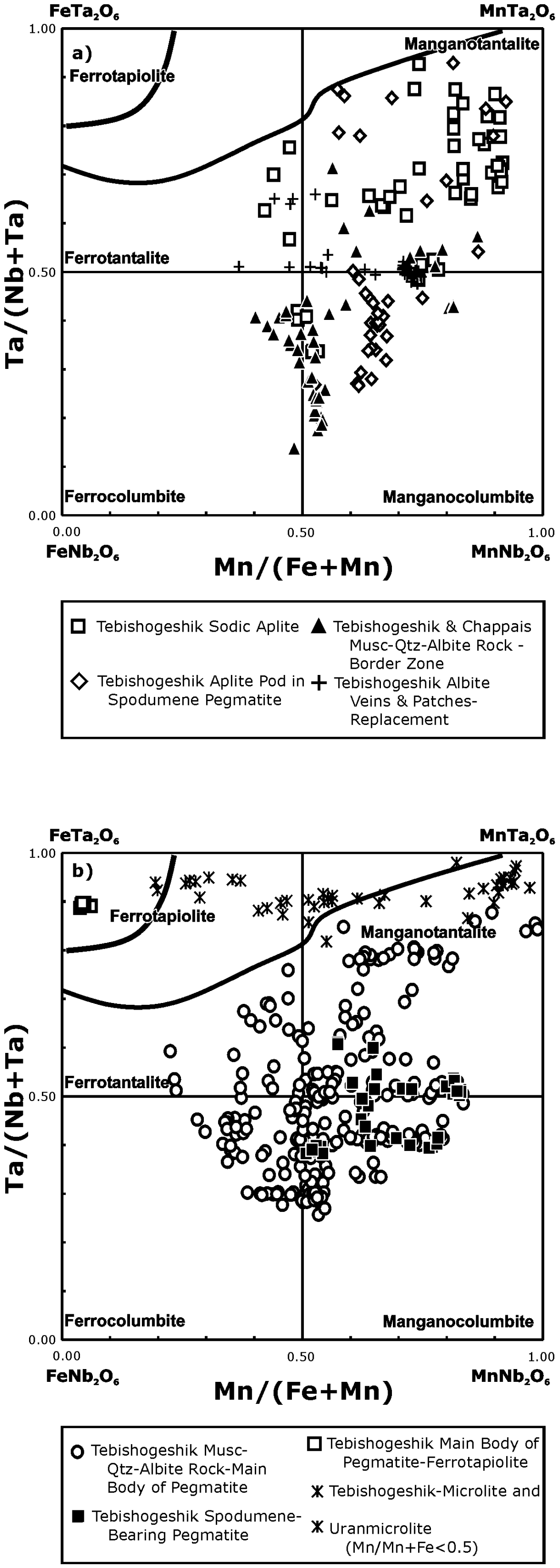
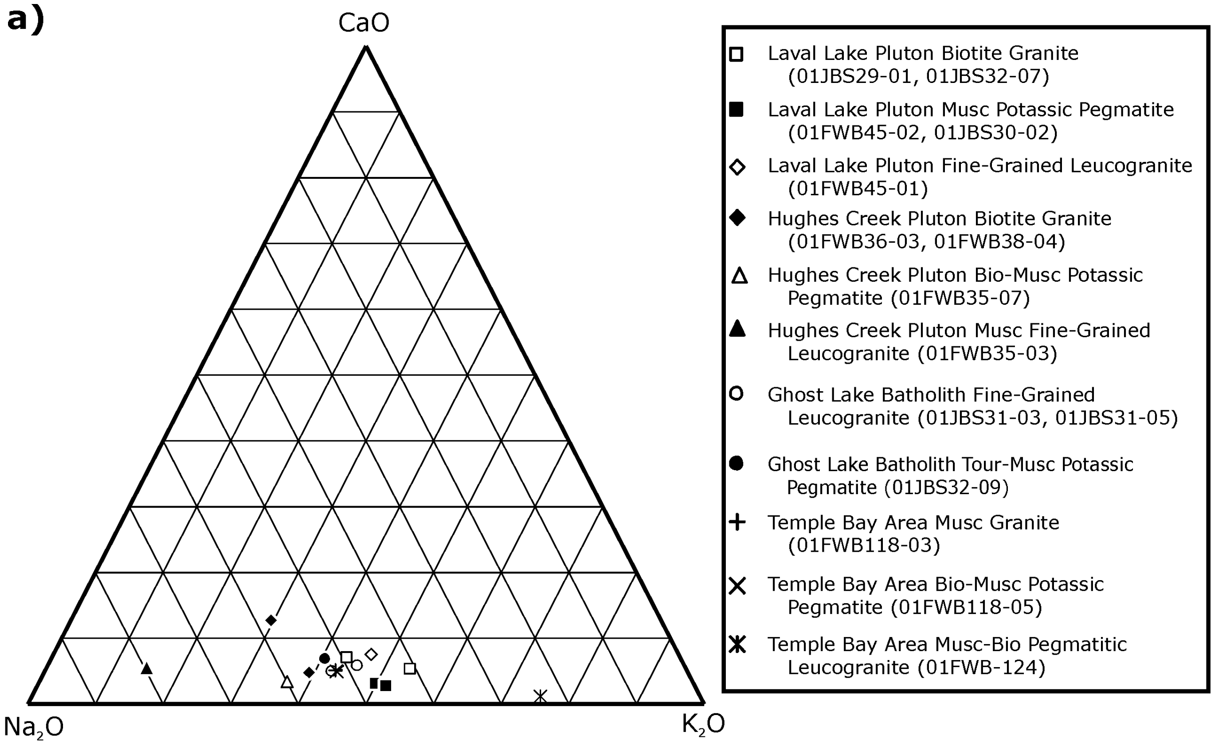


Figure 55. Ta/(Ta+Nb) versus Mn/(Mn+Fe) for columbite-tantalite compositions from Tebishogeshik.



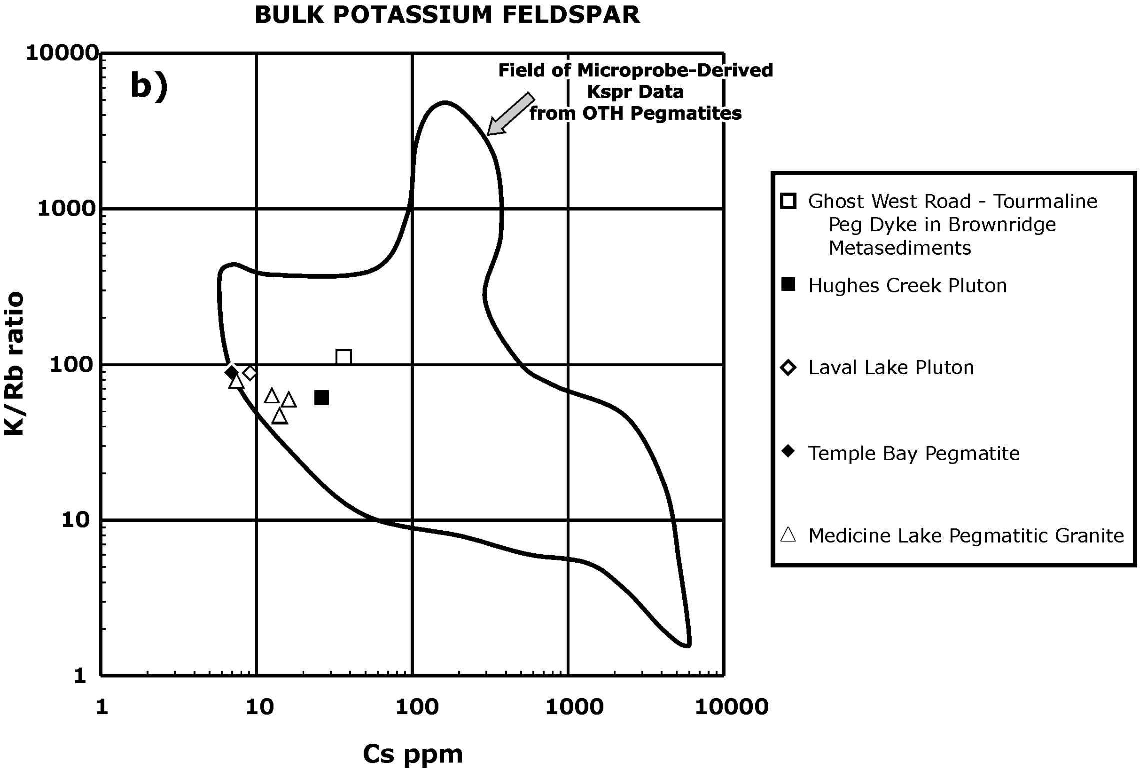


Figure 56. a) CaO–Na_2O–K_2O diagram for whole rock data from Sioux Lookout domain. b) K/Rb versus Cs (ppm) for bulk potassium feldspar from Sioux Lookout domain.

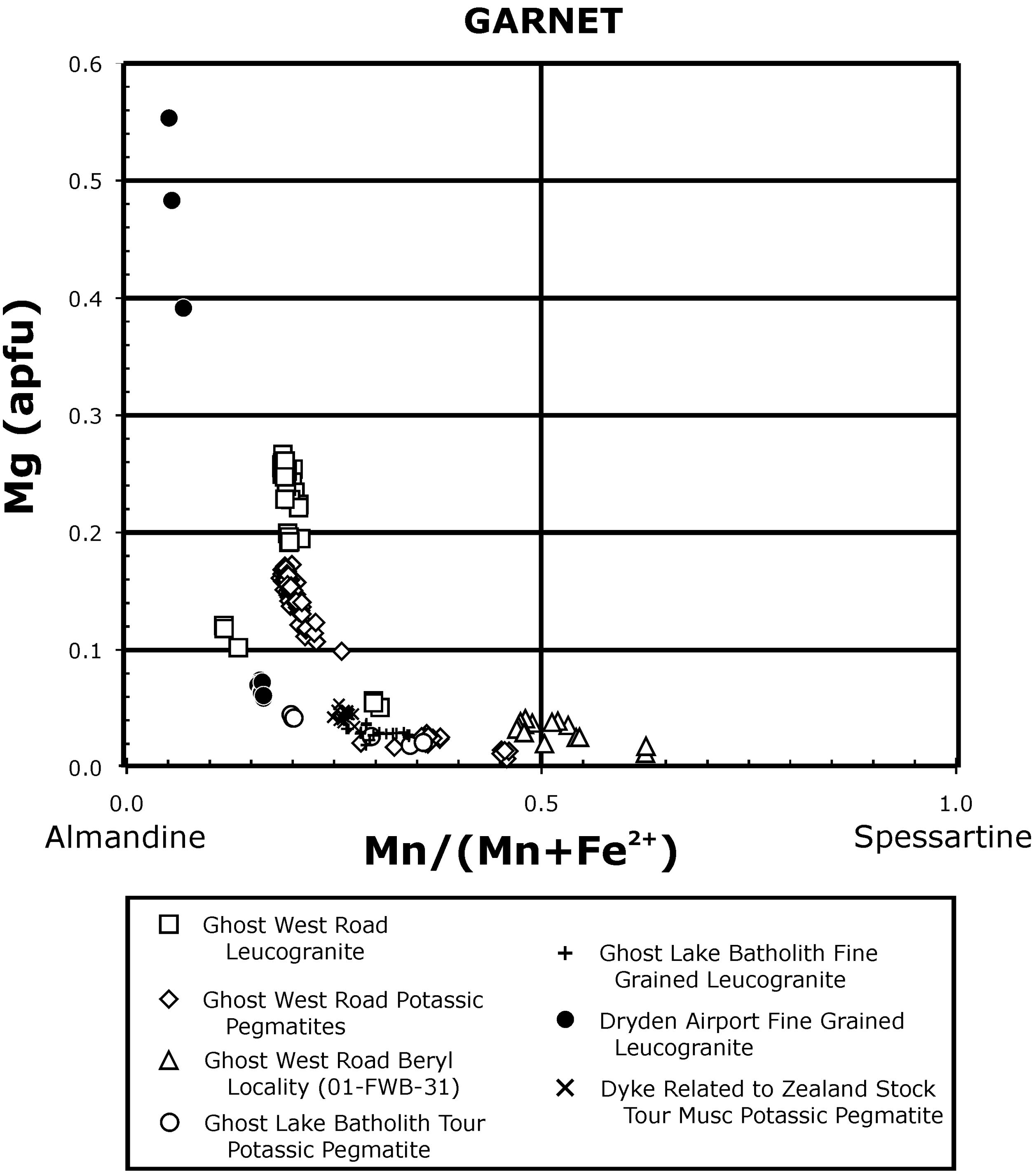


Figure 57. Mg (*apfu*) versus Mn/(Mn+Fe) for garnet (almandine and spessartine) from Ghost West road, Ghost Lake batholith, Dryden airport outcrop and Zealand stock.

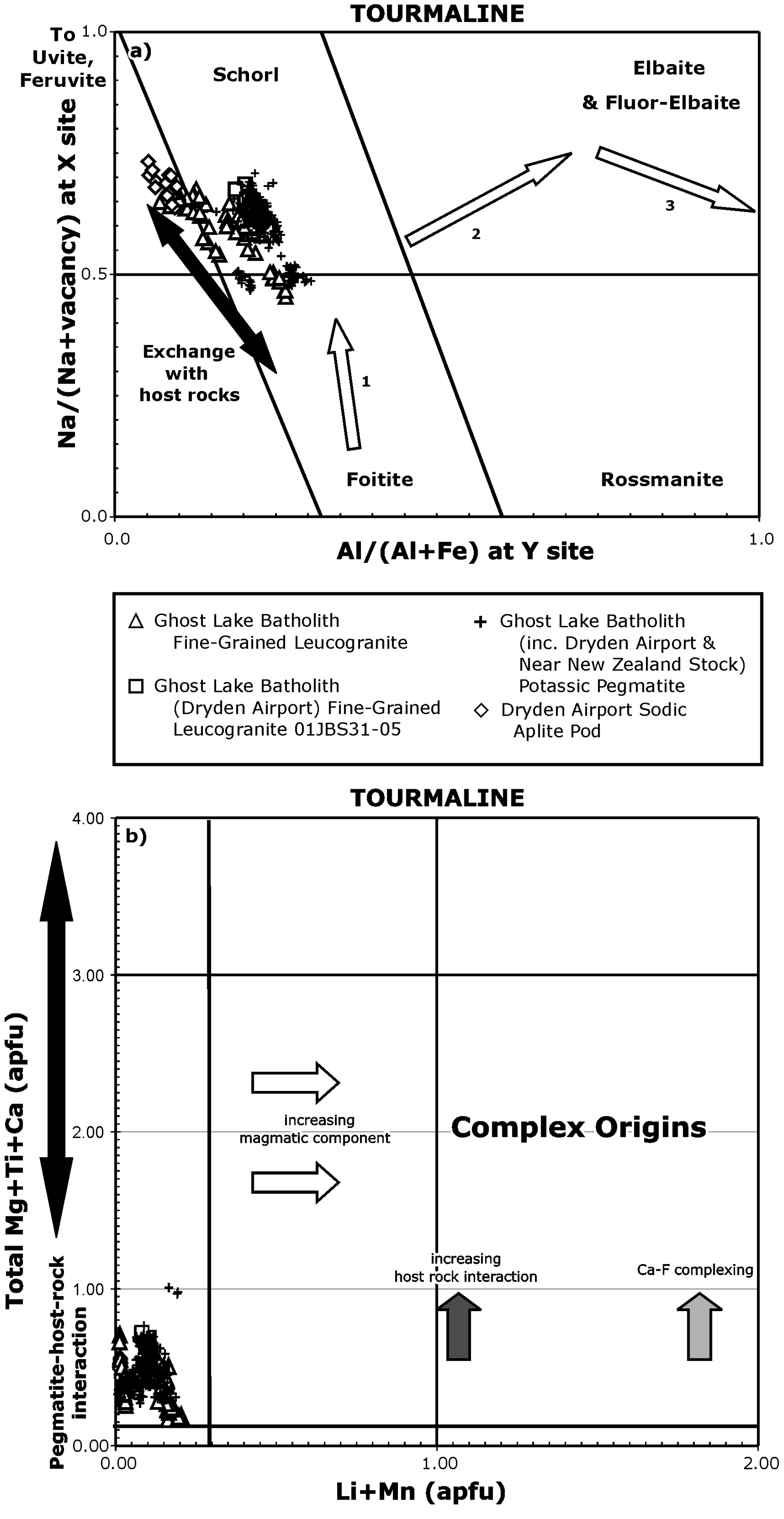


Figure 58. Tourmaline compositions from the Ghost Lake batholith: a) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site and b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

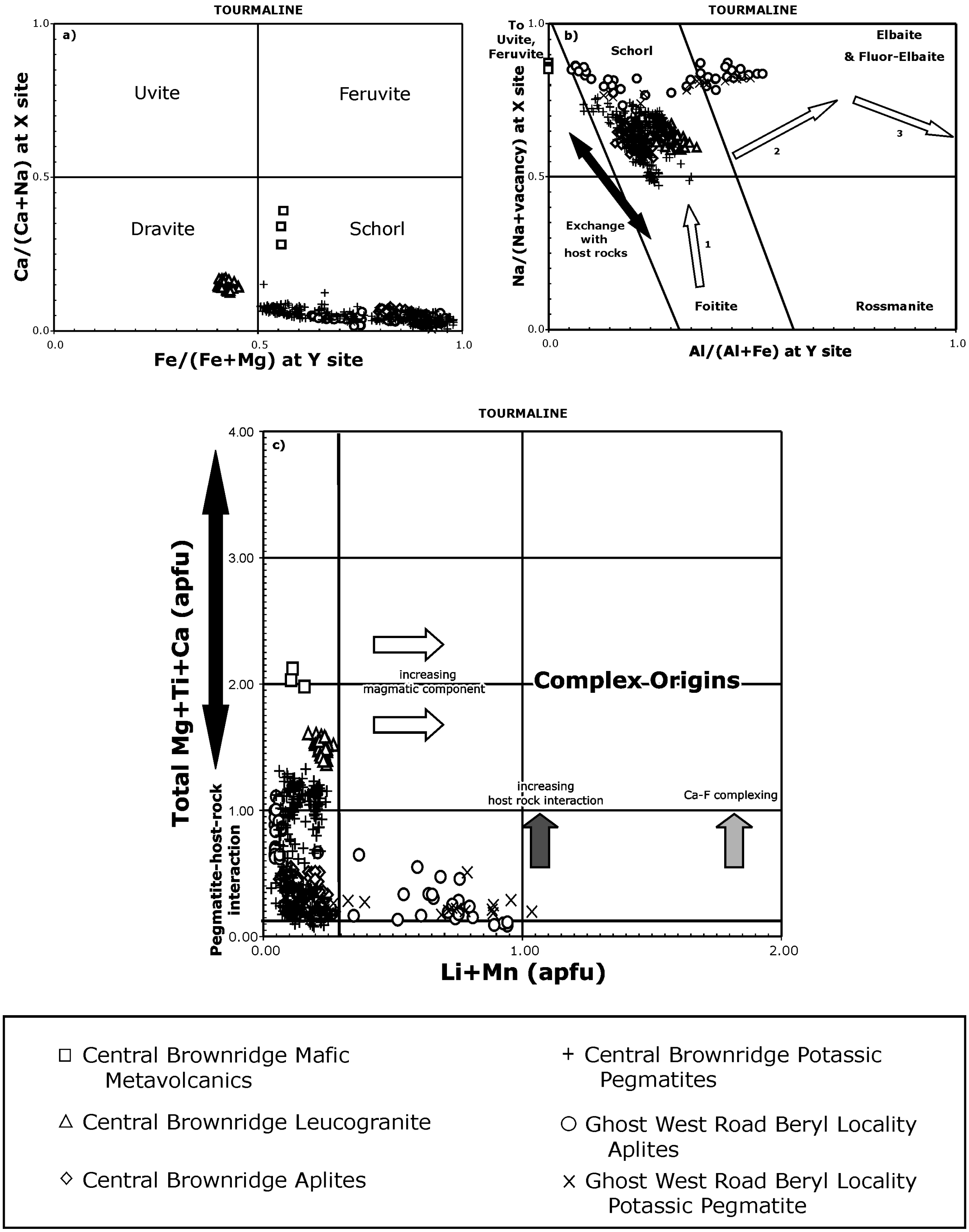


Figure 59. Tourmaline compositions from Central Brownridge Township and Ghost West road beryl locality: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, c) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

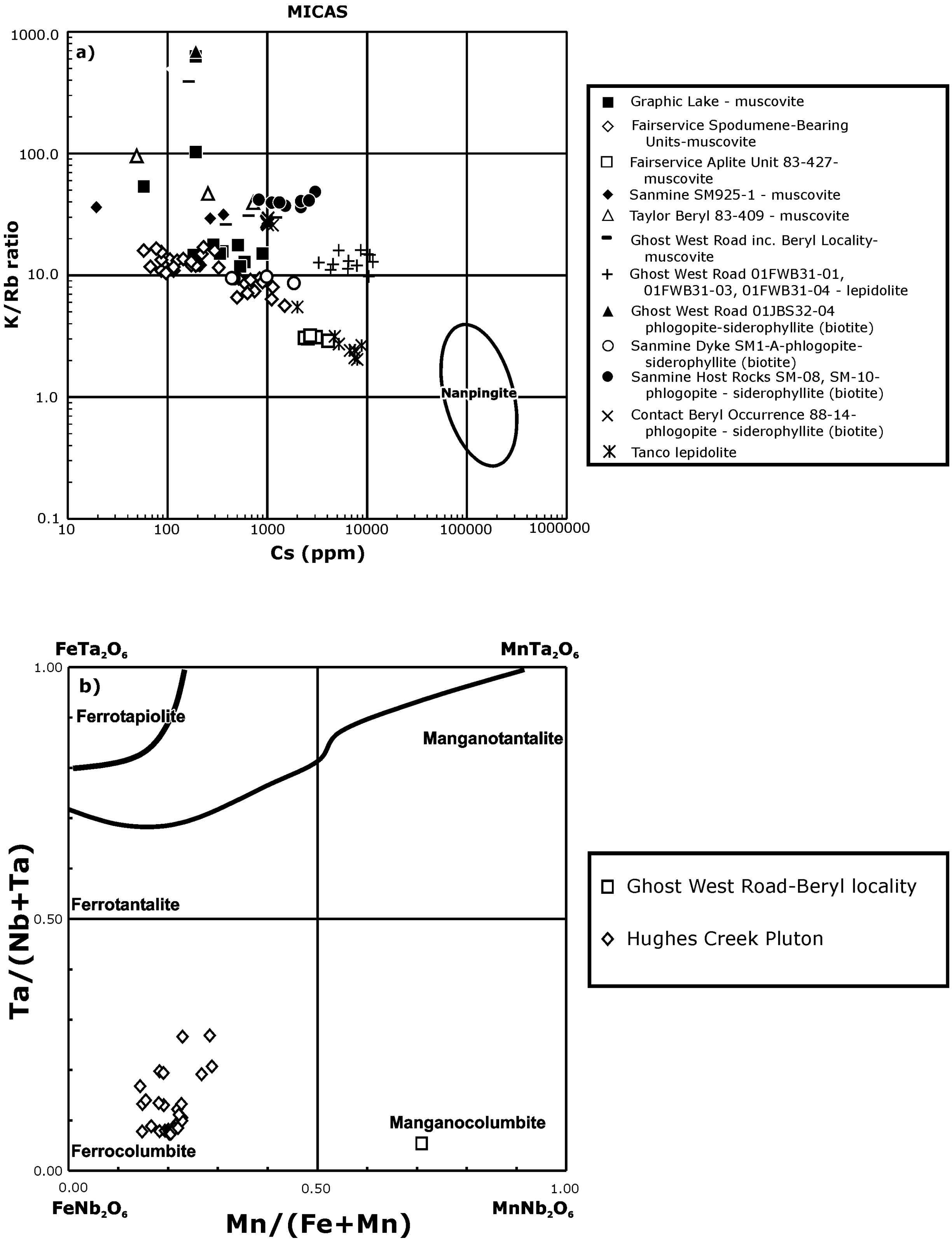


Figure 60. a) K/Rb versus Cs (ppm) for mica from Sioux Lookout domain. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite) from Ghost West road beryl locality and Hughes Creek pluton.

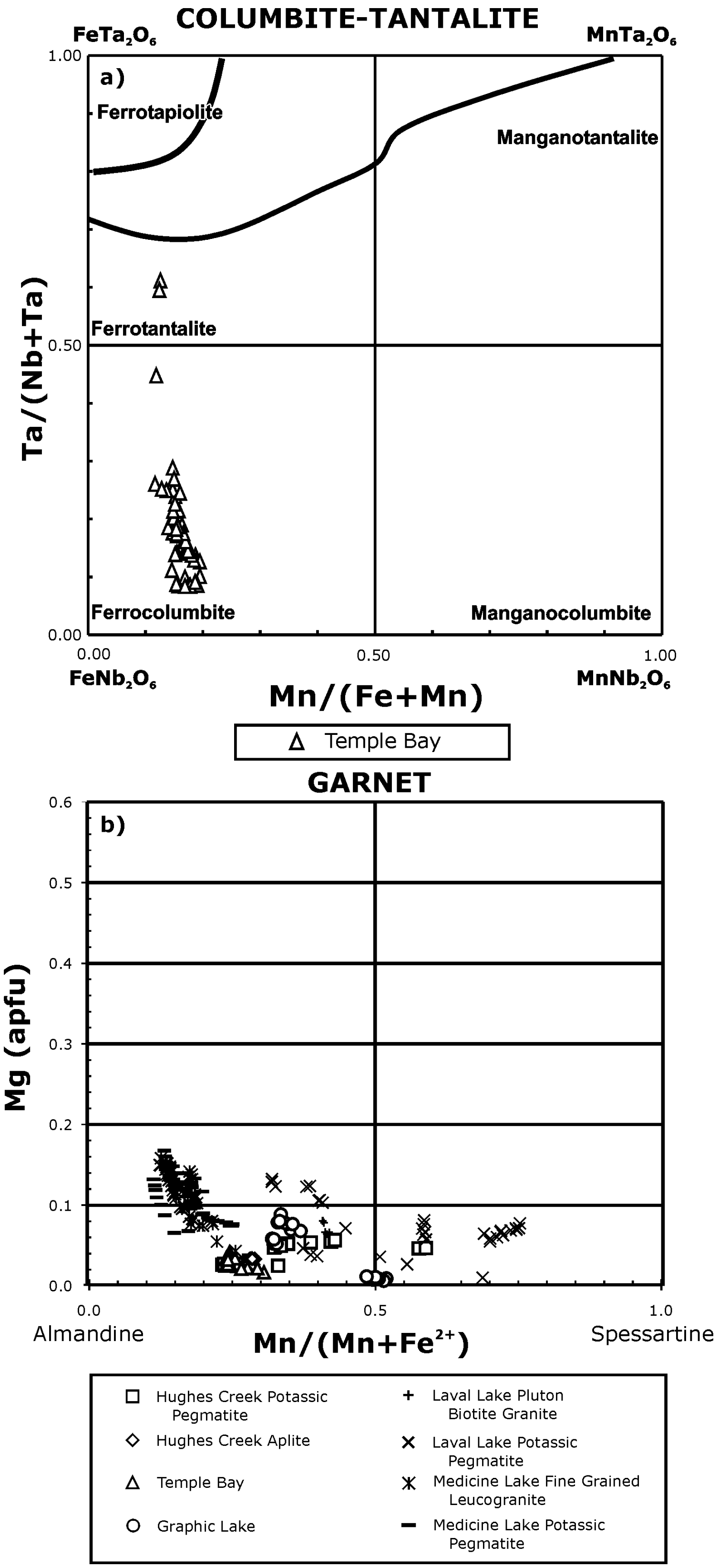


Figure 61. a) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite) from Temple Bay. b) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet (almandine and spessartine) from Sioux Lookout domain.

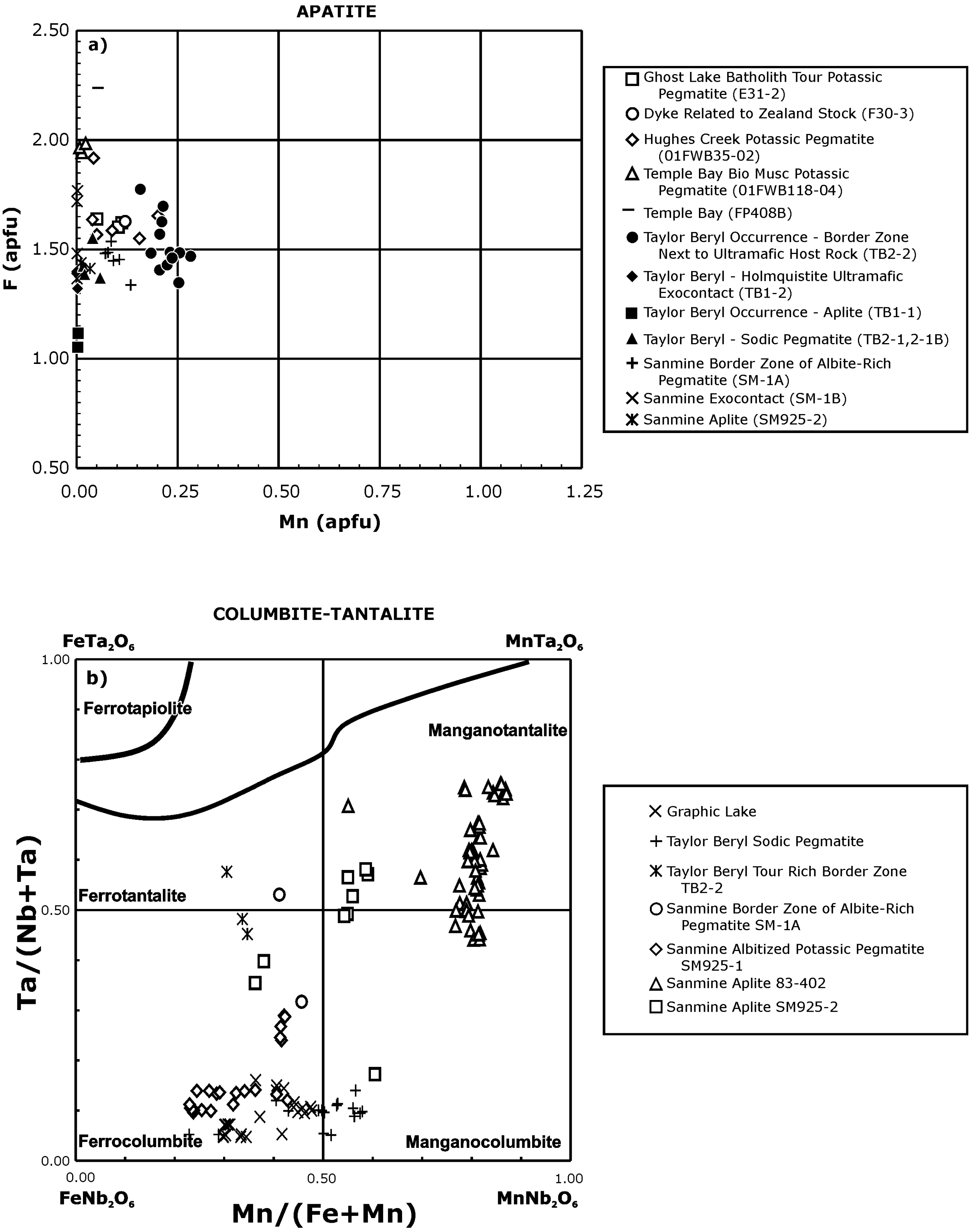


Figure 62. a) F versus Mn (*apfu*) for fluorapatite from Sioux Lookout domain. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite and manganotantalite) from Graphic Lake, Taylor Beryl and Sanmine.

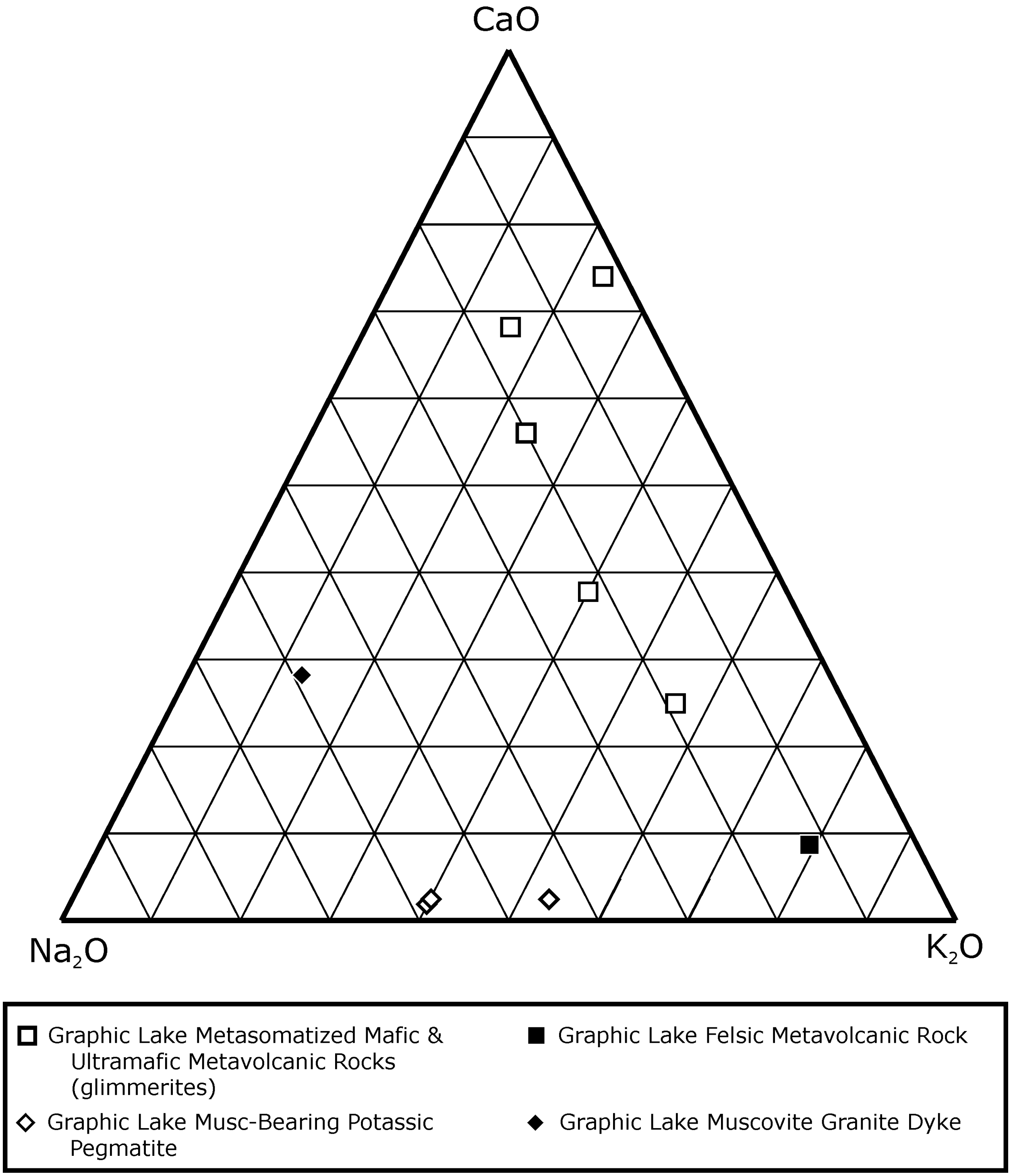


Figure 63. CaO–Na_2O–K_2O diagram for whole rock data from Graphic Lake.

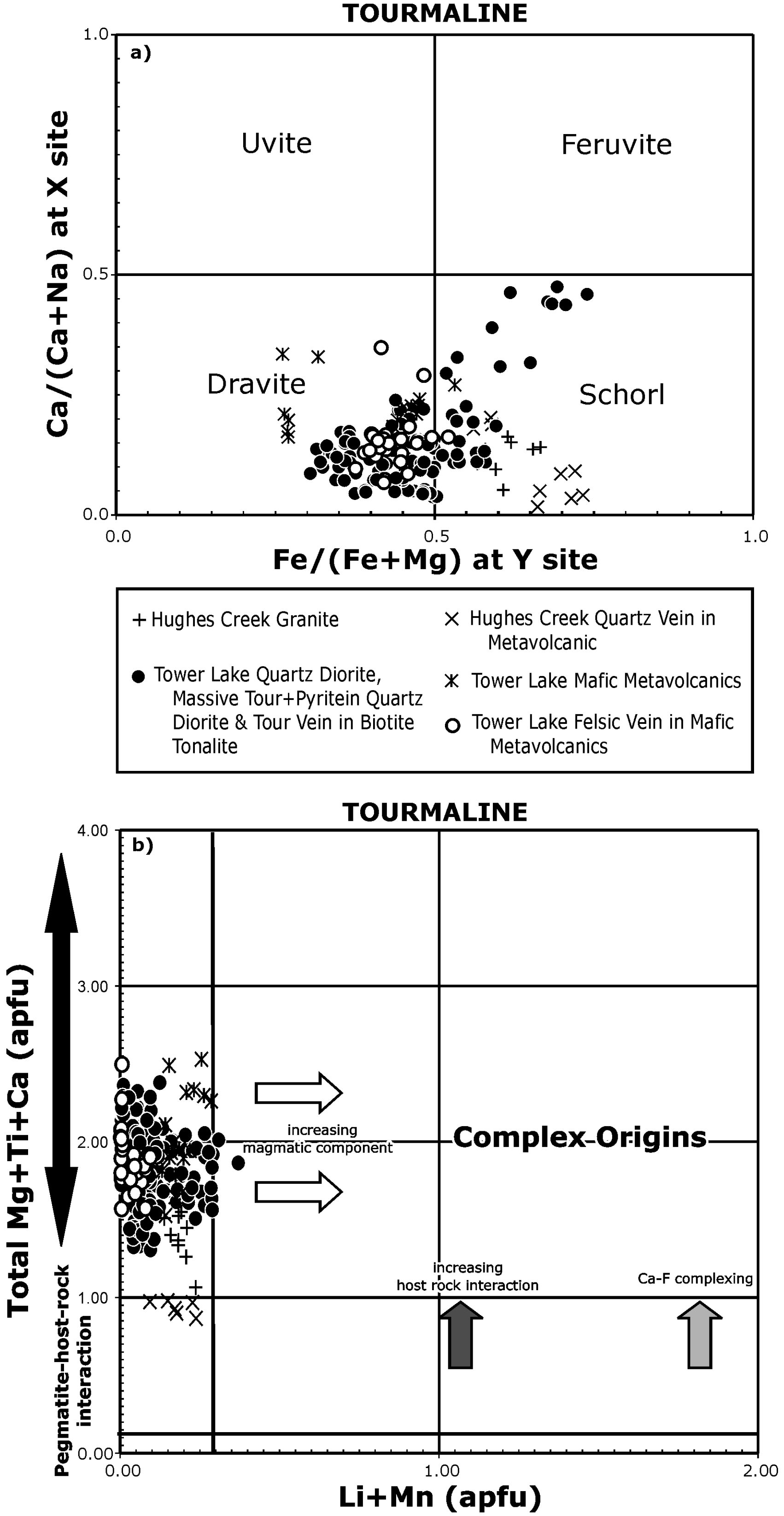


Figure 64. Tourmaline compositions from Hughes Creek and Tower Lake: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

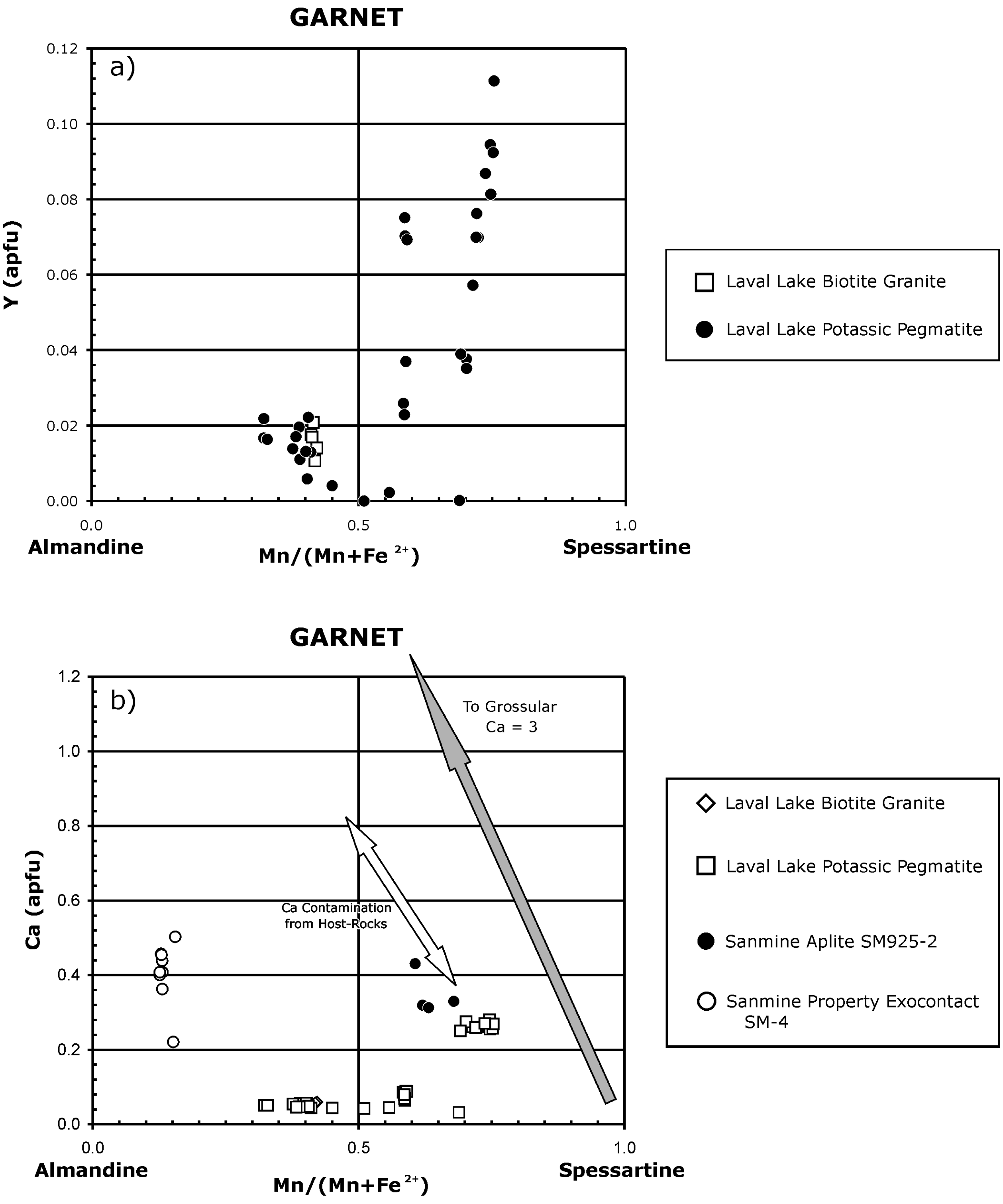


Figure 65. Garnet (almandine and spessartine) compositions from Laval Lake and Sanmine property: a) Y (*apfu*) versus Mn/(Mn+Fe) and b) Ca (*apfu*) versus Mn/(Mn+Fe).

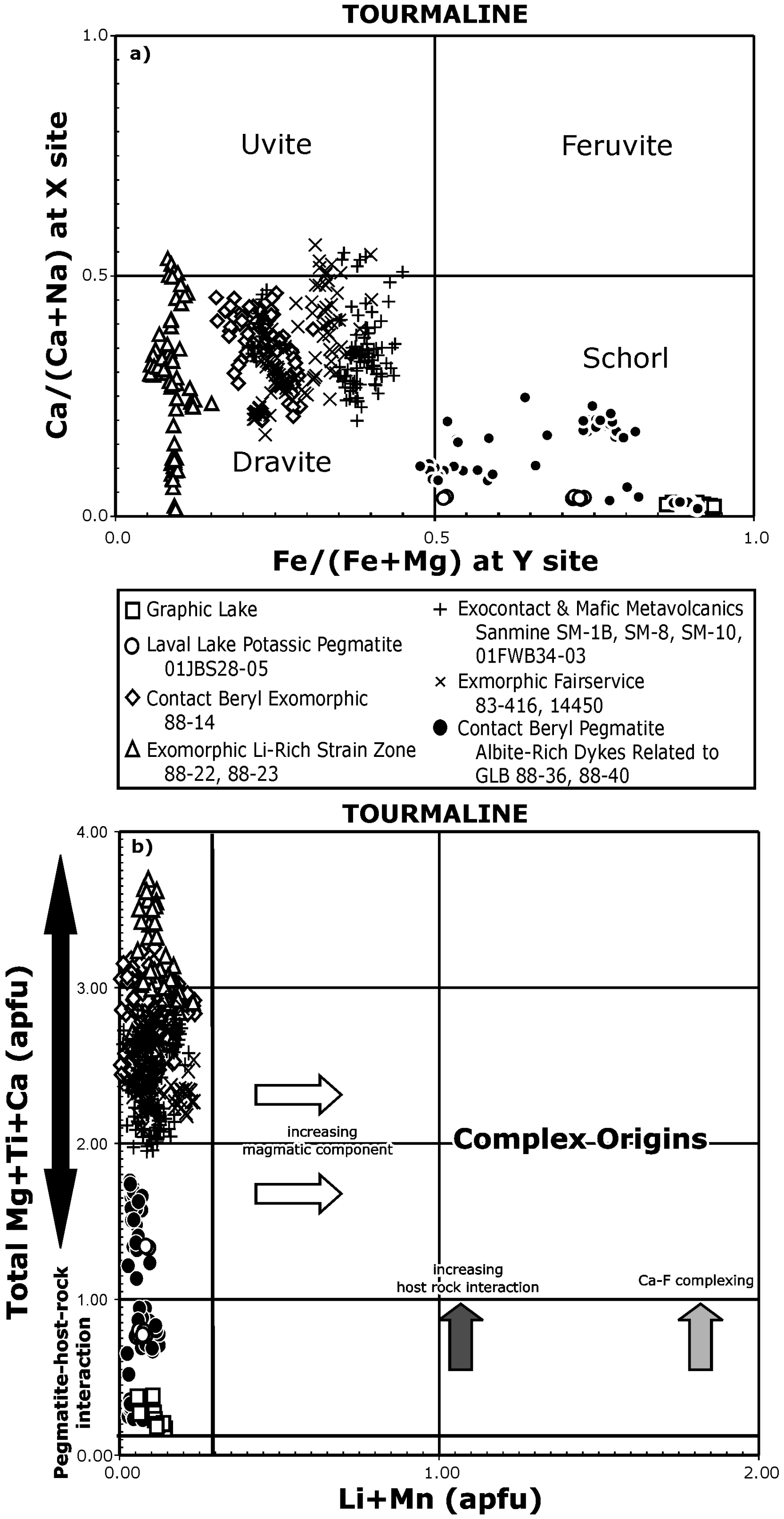


Figure 66. Tourmaline (mostly dravite and schorl) compositions from Graphic, Laval and Mavis Lakes: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

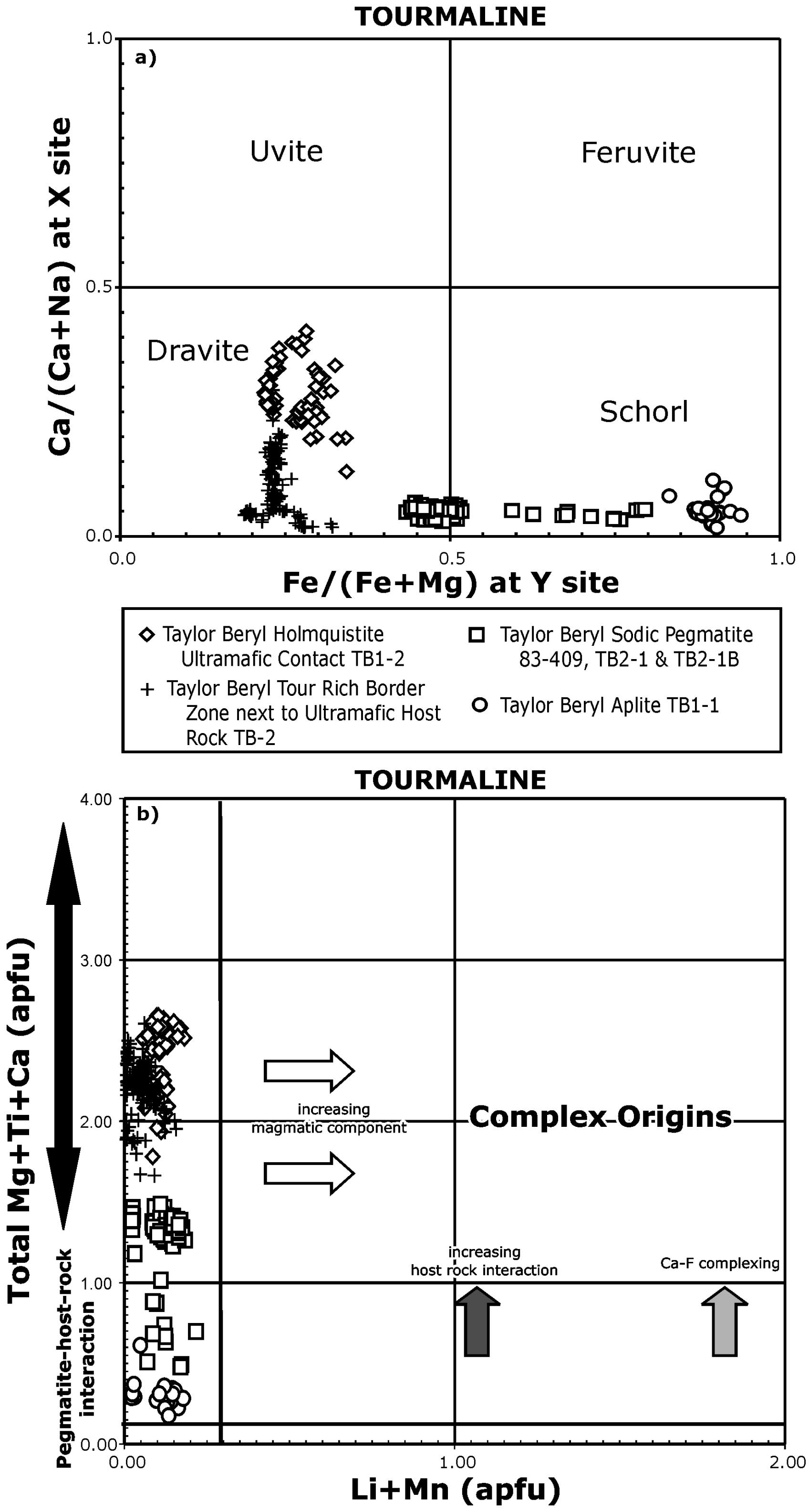


Figure 67. Tourmaline (dravite and schorl) compositions from Taylor Beryl pegmatite dikes: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

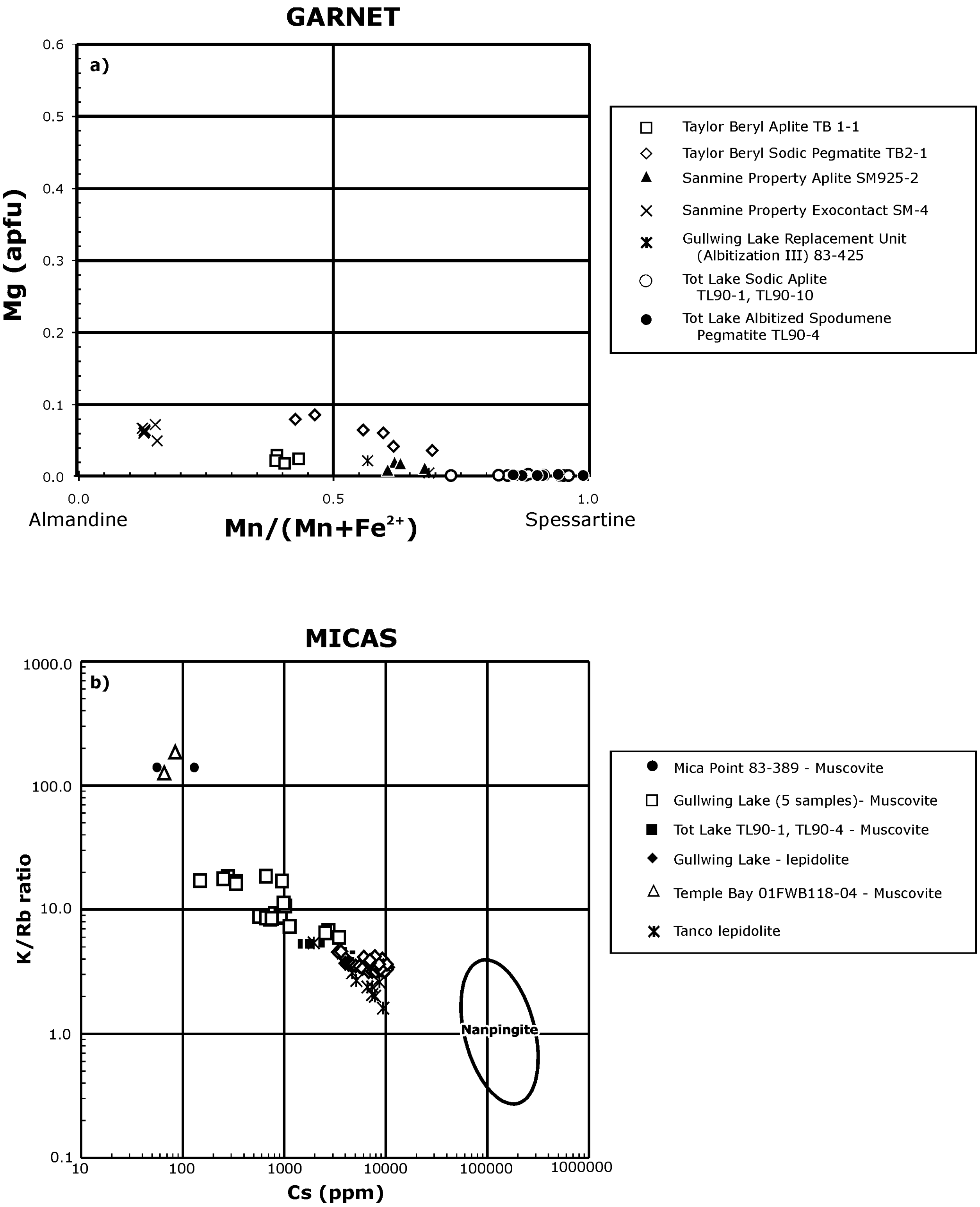


Figure 68. a) Garnet (almandine and spessartine) compositions from Sioux Lookout domain pegmatites: Mg (*apfu*) versus Mn/(Mn+Fe). b) Mica compositions from Sioux Lookout domain pegmatites: K/Rb ratio versus Cs (ppm).

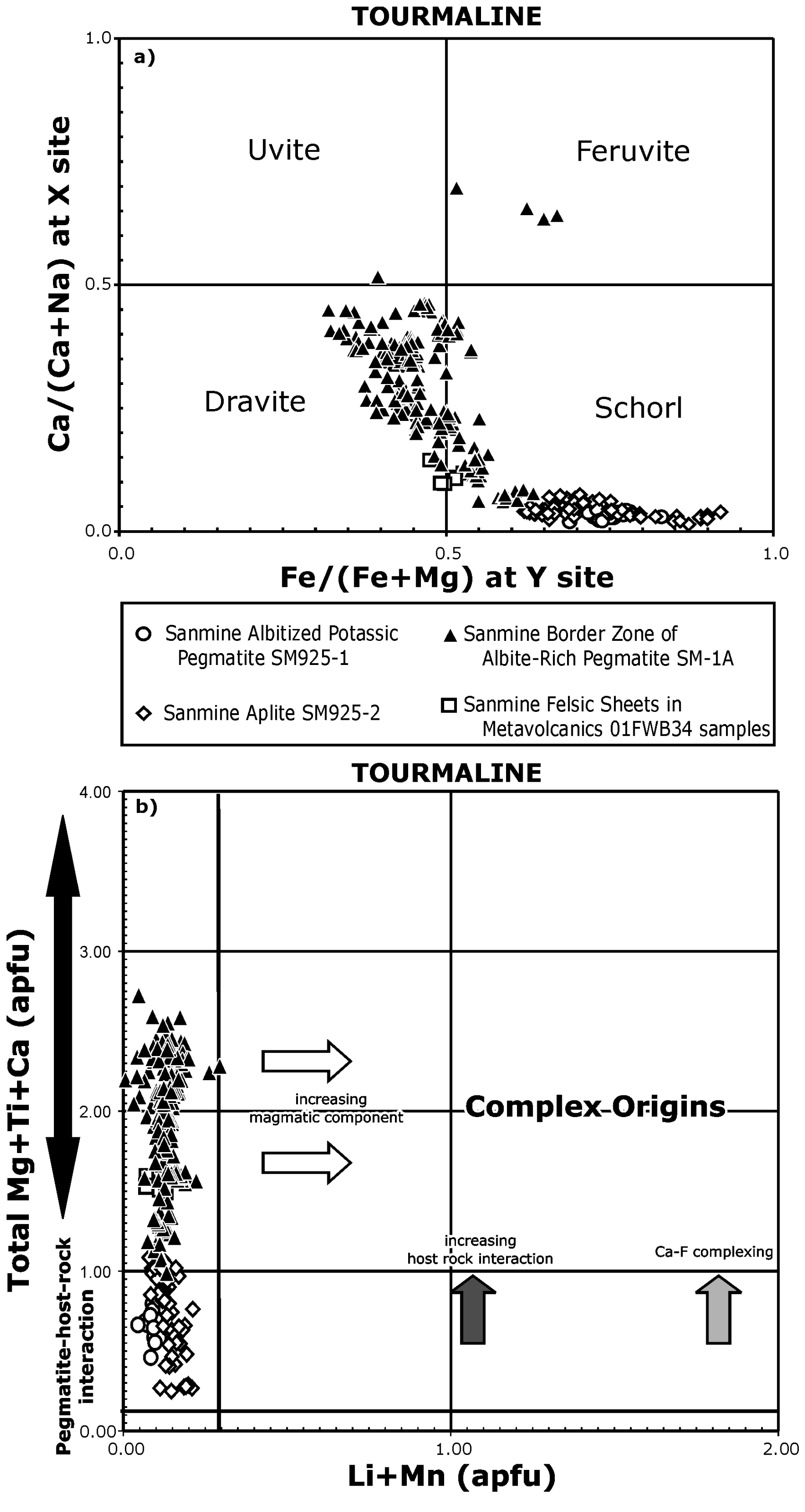


Figure 69. Tourmaline (calcium-rich dravite and schorl) compositions from Sanmine property: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

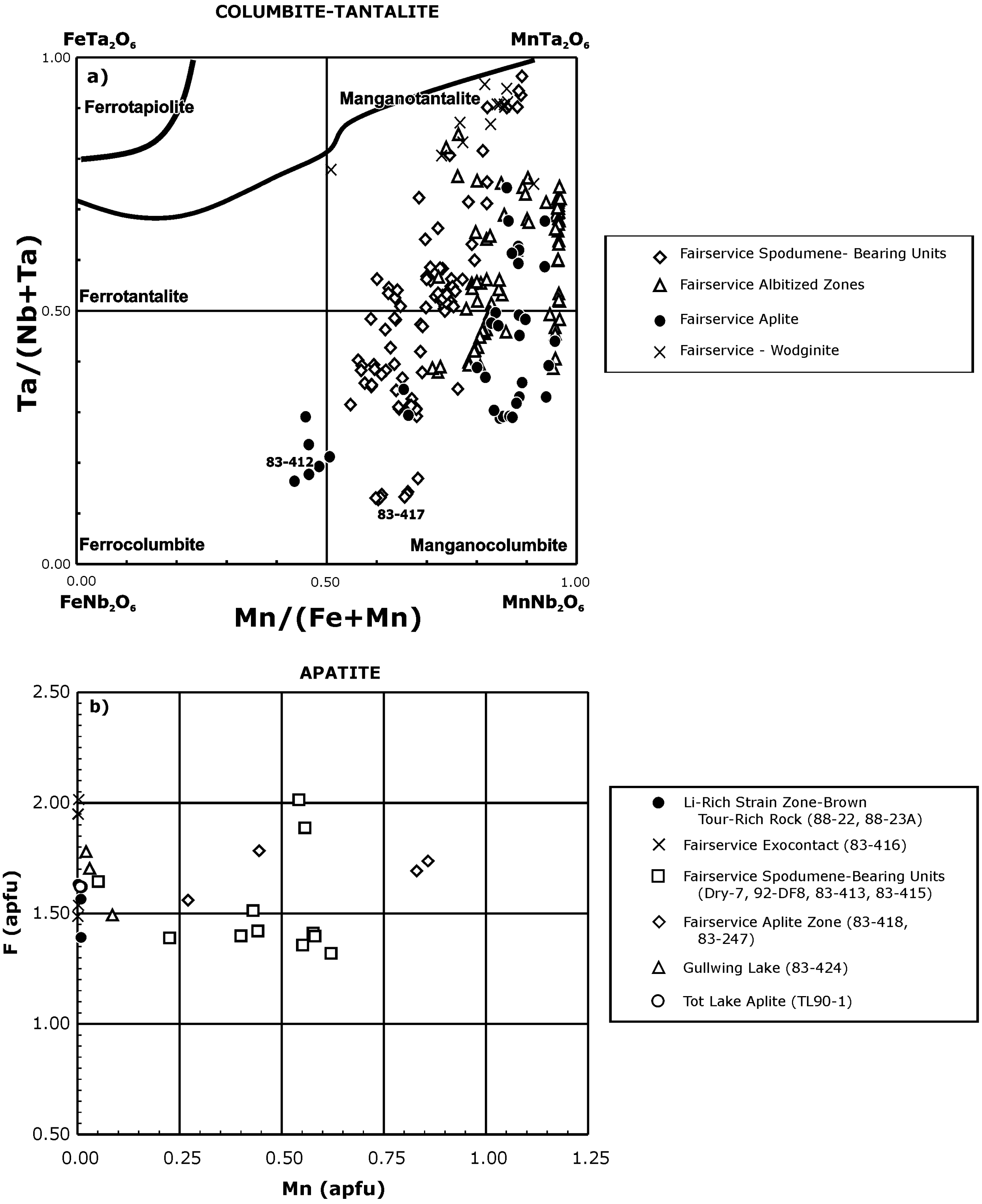


Figure 70. a) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly manganocolumbite and manganotantalite) from Fairservice pegmatites. b) F versus Mn (*apfu*) for fluorapatite compositions from Fairservice, Gullwing and Tot Lake pegmatites.

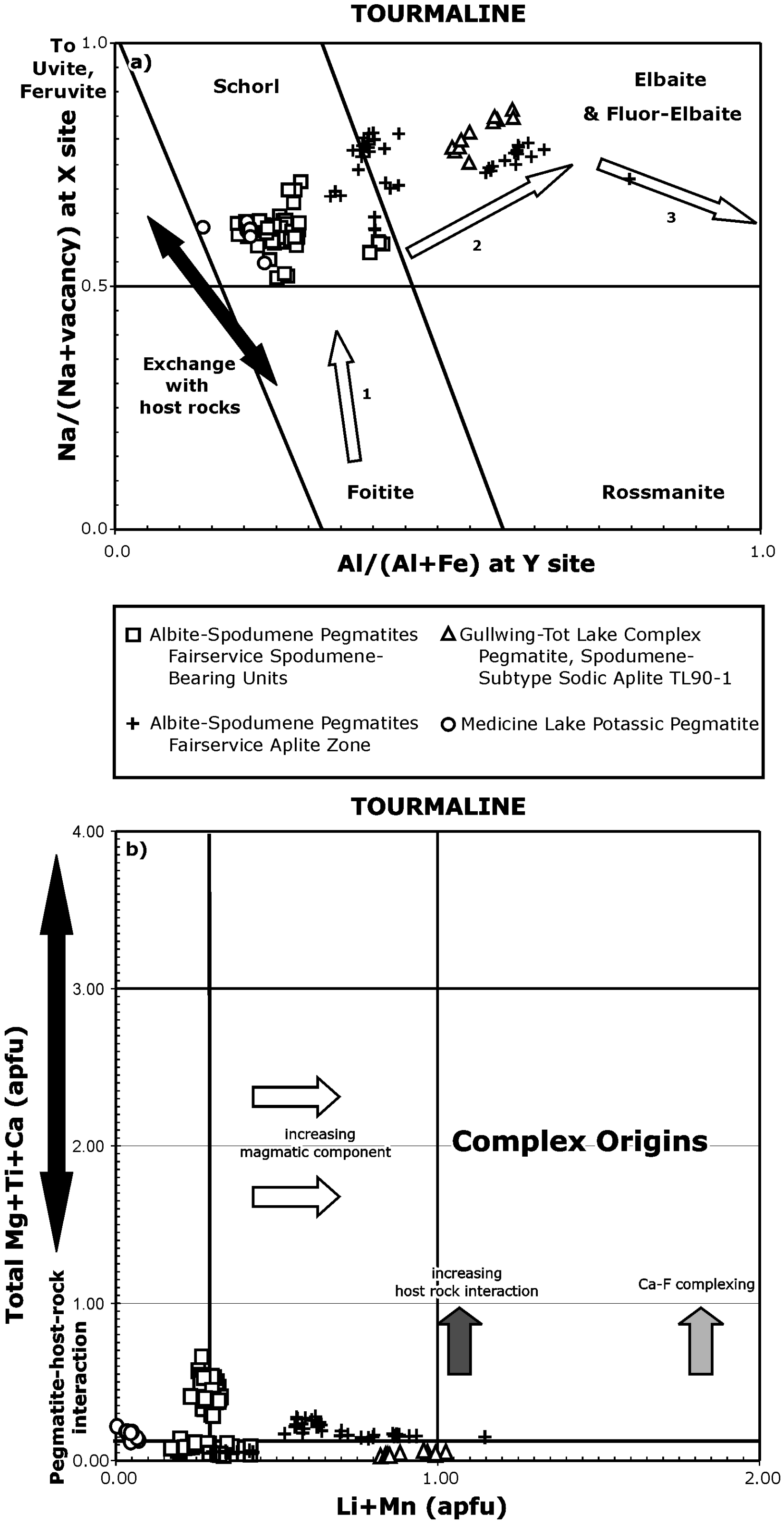


Figure 71. Tourmaline compositions (schorl and elbaite) from Fairservice, Gullwing–Tot Lake and Medicine Lake pegmatites: a) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, b) (total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

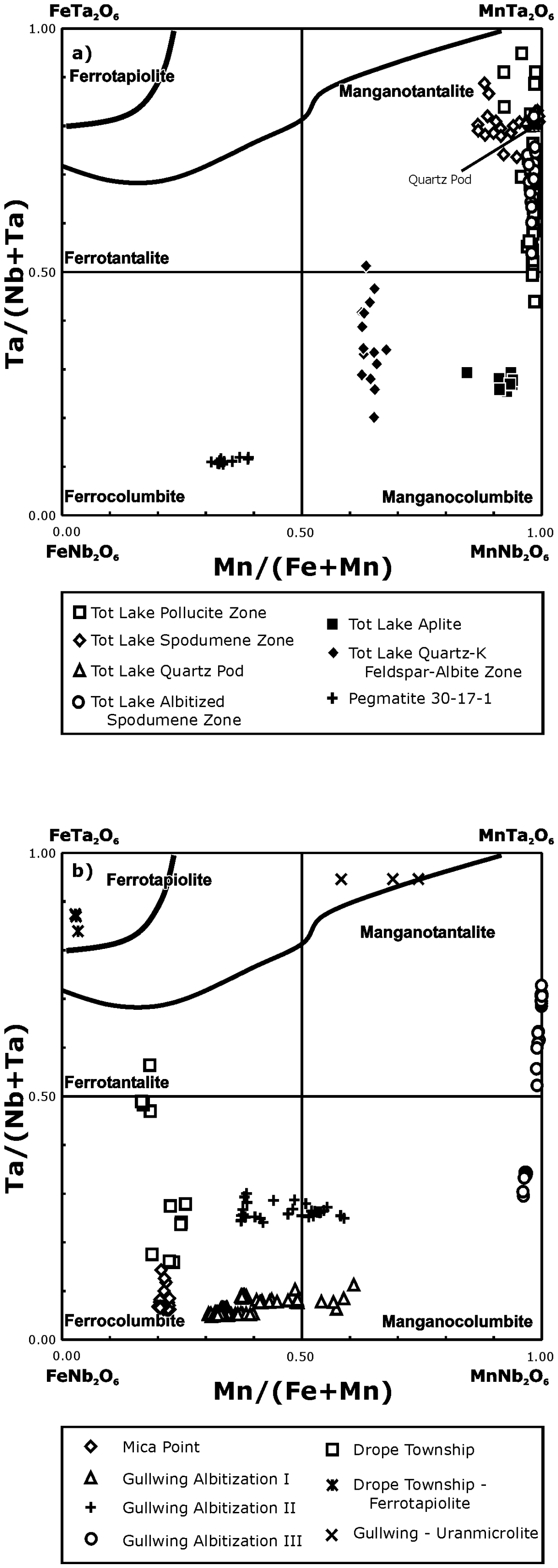


Figure 72. a) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly manganocolumbite and manganotantalite) from Tot Lake pegmatite and Pegmatite 30-17-1. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite) from Mica Point, Gullwing pegmatite and Drope Township.

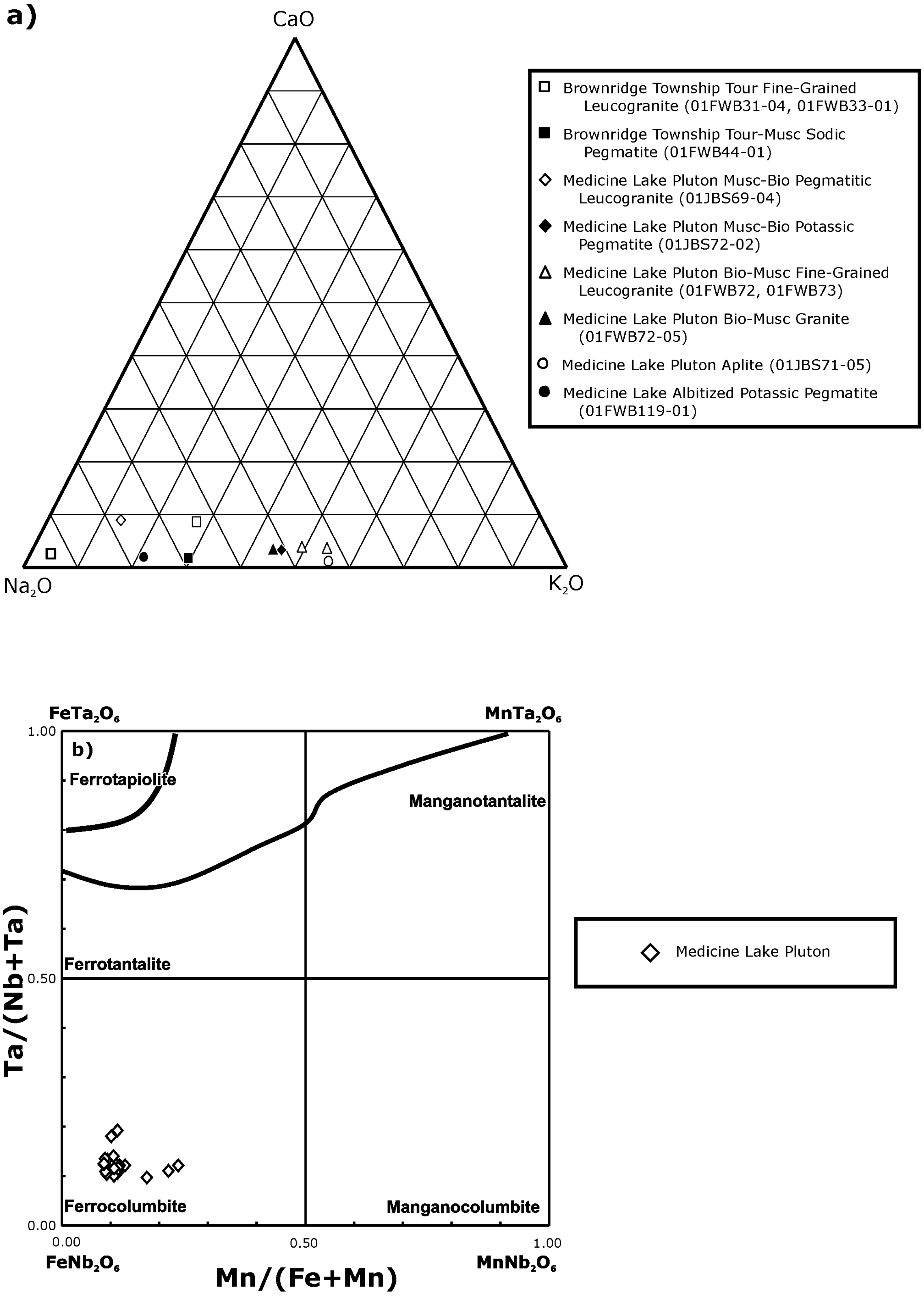


Figure 73. a) CaO–Na$_2$O–K$_2$O diagram for whole rock data from Brownridge Township and Medicine Lake pluton. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for ferrocolumbite from Medicine Lake pluton.

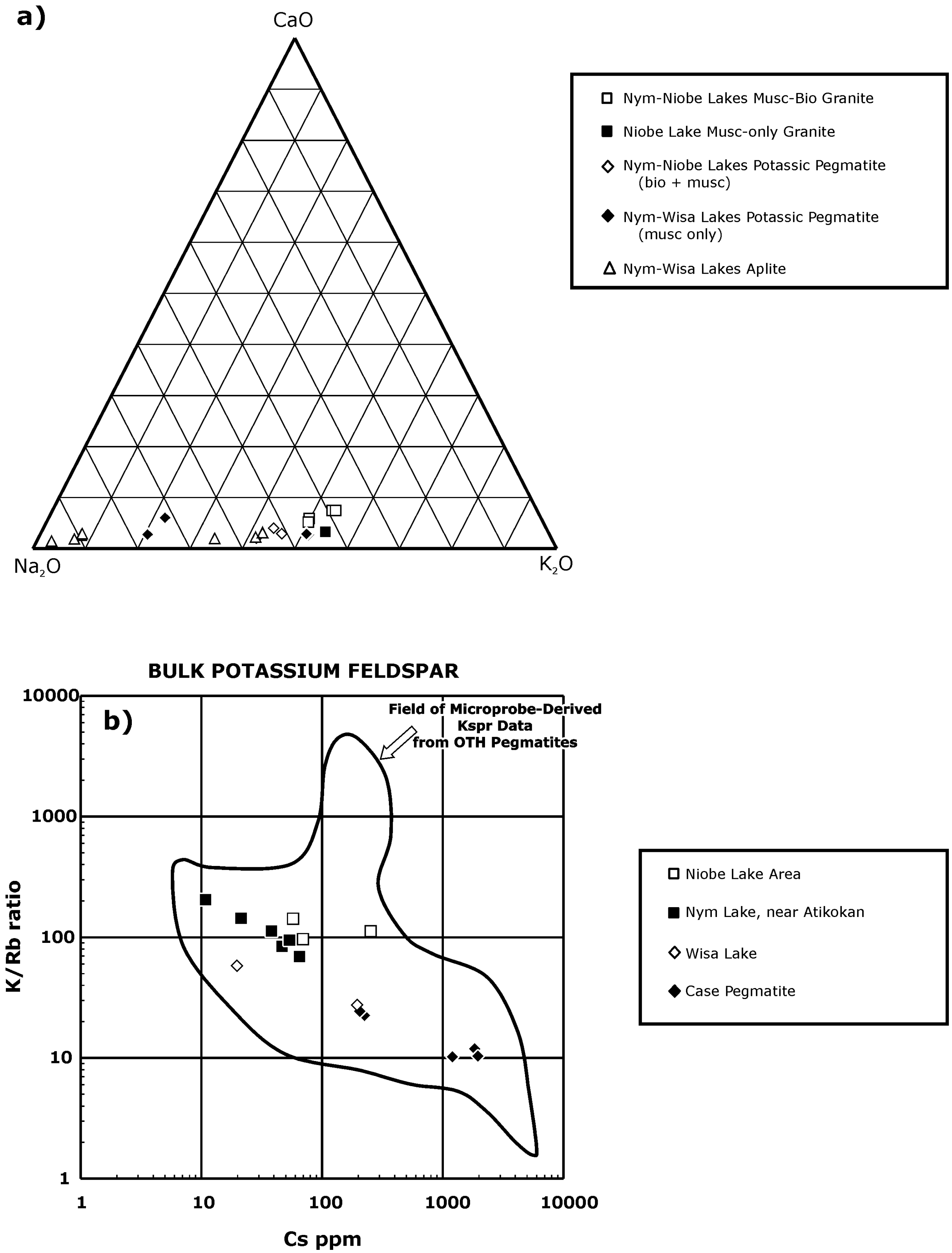


Figure 74. a) CaO–Na$_2$O–K$_2$O diagram for whole rock data from Nym–Niobe lakes and Wisa Lake. b) K/Rb ratio versus Cs (ppm) for bulk potassium feldspar data from Nym–Niobe lakes, Wisa Lake and Case batholith.

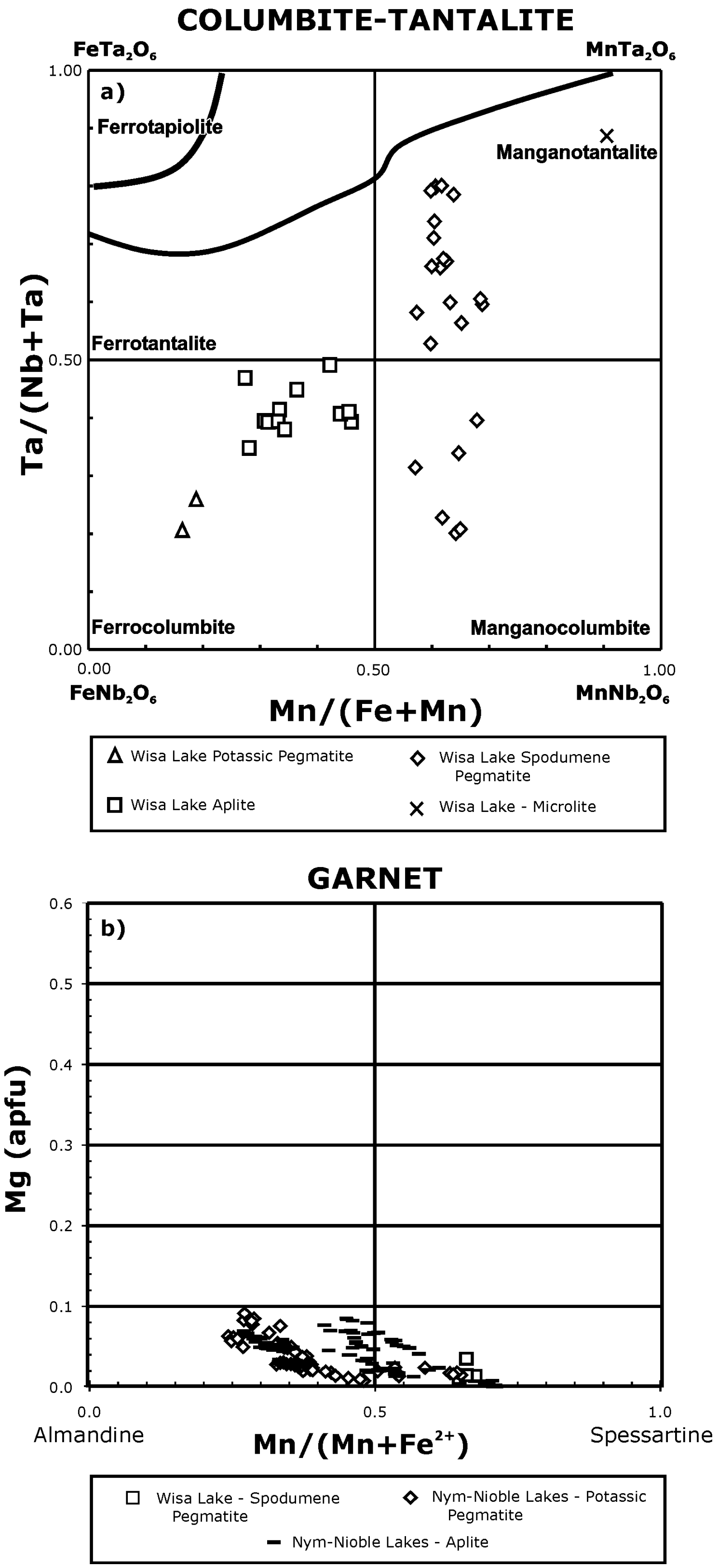
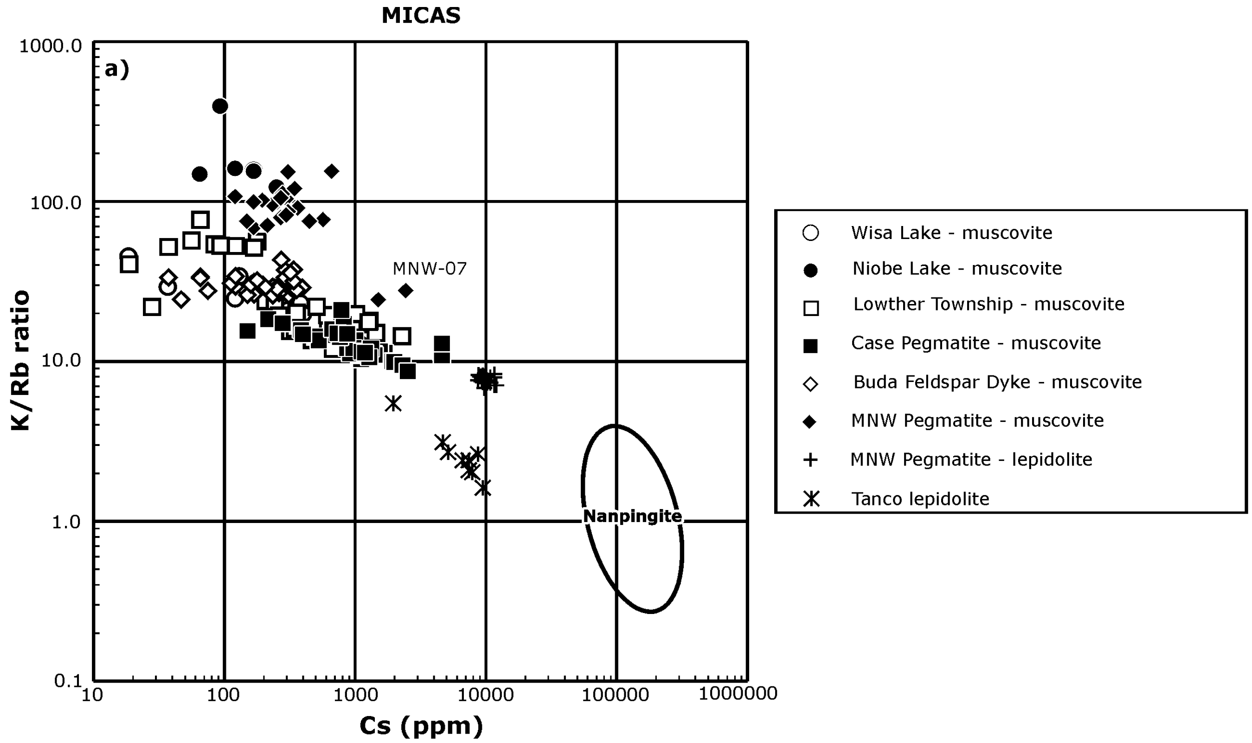


Figure 75. a) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite and manganotantalite) from Wisa Lake pegmatite. b) Mg (*apfu*) versus Mn/(Mn+Fe) for garnet compositions (almandine and spessartine) for Wisa Lake and Nym–Niobe lakes.



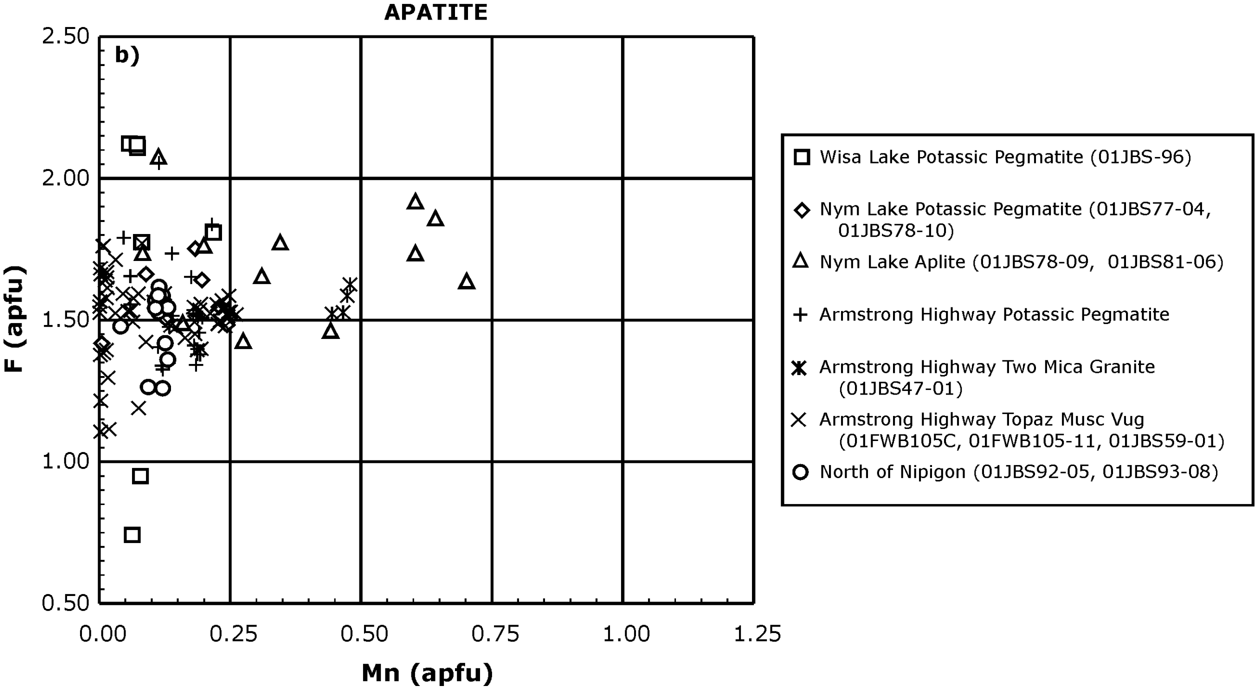


Figure 76. a) K/Rb ratio versus Cs (ppm) for micas (muscovite and lepidolite) from Quetico Subprovince. b) F versus Mn (*apfu*) for fluorapatite from Wisa Lake, Nym Lake, Armstrong highway and Nipigon.

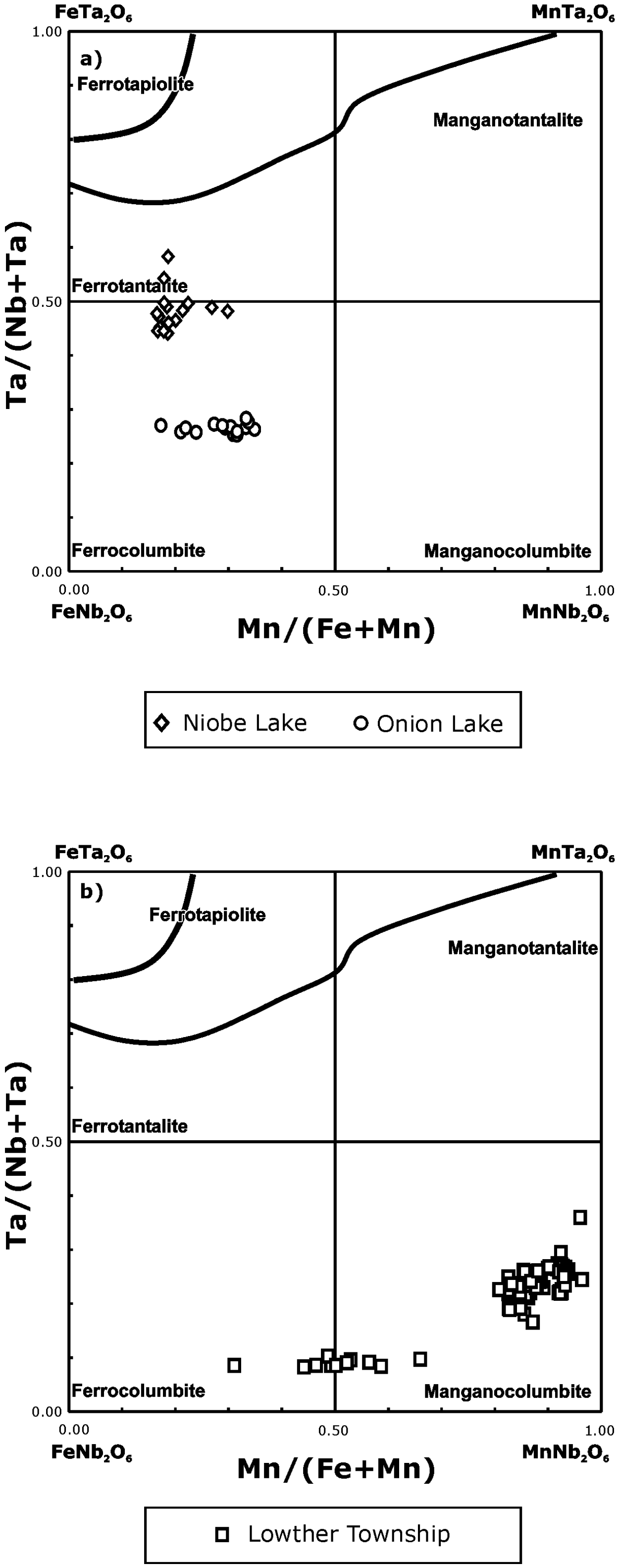


Figure 77. a) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly ferrocolumbite) from Niobe and Onion lakes. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals (mostly manganotantalite) from Lowther Township pegmatite.

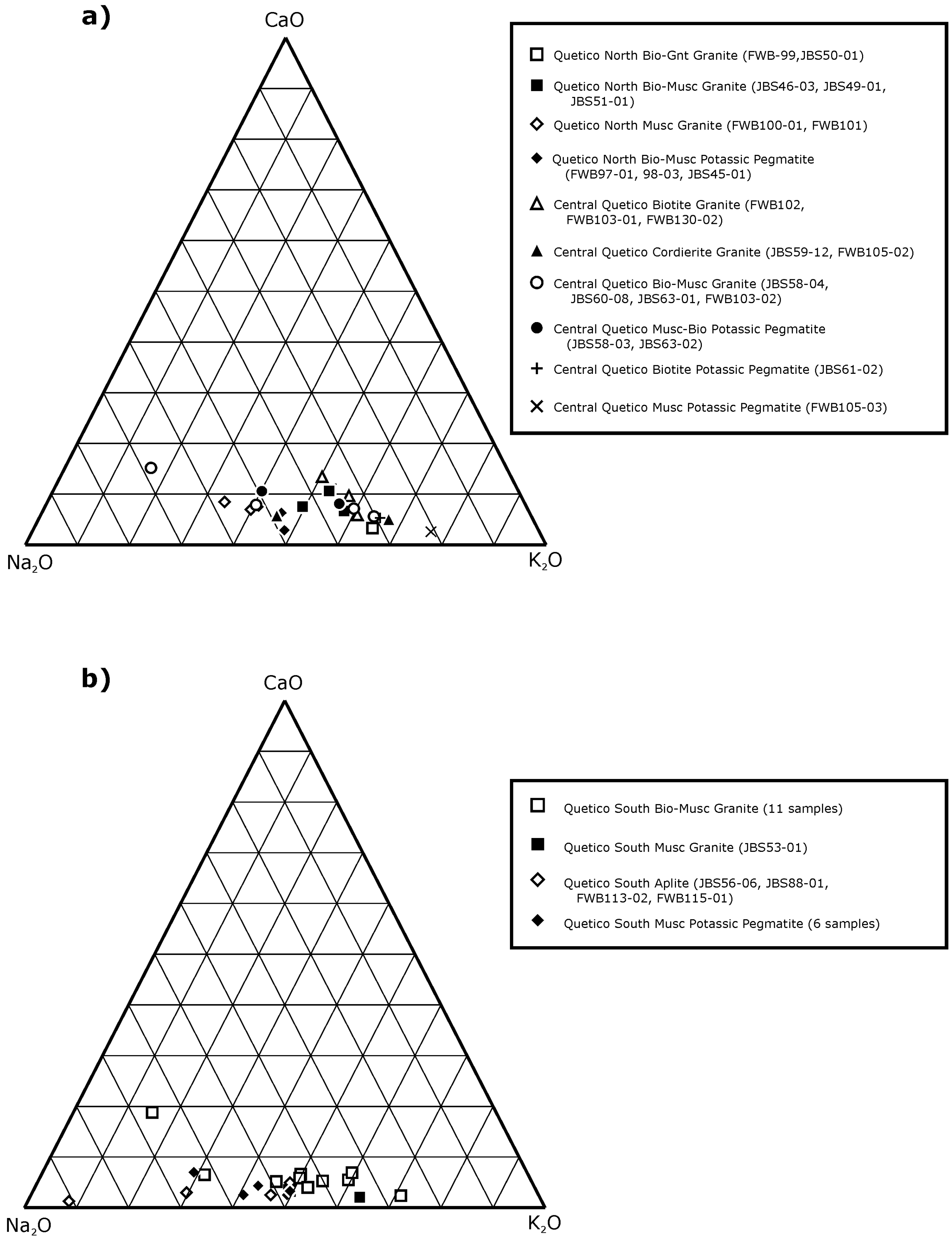


Figure 78. CaO–Na$_2$O–K$_2$O diagrams for whole rock data from a) Quetico North and Central Quetico, and b) Quetico South.

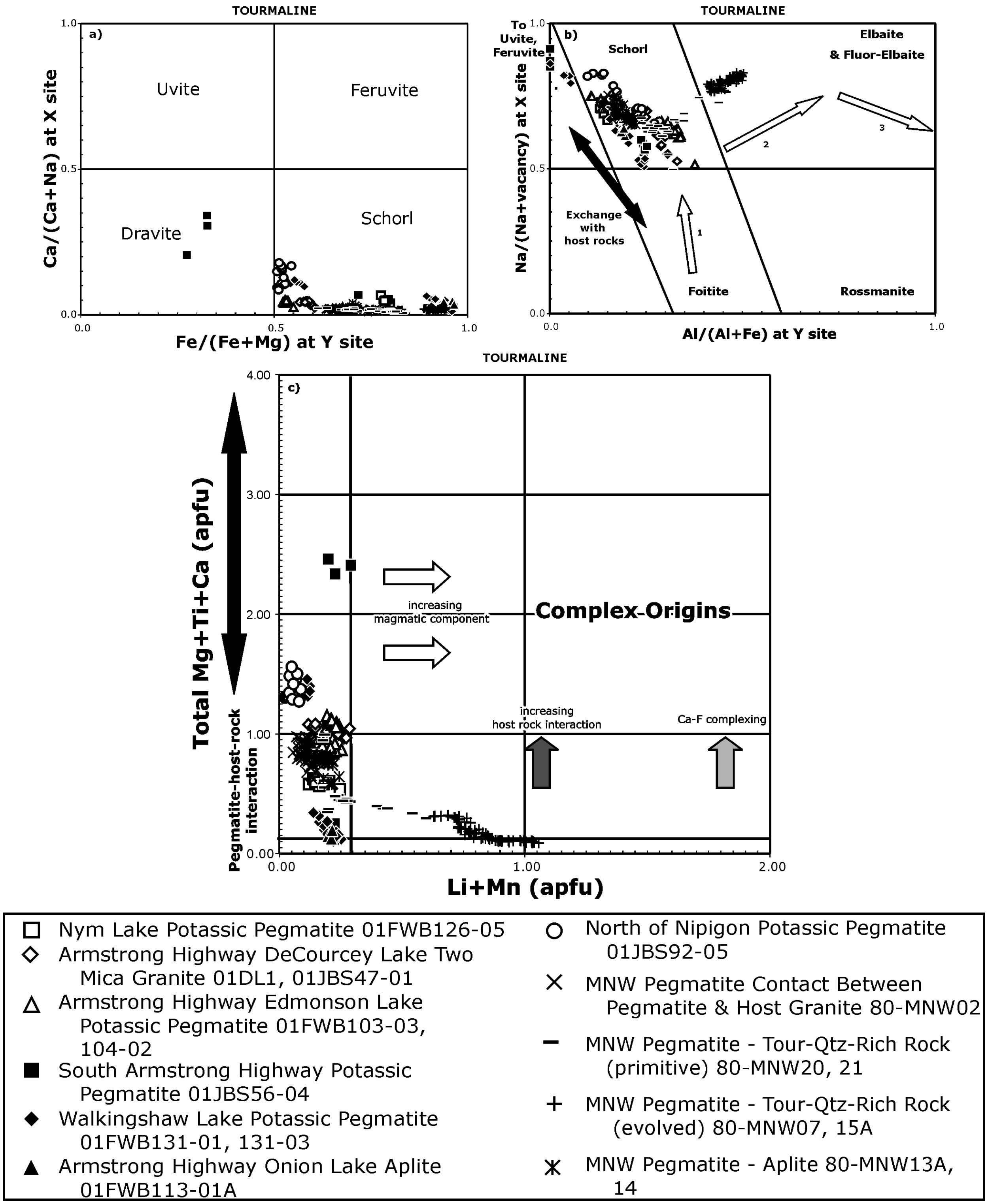


Figure 79. Tourmaline compositions from Nym Lake, Armstrong highway, Nipigon and the MNW pegmatite: a) Ca/(Ca+Na) at the X-site versus Fe/(Fe+Mg) at Y-site, b) Na/(Na+vacancy) at X-site versus Al/(Al+Fe) at Y-site, c) (Total Mg+Ti+Ca) versus (Li+Mn) (*apfu*).

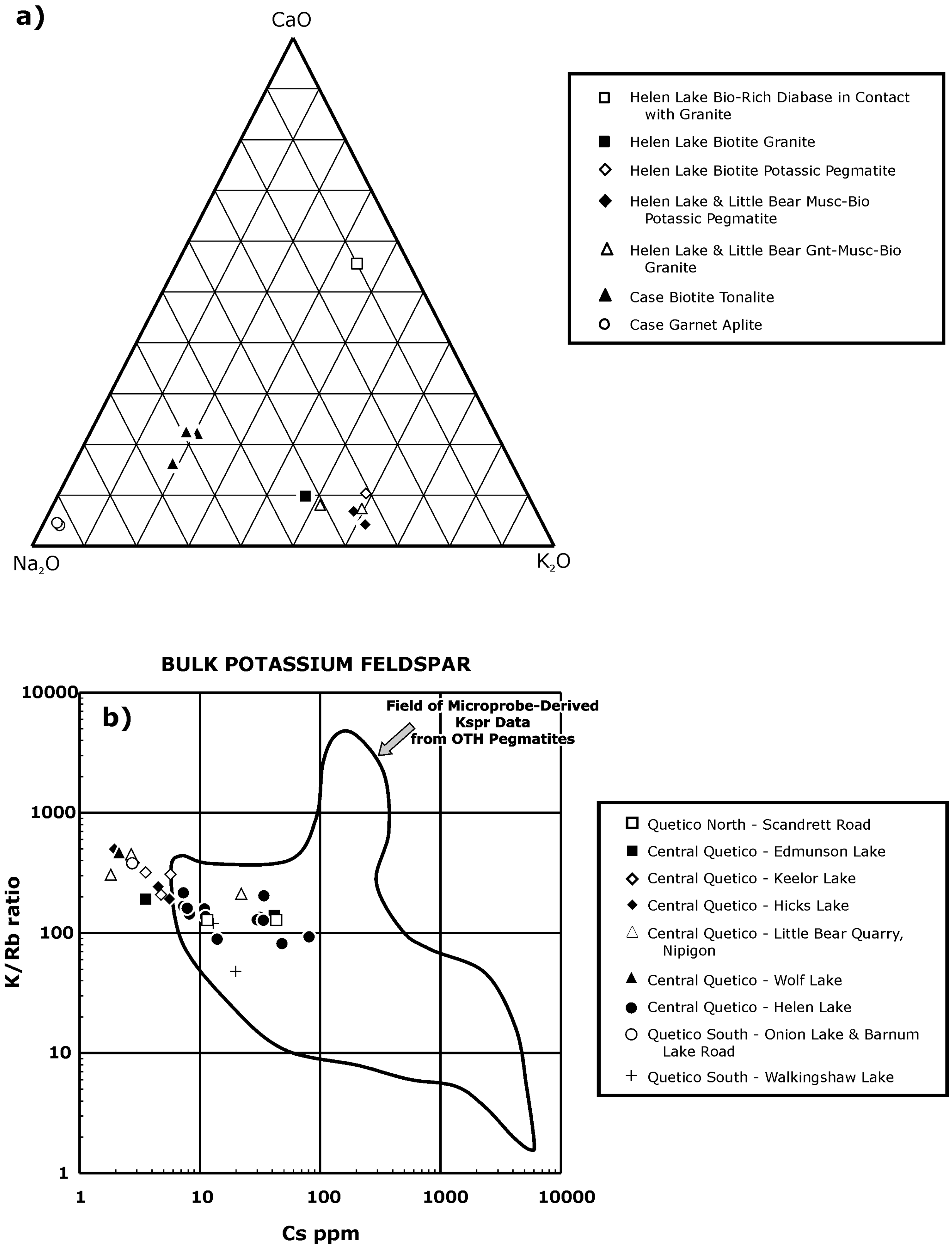


Figure 80. a) CaO–Na$_2$O–K$_2$O diagram for whole rock data from Helen Lake and Case pegmatite. b) K/Rb ratio versus Cs (ppm) for bulk potassium feldspar from Armstrong highway.

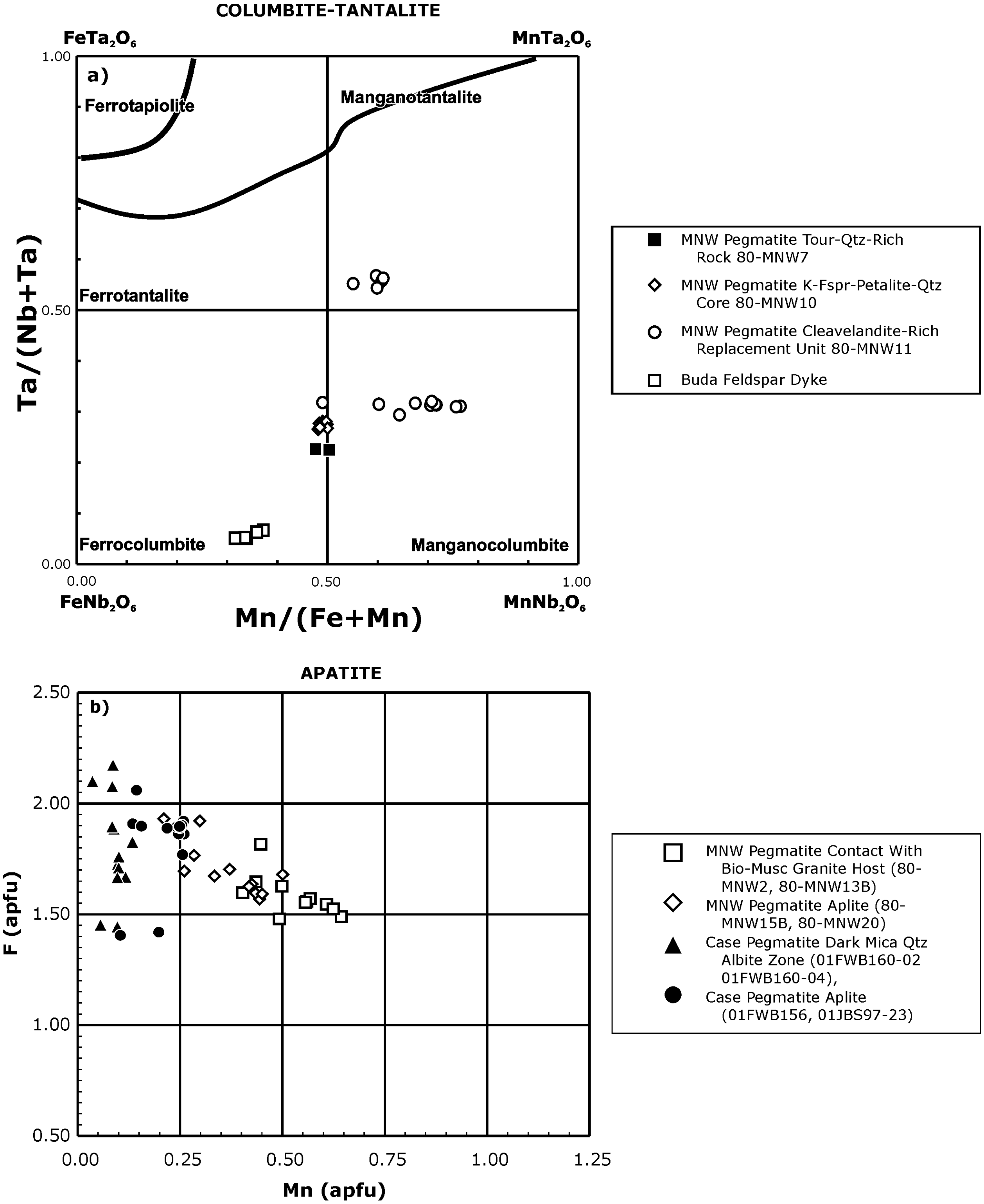


Figure 81. a) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals from the MNW pegmatite and Buda feldspar dike. b) F versus Mn (*apfu*) for fluorapatite from the MNW and Case pegmatite.

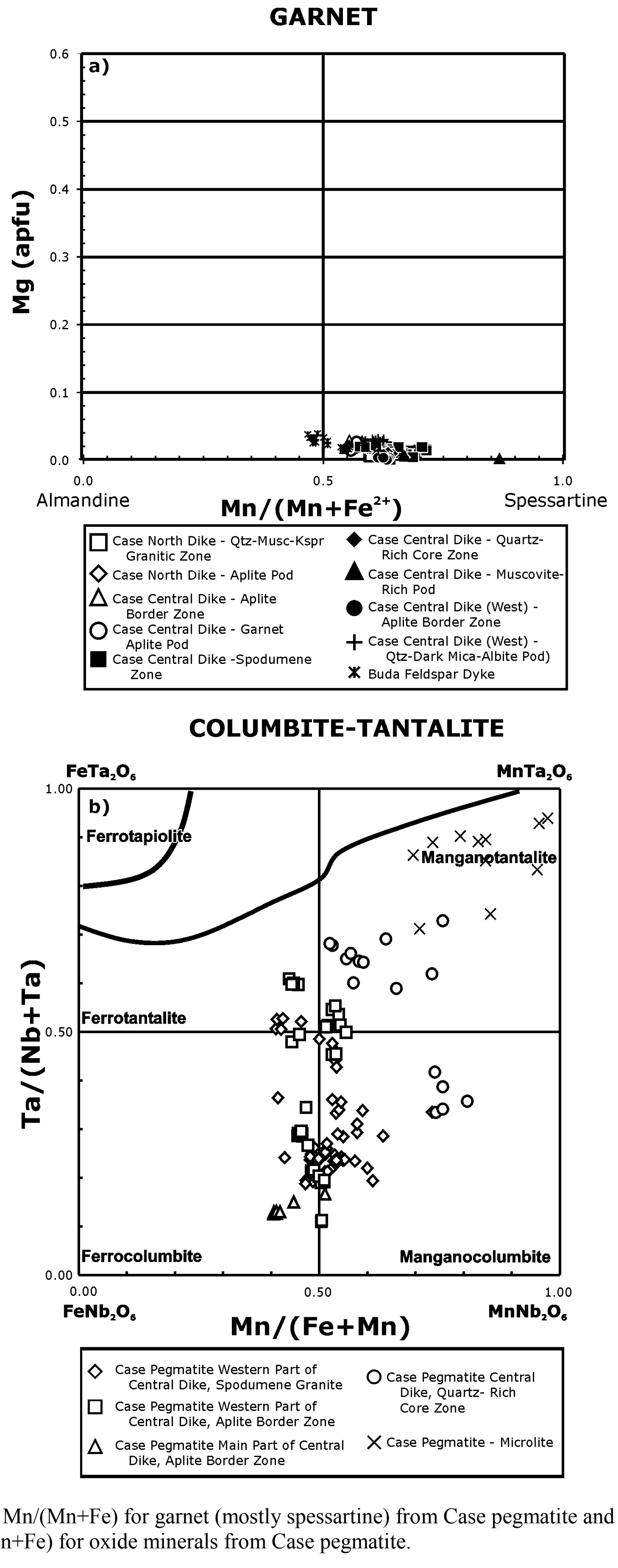


Figure 82. Mg (*apfu*) versus Mn/(Mn+Fe) for garnet (mostly spessartine) from Case pegmatite and Buda feldspar dike. b) Ta/(Ta+Nb) versus Mn/(Mn+Fe) for oxide minerals from Case pegmatite.

Appendix 2

Tables of Reference Information

Table 2. Definitions of common pegmatite terms.

A/CNK	a molecular ratio of $Al_2O_3/(CaO + Na_2O + K_2O)$ calculated from bulk whole rock analyses. A/CNK = (wt % Al_2O_3 in sample/101.96128)/[(wt % CaO in sample/56.08) + (wt % Na_2O in sample/61.979) + (wt % K_2O in sample/94.197)]
albitization	fine-grained white albite crystallizes along the rims and cleavage planes in the potassium feldspar due to alteration by late-stage fluids
Apfu or *apfu*	atoms per formula unit. *Apfu* are the units for the tiny subscripted numbers in a mineral chemical formula, e.g., the formula for almandine garnet is $Fe_3Al_2Si_3O_4$, which indicates that the mineral contains 3 *apfu* of iron, 2 *apfu* of aluminum, 3 *apfu* of silicon and 4 *apfu* of oxygen.
aplite	mostly composed of fine-grained equant white albite (sodium-plagioclase) with accessory minerals of quartz, garnet, tourmaline, green muscovite, tantalum-oxide minerals and fluorapatite
cleavelandite	textural term referring to albite plagioclase with a platy habit
electron microprobe	analytical equipment that is capable of analyzing the composition of a 1-2 μm spot on a mineral grain usually defocussed to 10-20 μm to avoid sample damage
end-member	a unique ideal composition of a mineral
evolved	a rock that has experienced a significant amount of fractionation before it crystallized, e.g., a pegmatite rich in cesium
exocontact	the chemically altered host rock surrounding a pegmatite. The exocontact commonly ranges in width from 1 cm to 1 m.
fertile granite	the parental granite to rare-element pegmatite dikes
fractionation	a magmatic differentiation process in which the magma is depleted in elements that enter the crystal structure of the solid crystals and enriched in elements that remain in the liquid. Increasing fractionation will result in a liquid enriched in rare-elements (e.g., Li, Cs, Ta).
graphic	intergrowth of a mineral with quartz, usually potassium feldspar with numerous quartz inclusions
greisen	a rock composed of approximately 50 vol % quartz and 50 vol % muscovite
leucogranite	a rock that contains 2 feldspars (plagioclase and potassium feldspar), quartz, mica and Al-rich minerals (e.g., garnet and tourmaline)
metasomatized host rocks	alteration of the composition of the pegmatite's host rock due to an influx of rare-element-enriched fluids. The host rock becomes enriched in highly mobile alkali elements (i.e., Li, Rb, Cs) and volatile components (i.e., B, F).
pegmatite zone	a volume of rock within an individual pegmatite that can distinguished from the rest of the pegmatite by its mineralogy and/or texture
peraluminous	Al-rich rock (A/CNK > 1.0)
plumose muscovite	muscovite + quartz intergrowth
potassic pegmatite	a rock that consists of blocky white potassium feldspar, books of muscovite and quartz
primitive	a rock that has experienced very little fractionation before it crystallized, e.g., a granite rich in magnesium and calcium
rare-element	Li, Rb, Cs, Nb, Ta, Sn, F, B, Be, Tl, Ge
rare-element pegmatite	very coarse-grained granite with rare-element-rich minerals (e.g., beryl, tourmaline, spodumene, tantalum-oxides) and pegmatitic textures (e.g., aplite, graphic intergrowths, internal zoning)

Table 3. Factors for conversion of ppm rare element to weight % rare element to weight % rare-element oxide, with example calculations.

Weight % Rare Element	**Conversion Factor**	**Weight % Rare Element Oxide**
Beryllium (e.g., 0.50 % Be)	2.778	0.50% × 2.778 = 1.39 wt % BeO
Cesium (e.g., 500 ppm Cs)	1.060	500 ppm = 0.05% × 1.060 = 0.053 wt % Cs_2O
Lithium (e.g., 2.55 % Li)	2.152	2.55% × 2.152 = 5.49 wt % Li_2O
Niobium (e.g., 325 ppm Nb)	1.431	325 ppm = 0.0325% × 1.431 = 0.0465 wt % Nb_2O_5
Tantalum (e.g., 755 ppm Ta)	1.221	755 ppm = 0.0755% × 1.221 = 0.092 wt % Ta_2O_5
Rubidium (e.g., 15 000 ppm = 1.5% Rb)	1.099	1.5% × 1.099 = 1.65 wt % Rb_2O

Element ppm / 10 000 = element %; element % × conversion factor = oxide wt %.

Table 4. Common pegmatite minerals found in Superior Province, Ontario in this study.

Pegmatite Minerals Found in Ontario			
Mineral	**Species**	**Simplified Composition**	**Formula**
Amblygonite		Li-phosphate	$LiAlPO_4(F,OH)$
Andalusite (in host rocks)		aluminosilicate	Al_2SiO_5
Apatite	- Fluorapatite	F-apatite	$Ca_5(PO_4)_3(F, OH)$
	- Chlorapatite	Cl-apatite	$Ca_5(PO_4)_3Cl$
Beryl		Be-silicate	$Be_3Al_2Si_6O_{18}$
Cassiterite		Sn-oxide	SnO_2
Columbite-Tantalite	- Ferrocolumbite	(Fe,Nb)-oxide	$FeNb_2O_6$
	- Ferrotantalite	(Fe,Ta)-oxide	$FeTa_2O_6$
	- Manganocolumbite	(Mn,Nb)-oxide	$MnNb_2O_6$
	- Manganotantalite	(Mn,Ta)-oxide	$MnTa_2O_6$
Cordierite			$(Mg,Fe)_2A_{l4}Si_5O_{18}$
Feldspar	- Albite	Na-plagioclase	$NaAlSi_3O_8$
	- Potassium feldspar	K-feldspar	$KAlSi_3O_8$
Ferrotapiolite		(Fe,Ta)-oxide	$FeTa_2O_6$
Holmquistite (in host rocks)		Li-amphibole	$Li_2(Mg,Fe^{2+})_3Al_2Si_8O_{22}(OH)_2$
Gahnite		Zn-oxide	$ZnAl_2O_4$
Garnet	- Almandine	Fe-garnet	$Fe_3Al_2(SiO_4)_3$
	- Spessartine	Mn-garnet	$Mn_3Al_2(SiO_4)_3$
	- Grossular	Ca-garnet	$Ca_3Al_2(SiO_4)_3$
	- Pyrope	Mg-garnet	$Mg_3Al_2(SiO_4)_3$
	- Andradite	(Ca,Fe)-garnet	$Ca_3Fe^{3+}_2(SiO_4)_3$

Table 4. Continued

Pegmatite Minerals Found in Ontario

Mineral	**Species**	**Simplified Composition**	**Formula**
Mica	- Muscovite		$KAl_2(Si_3Al)O_{10}(OH,F)_2$
	- Lepidolite	Li-mica	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$
	- Zinnwaldite	(Li, Fe)-mica	$K(LiAlFe^{2+})(AlSi_3)O_{10}(F,OH)_2$
	- Siderophyllite	Fe-biotite	$K(Fe^{2+}{}_2Al)(Al_2Si_2)O_{10}(F, OH)_2$
	- Biotite		$K(Mg,Fe^{2+})_3(Al,Fe^{3+})Si_3O_{10}(OH, F)_2$
	- Phlogopite	Mg-biotite	$KMg_3(AlSi_3)O_{10}(F,OH)_2$
	- Nanpingite	Cs-mica	$Cs(Al,Mg,Fe^{2+},Li)_2(Si_3Al)O_{10}(OH, F)_2$
Microlite		(Ca,Ta)-oxide	$(Na,Ca)_2Ta_2O_6(O,OH,F)$
Molybdenite		Mo-sulphide	MoS_2
Monazite		REE-phosphate	$(Ce,La,Nd,Th)PO_4$
Montebrasite		Li-phosphate	$LiAlPO_4(OH,F)$
Petalite		Li-aluminosilicate	$LiAlSi_4O_{10}$
Pollucite		Cs-aluminosilicate	$(Cs,Na)AlSi_2O_6{\cdot}nH_2O$
Quartz			SiO_2
Rutile		Ti-oxide	TiO_2
Simferite		(Li, Mg)-phosphate	$Li(Mg, Fe^{3+}, Mn)_2(PO_4)_2$
Spodumene		Li-aluminosilicate	$LiAlSi_2O_6$
Strüverite		(Ti,Ta)-oxide	$(Ti,Ta,Fe^{3+})_3O_6$
Topaz		F-aluminosilicate	$Al_2SiO_4(F,OH)_2$
Tourmaline	- Schorl	(Na,Fe)-tourmaline	$NaFe_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$
	- Dravite	(Na,Mg)-tourmaline	$NaMg_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$
	- “Fluor-dravite”	(Na,Mg,F)-tourmaline	$NaMg_3Al_6(BO_3)_3Si_6O_{18}(OH)_3F$
	- Elbaite	(Na,Li)-tourmaline	$Na(Al,Li)_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$
	- “Fluor-elbaite”	(Na,Li,F)-tourmaline	$Na(Al,Li)_3Al_6(BO_3)_3Si_6O_{18}(OH)_3F$
	- Foitite	Fe-tourmaline	$\square(Fe_2Al)Al_6(BO_3)_3Si_6O_{18}(OH)_4$
	- Uvite	(Ca,Mg)-tourmaline	$CaMg_3(Al_5Mg)(BO_3)_3Si_6O_{18}(OH)_3F$
	- Feruvite	(Ca,Fe)-tourmaline	$CaFe_3(Al_5Mg)(BO_3)_3Si_6O_{18}(OH)_3F$
	- Liddicoatite	(Ca,Li)-tourmaline	$Ca(Li_2Al)Al_6(BO_3)_3Si_6O_{18}(OH)_3F$
Triphylite		(Li,Fe)-phosphate	$LiFePO_4$
Wodginite		(Mn,Sn,Ta)-oxide	$MnSnTa_2O_8$
Xenotime		Y-phosphate	YPO_4
Zircon		Zr-silicate	$ZrSiO_4$

$\square$ = vacancy at the *X*-site in tourmaline

Table 5. Physical properties of common pegmatite minerals found in Ontario.

Pegmatite Minerals Found in Ontario	
Mineral	**Important Physical Properties**
Albite	White, light pink and occasionally with "moonstone" appearance due to peristerite intergrowth. Transparent to translucent. Hardness 6 to 6.5. Albite has distinctive striations due to polysynthetic twinning that distinguishes the mineral from potassium feldspar of similar colour. Albite can occur as coarse blocky crystals in the quartz-rich core zone of sodic pegmatites or in graphic intergrowths with quartz. The cleavelandite variety of albite is very common in rare-element pegmatites where it is evident as radiating masses of tabular crystals.
Almandine and Spessartine Garnet	Euhedral, dodecahedral (diamond-shaped faces) or trapezohedral crystals are common; also occurs as rounded grains and in massive aggregates. Colour for almandine is red to magenta; spessartine has a distinctive orange. Luster is vitreous and hardness 7 to 7.5.
Amblygonite	Found as coarse subhedral crystals and rounded nodules. Colour is typically milky white but also light yellow; transparent to translucent. Luster is greasy to vitreous. Three cleavages (distinct to perfect). Crystal shape and colour may result in misidentification as plagioclase or white potassium feldspar. Amblygonite has lower hardness (5.5 to 6) and recessively weathers with a distinctive chalk-like crust, unlike the feldspars.
Andalusite	Prismatic crystals, fibrous aggregates and granular masses. Commonly light to deep pink in peraluminous granite and pegmatite. However, part or all of the crystals may be replaced by sericite and thus crystal shape of the pseudomorphs is the only means of recognition. Vitreous to dull luster; translucent to transparent. Hardness 6.5 to 7.
Apatite	Commonly found as hexagonal prisms, generally less than 1 cm in diameter. Colour is typically sea-green to blue-green but also includes brown, blue and orange. Transparent to translucent with a vitreous luster. Distinguished from beryl by its lower hardness and recessive weathering with chalk-like rind.
Beryl	Typical as euhedral to subhedral, rectangular-shaped prisms elongate along c-axis and basal hexagonal sections. Colour is variable but typically pale green, white and less commonly yellow, pink and blue. Hardness 7.5 to 8. Cleavage is often indistinct as a basal parting.
Cassiterite	Dark brown to black in Superior Province pegmatites. Luster is a distinctive adamantine to metallic in short prismatic and dipyramidal crystals that a transparent to opaque. Two cleavages present but commonly not apparent due to fine grain size. Hardness 6 to 7.
Columbite-Tantalite	Black, red-brown, black-brown crystals that are prismatic to tabular; also granular and massive. Platy crystals may have striations parallel to c-axis; luster is submetallic; one distinct cleavage. Translucent to opaque. Hardness 6 to 6.5. Fine-grained columbite-tantalite may be confused with black tourmaline of similar grain size. Columbite-tantalite is non-magnetic and hence distinction from magnetite can readily be made in the field.
Cordierite	Pale to dark blue, violet, grey, grey-green, grey-brown; vitreous, transparent to translucent. Hardness 7 to 7.5. Cordierite is commonly euhedral to subhedral in peraluminous granite and rare-element pegmatite in which rectangular to distinctive pseudohexagonal sections may be observed. Cordierite is susceptible to hydrothermal alteration and can be completely replaced by a soft intergrowth of secondary chlorite, muscovite, garnet and rare beryl. In this case, crystal shape of the cordierite pseudomorphs is the only means of mineral identification.
Ferrotapiolite	Black to brown, generally fine grained and typically intergrown with other black, Ta-Nb-bearing oxide phases. Hence, identification usually based upon electron microprobe analysis. Luster is submetallic, adamantine and resinous. Hardness 6 to 6.5.

Table 5. Continued

Pegmatite Minerals Found in Ontario	
Mineral	**Important Physical Properties**
Holmquistite	Slender, needle-like prisms and mats of radiating fibrous crystals with distinctive violet to deep blue colouration. Vitreous luster, hardness 5 to 6 and two cleavages intersecting at 54 and 126 degrees that usually are only seen in thin section. Generally found in mafic metavolcanic host rocks within 100 m of a rare-element pegmatite body.
Lepidolite	Typically occurs as purple to pink fine grained aggregates; may also be colourless, white, grey and yellow. Well-formed pseudohexagonal crystals are rare. Luster pearly to vitreous. Hardness 2.5 to 3 and perfect basal cleavage with flexible and elastic sheets.
Microlite	Brown, yellow, green and reddish octahedral crystals and granular masses. Vitreous to greasy, translucent to opaque and rarely transparent. Hardness 6 to 6.5. Microlite is difficult to recognize in the field owing to its fine grain size and common occurrence as late stage replacement patches and veins in primary Ta-Nb-bearing oxide phases.
Molybdenite	Found as tabular and prismatic hexagonal crystals or a scaly aggregates. Metallic luster with lead grey colour and blue-grey streak. Hardness 1 to 1.5. A common accessory mineral in rare-element pegmatites.
Petalite	Typically found as white, irregular masses or less common as tabular crystals elongated along {100} and flattened on {010}. Pink, grey and orange colors are less common. Polysynthetic twinning on {001} may give the false impression that plagioclase is present. However, petalite has only two cleavages ({001} perfect and {201} good that meet at 37 degrees) compared to the three cleavages for plagioclase that meet approximately at right angles.
Pollucite	Colorless, white or grey, vitreous, isometric crystals or more commonly as anhedral masses. Transparent to translucent. Hardness 6.5 to 7. Luster is vitreous to slightly greasy. Difficult mineral to identify in the field due to white color and massive nature that could easily be mistaken for quartz. Pollucite is susceptible to hydrothermal alteration and may be traversed by a polygonal network of mica-rich veins which is distinctive from quartz.
Potassium feldspar	Crystals usually short prismatic, tabular or elongated parallel to a- or c-axis. Commonly light pink but in peraluminous granites and pegmatites the color is typically white; blue grey and green (amazonite) colors less prevalent. Mineral has three cleavages that meet approximately at right angles. Perthitic texture with albite exsolution lamellae (tiger stripes) is widespread.
Rutile	Red, red-brown, brown, yellow and black short prismatic striated crystals. Hardness 6 to 6.5. Metallic to adamantine luster. Transparent to translucent.
Spodumene	Long prismatic crystals typically flattened and striated parallel to {100}. Colors most commonly pale green but also white, pink and orange. Luster is vitreous and pearly along the two predominate cleavages that meet at 87 degrees. A splintery appearance is caused by intersection of the two prismatic cleavages with a well developed basal parting.
Topaz	Occurs as well developed prismatic crystals in radiating and columnar aggregates. Also found in granular masses. Striations are oriented parallel to the c-axis. Colourless, white, pale blue, yellow, yellow-brown and orange. Luster is vitreous, transparent to translucent and hardness 8. One perfect cleavage on {001}. Massive white topaz is difficult to distinguish from quartz particularly if both minerals are transparent. Topaz may be variably replaced by fine-grained muscovite due to interaction with hydrothermal fluids.

Table 5. Continued

Pegmatite Minerals Found in Ontario	
Mineral	**Important Physical Properties**
Tourmaline group	Habit is typically prismatic and striated parallel to the long axis. Cross-sections are a distinctive rounded triangular shape. Also occurs in fibrous and massive aggregates. Colour is quite variable but is most commonly black to brown in Superior Province peraluminous granites and pegmatites. Also pink, green, blue or colourless in highly evolved pegmatites. Luster is vitreous, hardness 7 to 7.5. No cleavage present.
Wodginite	Red-brown, dark brown and black; present as sphenoidal and irregular grains generally between 1 and 10 mm diameter. Submetallic luster. Difficult to recognize in field especially when fine-grained and intergrown with other black Ta-Nb-bearing minerals. Recognition thus is largely dependent upon electron microscope analysis.
Zircon	Red, red-orange, red-brown, yellow-brown, brown. Typically occurs as small euhedral crystals that are vitreous, greasy to adamantine. Transparent to translucent. Hardness 7.5.

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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