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A Review of Rare-Element (Li-Cs-Ta) Pegmatite Exploration Techniques for the Superior Province, Canada, and Large Worldwide Tantalum Deposits

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Abstract — Rare-element pegmatites may host several economic commodities, such as tantalum (Ta-oxide minerals), tin (cassiterite), lithium (ceramic-grade spodumene and petalite), and cesium (pollucite). Key geological features that are common to pegmatites in the Superior province of Ontario and Manitoba, Canada, and in other large tantalum deposits worldwide, can be used in exploration.

An exploration project for rare-element pegmatites should begin with an examination of a regional geology map. Rare-element pegmatites occur along large regional-scale faults in greenschist and amphibolite facies metamorphic terranes. They are typically hosted by mafic metavolcanic or metasedimentary rocks, and are located near peraluminous granite plutons (A/CNK > 1.0). Once a peraluminous granite pluton has been identified, then the next step is to determine if the pluton is barren or fertile. Fertile granites have elevated rare element contents, Mg/Li ratio < 10, and Nb/Ta ratio < 8. They commonly contain blocky K-feldspar and green muscovite. Key fractionation indicators can be plotted on a map of the fertile granite pluton to determine the fractionation direction: presence of tourmaline, beryl, and ferrocolumbite; Mn content in garnet; Rb content in bulk K-feldspar; and Mg/Li and Nb/Ta ratios in bulk granite samples. Pegmatite dikes with the most economic potential for Li-Cs-Ta deposits occur the greatest distance (up to 10 km) from the parent granite.

Metasomatized host rocks are an indication of a nearby rare-element pegmatite. Metasomatic aureoles can be identified by their geochemistry: elevated Li, Rb, Cs, B, and F contents; and by their mineralogy: presence of tourmaline, (Rb, Cs)-enriched biotite, holmquistite, muscovite, and rarely garnet.

Once a pegmatite dike has been located, the next step is to assess its potential to contain Ta mineralization. Pegmatites with the highest degree of fractionation (and thus the most economic potential for Li-Cs-Ta) contain blocky K-feldspar with >3,000 ppm Rb, K/Rb < 30, and >100 ppm Cs; and coarse-grained green muscovite with >2,000 ppm Li, >10,000 ppm Rb, >500 ppm Cs, and >65 ppm Ta. Pegmatites with Ta mineralization usually contain Li-rich minerals (e.g., spodumene, petalite, lepidolite, elbaite, amblygonite, and lithiophilite) and may contain Cs-rich minerals (e.g., pollucite, Cs-rich beryl). The ore minerals of Ta are commonly manganotantalite, manganocolumbite, wodginite, and microlite; Ta-rich cassiterite is also commonly present. Tantalum mineralization tends to occur in albitic aplite, mica-rich (lepidolite, cleavelandite ± lepidolite), and spodumene/petalite pegmatite zones.

Introduction

Two families of rare-element pegmatites are common in Ontario and Manitoba, Canada: Li-Cs-Ta enriched (LCT) and Nb-Y-F enriched (NYF).

LCT pegmatites are associated with S-type, peraluminous (Al-rich), quartz-rich granites. S-type granites crystallize from a magma produced by partial melting of preexisting sedimentary source rock (Shelley, 1993), and have high K/Na, low Ca and Na, high Al, and low oxidation state. They are characterized by the presence of biotite and muscovite, and the absence of hornblende.

NYF pegmatites are enriched in rare earth elements (REE), U, and Th in addition to Nb, Y, F, and are associated with A-type, subaluminous to metaluminous (Al-poor), quartz-poor granites or syenites (Černý, 1991a). A-type granites are anorogenic and occur in rift zones and stable continental areas (Shelley, 1993). A-type granites have high K+Na, F, and Zr, low Al and Ca, and high Fe/Mg. They are characterized by the presence of Fe-rich micas, amphiboles, and pyroxenes.

In Ontario, LCT pegmatites typically occur in the Superior province, whereas NYF pegmatites occur in the Grenville province (Goad, 1990; Breaks et al., 2003). This paper focuses on LCT pegmatites, because they may host several economic commodities such as tantalum (Ta-oxide minerals), tin (cassiterite), lithium (ceramic-grade spodumene and petalite), rubidium (lepidolite and K-feldspar), and cesium (pollucite), collectively known as rare elements, and ceramic-grade feldspar and quartz.

Tantalum has several properties that make it a valuable commodity: high boiling point (5,425°C), high melting point (2,997°C), resistance to corrosion, ductile, alloys well, superconductivity, low coefficient of thermal expansion, and high coefficient of capacitance (capacity to store and release an electrical charge; www.sog.com.au). The electronics industry is the single largest consumer of Ta, accounting for 60% of total demand (www.sog.com.au and www.tanb.org). Tantalum's major application in the electronics industry is in the manufacture of capacitors, which are found in cell phones, video cameras, and laptop computers. Tantalum is also used as an alloy in the manufacture of turbine blades for power stations and jet engines, where it improves the structural integrity of the blades at high temperatures.

Spodumene (Li-aluminosilicate) is used in many glass and ceramic manufacturing processes as a flux (www.cabot-corp.com). Lithia (Li_2O) is a very powerful flux, especially when used in conjunction with potassium and sodium feldspars. In ceramics, Li lowers thermal expansion and decreases the firing temperature. Lithium also lowers the viscosity of molten glass (makes it more fluid) and lowers the melting point of the glass. In pyroceramics (e.g., Corning Ware), the very low coefficient of thermal expansion of Li minimizes "thermal shock" and permits production of "from freezer to cooker" type cookware (Černý et al., 1996). Spodumene can also be used to produce mold flux powders for continuous casting of steel (www.cabot-corp.com).

Pollucite is an ore mineral of cesium. An average of 31 microprobe compositions of primary pollucite from the Tanco pegmatite, Manitoba, contains 32.19 wt.% Cs_2O (Černý et al., 1998). Cesium can be converted to cesium formate, which is used as a high-density specialty drilling and completion fluid for high-temperature, high-pressure hydrocarbon exploration and development wells (www.cabot-corp.com). Cesium formate is environmentally friendly because it is nontoxic, biodegradable, and water-soluble.

The goal of this paper is to explain pegmatite exploration techniques that may be applied by prospectors and major exploration companies alike. This paper reviews exploration techniques that have been previously discussed in the literature (Beus et al., 1968; Trueman and Černý, 1982; Černý, 1989a,b; Breaks and Tindle, 1997a; Breaks et al., 2003) and adds new techniques based on mineral chemistry. It also provides several examples of the application of these techniques in the Superior province, Ontario (Breaks et al., 2003). The paper concludes with a comparison of geological features between large Ta deposits worldwide and pegmatites in the Superior province.

Simmons et al. (2003) is an excellent textbook for beginners who want additional information on the fundamentals of pegmatites.

Overview of Parental Fertile Granites

Identification of parental fertile granites is an important exploration tool in the search for rare-element pegmatites, because their discovery can greatly reduce the search area (Breaks and Tindle, 1997a). Rare-element pegmatites derived from a fertile granite intrusion are typically distributed over a 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 group at the English River-Winnipeg River subprovincial boundary (Fig. 1; Breaks and Tindle, 1996, 1997a,b). This paper examines two 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. The granitic melt first crystallizes several different units (see rock types below), due to an evolving melt composition, within a single parental fertile granite pluton. The residual melt from such a pluton can then migrate into the host rock and crystallize pegmatite dikes. The following discussion of fertile granites and their genetic relationship with rare-element pegmatites is based on work by Černý and Meintzer (1988), and Černý (1989a,b, 1991b), and on field observations by the authors during the summer field seasons of 2001 to 2003.

Characteristics of a Fertile Granite

Fertile granites differ from barren (common) granites in their geochemistry, mineralogy, and texture. Fertile granites tend to be large plutons or batholiths, typically greater than 10 km^2 in outcrop area (Breaks and Tindle, 1997a). They are silicic (quartz rich) and peraluminous (A/CNK > 1.0), resulting in crystallization of Al-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, and Ca, and have variable K_2O/Na_2O ratios (Černý and Meintzer, 1988). Fertile granites are slightly enriched in rare

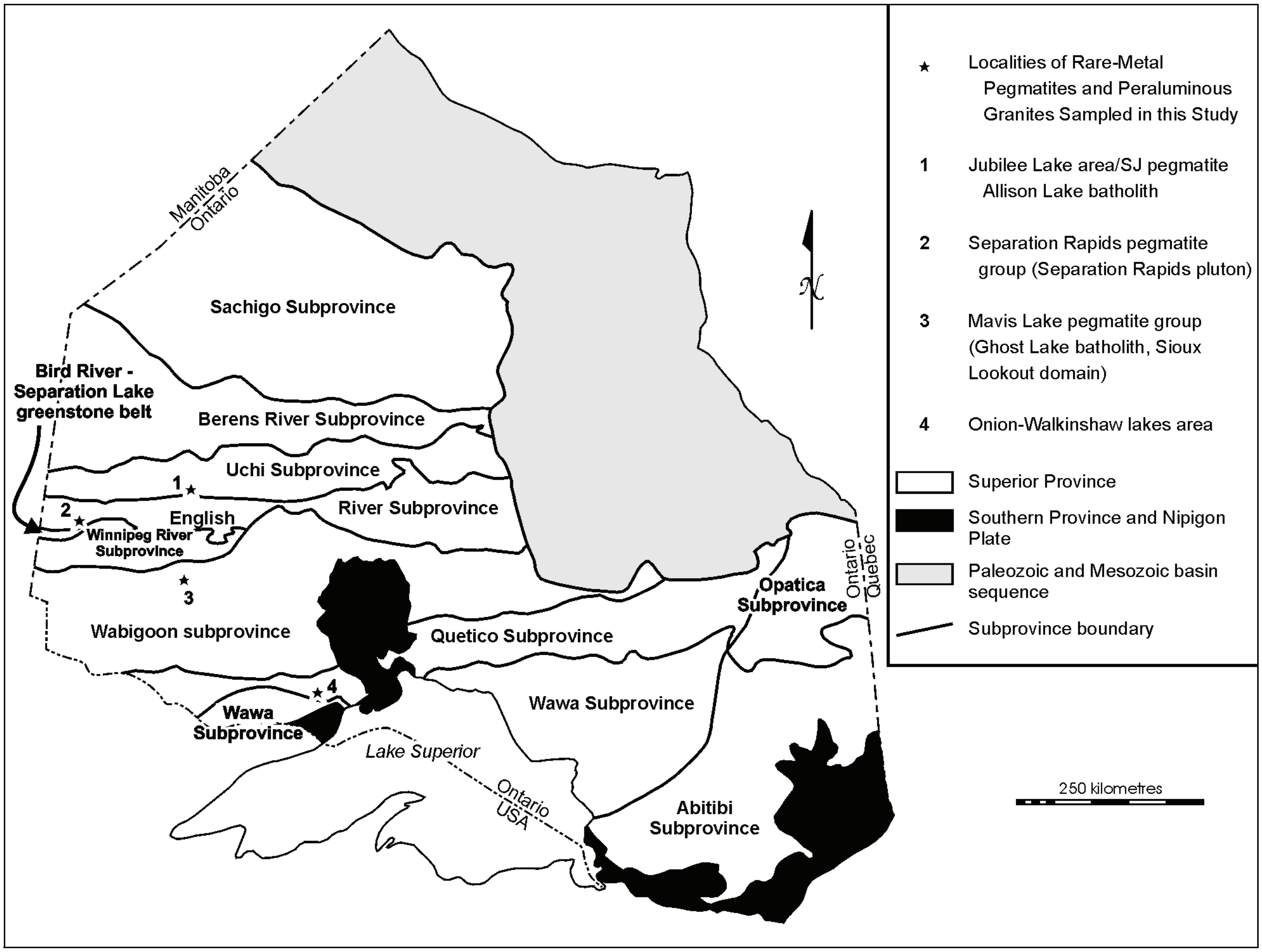

Fig. 1. Location of peraluminous fertile granites and rare-element pegmatites from Ontario examined in this study.

elements (Table 1), and have a wider range of accessory minerals than barren granites. Barren granites contain biotite and/or silver-colored muscovite as their minor minerals, and apatite, zircon, and titanite as accessory minerals, whereas fertile granites may contain 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 (Nb-oxide mineral), and Li-bearing tourmaline (Breaks and Tindle, 1997a).

Coarse-grained graphic textures are common in fertile granites: graphic K-feldspar, plumose muscovite (graphic muscovite), and rarely graphic tourmaline and graphic garnet. A graphic texture means that a mineral is intergrown with quartz. Sodic aplite may also be present in fertile granites (see below for description).

Rock Types

According to Černý and Meintzer (1988), fertile granite intrusions are typically heterogeneous, consisting of several units that are transitional to each other and in most cases are thought to be derived from a single batch of magma (Fig. 2a). Most of the rock types contain a characteristic assemblage of peraluminous accessory minerals. Černý and Meintzer (1988) have identified five possible rock types that may be part of a single fertile granite intrusion, from most primitive to most fractionated:

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 (dikes external to the fertile granite).

Table 1. Abundance and Ranges of Rare Elements in Crustal Rocks and Pegmatites

	Average Upper-Continental Crust (ppm)[1]	Internal Pegmatitic Granite Unit[2]						Separation Rapids Pluton[3]	
		Fine-Grained Leucogranite		Pegmatitic Leucogranite		Sodic Aplite			
		Mean (ppm)	Range (ppm)	Mean (ppm)	Range (ppm)	Mean (ppm)	Range (ppm)	Mean (ppm)	Range (ppm)
Be	3	4	<0.5–61	27	<0.5–604	6	1–34	6.2	3.3-25
Cs	3.7	8	<0.5–39	14	<0.5–51	16	<0.2–67	48	11.8-172
Ga	17	38	<10–81	20	<10–90	9	45–73	36	21-94
Li	20	81	1–1,400	51.7	6–288	82	7–324	235	71-1,629
Nb	25	24	<1–81	18	<1–135	-	45–138	66	32-120
Rb	112	305	33–1,050	473	32–5,780	169	9–559	890	341-1,240
Sn	5.5	9	<1–44	19	<1–112	13	2–25	62	10-652
Ta	2.2	4.5	2–8.5	2.7	0.5–8	-	3–435	19	6.6-29.7
K/Cs	7,630	11,000	794–78,400	7,880	246–38,500	3,020	166–14,900	852	35-1,526
K/Rb	252	159	42–418	165	13–576	85	24–332	34	0.5-51
Nb/Ta	11.4	5	0.1–11.9	1.71	0.1–7.17	-	0.32–0.62	4.5	0.9-6.9

Notes
[1]Data from Taylor and McLennan (1985).
[2]Internal units of fertile granites in the Superior province; data from Černý and Meintzer (1988).
[3]Fertile parent granite of the Separation Rapids pegmatites; data from Breaks and Tindle (2001) and the authors (unpublished).

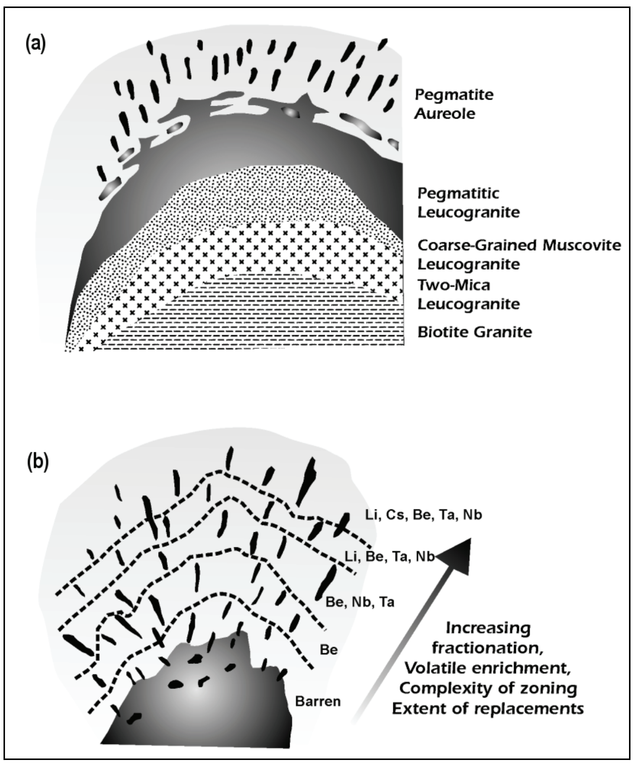

Fig. 2. Regional zoning in fertile granites and pegmatites (modified from Černý, 1991b): (a) regional zoning of a fertile granite (outward-fractionated) with an aureole of exterior lithium pegmatites; (b) schematic representation of regional zoning in a cogenetic parent granite + pegmatite group. Pegmatites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

Biotite granite is fine to coarse grained, locally with late, anhedral K-feldspar megacrysts. Biotite granite is normally a minor component of a fertile granite pluton, being the most primitive phase, and cannot be distinguished from barren biotite granite in hand sample. Biotite granite is enriched in Fe and Mg relative to the other five rock types, reflecting contamination by metasedimentary or mafic metavolcanic host rocks.

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

Pegmatitic leucogranite typically consists of megacrystic K-feldspar (5–150 cm) 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 (Zn-oxide) are accessory minerals. The matrix can locally contain patches of plumose muscovite + quartz intergrowths, with garnet or tourmaline in their centers. The pegmatitic leucogranite can also contain rare-element-rich pods.

Sodic aplite is mostly composed of fine-grained, equant white albite and quartz, with accessory garnet, tourmaline, green muscovite, Ta-oxide minerals, and fluorapatite. Aplites have a sugary texture and may crumble easily. They may be layered with stringers of garnet or tourmaline.

Potassic pegmatite usually consists of blocky white K-feldspar and local books of muscovite rimming a quartz core. The K-feldspar typically lacks quartz intergrowths. Garnet, tourmaline, beryl, ferrocolumbite (Nb-oxide), and molybdenite appear sporadically in the central parts of potassic pegmatites. Potassic pegmatite differs from leucogranite in that it only contains one feldspar (K-feldspar), whereas pegmatitic leucogranite contains two feldspars (plagioclase and K-feldspar).

Rare-element-enriched pegmatite contains one or more rare-element-bearing minerals, such as spodumene, petalite, lepidolite, tourmaline, Cs-bearing beryl, Ta-oxide minerals, and pollucite. Sodic aplite, potassic pegmatite, and rare-element pegmatite may form dikes external to the fertile granite pluton.

Geochemical Evolution of Granite and Pegmatite Magmas

Granitic magma is produced by melting of preexisting sedimentary rocks to produce S-type granites, or preexisting igneous rocks to produce I-type granites. S-type granite melts are usually enriched in rare elements, but I-type granite melts are not. S-type granites are characterized by peraluminous (Al-rich) compositions and commonly contain biotite and/or muscovite, whereas I-type granites are characterized by Ca-rich compositions and commonly contain hornblende and titanite.

Because the source rocks for granite magmas are composed of several minerals, each with their own melting temperatures, the entire rock does not instantly melt during heating. Rather, mixtures of minerals such quartz, alkali feldspars, and muscovite begin to melt at the eutectic temperature of the system, and other minerals such as biotite and cordierite melt later at higher temperature. This process is known as partial melting. Partial melting of a preexisting sedimentary source rock produces an S-type granitic melt, which may be enriched in Li, Cs, and Ta, due to the presence of metamorphic biotite (containing Li and Rb) and cordierite (containing Be; London, 2004). A high degree of partial melting of the source rock is needed to melt biotite and cordierite, and release these elements into the resulting granitic magma. Biotite- and cordierite-rich metasedimentary migmatites are common in the English River subprovince.

A crystallizing magma chamber will contain a mixture of solid crystals and liquid melt. Elements that prefer to partition into crystals over the coexisting melt phase are called compatible. Examples of compatible elements in granitic magmas are Si, Al, Na, and K, because they enter the crystal structure of common rock-forming minerals such as quartz, feldspar, and mica. Elements that partition preferentially into the melt phase over coexisting crystals are called incompatible, and include the large-ion lithophile elements (e.g., Cs^+, Rb^+, Ba^{2+}, and Sr^{2+}), high field strength elements (e.g., Ta^{5+}, Nb^{5+}, P^{5+}, REE^{3+}), and "pegmatophile elements" (e.g., Li^+, Be^{2+}, and B^{3+}; Simmons et al., 2003). These incompatible elements do not easily enter crystal structures of rock-forming minerals because large-ion lithophile elements have large ionic radii, high field strength elements have high ionic charge, and pegmatophile elements have a small ionic radii and low ionic charge.

Volatiles also behave incompatibly in granitic melts. Important volatiles in pegmatitic melts are H_2O, Li^+, F^-, BO_3^{3-}, and PO_4^{3-} (Simmons et al., 2003). These volatile components act as a fluxes, reducing the crystallization temperature of pegmatite minerals. They also promote the crystallization of a few large crystals from a melt and increase the ability of the melt to travel greater distances. This results in pegmatite dikes with coarse-grained crystals occurring in country rocks considerable distances from their parent granite intrusions.

Fractionation of a granitic melt is an important process in concentrating incompatible elements. The first product to crystallize during fractional crystallization of a granitic melt is a barren granite composed of common rock-forming minerals (i.e., quartz, K-feldspar, plagioclase, and mica). This type of granite is very common in the Superior province of Ontario. As these minerals crystallize and separate, the residual melt becomes increasingly enriched in incompatible rare elements and volatiles, and the resulting crystallization products evolve from barren to fertile granite.

The fertile granite melt continues to become enriched in incompatible rare elements and volatiles as minerals crystallize. The incompatible elements crystallize from the final residual melt into pegmatitic minerals, such as spodumene, tantalite, cassiterite, and pollucite.

Tantalum mineralization is usually associated with Li minerals in evolved pegmatites. Elevated Li and F contents in the silicate melt increase the solubility of Ta and delay tantalite crystallization (Linnen, 1998). Crystallization of Li (petalite or spodumene) or Li-F (lepidolite) minerals in the pegmatite, or diffusion of the Li and F out of the pegmatite and into the host rocks, results in a sudden drop in the solubility of Ta, with precipitation of columbite-tantalite. With increasing fractionation, the Nb/Ta ratio decreases and the composition of the columbite-tantalite group minerals evolves from manganocolumbite to manganotantalite.

In summary, several factors control whether or not a primitive granite melt will fractionate to produce a fertile granite melt and later a pegmatite melt:

- Composition of melt: Fertile granites are derived from a peraluminous S-type granitic melt.
- Degree of partial melting: Fertile granites require a high degree of partial melting of the source rock that produced the magma.
- Degree of fractionation: A high degree of fractionation is required to concentrate incompatible rare elements and volatiles in a granitic melt in order to crystallize a rare-element-rich pegmatite dike.

Exploration Techniques

Pegmatite exploration techniques can be divided into two types: grassroots and advanced exploration. The goal of grassroots exploration is to map a region looking for pegmatite dikes, and to evaluate their mineralization potential. Grassroots exploration includes examining the regional zoning of fertile granites and pegmatite dikes, and, using bulk whole-rock compositions and bulk K-feldspar and muscovite compositions, determining the degree of fractionation of the granite and pegmatite, and identifying the presence of Ta minerals. Grassroots exploration also includes bulk sampling of metasomatized host rocks, involving chip samples, channel samples, and drill core samples.

The goal of advanced exploration is to study the pegmatite dike in detail, such as the specific location of zones of Ta mineralization within a pegmatite dike. Advanced exploration includes metallurgical studies of pegmatite minerals using an electron microprobe and scanning electron microscope.

Regional Zoning in Fertile Granites and Pegmatite Dikes

Granite-pegmatite systems are largely confined to deep faults, preexisting batholithic contacts, or lithologic boundaries (Černý, 1989b). They typically occur along subprovince boundaries within the Superior province (e.g., the Uchi-English River and Wabigoon-English River subprovincial boundaries, and the 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 to post-tectonic, postdating the peak of regional metamorphism (Černý, 1989b). Granite-pegmatite systems are located in host rocks of the upper greenschist and lower amphibolite facies in low-pressure–high-temperature terranes (Abukuma-type; Černý, 1989b).

With increasing fractionation, the composition of the fertile granite changes from biotite granite in the deepest parts, to two-mica leucogranite, coarse-grained muscovite leucogranite, and finally to pegmatitic leucogranite with intercalated layers of sodic aplite and potassic pegmatite at the intrusion roof (Fig. 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, through 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, because the number of rock types exposed on the surface depends on the level of erosion.

The most fractionated part of the fertile granite intrusion (which may consist of any of the above five rock types) closest to the derived rare-element pegmatite dikes contains accessory rare-element minerals. For example, the interior beryl zone of the Separation Rapids pluton, parent to the Separation Rapids pegmatite group, contains accessory beryl, cassiterite, and ferrocolumbite, and rare ferrotantalite, manganocolumbite, and manganotantalite (Fig. 3; Breaks and Tindle, 1997a). The K-feldspar in the interior beryl zone of the Separation Rapids pluton is enriched in Rb (>4,000 ppm) and Cs (>50 ppm; Breaks and Tindle, 1997a). The interior beryl zone of the Ghost Lake batholith near Dryden, parent to the Mavis Lake pegmatite group, contains accessory beryl, and abundant tourmaline and Rb-Cs-enriched K-feldspar (Fig. 4; Breaks and Janes, 1991).

After most of the fertile granite pluton has crystallized, the residual fractionated granitic melt that remains generally concentrates at the roof of the pluton, and can intrude along fractures and faults in the host rock to form pegmatite dikes. These dikes increase in degree of fractionation, rare element content, volatile content, complexity of internal zoning, and extent of alteration (e.g., albitization of K-feldspar) with increasing distance from their parent granite (Fig. 2b; Černý, 1991b). With increasing distance from the parent fertile granite intrusion, the pegmatites contain the following index minerals: (1) beryl; (2) beryl and ferrocolumbite; (3) beryl, tantalite (ferrotantalite or manganotantalite), and Li-rich aluminosilicates (such as petalite or spodumene); and (4) beryl, manganotantalite, Li-rich aluminosilicates, and pollucite. Pegmatite dikes with the greatest economic potential (i.e., elevated Li, Cs, and Ta) occur the greatest distance (up to 10 km) from the parent granite because they contain abundant volatiles, which increase the mobility of the melt.

The peraluminous Separation Rapids pluton (4 km wide) is parent to the Separation Rapids pegmatites. Evidence for the genetic linkage between the Separation Rapids pluton and the Separation Rapids pegmatite group comes from geochronology. The age of the Separation Rapids pluton is 2644 ± 2 Ma (U-Pb on monazite; Labri et al., 1999), which is similar to a 2640 ± 7 Ma date obtained for the Greer Lake fertile granite, Manitoba (U-Pb on etched tantalite; Baadsgaard & Černý, 1993) within the same Bird River-Separation Rapids metavolcanic belt (Breaks et al., 1975). The undeformed petalite-subtype Marko's pegmatite has been dated at 2644 ± 7 Ma by U-Pb LA-MC-ICP-MS analysis of manganotantalite (Smith, 2001). Marko's pegmatite is the most evolved pegmatite in the Separation Rapids pegmatite group. The age of the Marko's pegmatite is similar to the U-Pb columbite-group age of 2640 ± 7 Ma for the petalite-subtype Tanco pegmatite, Manitoba (Baadsgaard and Černý, 2003). Thus, the age of the Separation Rapids pluton and the Marko's pegmatite are the same within analytical error, suggesting that they formed from the same intrusive event. The similarities between the ages of rare-element mineralization in the Separation Rapids pegmatite group in Ontario and the Winnipeg River pegmatite field in Manitoba further suggests that they formed from a common intrusive event within the Bird River-Separation Rapids metavolcanic belt.

There is a continuous evolution in composition from the central core of the Separation Rapids pluton to the petalite subtype pegmatites. The Separation Rapids pluton is internally zoned from a northern central core zone of biotite-muscovite granite, through an outer zone of pegmatitic granite, to a southern lobe of interior beryl zone (Fig. 3; Breaks and Tindle, 1997a). The pegmatites closest to the

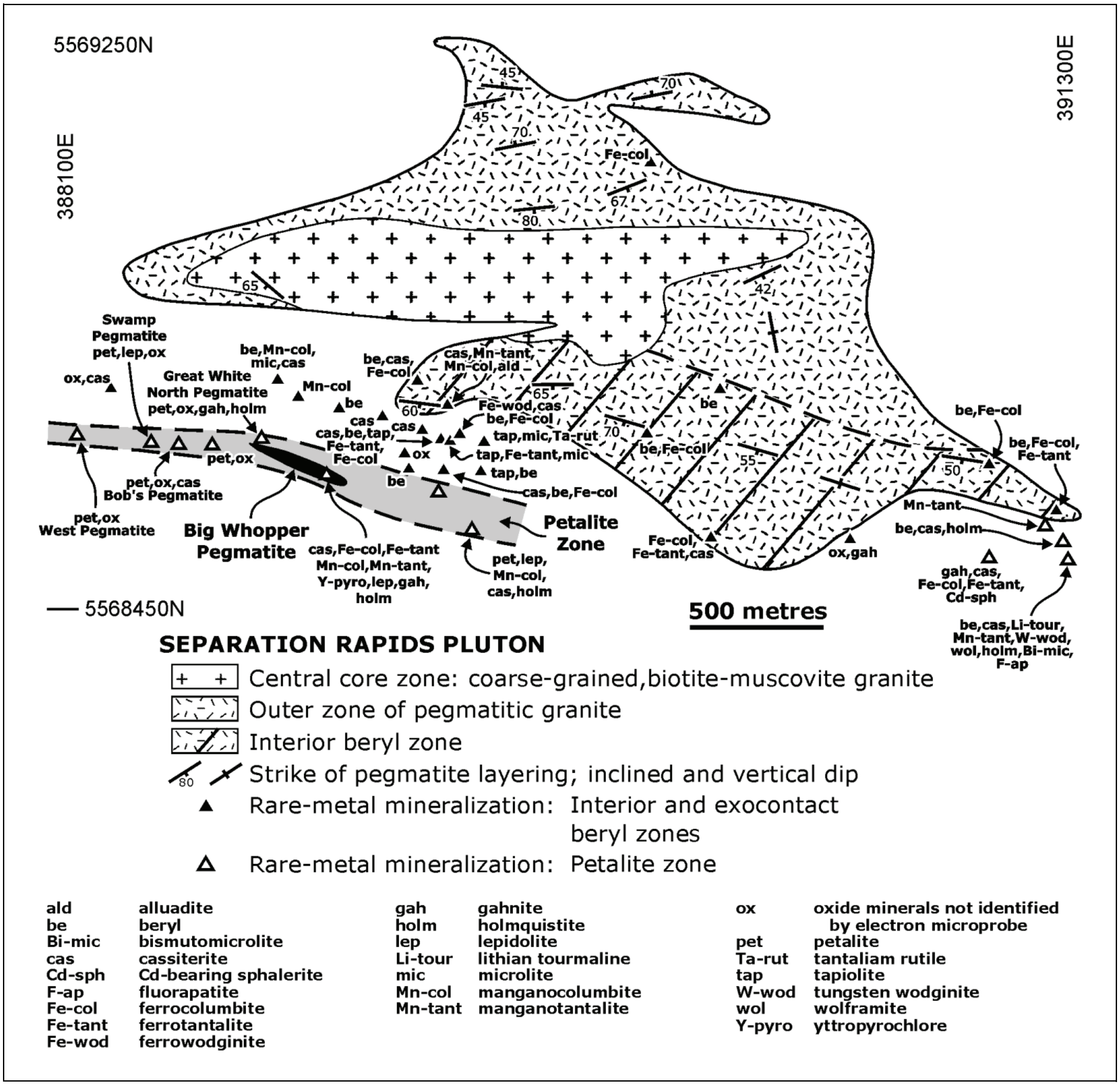

Fig. 3. Rare-element pegmatite zones and mineral occurrences of the southwest subgroup, Separation Lake area north of Kenora (modified from Breaks and Tindle, 1997a). UTM grid, zone 15, NAD 83.

Separation Rapids pluton are of the beryl-columbite subtype (exterior beryl zone) and the most fractionated pegmatites furthest from the pluton are of the petalite subtype (petalite zone), including the Big Whopper and Big Mack pegmatites. The Big Whopper occurs about 170 m and the Big Mack about 1.6 km from the parent Separation Rapids pluton (Breaks and Tindle, 1997a; Breaks et al., 1999).

The bulk composition of the K-feldspar also illustrates the genetic linkage between the Separation Rapids pluton and the Separation Rapids pegmatite group. There is an overlap in K/Rb ratios and Cs contents in K-feldspar from the Separation Rapids pluton, the eastern subgroup beryl zone, and the SW subgroup beryl zone (Breaks and Tindle, 1997a). The K-feldspar then decreases in K/Rb ratio and increases in Cs content to the SW subgroup petalite zone and to the eastern subgroup petalite zone. This evolutionary trend in K-feldspar compositions is continuous and does not contain any abrupt changes. The bulk composition of K-feldspar increases in total Rb and Cs contents from the northern part of the Separation Rapids pluton to the southwestern margin of the

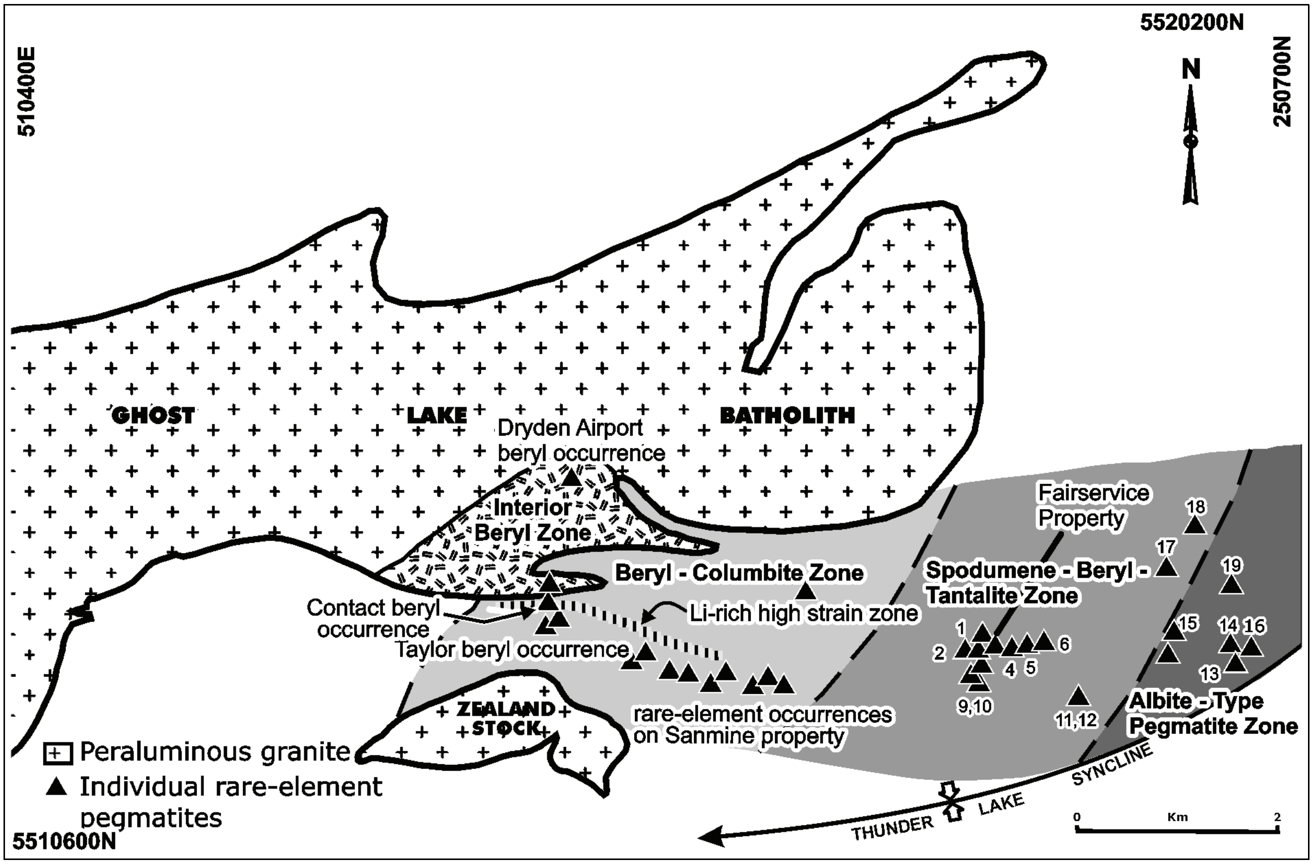

Fig. 4. Geology and distribution of zones of rare-element pegmatites in the Mavis Lake pegmatite group near Dryden (modified from Breaks and Janes, 1991). The numbers refer to the dikes that are part of the Fairservice pegmatite system. The pegmatites increase in fractionation from west to east. UTM grid, zone 15, NAD 83.

pluton in close proximity to the Big Whopper pegmatite (Breaks and Tindle, 1997a).

The peraluminous Ghost Lake batholith (80 km wide) is the parent to the Mavis Lake pegmatite group, which includes the albite-spodumene-type Fairservice pegmatites (Breaks and Janes, 1991; Breaks et al., 2003). The Ghost Lake batholith consists mostly of coarse-grained biotite and cordierite-biotite granite (Fig. 4). The eastern lobe of the Ghost Lake batholith is composed of several pegmatitic granite units: pegmatitic leucogranite, fine-grained leucogranite, and potassic pegmatite interlayered with sodic aplite (Breaks and Janes, 1991). The eastern lobe differs from the main mass by the abundance of tourmaline and books of primary muscovite, rarity of biotite, and the appearance of rare-element-rich minerals such as beryl, muscovite, and K-feldspar. The eastern lobe is known as the internal beryl zone. The pegmatites are regionally zoned with increasing distance from the Ghost Lake batholith, from an internal beryl zone, through beryl-columbite type pegmatites (beryl-columbite zone) and albite-spodumene-type pegmatites (spodumene-beryl-tantalite zone), to albite-type pegmatite zone (Breaks and Janes, 1991). The Fairservice pegmatites occur about 3.6 km west of the parent Ghost Lake batholith.

Using Whole-Rock Compositions as an Exploration Tool

Bulk whole-rock analysis is an excellent method to distinguish between barren granite and fertile granite, and to evaluate the degree of fractionation of a rare-element pegmatite. Regional bulk sampling and analysis of granites may provide a vector towards mineralized pegmatite dikes, because fertile granites become more enriched in rare elements closer to the pegmatite dikes. The rare element content in a pegmatite dike increases from the outermost zones to the innermost zones, so it is advisable to take bulk samples of the pegmatite zone surrounding the quartz core. Bulk whole-rock analysis can also be used to identify to the presence of Ta mineralization in a rock (especially aplites), because Ta-oxide minerals tend to be very small and difficult to identify with the naked eye.

In order to obtain a representative sample, the sample size should increase with the average grain size of the rock.

Each fine-grained aplite and granite bulk sample should fill a standard sample bag (12 17.5 inches), whereas each coarse-grained granite and pegmatite bulk sample should fill a 5-gallon pail. It may be difficult to obtain a large representative sample of a pegmatite with an average grain size greater than 10 cm. In this case, bulk sampling of K-feldspar and muscovite minerals is recommended (see below).

Table 1 provides some geochemical data that typify three 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 potentially fertile granite masses.

Major and trace element content in bulk whole-rock samples can be used to evaluate the degree of fractionation of fertile granites, aplites and fine-grained pegmatite zones. The molecular ratio A/CNK 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 Al-rich minerals, such as garnet and muscovite. Barren granites have a low A/CNK ratio, fertile granites a moderate, and rare-element pegmatites a high A/CNK ratio. The CaO-Na_2O-K_2O ternary diagram can be used to determine which alkali or alkali earth element is dominant. Metasomatized mafic or ultramafic rocks have high Ca contents, aplites have high Na contents, and muscovite-rich granites and potassic pegmatites have high K contents.

Fertile granites and pegmatites are enriched in rare elements, but to different degrees. Rare element contents that are at least three times that of the average upper continental crust (see Table 1) are of interest for pegmatite exploration. The bulk rare element content can be used to determine the degree of geochemical fractionation of the sample. The rare element content in a fertile granite increases with increasing degree of fractionation: Li, Be, B, F, P, Ga, Rb, Cs, Y, Nb, Sn, and Ta increase, but Ti, Sr, Ba, and Zr decrease (Černý and Meintzer, 1988). The ranges of trace elements in bulk whole-rock analyses of fertile granites are given in Table 2 (Černý, 1989a). Additional data for the best fractionation indicators (Be, Cs, Ga, Li, Nb, Rb, Sn, and Ta) are given in Table 1. Rare earth element abundances are low, usually less than 40 chondritic, and mostly between 20 chondritic and 1 chondritic (Černý and Meintzer, 1988; Černý, 1989a).

Ranges in trace-element ratios for fertile granites are given in Table 2 (Černý, 1989a). The following ratios are excellent fractionation indicators: K/Rb, K/Cs, Nb/Ta, and Mg/Li, all of which should be significantly lower than average upper continental crust (Table 1) in fertile systems. 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), whereas Nb/Ta for the average upper continental crust is 11.4. Pegmatites with the greatest economic potential for Li-Cs-Ta will have very low K/Rb, K/Cs, Nb/Ta, and Mg/Li ratios.

Table 2. Range of Bulk Trace Element Contents and Rare-Element Ratios in Fertile Granites (Černý, 1989a)

Trace Element	ppm	Element Ratio	ppm
Ti	<100–4,300	K/Rb	42–270
Sr	<1–445	K/Cs	1,600–15,400
Ba	6–900	K/Ba	48–18,200
Zr	<1–77	Rb/Sr	1.6–185
Li	1–3,540	Mg/Li	1.7–50
Be	1–604	Al/Ga	1,180–3,100
Ga	19–90	Zr/Hf	14–64
Rb	32–5,775		
Cs	3–51		
Y	3–102		
Sn	<1–112		

The Mg/Li ratio for bulk whole-rock analysis is one of the best indicators of the degree of fractionation of granites and pegmatites. According to Beus et al. (1968) and Černý (1989a), Mg/Li ratios less than 30 indicate a high degree of fractionation. An elevated Mg/Li ratio (e.g., Mg/Li = 50) indicates abundant Mg in a primitive rock (barren granite), whereas a low Mg/Li ratio (e.g., Mg/Li < 10) indicates elevated Li contents in an evolved rock (fertile granite). Spodumene pegmatites will have very low Mg/Li ratios (e.g., Mg/Li < 1.0). Lithium-rich rocks have more economic potential than Li-poor rocks because they tend to be associated with Ta mineralization.

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 its composition to form a metasomatic or dispersion halo. The chemically altered host rock surrounding a pegmatite is called the exocontact or the metasomatic aureole. The host rock becomes enriched in highly mobile alkali elements (i.e., Li, Rb, Cs) and volatile components (i.e., H_2O, B, F; Černý, 1989a). Beus et al. (1968) noted that a similar group of elements in dispersion halos are diagnostic of Ta-enriched pegmatites: B, Be, Li, Rb, Cs, and Sn.

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 most extensive Li anomaly associated with rare-element pegmatites delineated to date in Ontario has a width of 100 to 750 m and a length greater than 7 km (Pryslak, 1981). This halo surrounds the Fairservice pegmatite dikes 1 to 19 in the Mavis Lake area pegmatite field, near Dryden (Breaks, 1989). The dispersion halo in the mafic metavolcanic host rocks surrounding the Big Whopper pegmatite system at Separation Rapids extends for a minimum distance of 2 km (Breaks and Tindle, 1997a).

Lithium concentrations can have a wide range in the metasomatic halos. The mafic metavolcanic dispersion halo surrounding the Big Whopper pegmatite system has Li values that commonly exceed 80 ppm, with a maximum of 245 ppm (Breaks and Tindle, 1997a). Mafic metavolcanic rocks taken 0 to 2 cm from the contact of the Tot Lake pegmatite in the Dryden area contain 1,900 ppm Li (Breaks, 1989). The biotite-rich metasomatized mafic metavolcanic rocks in trench NA-5 of the North Aubry pegmatite contain 7,519 to 8,044 ppm Li within 4 cm of the pegmatite contact (Breaks et al., 2003). In contrast, the mean level of Li in mafic metavolcanic rocks away from rare-element mineralization in the Superior province of Ontario is 16 ppm Li (Breaks, 1989).

Elevated Cs contents (>1.06 wt.% Cs_2O) in highly altered metavolcanic host rocks immediately adjacent to pegmatites closely correlate with the presence of pollucite in the adjacent rare-element pegmatite system (Breaks and Tindle, 1997a). For example, the mafic metavolcanic metasomatized host rock surrounding the pollucite-bearing Marko's pegmatite, Separation Rapids, contains up to 1.06 wt.% Cs_2O (or 10,000 ppm Cs; Breaks and Tindle, 1997a), and host rocks 0 to 2 cm from the contact with the pollucite-bearing Tot Lake pegmatite contain up to 1.70 wt.% Cs_2O (Breaks, 1989).

The metasomatized host rocks immediately adjacent to a rare-element pegmatite (or exocontact) commonly have unusual mineral assemblages: holmquistite (lithium-amphibole), (Li, Rb, Cs)-rich "biotite" (more correctly phlogopite-siderophyllite or zinnwaldite), and/or tourmaline. These minerals occur in altered mafic metavolcanic host rocks due to the influx of rare-element fluids (London et al., 1996). All three minerals locally occur in the metasomatized mafic metavolcanic host rocks surrounding the North Aubry pegmatite, Ontario, and Tanco pegmatite, Manitoba (Morgan and London, 1987; Selway et al., 2000b). Metasomatic aureoles in clastic metasedimentary host rocks may contain tourmaline (e.g., Sandy Creek pegmatite, Ontario), biotite, and/or green muscovite (e.g., Superb Lake pegmatite, Ontario; Breaks et al., 2002, 2003).

The compositions of the metasomatic holmquistite, biotite, and tourmaline usually reflect a mixture of the composition of the host rocks and the pegmatite melt. Holmquistite has the appearance of purple/dark blue/indigo blue matted needles, and is an excellent exploration indicator because it only occurs in metasomatized host rocks within 10 m of a rare-element pegmatite, and can thus indicate pegmatites hidden at depth less than 10 m away (London, 1986). Holmquistite can be difficult to identify with the naked eye if it is in low modal abundance in a rock, but its dark to pale purple pleochroism is easy to identify in thin section.

A K/Rb versus Cs plot is useful for evaluating the degree of metasomatism of the host rock, because metasomatic "biotite" associated with rare-element pegmatites has elevated Rb and Cs contents, yielding values of K/Rb < 10 and Cs > 1000 ppm (Breaks et al., 2003).

The composition of metasomatic black tourmaline usually reflects the bulk composition of the host rock: e.g., metasomatized mafic metavolcanic rocks contain Ca-Mg-rich tourmaline (dravite, uvite, feruvite), whereas metasomatized metasedimentary host rocks contain Mg-Fe-rich tourmaline (dravite, schorl and foitite). 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).

Mineral Compositions as an Exploration Tool

As a granitic melt crystallizes and fractionates, minerals become enriched in rare elements: K-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 Li-Be-B-Ta-Cs-bearing minerals such as Li-rich minerals (spodumene, petalite, lepidolite, elbaite, liddicoatite, amblygonite/montebrasite, and lithiophilite), beryl (Be), and tourmaline (B). Pegmatites can be viewed as host rocks for ore deposits of rare elements. For example, manganotantalite, ferrotapiolite, microlite, and wodginite are the most common ore minerals of Ta; pollucite is the ore mineral of Cs; and spodumene and petalite are used in the making of ceramics and mold flux powders, and are ore minerals of Li.

The presence of common rock-forming minerals with elevated contents of rare elements in fertile granites is 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 predict whether rare-element-enriched pegmatite bodies are likely to be nearby.

K-feldspar

K-feldspar is abundant in barren granites, fertile granites, and pegmatites. K-feldspar tends to be pink and medium-grained in barren granites, whereas in potassic granites and pegmatites it tends to be white and blocky (>5 cm in size). K-feldspar in pegmatites can also be gray, peach, pink, or green. Graphic intergrowths of K-feldspar and quartz are common in fertile granites and pegmatites.

Bulk analysis of blocky K-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 five key elements in the bulk analysis of K-feldspar are K, Na, Si, Rb, and Cs. Elevated Na contents indicate albite contamination or misidentification of K-feldspar, and elevated Si contents indicate quartz contamination. Elevated Rb and Cs contents indicate that the feldspar is from a highly fractionated pegmatite (Table 3). For example, the most fractionated parts of the fertile Separation Rapids pluton have K-feldspars with >6,000 ppm Rb and >150 ppm Cs (Breaks and Tindle, 1997a). The K/Rb versus Cs plot for K-feldspar is one of the standard plots used to evaluate the degree of fractionation of a pegmatite (Fig.

5a), and is a measure of the degree of substitution of K by Rb in the K-feldspar crystal structure. One advantage of using the K/Rb ratio is that it is not affected by minor amounts of albite contamination, because albite incorporates neither element in its crystal structure. Pegmatites with the highest degree of fractionation (and thus the greatest economic potential for Li-Cs-Ta-enrichment) contain white blocky K-feldspar with >3,000 ppm Rb, K/Rb < 30, and >100 ppm Cs (Table 3).

Bulk analysis of K-feldspar is an excellent tool to determine the direction of regional fractionation within a fertile granite intrusion and pegmatite dikes. K-feldspar samples should be collected from the most fractionated zone within each outcrop. K-feldspar samples from quartz pods in fertile granites tend to be more enriched in Rb and Cs than the rest of the fertile granite (e.g., biotite granite zone). Similarly, K-feldspar samples from the interior pegmatite zones are usually more enriched in Rb and Cs than samples from the exterior zones.

Careful sample preparation of bulk K-feldspar samples is important to the interpretation of the data. Samples for bulk analysis must be pure, because graphic quartz and albitization can dilute the K, Rb, and Cs contents, and muscovite alteration can raise Rb and Cs. It is recommended that each chip of K-feldspar be checked under a microscope or a hand lens to remove contamination. Microprobe analysis of K-feldspar commonly gives different results from bulk analysis, because the microprobe can avoid analysis of albitic perthitic lamellae and microscopic sericite alteration. Nevertheless, bulk analysis is preferred over microprobe analysis for grassroots exploration because of time and cost implications.

Bulk K-feldspar compositions were used as an exploration tool for the Allison Lake batholith fertile granite, east of Red Lake, Ontario (Fig. 6; see below for more detailed discussion). Bulk K-feldspar samples were collected throughout the batholith. K-feldspar analyses with >1,000 ppm Rb, >50 ppm Cs, and K/Rb < 100 indicate the batholith's fertile status, but they only occur along the western contact zone and the tail of the batholith (see fig. 35 of Breaks et al., 2003). The central and eastern parts of the batholith have bulk K-feldspar analyses with 322 to 909 ppm Rb, 4 to 29 ppm Cs, and K/Rb = 119 to 357, which are not as favorable as the previous analyses (Tindle et al., 2002b). Thus, the batholith is geochemically fractionated from east to west, and the most fractionated part of the batholith is the western contact zone and the tail. The area to the west of the batholith has the greatest potential to contain rare-element pegmatite dikes.

Micas

The color and grain size of muscovite changes with increasing fractionation: muscovite in barren granites tends to be silver colored and medium grained, whereas muscovite in fertile granites and pegmatites tends to be green (but may also be brown, silver, and rarely pink) and coarse grained (>2 cm across). The green muscovite usually has the composition of lithian muscovite. Zinnwaldite is an uncommon Fe-Li mica that ranges in color from brown to silver to green. In highly fractionated pegmatites, green muscovites may have thin rims of lepidolite (Li mica). Generally, lepidolite is purple mica in highly fractionated pegmatites. With increasing fractionation, the composition of the mica will change from muscovite to lithian muscovite to lepidolite. Thus, mica from the innermost pegmatite zones should be more Li-rich than mica in the outermost zones.

Bulk analysis of muscovite books is also an excellent exploration tool because it occurs in both fertile granites and rare-element pegmatites, and is a good indicator of possible Ta mineralization (Gordiyenko, 1971; Černý, 1989a; Morteani and Gaupp, 1989). However, this technique is limited because fertile granite may contain only fine- to medium-grained rather than coarse-grained muscovite, which may make collecting enough sample for bulk analysis very time consuming. The five key elements in bulk analysis of muscovite are: Li, K, Rb, Cs, and Ta (Table 3). The Ta versus Cs plot (Fig. 7) is an excellent exploration tool, because pegmatites containing muscovite with >65 ppm Ta and >500 ppm Cs have a high probability of containing Ta-Nb mineralization (Gordiyenko, 1971; Morteani and Gaupp, 1989). Tantalum-oxide inclusions between muscovite sheets can produce artificially high tantalum values, and thus samples should be screened with a microscope before submitting for bulk analysis.

In addition to muscovite, some pegmatites also contain lepidolite, rich in Li, Rb, and Cs. 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. Because it may be difficult to find sufficient coarse-grained lepidolite suitable for bulk analyses, and Rb and Cs contents may exceed maximum detection limits for XRF, an electron microprobe may be better suited for analysis of lepidolite and fine-grained primary muscovite. The main limitation of electron microprobe analysis of micas is that Li cannot be determined except with specially equipped instruments.

Table 3. Ranges of Compositions of Bulk K-Feldspar and Muscovite Analyses

K-Feldspar		**Rb (ppm)**	**Cs (ppm)**	**K/Rb**	
Barren granite		<400	<10	>150	
Fertile granite		500–3,000	20–100	30–150	
Rare-element pegmatite		>3,000	>100	<30	
Muscovite	**Li (ppm)**	**Rb (ppm)**	**Cs (ppm)**	**K/Rb**	**Ta (ppm)**
Fertile granite	200–500	1,000–1,500	10–100	50–100	10–65
Beryl-type pegmatite	500–2,000	1,500–10,000	100–500	20–50	10–65
Spodumene-subtype pegmatite	>2,000	>10,000	>500	<20	>65

Note

Data from Tindle et al. (2002b) and unpublished data of the authors.

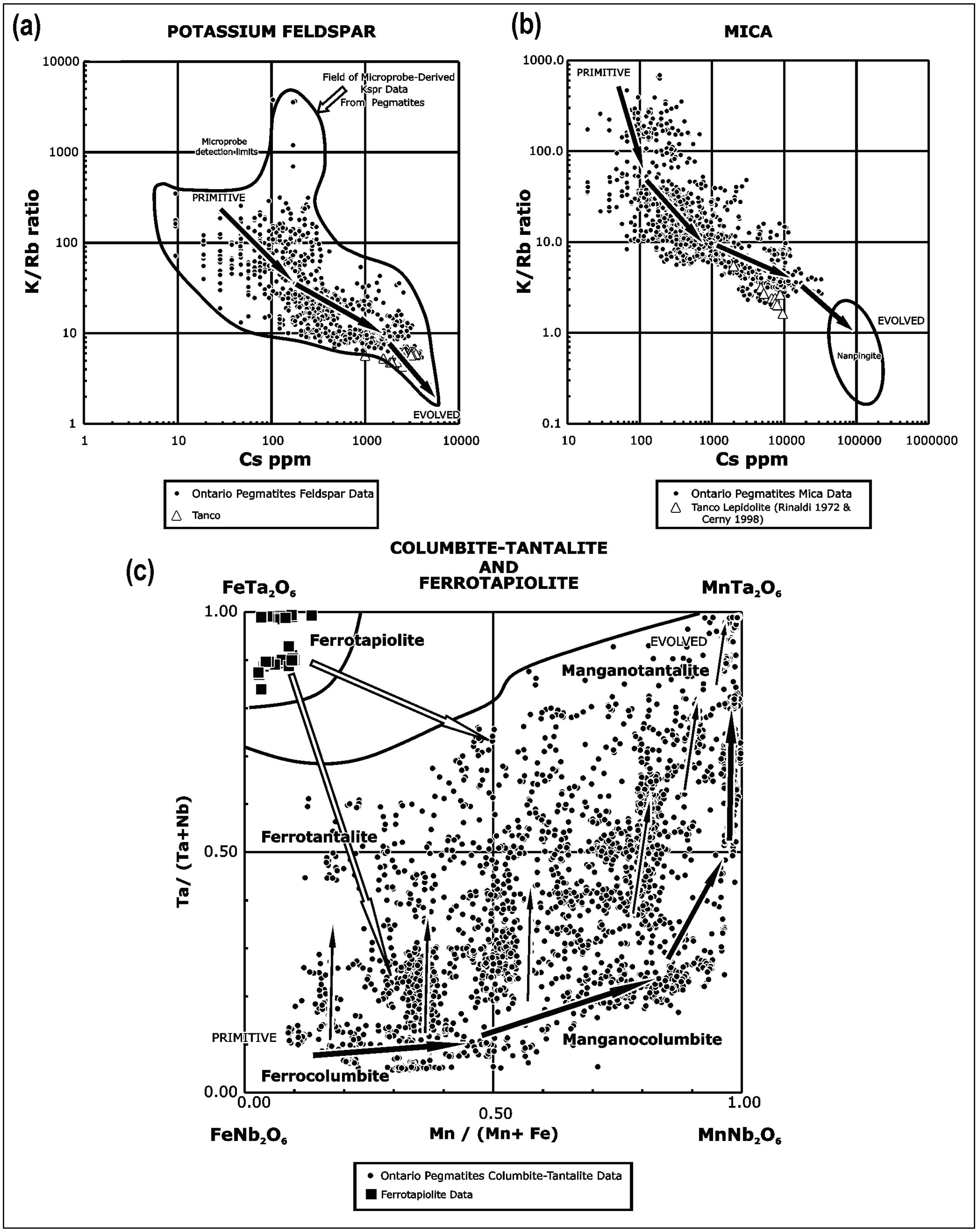

Fig. 5. General fractionation trends for key pegmatite indicator minerals (modified from Breaks et al., 2003). All potassium feldspar, mica, columbite-tantalite, and ferrotapiolite compositions measured from the review of Ontario pegmatites by Breaks et al. (2003) are plotted, and compositions from Tanco pegmatite are also shown for comparison. (a) K/Rb vs. Cs for potassium feldspar, and (b) for mica. Data in (b) for the Tanco lepidolite are from Rinaldi et al. (1972) and from Černý et al. (1998). (c) Ta/(Ta+Nb) vs. Mn/(Mn+Fe) for columbite-tantalite and ferrotapiolite. The thick solid arrows represent the general fractionation trend from primitive ferrocolumbite to manganocolumbite to evolved manganotantalite. The thin solid arrows represent the fractionation trends of increasing Ta within individual pegmatites. The hollow arrows represent host rock contamination, which changes the composition of the Ta-oxide minerals from Ta-rich ferrotapiolite to Ta-poor ferrocolumbite or manganotantalite.

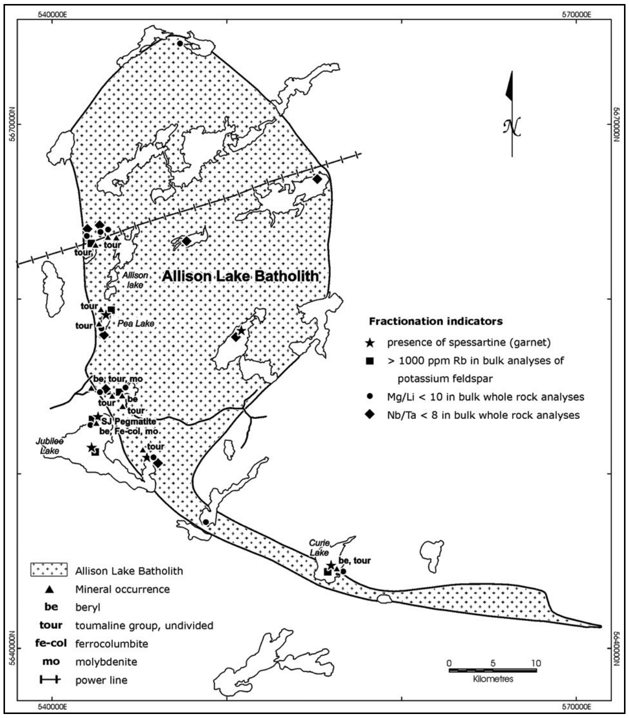

Fig. 6. Key fractionation indicators plotted on the map of Allison Lake batholith: presence of spessartine content of garnet (based on microprobe data); Rb content in K-feldspar bulk analyses; and Mg/Li and Nb/Ta ratios in bulk whole-rock analyses (modified from Breaks et al., 2003). See Figure 10 for the location of the Allison Lake batholith along the English River-Uchi subprovincial boundary.

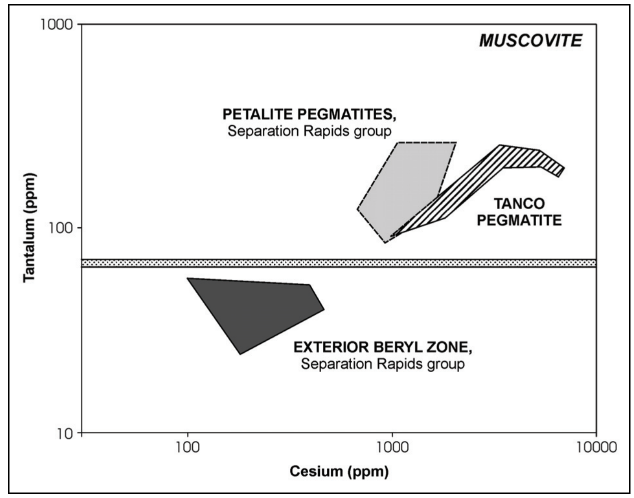

Fig. 7. Ta vs. Cs plot for bulk muscovite. According to Gordiyenko (1971), muscovite with greater than 65–70 ppm Ta indicates that the pegmatite likely contains Ta-oxide minerals. Data fields for Tanco are from Morteani and Gaupp (1989), and Separation Rapids from the authors (unpublished).

As for K-feldspar, a plot of K/Rb versus Cs in mica can be used to evaluate the degree of fractionation of a pegmatite (Fig. 5b). The K/Rb ratio measures the degree of substitution of Rb for K in the mica's crystal structure. Muscovites from spodumene pegmatites usually have K/Rb greater than 20 and less than 500 ppm Cs, whereas lepidolites in pegmatites have much higher Rb and Cs contents, with K/Rb usually < 10 and Cs usually > 1,000 ppm (Breaks et al., 2003).

Pegmatites with the greatest potential for Li-Cs-Ta mineralization contain coarse-grained green muscovite with >2,000 ppm Li, >10,000 ppm Rb, >500 ppm Cs, and >65 ppm Ta (Table 3). Many potentially economic rare-element pegmatites contain lepidolite in the most fractionated pegmatite zones.

Garnet

Garnet is a mineral group with the general formula $A_3B_2(SiO_4)_3$ and a number of solid solution series between the end members (e.g., almandine-spessartine, pyrope-grossular). The most common garnet compositions in pegmatites are almandine (where A = Fe, B = Al) and spessartine (where A = Mn, B = Al). 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, because barren granites do not contain garnet. Garnet is an excellent exploration tool because it is relatively common in fertile granites and pegmatites, and its color and composition change with increasing fractionation of the granitic melt: fertile granites contain red Fe-rich almandine garnet, and the innermost zone of a rare-element pegmatite may contain orange Mn-rich spessartine garnet. Red almandine is the most common species of garnet in fertile granites and pegmatites, and its Fe content and Fe/Mn ratio decrease, and Mn content increases, with increasing fractionation of the pegmatite melt (Fig. 8a; Černý, 1989a; Whitworth, 1992). 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 almost equal to Fe occurs in intermediate mineral assemblages, and Mn-rich garnet (27–41 wt.% MnO) occurs in the inner and replacement zones. This decreasing Fe/Mn ratio with increasing pegmatite fractionation is also seen in other minerals, such as ferrocolumbite to manganocolumbite, triphylite to lithiophilite, and schorl to Mn-rich elbaite. Pure spessartine garnet is typical of replacement and quartz-rich core zones of pegmatites containing Li minerals such as spodumene, lepidolite, petalite, and amblygonite (Baldwin and von Knorring, 1983). Garnet is common in some highly evolved pegmatites such as the Tot Lake spodumene-subtype pegmatite (Breaks and Janes, 1991) and the Case spodumene-subtype pegmatite (Breaks et al., 2003), but is rare to absent in other highly evolved pegmatites (e.g., the Tanco petalite-subtype and North Aubry spodumene-subtype pegmatites; Černý et al., 1998, and Breaks et al., 2003, respectively).

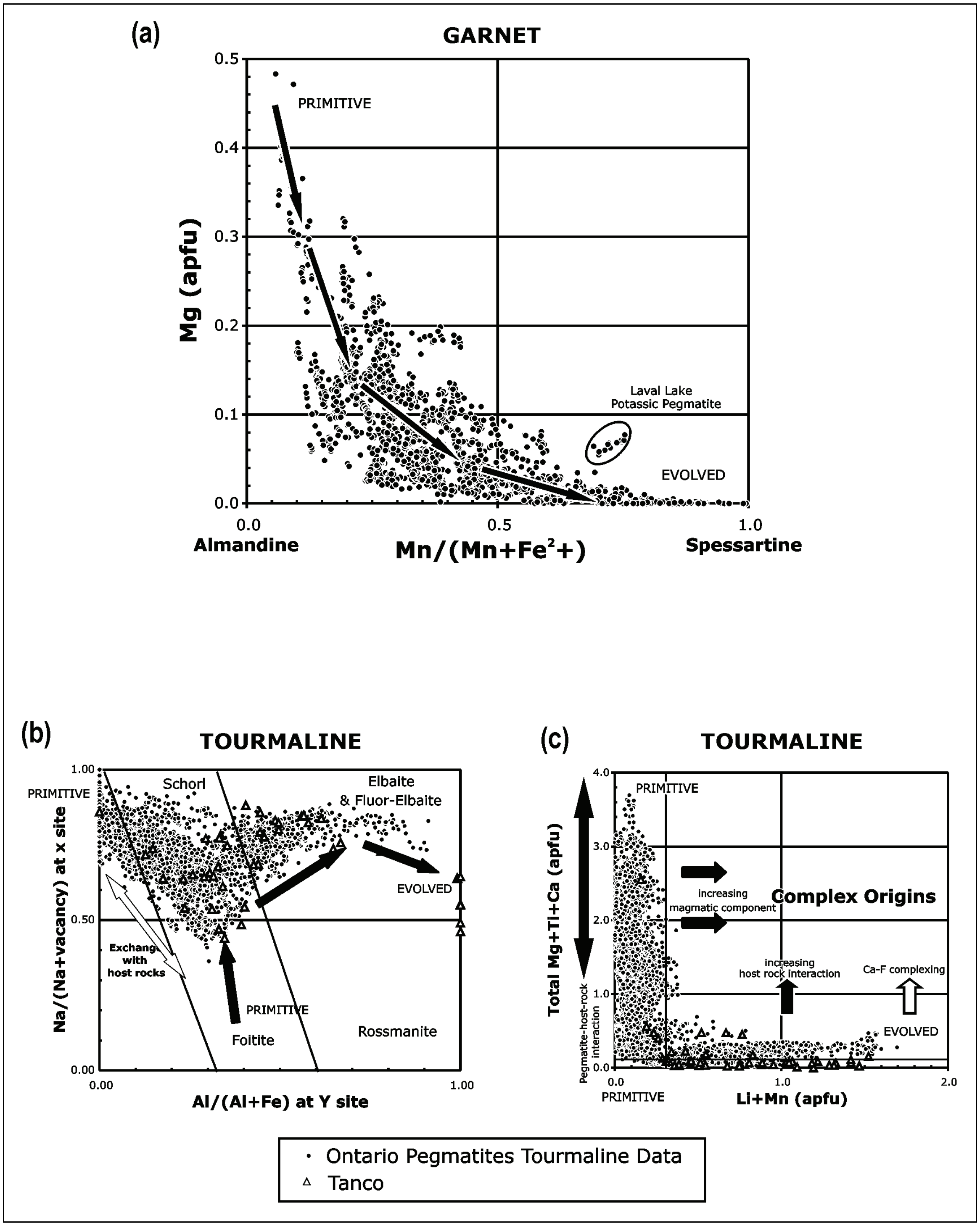

Fig. 8. General fractionation trends for key pegmatite indicator minerals (modified from Breaks et al., 2003). All of the tourmaline and garnet compositions measured from the review of Ontario pegmatites by Breaks et al. (2003) are plotted, and compositions from the Tanco pegmatite are added for comparison. (a) Mg (apfu) versus Mn/(Mn+Fe) for garnet compositions in Ontario pegmatites (apfu stands for atoms per formula unit; i.e., the subscripted numbers in a mineral's formula). (b) Na/(Na+vacancy) at the X-site versus Al/(Al+Fe) at the Y-site for tourmaline compositions. The hollow arrow indicates tourmaline compositions which are contaminated by host rocks; the solid arrows show the magmatic fractionation trend from primitive foitite to evolved elbaite. (c) Total Mg+Ti+Ca (apfu) versus Li+Mn (apfu) for tourmaline compositions. Tourmalines contaminated by host rocks have elevated Mg, Ti, and Ca contents, whereas uncontaminated magmatic tourmalines have elevated Li and Mn contents.

Elevated Mg contents in pegmatitic garnet likely indicate either a less fractionated granitic melt (Fig. 8a), contamination of the granitic melt by hydrothermal fluids from a Mg-rich host rock (usually mafic metavolcanic rocks), or assimilation of the host rock into the granitic melt (Černý and Hawthorne, 1982). Granites and outermost pegmatite zones contaminated by Mg-rich fluids from host rocks are generally not economic, although uncontaminated inner pegmatite zones within the same body may be so.

Garnet was used as an exploration tool for two fertile granites in this study: 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 (Fig. 6; see below for a more detailed discussion). The purpose was to determine the direction in which the granite-forming melt (which now forms the batholith) had fractionated, in order to predict the location of pegmatite dikes. Garnet samples were collected and analyzed from throughout the batholith, and it was discovered that Mn-rich spessartine only occurs along its western contact. Thus, the Birch-Uchi greenstone belt west of the Allison Lake batholith is suggested to have the potential to contain rare-element pegmatite dikes.

Fertile granites occur along a 45-km stretch of the Armstrong Highway between Walkinshaw and DeCourcey lakes (Fig. 9; see below for a more detailed discussion). Garnets were collected and analyzed from throughout this area, and it was found that Mn-rich garnets (>30% spessartine component) only occur at the south end of the Armstrong Highway near Onion and Walkinshaw lakes, whereas the rest of the highway section contains Fe-rich garnet. Thus, the south end of the Armstrong Highway is concluded to have the potential to contain rare-element pegmatite dikes.

In conclusion, by spatially mapping the distribution of Mn-rich garnet, it is possible to locate the most evolved part of a granite pluton, which in turn may lead to the discovery of pegmatites with rare-element mineralization.

Tourmaline

Tourmaline has the general formula $XY_3Z_6(BO_3)_3(Si_6O_{18})(OH)_3(OH, F)$, with solid solution series between end members (e.g., schorl-elbaite). The most common tourmaline species in pegmatites are schorl (X = Na, Y = Fe, Z = Al) and elbaite (X = Na, Y = Al-Li, Z = Al). Tourmalines with ideal end-member composition are rare in nature, because so many elements may substitute into the crystal structure.

Tourmaline is the most common B-bearing silicate mineral in granites and pegmatites. Boron behaves as an incompatible element in granitic melts, and is thus concentrated in evolved magmas. It is also an important volatile component (in addition to H_2O, P, F) in peraluminous silicic melts, and helps the melt to concentrate Group 1 elements (in the order of H Li >> Na > K > Rb > Cs) and high-field strength cations (e.g., Fe, Mn, Nb, Ta, Sn; London, 1987). Boron thus promotes the formation of rare-element-rich silicate melts (London, 1987).

The presence of tourmaline in a granite indicates that the granite is more likely to be fertile, because barren granites do not usually contain tourmaline, whereas B-bearing peraluminous fertile granite commonly does. Tourmaline is prismatic, and can be easily distinguished from hornblende by its rounded triangular cross section and conchoidal fracture. Tourmaline is an excellent exploration indicator mineral because its color and composition change with increasing fractionation: fertile granites contain black iron-rich tourmaline (schorl), whereas the innermost zone of a rare-element pegmatite may contain pink, green, or blue Li-rich tourmaline (elbaite). Schorl is the most common species of tourmaline in fertile granites and pegmatites. As a pegmatite-forming melt crystallizes, it becomes depleted in Fe and enriched in Li, and the composition of tourmaline changes from schorl to elbaite (Fig. 8b,c; London, 1999). If a pegmatite-forming melt is capable of crystallizing elbaite, it is likely also enriched in other rare elements such as Rb, Cs, or Ta (e.g., the McCombe spodumene-subtype pegmatite, Ontario, and Tanco pegmatite, Manitoba; Breaks et al., 2003, and Černý et al., 1998, respectively). Some pegmatite melts do not crystallize any tourmaline (e.g., Tebishogeshik and Case spodumene-subtype pegmatites, Ontario) due to the lack of B in the melt (Breaks et al., 2003). The use of tourmaline as a petrogenetic indicator mineral has been reviewed by Henry and Guidotti (1985), Jolliffe et al. (1986), and London et al. (1996).

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

Elevated Ca or Mg contents in tourmaline in a pegmatite likely indicate contamination of the granitic melt by Ca-Mg-rich host rocks (usually mafic metavolcanic rocks; Fig. 8c; London et al., 1996; London, 1999; Tindle et al., 2002a). Granites and outermost pegmatite zones contaminated with Mg from host rocks are generally not economic, although uncontaminated inner pegmatite zones within the same body may be so. For example, the tourmaline in the border and wall zones of the Tanco pegmatite is black Ca-Mg-rich schorl, but tourmaline in the most fractionated pegmatite zones can be pink elbaite (Selway et al., 2000a).

Fluorapatite

The presence of blue or green fluorapatite in a granite, pegmatite, or aplite indicates crystallization from a P-F-rich melt. If such a melt is allowed to fractionate, it may produce elevated Mn contents (>2.0 wt.% MnO) in fluorapatite, and concentrate rare elements in the pegmatite (Breaks et al., 2003). For example, fluorapatite in the North Aubry

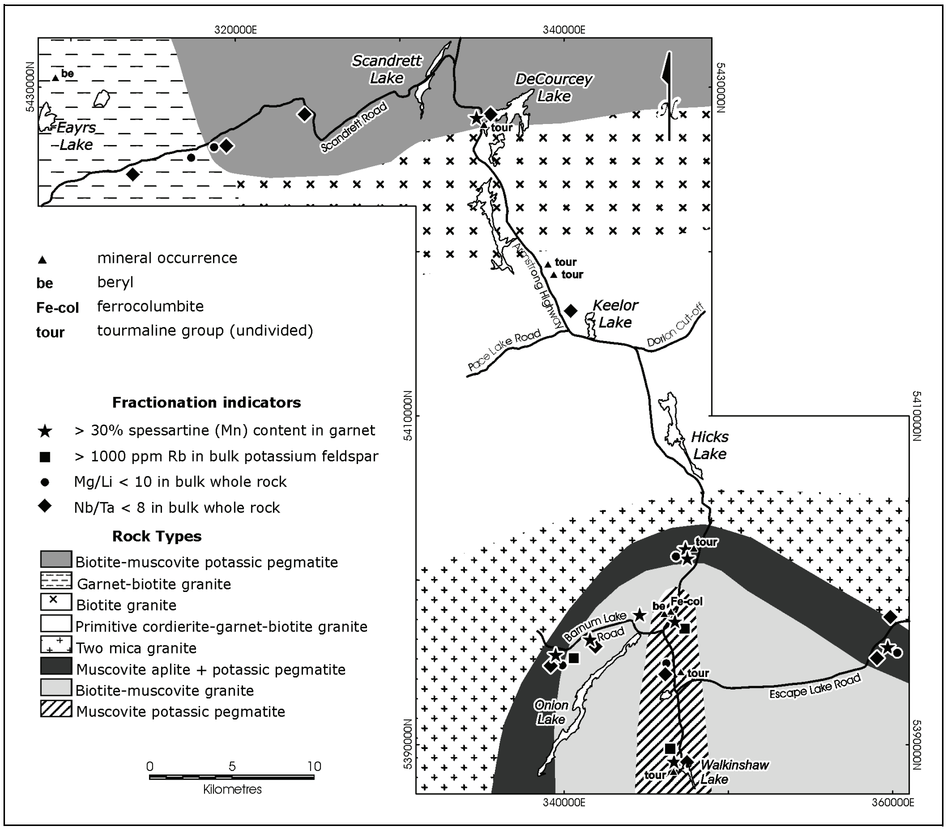

Fig. 9. Key fractionation indicators in granite outcrops along the Armstrong Highway (Highway 527), Ontario: spessartine content of garnet based on microprobe data; Rb content (ppm) in potassium feldspar bulk analyses; and Mg/Li and Nb/Ta ratios in bulk whole-rock analyses (modified from Breaks et al., 2003). This is a cross section through the Quetico subprovince, northeast of Thunder Bay and west of Lake Nipigon.

spodumene-subtype pegmatite contains up to 6.1 wt.% MnO (Breaks et al., 2003). Some pegmatites crystallize Mn-poor fluorapatite due to a lack of Mn, or the preferential partitioning of Mn into garnet or oxide minerals over fluorapatite. For example, the McCombe spodumene pegmatite contains fluorapatite with 0.8 wt.% MnO associated with Mn-rich garnet (spessartine) and oxide minerals (manganotantalite).

The presence of blue or green Mn-rich fluorapatite indicates that the pegmatite has economic potential for Li-Cs-Ta, although not very many Ta-mineralized pegmatites contain Mn-rich fluorapatite.

Ta-Nb-Oxide Minerals

The presence of Ta-Nb-oxide minerals (Ta > Nb; e.g., manganotantalite, wodginite, microlite) in a pegmatite is a definite indicator of a rare-element pegmatite, because these are the main ore minerals for Ta (Foord, 1982; Černý and Ercit, 1989; Ercit et al., 1992a,b). Tantalum-niobium-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 may also occur as masses or fracture fillings. They are usually difficult to identify even with a hand lens. It is almost impossible to distinguish fine-grained Nb-rich oxide minerals (not economic in granitic pegmatites) from Ta-rich oxide minerals (economic) by eye. These minerals are also sometimes mistakenly identified as cassiterite (a hard, black, ore mineral of tin) or black tourmaline. They are also confused with ilmenite and magnetite, which are the common Fe-Ti-oxide phases in barren granites. The best way to distinguish them is by use of an electron microprobe, because individual oxide grains are often an intergrowth of several Ta-oxide minerals. It is recommended that prospectors submit nonmagnetic oxide mineral grains to analytical labs for electron microprobe analysis, or have bulk analyses undertaken on rock samples rich in possible Ta-Nb-bearing oxide minerals to determine if Ta > Nb.

Tantalum mineralization is usually concentrated in albite-rich assemblages (aplite or cleavelandite) or in greisen-like assemblages (muscovite + quartz and lepidolite; Černý, 1989b). Tantalum mineralization also 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, and wodginite), whereas lepidolite-subtype pegmatites have microlite dominant over manganotantalite (Černý, 1989b). The Swole Lake lepidolite pegmatite boulders in Ontario are an exception with Mn-rich manganocolumbite and manganotantalite dominant over microlite (Breaks et al., 2002). The extreme Mn enrichment and absence of Fe in the columbite-tantalite minerals at Swole Lake indicates that this pegmatite is lepidolite subtype (Černý, 1989b).

The most common Ta-Nb-oxide minerals are members of the columbite-tantalite mineral group: ferrotantalite ((Fe>Mn)(Ta>Nb)$_2$O$_6$), ferrocolumbite ($FeNb_2O_6$), manganocolumbite ($MnNb_2O_6$), and manganotantalite ($MnTa_2O_6$) (Fig. 5c). The columbite-tantalite group minerals have orthorhombic crystal structures and show solid solution between end members (Ercit et al., 1995). Ferrotapiolite ($FeNb_2O_6$) has a similar composition to ferrotantalite, but it has a tetragonal crystal structure. There is a compositional gap between orthorhombic ferrotantalite and tetragonal ferrotapiolite, because columbite-tantalite minerals with compositions within this gap are metastable under normal conditions of crystallization (Černý et al., 1992). The boundaries of this compositional gap are controlled by temperature, oxygen fugacity, structural state of coexisting phases, and impurities that affect their stoichiometry, and probably also pressure during crystallization (Černý et al., 1992).

As a pegmatitic melt crystallizes, the composition of the columbite-tantalite minerals change due to fractionation of the melt. 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, F; Fig. 5c). This trend indicates that the pegmatitic melt fractionated with increasing Mn and Ta contents (similar to that seen in garnet) followed by an increase in Ca, Ta, and F. This trend is typical of highly evolved, F-rich, lepidolite- and/or pollucite-bearing complex petalite-, spodumene-, and amblygonite-subtype pegmatites (Černý, 1989b). Tindle and Breaks (1998) referred to petalite-subtype pegmatites following this trend at Separation Rapids as the Mn suite. The columbite-tantalite group minerals in lepidolite-subtype pegmatites follow a similar trend, except for the absence of ferrocolumbite and the extreme Mn enrichment of manganocolumbite and manganotantalite (Mn/(Mn+Fe) > 0.9; Černý, 1989b; Breaks et al., 2003).

Another common compositional trend of columbite-tantalite minerals is ferrocolumbite (Fe, Nb) to ferrotantalite (Fe, Ta; Fig. 5c). This trend indicates that the Mn-poor pegmatitic melt fractionated with increasing Ta content, or that the pegmatitic melt was contaminated by Fe-rich fluids. This trend is typical of primitive, F-poor, beryl-type and spodumene-subtype pegmatites (Černý, 1989b). Tindle and Breaks (1998) referred to pegmatites following this trend at Separation Rapids as the Fe suite. Ferrotantalite is perhaps the most uncommon columbite-tantalite species (Breaks et al., 2003).

A third rare compositional trend of columbite-tantalite is ferrotapiolite (Fe, Ta) to ferrotantalite (Fe, Ta) to ferrocolumbite (Fe, Nb; Fig. 5c; Breaks et al., 2003). This trend represents an increase in Nb and Mn and is likely due to pegmatite-host rock interaction/contamination. For example, the oxides in the primitive Drope Township columbite-molybdenite pegmatite in Ontario show this trend (Breaks et al., 2003).

Many pegmatitic Ta deposits are exploited for Sn in addition to Ta, in the form of wodginite or cassiterite. Wodginite ($MnSnTa_2O_8$) is a wedge-shaped mineral, and is the main Ta ore mineral at the Tanco mine, Manitoba (Černý et al., 1996). Wodginite is uncommon in pegmatites in Ontario, but many varieties of it were recorded in the Separation Rapids pegmatites (Tindle et al., 1998). Wodginite is difficult to recognize in the field, because dark brown wodginite could be mistaken for cassiterite. Tantalum-niobium-oxide minerals may be associated with cassiterite (SnO_2) and Ta-rich rutile (strüverite), both of which usually contain a few percent of Ta_2O_5. Cassiterite contains up to 11 wt.% Ta_2O_5 in Pegmatite #5, Separation Rapids (Tindle and Breaks, 2000), whereas strüverite contains up to 55 wt.% Ta_2O_5 in the Big Mack pegmatite, Separation Rapids (Breaks et al., 1999). Cassiterite can be distinguished from Ta-Nb-oxide minerals by its admantine luster, whereas Ta-Nb-oxide minerals have a submetallic luster; however, in the field they are difficult to tell apart, especially if they are fine grained. The best way to distinguish cassiterite from Ta-Nb-oxide minerals is by electron microprobe analysis, or to analyze a rock chip with abundant black grains using bulk methods to determine if Ta > Sn.

Beryl

The presence of beryl indicates that the granite is fertile and peraluminous, because barren granites do not contain beryl. Beryl is a good exploration tool because its color and composition change with increasing fractionation of a granitic melt: fertile granite intrusions contain green Cs-free beryl, and the innermost zone of a rare-element pegmatite may contain white or pink Cs-rich beryl. For example, white beryl from the North Aubry spodumene pegmatite contains up to 3.2 wt.% Cs_2O (Breaks et al., 2003). Beryl crystals may be zoned with Cs-poor cores and Cs-rich rims due to the evolving melt composition. Pegmatites with economic potential for Li-Cs-Ta may contain white Cs-rich beryl.

Case Studies

The above exploration techniques have been used by the authors throughout the Superior province of Ontario. Two case studies from Allison Lake batholith and Armstrong Highway cross section are described below.

Allison Lake Batholith Fertile Granite

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 Ventures Ltd's Web site: http://www.avalonventures.com) in the Fort Hope area (Fig. 10). The Allison Lake batholith (associated with the Jubilee Lake

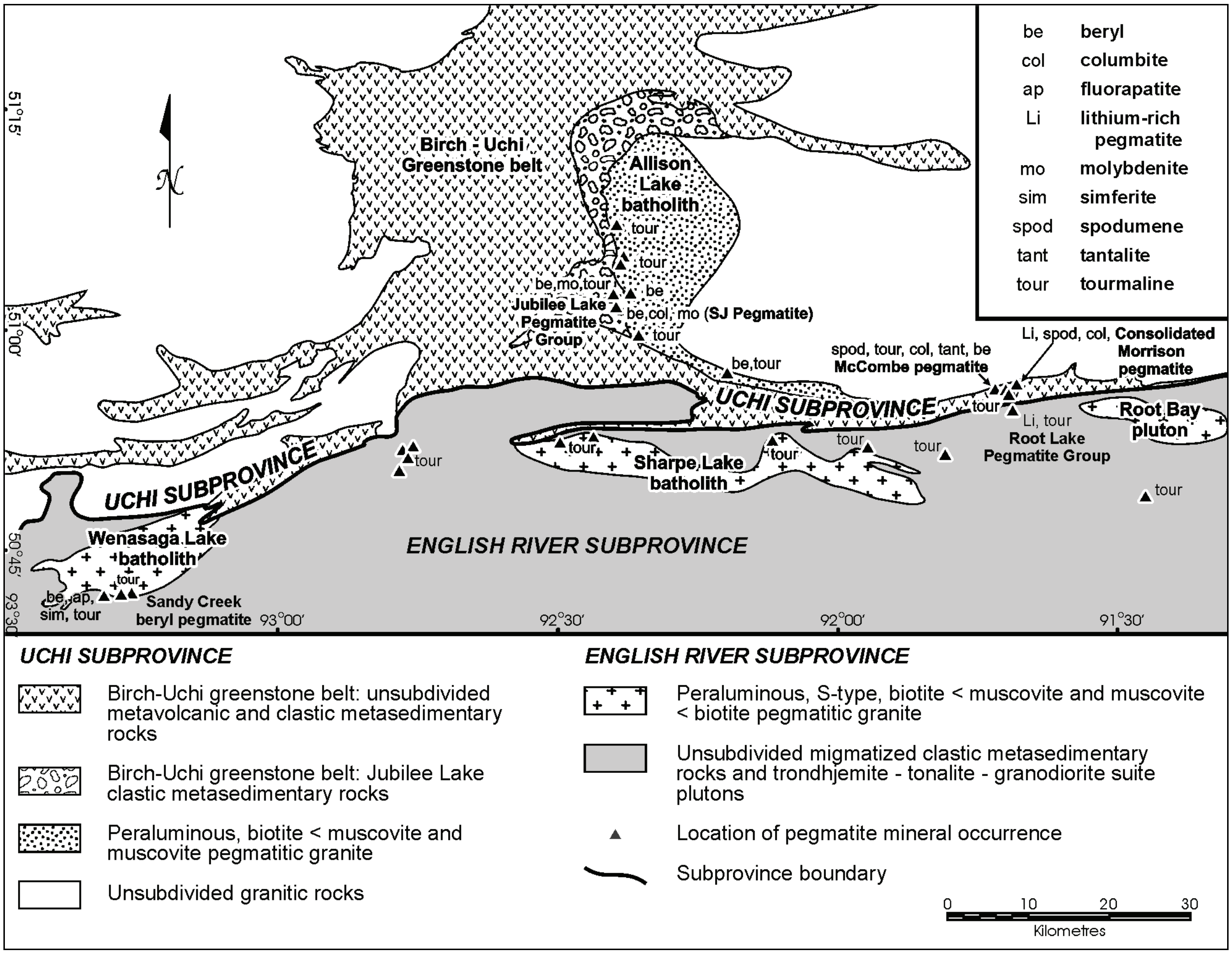

Fig. 10. General geology and location of peraluminous granite masses and rare-element mineralization in the English River-Uchi subprovincial boundary zone between Lake St. Joseph and Ear Falls (geology compiled from Thurston, 1985a,b and Breaks and Bond, 1993).

pegmatite group and possibly the Root Lake pegmatite group) is considered to be a fertile, peraluminous parent granite.

Previous geological work (Bateman, 1939; Breaks et al., 1976, 1979; Thurston, 1985a,b) in the vicinity of the Allison Lake batholith (Figs. 6 and 10) encompassed only small portions of this extensive, 16 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) 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 has indicated that the Allison Lake batholith is the largest known fertile, peraluminous, granite mass in northwestern Ontario (Breaks et al., 2003). A regional geophysical gravity survey was conducted over the Allison Lake batholith and detected a significant –680 to –700-mgal Bouguer gravity low ("Allison-Sesikinaga low") that corresponds with the main mass of the batholith (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). The following discussion of the petrochemistry and mineral chemistry of the Allison Lake batholith is from Breaks et al. (2003).

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) that are typical of fertile granite plutons (e.g., Separation Rapids pluton; Breaks and Tindle, 1996, 1997a,b). 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 K-feldspar crystals that range from 30 to 100 cm in length. Pale green crystals of beryl (2 cm in size) occur sporadically in the quartz-rich patches (e.g., at Curie Lake) along the “tail” of the batholith (Fig. 6). Veins and dikes of potassic pegmatite transect the fine- to medium-grained granite.

In order to determine the direction of increasing fractionation within the Allison Lake batholith, bulk whole-rock (granite and aplite) and bulk K-feldspar samples were collected throughout the batholith, and four key fractionation indicators were plotted on a map of the batholith (Fig. 6): (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 pure K-feldspar; and (4) the presence of spessartine garnet ($Mn/(Mn+Fe) > 0.5$).

The western contact and southeast tail of the Allison Lake batholith are the most fractionated parts of the batholith, because they have low Mg/Li ratios (<10) and low Nb/Ta ratios (<8) in bulk samples, elevated Rb contents (>1,000 ppm Rb) in K-feldspar, elevated Mn contents in garnet (i.e., presence of spessartine), common presence of tourmaline, and rare presence of 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 Li and Cs levels in bulk granitic samples. The highest values of Cs occur on the power line just west of Allison Lake, where samples containing 45 ppm and 90 ppm Cs were detected in granite. Locally anomalous values up to 587 ppm Rb in potassic muscovite pegmatite were found adjacent to the western contact in the Allison Lake area. Bulk K-feldspar samples with over 1000 ppm Rb and 50 ppm Cs occur within the western contact zone of the batholith in the Pea Lake area, along the power line 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 increase from east to west with the highest values occurring along the western contact and southeast tail. Thus, the Birch-Uchi greenstone belt west of the Allison Lake batholith has the potential to contain rare-element pegmatite dikes.

Armstrong Highway Cross Section Fertile Granites

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 (Highway 527) between Walkinshaw Lake north to DeCourcey Lake (Fig. 9; Breaks et al., 2003). Detailed rock sampling was undertaken along this highway and adjacent areas, including the DeCourcey-Eayrs Lakes area along the Quetico-Wabigoon subprovincial boundary zone, where beryl was reported by Joliffe (1933) about 1.8 km northeast of Eayrs Lake. Granites and pegmatites that contain garnet, tourmaline, and muscovite were previously mapped within this area by Kaye (1969). The following discussion on the petrochemistry and mineral chemistry of the granitic rocks along the Armstrong Highway is from Breaks et al. (2003).

Dikes and foliation-concordant peraluminous granites and pegmatites were emplaced into Quetico subprovince metasedimentary rocks during at least three intrusive episodes, characterized by the following rock types: fine- to medium-grained, gray, garnet-biotite granite; cordierite and garnet-cordierite granite; sheets of pegmatitic leucogranite and associated quartz-rich patches.

The discussion of the data is divided into three zones of the Quetico subprovince (Fig. 9):

1. North subprovince boundary zone area: a 10-km-wide zone from DeCourcey Lake west to the Eayrs Lake area (along Scandrett Road) and north to the contact with metavolcanic-dominant rocks of the Wabigoon subprovince;
2. Central Quetico subprovince: Edmundson Lake south to Hicks Lake (along Pace Lake Road and Dorion cutoff), a 20-km distance along the Armstrong Highway;
3. South Quetico subprovince boundary zone: a 15 20-km-wide area from Onion Lake (along Barnum Lake Road and Escape Lake Road), west to Basher Lake, and south to the contact with the metavolcanic-dominant Wawa subprovince.

Pegmatite sheets, at least 5 m thick, are evident on the Armstrong Highway near Keelor Lake, central Quetico subprovince. These sheets consist of coarse-grained garnet-muscovite-cordierite granite that contain 15 to 20 vol.% cordierite crystals, pervasively altered to soft, dark green-black pseudomorphs. The coarse granite is gradational into muscovite-rich, miarolitic cavity-bearing, pegmatite patches (blocky K-feldspar, muscovite, cleavelandite, quartz, brown-black pyroxene, and green fluorapatite).

Rare-element mineralization was discovered by Breaks et al. (2003) within an extensive swarm of pegmatitic granite dikes in the south Quetico subprovince at Onion Lake (south of Barnum Lake Road) near Thunder Bay (Fig. 9). The lens-shaped dikes of this swarm, as seen in the area near the junction of Highway 527 and the Barnum Lake Road, occur as NE-striking, “whaleback” glacial erosional remnants that achieve a maximum size of 100 by 300 m. The internal units of these dikes comprise: muscovite-rich potassic pegmatite; quartz-rich patches with blocky K-feldspar, coarse muscovite books, and sparse beryl; and 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 in length, as at Onion Lake. Black, Nb-Ta-oxide minerals (ferrocolumbite: 27–31 wt.% Ta_2O_5, 3 3 5 mm), were discovered and are apparently associated with local albitization of K-feldspar megacrysts. Blocky K-feldspar megacrysts up to 50 cm long, and muscovite books up to 10 cm thick, were noted in the potassic pegmatite and enclosed quartz-rich patches.

Key mineral fractionation indicators are shown on a map of the Armstrong Highway (Fig. 9) 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 is the presence of tourmaline, and Nb/Ta < 8 in bulk samples at Keelor Lake. The Scandrett Road and Hanrahan Lake occurrences in the north Quetico subprovince have Mg/Li < 10 and Nb/Ta < 8 in bulk whole-rock samples, and tourmaline and Mn-rich garnet occur only at Hanrahan Lake. This indicates that the area has a moderate degree of fractionation in the granitic rocks.

The South Quetico subprovince displays the highest degree of fractionation in granitic rocks along the Armstrong Highway (Fig. 9), as shown by Mg/Li < 10 and Nb/Ta < 8 in bulk granitic samples, and Rb > 1,000 ppm in bulk K-feldspar samples. Key mineral indicators also occur in this area: Mn-rich garnets are widespread, tourmaline occurs along the Armstrong Highway, and beryl and ferrocolumbite occur at Onion Lake.

Garnets were analyzed along the Armstrong Highway and their compositions are plotted in Figure 11. Most of the garnet along the Armstrong Highway is almandine, except for some spessartine at Walkinshaw Lake. The plots in Figure 11 show 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 thus most highly fractionated.

Potassium feldspar from the South Quetico subprovince (Onion Lake, Barnum Lake Road, and Walkinshaw Lake), a sample from Edmundson Lake, and a sample from Scandrett Road have low K/Rb ratios and elevated Cs contents, which suggest that they have the most evolved compositions 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 Ta mineralization (Gordiyenko, 1971).

This reconnaissance work indicates that chemically evolved pegmatitic rocks are likely to 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 sample and mineralogical data indicate that these zones are favourable 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.

Review of Rare-Element Pegmatites in the Superior Province

Rare-element pegmatite dikes within the Superior province in Ontario and Manitoba usually cluster to form pegmatite fields that contain one or two large highly fractionated pegmatites and numerous small pegmatite dikes. For example, the Bernic Lake pegmatite group, part of the Cat Lake-Winnipeg River pegmatite field in southeastern Manitoba, contains the petalite-subtype Tanco pegmatite (1.99 km long 1.06 km wide 100 m thick; Stilling, 1998) and eight other smaller, less-fractionated pegmatite dikes (Černý et al., 1981). The Separation Rapids pegmatite group lies to the east of the Cat Lake-Winnipeg River pegmatite within the same metavolcanic Bird River-Separation Lake belt (Breaks et al., 1975). The Separation Rapids pegmatite group contains two large highly fractionated petalite-subtype pegmatites: Big Whopper (350 m in strike length 60 m thick) and Big Mack (30 100 m; Breaks and Tindle, 1997b; Breaks et al., 1999). The Big Whopper and Big Mack pegmatites are members of the Southwestern pegmatite subgroup, which contains at least 23 additional smaller pegmatite dikes, eight of which are petalite subtype (Breaks and Tindle, 1997b; Breaks et al., 1999). Additional large pegmatite fields in the Superior province of Ontario with economic potential include: the Dryden pegmatite field, which includes the highly fractionated spodumene-subtype Fairservice pegmatite dikes and Tot Lake pegmatite, and the Seymour Lake pegmatite group, which includes the highly fractionated spodumene-subtype North Aubry and South Aubry pegmatites (Breaks et al., 2003). The North and South Aubry pegmatites are classified as spodumene subtype rather than albite-spodumene type because spodumene is the dominant Li mineral, the pegmatites contain numerous pegmatite zones, K-feldspar is more abundant than albite, and muscovite is abundant (Breaks et al., 2003). These pegmatites are more fractionated than albite-spodumene type pegmatites, because they contain elevated Rb, Cs, Be, and Ta contents. The spodumene-subtype Case pegmatite in northeastern Ontario, is unique in that it is a large fractionated pegmatite with no identified associated smaller pegmatite dikes, likely due to thick overburden (Breaks et al., 2003).

There are several geological features that are common in the pegmatites of the Superior province of Ontario (Breaks and Tindle, 2001; Breaks et al., 2003) and Manitoba (Černý et al., 1981; Černý et al., 1998):

1. *Subprovincial Boundaries:* The pegmatites tend to occur along subprovincial boundaries. For example, Tanco (Manitoba) and Separation Rapids (Ontario) pegmatites within the Bird Lake-Separation Lake metavolcanic belt occur along the boundary between the English River and Winnipeg River subprovinces; the beryl-phosphate Sandy Creek, spodumene-subtype McCombe pegmatites, and lepidolite-subtype Lilypad Lake pegmatite field occur along the Uchi-English River subprovincial boundary; the Dryden pegmatite field occurs within the

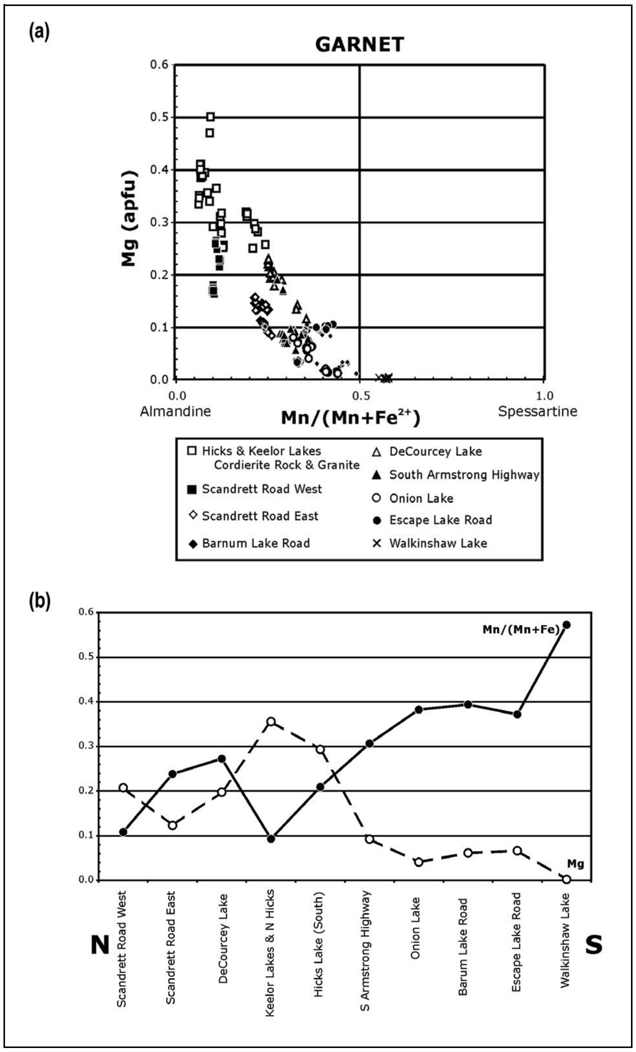

Fig. 11. (a) Mg (apfu) versus Mn/(Mn+Fe) for garnet from the Armstrong Highway. (b) North–south traverse of the average Mg (apfu) and Mn/(Mn+Fe) values from garnet for each lake and road along the Armstrong Highway section (modified from Breaks et al., 2003).

Sioux Lookout Domain along the Winnipeg River-Wabigoon subprovincial boundary; and the spodumene-subtype North Aubry, South Aubry, and Tebishogeshik pegmatites occur along the English River-Wabigoon subprovincial boundary north of Armstrong.

2. *Metasedimentary-Dominant Subprovince:* Most pegmatites in the Superior province occur along subprovince boundaries, except for those that occur within the metasedimentary Quetico subprovince. Examples of pegmatites occuring in this area from west to east are: Wisa Lake (south of Atikokan), the Georgia Lake pegmatite field (north of Nipigon), and the Lowther Township (south of Hearst) pegmatites.

3. *Greenschist to Amphibolite Metamorphic Grade:* Pegmatites are absent in the granulite terranes of the Quetico and English River subprovinces.

4. *Fertile Parent Granite:* Most pegmatites in the Superior province are genetically derived from a fertile parent granite. The Cat Lake-Winnipeg River pegmatite field (Manitoba) contains six two-mica to garnet-muscovite leucogranite intrusions (Greer Lake, Eaglenest Lake, Axial, Rush Lake, Tin Lake, and Osis Lake) emplaced along east-trending faults, which are parents to numerous pegmatites (Černý et al., 1981; Černý et al., 1998). In contrast, the Tanco pegmatite has no fertile granite outcropping in reasonably close vicinity that could be its potential parent (Černý et al., 1998). The peraluminous Separation Rapids pluton (4 km wide) is the parent to the Separation Rapids pegmatite field, including the petalite-subtype Big Whopper and Big Mack pegmatites, north of Kenora, Ontario. The peraluminous Ghost Lake batholith (80 km wide) is the parent to the Mavis Lake pegmatite group, including the spodumene-subtype Fairservice pegmatite dikes, north of Dryden, Ontario.

5. *Host Rocks:* Highly fractionated spodumene- and petalite-subtype pegmatites are commonly hosted by mafic metavolcanic rocks (amphibolite) in contact with a fertile granite intrusion along subprovincial boundaries, whereas numerous beryl-type pegmatites are hosted by metasedimentary rocks (metawacke or metapelite) of the Sioux Lookout Domain. Pegmatites within the Quetico subprovince are hosted by metasedimentary rocks or their fertile granitic parents. For example, the spodumene-subtype Wisa Lake pegmatite is hosted by metasedimentary rocks south of Atikokan, Ontario. The MNW petalite-subtype pegmatite, north of Nipigon, Ontario, is enclosed within a medium-grained biotite-muscovite granite of the MNW stock, which is presumed to be its parent (Pye, 1965). The lepidolite-subtype Lowther Township pegmatite, south of Hearst, Ontario is enclosed within its parent garnet-biotite pegmatitic granite (Breaks et al., 2002). The spodumene-subtype Case pegmatite system is hosted by orbicular biotite tonalite in the southeastern part of the Case batholith north of Cochrane, Ontario, within the Opatica subprovince.

6. *Metasomatized Host Rocks:* Biotite and tourmaline are common minerals, and holmquistite is a minor phase in metasomatic aureoles in mafic metavolcanic host rocks to spodumene- and petalite-subtype pegmatites. Tourmaline, muscovite, and biotite are common, and holmquistite is rare in metasomatic aureoles in metasedimentary rocks.

7. *Li Minerals:* Most of the complex-type pegmatites of the Superior province contain spodumene and/or petalite as the dominant Li mineral, except for Lilypad Lake, Swole Lake, and Lowther Township pegmatite (all in Ontario), and Red Cross Lake lithium pegmatite (Manitoba), which have lepidolite as the dominant Li mineral. Amblygonite- and elbaite-dominant pegmatites have not yet been found in the Superior province, although amblygonite and elbaite occur in the Tanco pegmatite.

8. *Cs Minerals:* Cesium-rich minerals only occur in the most extremely fractionated pegmatites. Pollucite occurs in the Tanco, Marko's, and Pakeagama petalite-subtype pegmatites, the Tot Lake spodumene-subtype pegmatites, and the Lilypad Lake lepidolite-subtype pegmatites (Teertstra and Černý, 1995). The Pakeagama pegmatite is located in northwestern Ontario along the Sachigo-Berens River subprovincial boundary. Cesium-rich beryl occurs in the spodumene-subtype North Aubry, South Aubry, Case, Tot Lake, and McCombe pegmatites and the lepidolite-subtype Lowther pegmatite, all in Ontario, and in the Tanco pegmatite, Manitoba.
9. *Ta-Sn Minerals:* Most pegmatites in the Superior province contain ferrocolumbite and manganocolumbite as the dominant Nb-Ta-bearing minerals. Some pegmatites contain manganotantalite as the dominant Ta-oxide mineral, for example the North Aubry, South Aubry, Fairservice, Tot Lake, and Tebishogeshik pegmatites. The Tanco pegmatite contains wodginite as the dominant Ta-oxide mineral. Tantalum-bearing cassiterite is relatively rare in pegmatites of the Superior province, except for the Separation Rapids and Tanco pegmatites.
10. *Pegmatite Zone Hosting Ta Mineralization:* Fine-grained Ta-oxides (e.g., manganotantalite, wodginite, and microlite) commonly occur in the aplite, albitized K-feldspar, mica-rich, and spodumene core zones in pegmatites in the Superior province. At Tanco, Ta mineralization occurs in the albitic aplite zone (30), central intermediate muscovite-quartz after microcline zone (60), and lepidolite zone (90).

Comparison of Large Tantalum Deposits

Australia supplies over 50% of the global demand for Ta. The Sons of Gwalia Ltd.'s Ta mines in Western Australia, Greenbushes and Wodgina, contain approximately 75% of the global defined Ta reserve base, and are the two largest Ta mines in the world (www.sog.com.au). Other significant Ta suppliers are Brazil (Pitinga and Nazareno mines), China (Yichun and Nanjing mines), Canada (Tanco mine), Ethiopia (Kenticha mine), East Africa, Namibia, and Asia.

The geological features that are common in the Superior province of Ontario and Manitoba are also present in large Ta deposits worldwide. Key geological features for seven world-class Ta deposits (Greenbushes, Wodgina main lode, Mount Cassiterite, Main Kenticha, Morrua, Tanco, and Yichun pegmatites) are summarized in Table 4. Several of the key geological features of Ta-mineralized pegmatites have been previously identified by other studies (e.g., Černý, 1989a,b; Morteani and Gaupp, 1989; Breaks and Tindle, 1997a).

These features include:

1. *Regional Faults:* Large Ta-bearing pegmatites tend to occur in close proximity to regional faults.
2. *Metamorphic Grade:* Pegmatites tend to occur in greenschist to amphibolite metamorphic grade.
3. *Fertile Parent Granite:* The residual melts from the crystallization of a peraluminous fertile granite migrate out into the host rock to form the pegmatites. The majority of Ta-rich pegmatites occur within 10 km of a large fertile granite, except for the Greenbushes and Tanco pegmatites, where the fertile parent has not been identified and is assumed to be hidden at depth.
4. *Host Rocks:* Amphibolites and metamorphosed ultramafic rocks are the most common host rock for world-class Ta pegmatites.
5. *Metasomatized Host Rocks:* The most common metasomatic minerals that occur in mafic metavolcanic host rocks of Ta-rich pegmatites are holmquistite, (Rb, Cs)-rich biotite, and tourmaline. Muscovite and garnet (almandine) may also occur in metasomatic aureoles.
6. *Pegmatite Classification:* Tantalum deposits tend to occur in pegmatites with spodumene or petalite as the dominant Li-bearing mineral. Greenbushes, Main Kenticha, and Morrua pegmatites are spodumene subtype, Tanco pegmatite is petalite subtype, and Mount Cassiterite pegmatite is albite-spodumene type. Tanco is classified as petalite subtype because of the abundance of spodumene-quartz intergrowths (SQUI), which formed by the breakdown of petalite during cooling of the pegmatite melt (London, 1984). Wodgina main lode pegmatite is albite type, because spodumene is a minor component.
7. *Li-Cs Minerals:* Spodumene is the most common Li-bearing mineral in Ta-rich pegmatites. Other Li-bearing minerals within these pegmatites are lepidolite, amblygonite, lithiophilite, petalite, and eucryptite. Pollucite only crystallizes from pegmatite melts that have reached the most advanced level of fractionation. Pollucite occurs in all of the large Ta-rich pegmatites listed in Table 4, except for the Wodgina main lode and Mount Cassiterite pegmatites. Cesium-rich beryl occurs in the Wodgina main lode and Tanco pegmatites.
8. *Ta-Sn Minerals:* The most common ore minerals of Ta are manganotantalite, manganocolumbite, wodginite, and microlite. Other ore minerals of Ta are tapiolite, stibiotantalite, ixolite, and simpsonite. Tantalum-rich cassiterite is often associated with Ta-oxides in Ta deposits.
9. *Pegmatite Zone Hosting Ta Mineralization:* In most pegmatites, Ta is enriched in the albite-rich zone, commonly with an aplite texture, and mica-rich zones such as the cleavelandite + lepidolite zone. Tantalum-oxide minerals within aplites tend to be fine grained, whereas they are coarse grained in spodumene zones. The wodginite from the albitic aplite zone at Wodgina, equivalent to Tanco's albitic aplite zone (30), is coarse grained (P. Vanstone, pers. commun., 2004). At Tanco, arcuate sodic aplite bands along the footwall wall zone generally do not contain Ta-oxides, whereas banded aplites (ribbon rock) in the interior zones may do so (P. Vanstone, pers. commun., 2004). Tanco's main Ta ore zone is a zone of muscovite + quartz after microcline (zone 60), and the

Table 4. Summary of Geological Features of Large Ta Deposits

Pegmatite Names	Regional Faults	Metamorphic Grades	Fertile Parent Granites	Host Rocks	Metasomatic Minerals in Host Rocks	Pegmatite Class	Li-Cs Minerals	Ta-Sn Ore Minerals	Pegmatite Zone Hosting Ta-Mineralization	Refs.
Greenbushes, Western Australia	Donnybrook-Bridgetown shear zone	Mid-amphibolite	Not identified	Amphibolite and ultramafic schists (hanging wall); granofels (footwall)	Biotite, scapolite, muscovite, tourmaline, holmquistite	Spodumene subtype	Spodumene, pollucite	Cassiterite, tantalite, subordinate stibiotantalite, microlite, wodginite, tapiolite	Tourmaline-rich subzones in albite zone	1
Wodgina main-lode pegmatite, Western Australia	Wodgina-Strelley lineament	Greenschist-lower amphibolite	About 1.5 km from Numbana monzogranite	Metakomatiite	Phlogopite, serpentine hornfels	Albite-type	Spodumene, lepidolite, lithiophilite, Cs-rich beryl	Manganotantalite; subordinate manganocolumbite, wodginite; minor cassiterite, microlite	Mainly in cleavelandite zones also in aplite and lepidolite replacement zones	2
Mount Cassiterite pegmatite, Western Australia	Wodgina-Strelley lineament	Greenschist-lower amphibolite	About 1 km from Numbana monzogranite	Quartzite, chert, biotite metapelite rocks	Alkali muscovite, holmquistite, pink garnet, rare pockets of blue tourmaline	Albite-spodumene type	Spodumene, lepidolite	Wodginite, Ta-rich cassiterite, tapiolite; subordinate manganotantalite, manganocolumbite, microlite	Throughout pegmatite sheets and in cassiterite-quartz-mica-tourmaline veins	2
Main Kenticha pegmatite, Ethiopia	Deep-seated north-south regional fault	Amphibolite	About 7.5 km from two-mica granite	Serpentinites	Biotite, chlorite, talc, tremolite-actinolite schists	Spodumene subtype	Spodumene, amblygonite, lithiophilite, lepidolite, pollucite	Manganotantalite, manganocolumbite, ixolite	Spodumene zone, greisen and lepidolite zone	3
Morrua pegmatite, Mozambique	Lurio and Namama thrust belts	Amphibolite	Late equigranular granite	Amphibolite	Holmquistite, biotite	Spodumene subtype	Spodumene, amblygonite, pollucite	Manganotantalite, microlite, stibiotantalite	Associated with cleavelandite and lepidolite	4
Tanco pegmatite, Canada	Winnipeg River-Bird River subprovince boundary	Amphibolite	Not identified	Amphibolites (metagabbro)	Biotite, tourmaline, holmquistite	Petalite subtype	Spodumene, lepidolite, amblygonite, lithiophilite, petalite, eucryptite, pollucite, Cs-rich beryl	Wodginite, subordinate Ta-rich cassiterite, manganotantalite, microlite, simpsonite, tapiolite	Central intermediate, albitic aplite and lepidolite zones	5
Yichun topaz-lepidolite granite, South China	Yangtze Block-Caledonian fold belt boundary	Yashan batholith is not metamorphosed	Yashan batholith protolithionite-muscovite granite	Hosted by parent Yashan batholith	Not applicable, hosted by parent granite	Lepidolite subtype	Lepidolite, amblygonite, pollucite	Manganotantalite, manganocolumbite, Ta-rich cassiterite, minor microlite, wodginite	Associated with lepidolite and albite in topaz-lepidolite granite	6

Notes

[1]Greenbushes: Partington, 1990; Partington et al., 1995; Fetherston, 2004.

[2]Wodgina and Mount Cassiterite: Sweetapple et al., 2001; Sweetapple and Collins, 2002; Fetherston, 2004.

[3]Kenticha: Tadesse and Zerihun, 1996; Tadesse, 2001.

[4]Morrua: von Knorring, 1962; Pinna et al., 1993; Teertstra et al., 1999; Dias and Wilson, 2000.

[5]Tanco: Černý et al., 1998.

[6]Yichun: Yin et al., 1995; Belkasmi et al., 2000.

second main Ta ore zone is the aplitic albite zone 30 (P. Vanstone, pers. commun., 2004).

Tantalum-Niobium Contents in Large Tantalum Deposits

Table 5 summarizes the known Ta contents in large tantalum deposits. Note that Ta contents in bulk pegmatite samples and within oxide minerals are considered confidential information by many mining companies, and thus Table 5 is incomplete.

Holly (1993), mining manager for the Greenbushes mine, Australia noted that the hard rock Ta-Sn ore cutoff grade was 200 g/t Ta_2O_5 (0.020% Ta_2O_5), but this would not be considered "ore" grade in Canada. For example, the pre-production ore reserves for the Tanco mine were 1.879 Mt @ 0.216% Ta_2O_5 (2,160 g/t Ta_2O_5; Černý et al., 1998). Many factors have to be taken into account before determining a cutoff grade for a Ta deposit. Because each deposit is different, each must be evaluated on its own merits. Some of the factors contributing to cutoff grade determinations include geographical location, regulatory regime, labour and material costs, deposit size and grade, open pit or underground, stripping ratio or depth, hard rock or soft rock ore, rock mechanics, existing infrastructure, deposit/ore zone geometry, mining method, throughput, ore and gangue size and composition, ore metallurgy, and market conditions (P. Vanstone, pers. commun., 2004).

Tantalum-oxide minerals in Ta deposits can contain a wide range of Ta contents. The Ta contents for manganotantalite is 55 wt.% Ta_2O_5 for the albite-K-feldspar facies of the Yichun granite. The columbite-tantalite group of

Table 5. Summary of Ta Contents in Large Tantalum Deposits

Pegmatite Name	Bulk Ta Content	Ta Reserves/Grades	Ta Content in Oxides	Ref.
Greenbushes, Western Australia	*Average*: 0.0183% Ta_2O_5 in Greenbushes pegmatite 0.0246% Ta_2O_5 in northern pegmatites 0.0233% Ta_2O_5 in albite zone	*2002 proven and probable reserves:* 88.6 Mt @ 0.022% Ta_2O_5	Unknown	1
Wodgina main-lode pegmatite, Western Australia	*Wodgina North pit:* 2 m @ 0.0530% Ta_2O_5 to 14 m @ 0.6851% Ta_2O_5	*1988 proven reserves:* 0.402 Mt @ 0.128% Ta_2O_5	Unknown	2
Mount Cassiterite pegmatite, Western Australia	33 m @ 0.0222% Ta_2O_5 to 3 m @ 0.1030% Ta_2O_5	*2002 proven and probable reserves:* 63.5 Mt @ 0.037% Ta_2O_5	~3 wt.% Ta_2O_5 in cassiterite	2
Main Kenticha pegmatite, Ethiopia	Unknown	*Proven low-grade reserves*: 116 Mt	65.41-70.90 wt.% Ta_2O_5 in manganotantalite in spodumene intermediate zone; 83.95-84.61 wt.% Ta_2O_5 in manganotantalite in greisen zone	3
Morrua pegmatite, ozambique	Unknown	*Reserves:* 7.5 Mt @ 0.07% Ta_2O_5	64.12, 82.64, 84.39 wt.% Ta_2O_5 in manganotantalite	4
Tanco pegmatite, Canada	*Bulk composition of entire pegmatite:* 0.02% Ta_2O_5	*Pre-production reserves:* 1.879 Mt @ 0.216% Ta_2O_5	59.89-85.00 wt.% Ta_2O_5 in wodginite; 58.61 wt.% Ta_2O_5 average and 40-85 wt.% Ta_2O_5 range for columbite-tantalite; 5.67 wt.% Ta_2O_5 average for cassiterite	5
Yichun topaz-lepidolite granite, South China	*Average:* 137 ppm Ta = 334 g/t Ta_2O_5 = 0.0334% Ta_2O_5 in granite	*Proven reserves:* 6800 t @ 0.017-0.020% Ta_2O_5	55.15 wt.% Ta_2O_5 in manganotantalite in ab-kfs facies; 78.83 wt.% Ta_2O_5 in manganotantalite in ab-rich facies; 0.23-5.49 wt.% Ta_2O_5 in cassiterite in ab-rich facies; up to 7.8 wt.% Ta_2O_5 in cassiterite	6

Notes
All of the reserves, except for Tanco, are from Fetherston (2004).

[1]Greenbushes: Partington et al., 1995; www.sog.com.au.

[2]Wodgina and Mount Cassiterite: Sweetapple et al., 2001; Sweetapple and Collins, 2002; M. Sweetapple, pers. commun. 2003; P. Vanstone, pers. commun. 2004; www.sog.com.au.

[3]Kenticha: Tadessa and Zerihun, 1996.

4Morrua: von Knorring, 1965; von Knorring et al., 1966.

[5]Tanco: Černý et al., 1996; Černý et al., 1998; Stilling, 1998; Černý, 2004; www.cabot-corp.com.

[6]Yichun: Yin et al., 1995; Belkasmi et al., 2000; Huang et al., 2002.

minerals contain 40 to 85 wt.% Ta_2O_5 in the Tanco pegmatite (P. Vanstone, pers. commun. 2004). The Ta contents in manganotantalite ranges from 64 to 84 wt.% Ta_2O_5 for the Main Kenticha and Morrua pegmatites, and albite-rich facies of the Yichun granite. Wodginite with 60 to 85 wt.% Ta_2O_5 is the main Ta-ore mineral rather than manganotantalite at Tanco. Tantalum-oxide minerals are often associated with Ta-rich cassiterite. The Ta content of cassiterite ranges from 3 to 5 wt.% Ta_2O_5 in the Mount Cassiterite and Tanco pegmatites, and 0.2 to 7.8 wt.% Ta_2O_5 in the Yichun granite. Thus, Ta-oxide minerals commonly contain 55 to 85 wt.% Ta_2O_5 in large Ta deposits, and Sn may be mined as a by-product if cassiterite is also present in sufficient quantities in the pegmatite.

Conclusions

Key geological features that are common to rare-element pegmatites in the Superior province and in large Ta deposits can be used in exploration for additional deposits.

An exploration project for rare-element pegmatites should begin with an examination of a regional geology map. Rare-element pegmatites occur along large regional-scale faults in greenschist and amphibolite metamorphosed terranes. They commonly have mafic metavolcanic or metasedimentary host rocks and are located near peraluminous granite plutons (A/CNK > 1.0). If no peraluminous parent granites crop out in the area, then a lithogeochemical survey of Li, Rb, Cs, and B contents in mafic metavolcanic and metasedimentary rocks should be performed to identify metasomatized host rocks. Note that B analysis of host rocks can be very costly, so Li, Rb, and Cs analyses are more commonly used.

If a peraluminous granite pluton has been identified, then the next step is to determine if the pluton is barren or fertile. Bulk whole-rock samples of granites and aplites should be collected to determine their rare element content. Fertile granites have rare element contents at least three times that of the average in the upper continental crust (Table 1). Fertile granites have Mg/Li < 10 and Nb/Ta < 8. Potassium feldspar tends to be pink and medium grained in barren granites, but in potassic pegmatite and rare-element pegmatites, it tends to be white (but also may be gray, pink, or peach) and blocky (>5 cm). Muscovite in a barren granite tends to be silver colored and medium grained, whereas muscovite in fertile granites tends to be green and coarse grained (>2 cm across). Fertile granites have accessory garnet, tourmaline, fluorapatite, and/or cordierite, which are absent in barren granites. Graphic textures are common in fertile granites: intergrowths of K-feldspar + quartz, muscovite + quartz, tourmaline + quartz, and rarely garnet + quartz.

Once a fertile granite pluton has been identified, the geographic direction in which it is fractionating must be determined. With increasing fractionation, the fertile granite changes in composition from biotite granite, to two-mica leucogranite, to coarse-grained muscovite leucogranite, and finally to pegmatitic leucogranite with intercalated layers of potassic pegmatite and sodic aplite (Fig. 2a). The mica assemblage changes from biotite-only, to biotite + muscovite, to muscovite-only. Beryl and ferrocolumbite occur in the most fractionated parts of the fertile granite (e.g., interior beryl zones of the Separation Rapids pluton and Ghost Lake batholith, and the western contact of Allison Lake batholith; Figs. 3, 4, 6). Key fractionation indicators can be plotted on a map of the pluton to determine the fractionation direction, such as: the presence of tourmaline, beryl and ferrocolumbite; Mn content in garnet; Rb content in bulk K-feldspar; and Mg/Li and Nb/Ta ratios in bulk whole-rock samples (Figs. 6 and 9).

Rare-element pegmatites may be found at the furthest extent of these physical and chemical fractionation trends (Fig. 2b). The residual fractionated granitic melt that remains after crystallization of a fertile granite intrusion can intrude along fractures in the host rock to form pegmatite dikes. With increasing distance from the parent fertile granite, the pegmatite dikes will contain the following index minerals: (1) beryl; (2) beryl and ferrocolumbite; (3) beryl, tantalite (ferrotantalite or manganotantalite), and Li-rich aluminosilicates (such as petalite or spodumene); and (4) beryl, manganotantalite, Li-rich aluminosilicates, and pollucite.

Pegmatite dikes with the most economic potential for Li-Cs-Ta deposits occur the greatest distance (up to 10 km) from the parent granite.

Metasomatized host rocks are an indication of a rare-element pegmatite nearby, because pegmatitic fluids commonly alter the composition of the host rocks. Metasomatic aureoles can be identified by their geochemistry: they contain elevated Li, Rb, Cs, B, and F contents. Anomalies from a systematic lithogeochemical survey should indicate metasomatized host rocks in close proximity to pegmatite dikes. Metasomatic aureoles can also be identified by their mineralogy: presence of tourmaline, (Rb, Cs)-enriched biotite, holmquistite, muscovite, and rarely garnet. Purple holmquistite is a good indicator mineral, because it usually occurs within 10 m of a rare-element pegmatite (London, 1986).

Compositions of bulk K-feldspar and muscovite are excellent exploration tools because these minerals are common in barren granite, fertile granite, and rare-element pegmatites. The Rb and Cs contents increase in K-feldspar and muscovite with increasing fractionation of the granitic melt. Pegmatites with the highest degree of fractionation (and thus the most economic potential for Li-Cs-Ta) contain blocky K-feldspar with >3,000 ppm Rb, K/Rb < 30, and > 100 ppm Cs (Table 3). Pegmatites with the most economic potential contain coarse-grained green muscovite with >2,000 ppm Li, >10,000 ppm Rb, >500 ppm Cs, and >65 ppm Ta. Pegmatite samples containing muscovite with >65 ppm Ta have a high probability of containing Ta-Nb mineralization (Fig. 7; Gordiyenko, 1971).

Once a pegmatite dike has been located, the next step is to assess its degree of fractionation and, thus, its potential for containing Ta mineralization. Bulk whole-rock analysis of pegmatitic and aplite zones will contain elevated rare element contents (e.g., Li, Rb, Cs, Nb, Ta, Sn) in highly evolved pegmatites. Pegmatites with Ta mineralization usually also contain Li-rich minerals (e.g., spodumene, petalite, lepidolite, elbaite, amblygonite, lithiophilite, eucryptite) and may contain Cs-rich minerals (e.g., pollucite, Cs-rich beryl). Pegmatites with Cs-rich minerals have greater probability of containing economic Ta mineralization than pegmatites without Cs-rich minerals.

The final step is to locate the Ta-Nb-oxide minerals in the Li-rich pegmatites. Pegmatites with potential to become Ta deposits should contain low Nb/Ta ratios and Ta/Sn > 1 in bulk analyses, and abundant Ta-rich oxide minerals. Tantalum-niobium-oxide minerals are usually small (1–2 mm) and black with a metallic luster, so careful examination of samples is required for identification. It is almost impossible to distinguish fine-grained Nb-rich oxide minerals (not economic in granitic pegmatites) from Ta-oxide minerals (economic) by eye. It is recommended that prospectors submit non-magnetic oxide mineral grains for electron microprobe analysis, or have bulk analyses undertaken on rock samples rich in possible Ta-Nb-oxide minerals to determine if Ta > Nb. The ore minerals of Ta are commonly manganotantalite, manganocolumbite, wodginite, and microlite. Tantalum-rich cassiterite is often associated with Ta-oxides in Ta deposits. Tantalum mineralization tends to occur in albitic aplite, mica-rich zones (e.g., lepidolite, cleavelandite + lepidolite), and spodumene/petalite pegmatite zones. Tantalum might be recovered as a by-product from spodumene/petalite pegmatite zones, but the Ta grades are often low and Li would be the main economic element.

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