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The main types of rare metal mineralization (Y-Zr-Nb-Ta-Be-Li-REE) in Québec

Michel Boily, Charles Gosselin

Niobium (Niobec) mine in the Saint-Honoré Alkaline Complex, Saguenay region.

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Québec

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Summary

This report is the result of a compilation of the main rare metal showings, prospects and deposits in the province of Québec. It presents the principal uses for these metals in industrial and consumer products, particularly in the high-tech fields of semiconductors, superconductors, electromagnets, ceramics and alloys.

A genetic classification was established for the main types of rare metal mineralization in Québec. These are: Type I – Li, Be, Ta, Cs, Rb, ± Mo, ± Nb, ± F mineralization in granite pegmatites associated with peraluminous granite plutonic complexes; Type II – Nb, Ta, REE and P mineralization associated with carbonatite complexes; Type III – REE, Y, Zr, F, ± Be, ± Nb, ± Th mineralization associated with pegmatites injected internally within intrusions of peralkaline granite and syenite; Type IV – Fe, Ti, ± Zr, ± REE mineralization associated with placers or paleoplacers; Type V – iron oxide mineralization with Cu, ± Au, ± U, ± P, ± REE (Olympic Dam/Kiruna); Type VI – Mo, U, Th, Zr and REE mineralization in granite pegmatites and migmatites associated with peraluminous to metaluminous granites; and Type VII – Th, U, ± Mo, ± REE mineralization in skarns (mineralized calcsilicate rocks). A list of the main world-class deposits for each type is presented, and mineralized sites in Québec are described, with an emphasis on the largest or otherwise most significant prospects and deposits. Exploration criteria are also proposed.

Analytical results for granites and syenites in Québec were taken from the SIGEOM database and the results used to identify fertile intrusives associated with, or likely to contain, zones of rare metal mineralization. These granitoids are found in six large regions of Québec. The four most significant groups are: 1) Grenvillian intraplate granites of the Manitou-Wakeham region associated with iron oxide, Cu, REE, Y, P, F, Ag mineralization (Type V; Olympic Dam/Kiruna); 2) anorogenic granitic and syenitic plutons of the Rae Province, related to the formation of a pan-continental Proterozoic rift and likely to contain REE, Y, Zr mineralization (Type III); 3) monzogranites and granite pegmatites of the James Bay region (Vieux-Comptoir Granite, Lower and Middle Eastmain Belt) containing Li, Be, Ta mineralization (Type I); and 4) Li- and Be-mineralized monzogranite intrusions and granite pegmatites of the Frotet-Evans Volcano-sedimentary Belt (Type I).

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Direction générale
Robert Giguère (p.i.)

Direction de l'information géologique
Luc Charbonneau

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Jean-Yves Labbé

Bureau de l'exploration géologique
Patrice Roy

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Pierre Doucet

Editing
Jean-Pierre Lalonde

Translation
Venetia Bodycomb

Drawing
Michel Boily
Charles Gosselin

Graphic Design
Marie-Eve Lagacé

Technical Supervision
Charlotte Grenier

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INTRODUCTION

Industrialized countries are facing growing competition to create new high-technology products using semiconductors, superconductors, electromagnets, ceramics, and a variety of metal alloys in which rare metals constitute a dominant component. Over the past two years, prices for Nb-Ta concentrates have gone up. Rising prices and growing demand have led to renewed interest for rare metal exploration in granitic pegmatites and peraluminous granites located in the Superior Province. This interest from mining companies prompted the Ontario Geological Survey (OGS) to complete a thematic study aiming to develop a geochronology, geochemistry, and mineralogy database on fertile granites and their granitic pegmatite suites hosted in the Superior Province (Breaks *et al.,* 2002). The latter study not only inventories a number of high-potential occurrences, it has also led to the discovery of new rare metal showings (Li, Ta and Cs) within the Quetico, Wabigoon, English River, and Uchi subprovinces.

It is quite likely that the Superior Province in Québec shows just as much potential as in Ontario, as illustrated by the numerous Li and Ta deposits and showings reported in granitic pegmatites associated with the Preissac-Lacorne Plutonic Complex (Figure 1) in the Abitibi Subprovince (Boily, 1995). Furthermore, the extensions of Archean subprovinces enriched in rare metals in northwestern Ontario were recognized in the Baie-James area (Opatica, La Grande, Nemiscau and Opinaca subprovinces; Goutier *et al.,* 1999a, b). However, other than the small region around Preissac-Lacorne, no systematic study of the economic potential for rare metals has ever been conducted in the Superior Province of Québec. In addition, Québec contains several major rare metal deposits within the Grenville and Rae geological provinces, such as the Niobec, Strange Lake and Kipawa deposits (Figure 1). In light of this, the *Ministère des Ressources Naturelles, de la Faune et des Parcs* (MRNFP) of Québec launched a project in 2002 to define the rare metal potential throughout the province.

Methodology

A study to identify and compile all known rare metal (Y, Zr, Nb, Ta, Be, Li and REE) occurrences across the province of Québec was carried out. We updated mineral deposit files of showings, prospects, deposits and mines inventoried in the SIGEOM database. Uranium and thorium showings were also considered when associated with geological settings likely to offer rare metal potential. Finally, all mineral occurrences were divided into 7 genetic types mainly reflecting the geological processes leading to their formation and their association with certain rock types. A total of 297 rare metal showings, prospects and deposits were compiled and the results published in a CD-ROM (Gosselin *et al.,* 2003). The latter included a map of rare metal (Y, Zr, Nb, Ta, Be, Li and REE) occurrences, as well as a database providing information on each mineral occurrence. A hyperlink providing direct access to the complete descriptive file of the showing or deposit via the "E-SIGEOM à la carte" website was also integrated into the database.

This report complements the CD-ROM accompanying the report by Gosselin *et al*. (2003). The numbers used herein to identify mineral occurrences correspond to the same numbers used in that publication. These numbers and their corresponding identification numbers in the former COGITE database used in earlier publications are listed in Appendix 1. In addition, this report provides a brief overview of the main uses for rare metals in industrial and consumer products. It also includes a description of the 7 types of rare metal mineralization found in Québec, a presentation of a few important prospects or deposits, a list of useful assessment criteria for exploration, and a discussion of the geochemistry aspect. For the latter, lithogeochemistry analyses were retrieved from the SIGEOM database and processed to identify so-called "fertile" granitoid rocks for rare metal mineralization. This data was used to conduct a more thorough assessment of the genuine potential of many areas with known mineralization across Québec.

MAIN USES FOR RARE METALS

The definition of a rare metal is based on its abundance, current market price, and the industrial uses for the element. However, scientists, prospectors, geologists and engineers in the mining industry consider the following elements as members of the rare metal group (Cerny, 1981, 1989; Boily, 1989): zirconium (Zr), niobium (Nb), tantalum (Ta), beryllium (Be), lithium (Li), hafnium (Hf), rubidium (Rb), and thorium (Th), as well as all rare earth elements (REE). Rare earth elements include the lanthanides, a group of 15 elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), as well as yttrium (Y). A brief description of the main uses for various rare metals is provided below. Much of this information was taken from documents published by the United States Geological Survey (USGS). More detailed information is available at the following website:

http://minerals.usgs.gov/minerals/pubs/commodity/myb/.

Lithium (Li)

Lithium (Li) is used in industrial products in its metal form, in compounds, or as a mineral. Its low density, small ionic radius, high electropositivity, and low melting point make it very popular for use in ceramics, batteries and the nuclear industry.

<u>Batteries:</u> The ionic properties of Li are favourable for its use in long-lasting rechargeable batteries. <u>Metallurgy:</u> Lithium carbonate is used as an electrolyte in the production of aluminium, whereas lithium metal is added to aluminium

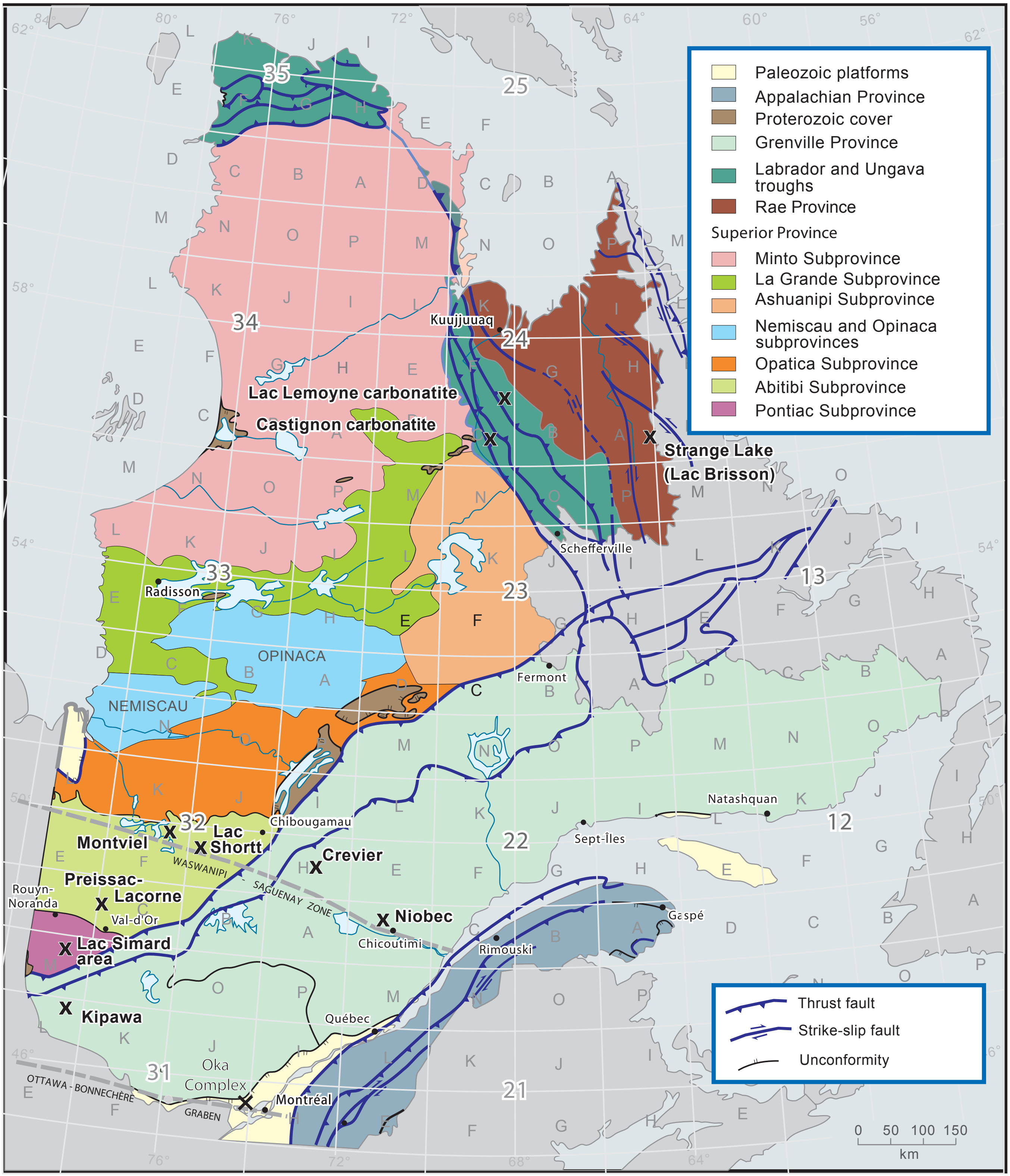

FIGURE 1 - Map showing the major tectonostratigraphic divisions of Québec and the main areas and deposits mentioned in the text.

to produce a resistant alloy. Nuclear energy: Inside a nuclear fusion reactor, liquid lithium promotes the effective production of tritium fuel while acting as a coolant and insulator. Chemical industry: Lithium is used to manufacture rubber products (neoprene), air conditioning systems, lubricants and pharmaceuticals. Ceramics: The lithium minerals petalite and/or spodumene are essential in the fabrication of heat-resistant cookware (Corningware). Glass: Petalite and spodumene increase the resistance of glass flux and also lead to power savings in production plants.

Rubidium (Rb) and Cesium (Cs)

Rubidium (Rb) and caesium (Cs) are alkali metals. Their high electropositivity makes them indispensable in research and development, particularly in the fields of chemistry and electronics.

Biomedical research: Rb and Cs compounds are used as catalysts to generate new products derived from biomedical and chemical research (*e.g.*, separating genes from DNA molecules). Photoelectricity: the low ionic potentials of Cs and Rb are conducive for use in the production of photoelectric cells. Ceramics: Potassium-cesium feldspars are incorporated in high-voltage ceramic insulators. Glass: Rb-carbonate glass is used in optical devices. Ionic propulsion: Cs may be used in ionic propulsion systems for space.

Tantalum (Ta)

Tantalum (Ta) has an extremely high melting point (3,017°C), a tensile strength nearly double that of steel alloys, and is acid-resistant.

Electronics: Approximately two thirds of all the tantalum extracted is used to produce electronic components, namely capacitors. Metallurgy: Ta alloys, highly resistant and able to sustain high temperatures, are used to manufacture aircraft engines. Metal Ta, given its corrosion- and heat-resistant qualities, is used as a sealant in chemical and nuclear plants. Resistant products: The extreme hardness of Ta-carbide makes it useful to manufacture cutting tools, drill bits, and other mining equipment. Glass: Ta oxide is added to glass to increase its refraction index and to produce lighter eyeglass and camera lenses. Medical industry: Ta's resistance to corrosion is conducive for use in manufacturing implants and surgical instruments.

Zirconium (Zr) and Hafnium (Hf)

Zirconium (Zr) and hafnium (Hf) are two transition elements characterized by a very high ionic charge/ionic radius ratio and are known as high field strength elements (HFSE). These elements are extremely resistant to corrosion by common acids, alkalis, seawater, etc.

Jewellery: Zirconium oxide is used to make cubic zirconia, a diamond substitute. Nuclear and chemical industries: Zirconium is used to manufacture radiation shields for nuclear reactors, as well as control rods in reactors. It is also used in piping as an anticorrosion agent. Alloys: Several types of heat- and corrosion-resistant alloys contain Zr and Hf.

Rare earth elements (REE)

REE include the lanthanides and yttrium. In their metal form, they are ductile, malleable and highly reactive at high temperatures, making them useful in a wide variety of applications.

Electronics: Nd is an essential component of alloys used as high-strength supermagnets (*e.g.,* B-Fe-Nd magnets). It is also used to manufacture new long-lasting rechargeable batteries (for cell phones and laptop computers). Nd is also incorporated into $LiNb0_3$ crystals in lasers. Miscellaneous: REE and Y are used in the production of phosphates, abrasives, additives for gas, automotive catalytic converters, non-toxic plastic dyes and liners. Light alloys made of Mg-Y-Nd-Zr are commercially available and can tolerate temperatures up to 250°C. Cerium (Ce) and titanium oxide are ingredients used in the composition of viscous fluids in automobile transmissions and power rims. Y is used in anti-corrosion paints and REE are incorporated in tools in the form of carbide cement, to increase their resistance.

Beryllium (Be)

Beryllium (Be) is the lightest of the rare metals. It is stiff and has one of the highest melting points (1,278°C). These properties make it one of the most popular elements for use in the aerospace and defence industries.

Electronics: Be-Cu alloys are used in a wide variety of electronic products given their excellent thermal and electrical conductivity, hardness, non-magnetic nature and resistance to corrosion. This type of alloy is used in connectors, coils and switches in automobiles, computers, home appliances, radars, control instruments, and telecommunications equipment. Ni-AI-Be alloys are used to fabricate miniaturized electronic components. Be oxide is a good heat conductor and is used as an electric insulator in electronic circuits, automotive ignition systems, lasers and electronic radar systems. Aerospace and military industries: Be metal is included in guidance systems, brakes for military aircraft, satellite structures, and optical systems for use in space. Co-Be tubes are used in aircraft landing gear and molds for the aerospace industry. Nuclear industry: Be serves as a neutron moderator and is used in control rods in nuclear fission reactors.

Niobium (Nb)

Niobium (Nb), like tantalum, is a good electrical and thermal conductor. It has a high melting point (2,470°C) and is resistant to chemical corrosion.

Steelmaking: Ferroniobium and niobium-nickel alloys are used in the steel industry. Industry: New Fe-Ni-Nb superalloys are used in the aerospace industry, to build gas-powered generating turbines, as well as in heat-resistant combustion equipment and for rocket engines.

Thorium (Th)

Thorium (Th) is a heavy, soft and very ductile metal in the actinide series. It is mainly used in alloys.

Electronics and appliances: Th nitrate is used to produce welding electrodes and magnetron cathodes included in radar systems for airspace control, meteorology, defence systems, and in microwave ovens. As a catalyst, Th enters in the fabrication of electron tubes, electric light bulbs, highly refractive glass and in radiation detectors. Aerospace: Th-Mg alloys are used in the aerospace industry as they are light and resistant to high temperatures.

CLASSIFICATION OF RARE METAL DEPOSITS

This chapter deals with the main classification criteria for rare metal deposits in Québec. Table 1 presents a condensed version of the set of criteria for each deposit type.

Type I: Li, Be, Ta, Cs and Rb deposits associated with peraluminous granite complexes

Description

Li-Be-Ta-Cs-Rb ± Mo ± Nb ± F mineralization concentrated in granite pegmatite dyke swarms of Archean age. These dykes intrude metavolcanic or metasedimentary rocks. The pegmatite dykes surround and are genetically related to late tectonic to post-tectonic plutonic complexes of peraluminous monzogranite.

Tectonic Environment

The peraluminous monzogranites and accompanying granite pegmatite dykes are found within metamorphosed greenstone belts (greenschist to amphibolite facies) or intruding belts of highly metamorphosed paragneiss and orthogneiss. Monzogranites crop out along the edges of major deformation corridors defining the boundaries of structural blocks containing a variety of lithologies.

Age of mineralization

Precambrian to Proterozoic, with rare Mesozoic to Cenozoic occurrences.

Host rocks and associated rocks

Host rocks: Dykes of potassic granite pegmatite, sodic aplite, albitite, fine-grained or porphyroblastic biotite monzogranite, fine-grained monzogranite containing biotite, muscovite, ±garnet, and pegmatitic monzogranite. Associated rocks: TTG suite intrusives (tonalite-trondjhemite-granodiorite), metavolcanics (metabasalt, amphibolite), biotite schist (metagraywacke, orthogneiss and paragneiss).

Deposit form

1- A swarm of granite pegmatite dykes, homogenous to broadly zoned, steeply dipping, metres to decametres thick and decametres to kilometres long. 2- A pegmatitic body of variable form (mushroom-shape, sill) moderately to highly differentiated and metasomatized in places, displaying monomineralic zones or layers (e.g., albite, tantalite, petalite).

Zonation and type of pegmatite

The granite pegmatites become increasingly differentiated moving away from the parent monzogranite. An idealized sequence based on the paragenesis proposes 7 zones: 1) barren biotite-magnetite pegmatites; 2) barren plagioclase-microcline pegmatites with biotite and tourmaline; 3) pegmatites containing microcline, tourmaline, muscovite and beryl; 4) zoned pegmatites containing microcline, albite, tourmaline, muscovite and beryl; 5) zoned microcline-albite pegmatites mineralized with Li, Rb, Cs, Be and Ta, and enriched in B, P and F; 6) albite pegmatites mineralized with Li, Be, Sn and Ta; 7) homogenous albite-spodumene pegmatites; and 8) veins of quartz ± feldspar ± beryl ± cassiterite ± wolframite.

Pegmatite mineralogy

Gangue: albite (cleavelandite), quartz, microcline (at times graphic), muscovite, garnet (spessartite). Ore: lithium (spodumene, petalite, lepidolite, tryphilite-lithiophylite, amblygonite-montebrasite), tantalum (colombo-tantalite, wodginite, microlite), beryllium (beryl) and cesium (pollucite).

Alteration

Pegmatite: Internal metasomatism within the pegmatites: albitization (often associated with Ta mineralization), tourmalinization, leaching of Li from spodumene. Country rock: Tourmalinization (B); biotitization (biotite-zinnwaldite; Li, K); holmquistite (Li); fluorite (F).

Structural control

The granite pegmatites fill fractures and joints in granitoids, and are emplaced along fractures and foliation planes in

TABLE 1 - Summary of the main classification criteria for rare metal deposits.

Type	Mineralization	Host rocks and associated rocks	Form	Mineralogy	Alteration
I	Li, Be,Ta,Cs,Rb, ±Mo, ±Nb and ±F	Pegmatite dykes, aplites, albitites, biotite + muscovite ± garnet monzogranites, monzogranite pegmatites. Associated rocks: TTG intrusions, metavolcanics, biotite schists.	Swarms of granite pegmatite dykes, homogenous to broadly zoned. Pegmatitic masses of variable forms (moderately to highly differentiated).	Li: spodumene, petalite, lepidolite, tryphilite-lithiophylite, amblygonite-montebrasite. Ta: colombo-tantalite, wodginite, microlite. Be: beryl, Cs: pollucite.	Pegmatite: albitization, tourmalinization, leaching of Li from spodumenes. Country rock: tourmalinization (B); biotitization (biotite-zinnwaldite; Li, K); holmquistite (Li); fluorite.
II	Nb, Ta, REE and P	Carbonatites: sovites, rauhaugites, beforsites. Associated rocks: magnetite + olivine + apatite ± phlogopite intrusions, nephelinites, syenites, pyroxenites, peridotites, and phonolites.	Circular, elliptical or irregular masses. Dykes and sills. Mineralization forms a steeply dipping crescent shape in circular/elliptical bodies.	Magmatic: REE: bastnaesite, parisite, apatite, monazite. Nb,Ta: pyrochlore. P, REE: apatite. Hydrothermal/metasomatic: fluorite, vermiculite, bornite, chalcopyrite. Residual: pyrochlore, apatite, crandallite (P, REE).	Fenetization halo (alkali ± Fe metasomatized country rocks accompanied by desilicification) around the carbonatite.
III	REE, Y, Zr, ±Be, ±Nb, ±Th	Peralkaline pegmatites, silica-oversaturated: aegirine+riebeckite, fluorite; silica-undersaturated: nepheline. Associated rocks: augite+nepheline syenites, peralkaline aegirine-arvfedsonite granites, lujavrites, kakortokites, biotite monzogranites.	Dykes and sills filling cooling fractures and/or magmatic/hydrothermal disseminations at the summits of albitized intrusive cupolas.	Zircon, monazite, pyrochlore, bastnaesite, beryl, eudyalite (Zr), gittinsite (Zr), thorite, tantalite, elpidite (Zr), gagarinite (REE, Y), britholite, kainosite (REE, Y), mosandrite (REE), gadolinite (Y, Be, REE), loparite (REE, Nb, Ta).	Albitization of parent granitoids in the cupola. Destabilization and hematization of amphiboles and feldspars. Circulation of low-temperature meteoric fluids leading to the replacement of sodic silicates with calcic silicates. Silicification.
IV	Fe, Ti, ±Zr, ±REE (Placers and paléoplacers)	Marine: coarse- to medium-grained sand, well sorted, overlying finer-grained shallow marine deposits. Continental: fine- to coarse-grained sand, well sorted, rounded.	Marine: along coastlines, thin (<1 m thick), long (>100 m) and narrow (> 50 m). Continental: discontinuous lenses (<2 m).	Native gold, ilmenite, cassiterite, zircon, PGE, magnetite, monazite, garnet.	
V	Iron oxide, Cu, REE, Y and U (Olympic Dam/ Kiruna)	Veins and breccias, discordant or concordant, in felsic volcanic breccias, tuffs, clastic sedimentary rocks, and A-type alkaline granites.	Discordant masses, veins, dykes, tabular bodies, and stockworks.	Hematite, magnetite, specularite, bornite, chalcopyrite, chalcocite, pyrite, pitchblende, coffinite (U), branerite (U), bastnaesite, monazite, xenotime. Gangue (breccias or veins): sericite, carbonate, chlorite, quartz, fluorite, barite.	Olympic Dam: intense sericite and hematite at surface and chlorite + potassium feldspar at depth. Kiruna: scapolite and albite; actinolite + epidote in mafic host rocks.
VI	U, Th, ±REE, ±Nb, ±Zr and ±Y	Potassic granite dykes, granite migmatites, biotite ± muscovite granites, TTG suite intrusives. Associated rocks: metavolcanics, biotite schists, orthogneiss and paragneiss, calcsilicate rocks.	Swarms of granite pegmatite dykes, homogenous to broadly zoned. Heterogeneous masses of granite migmatites and granites.	Monazite, xenotime, allanite, zircon, magnetite, uraninite, pitchblende, thorite, thorianite, pyrochlore, samarskite (Nb, Ta, U), coffinite (U), uranophane, fergusonite (Y, Nb, Ta), gadolinite, ferrocolombite.	Pegmatite: albitization, chloritization, oxidation and hydrous alteration.
VII	Th, U, ±Mo and ±REE (skarn)	Associated rocks: granite pegmatites, granites, syenites, pyroxenites (pyroxene skarn), calcsilicate gneiss, marbles, volcanics.	Irregular zones along intrusive contacts.	Ore: uraninite, monazite, xenotime, allanite, zircon, magnetite, uraninite, pitchblende, thorite, thorianite, pyrochlore, molybdenite, allanite. Skarn: clinopyroxene, garnet, wollastonite, hornblende, epidote, olivine.	

TABLE 1 - Summary of the main classification criteria for rare metal deposits (continued).

Type	Structural Control	Origin	Examples	Exploration Criteria
I	The pegmatites fill fractures, joints, and foliation planes in granitoids and country rocks. The monzo-granite intrusions are controlled by major faults and deformation corridors that mark the boundaries of structural blocks.	Magmatic.	Greenbushes and Wodgina mines (Australia), Tanco mine (Canada), Québec Lithium mine (Québec)	Late to post-tectonic peralumi-nous monzogranite complexes. Deformation corridors marking the boundaries of major structural blocks. Mineralized granite pegma-tites crop out in metasedimentary and/or metavolcanic country rocks within a 1-2 km radius from the contact with the parent monzo-granites.
II	Magmatic: the shape of the intrusion and its crystallization his-tory. Hydrothermal/metasomatic: tectonics and structures. Residual: erosion and the drainage pattern.	Magmatic, metasomatic/hydro-thermal, residual.	Mountain Pass (California), St-Lawrence Columbium and Niocan (Oka, Québec), Niobec mine (St-Honoré, Québec).	The carbonatites are associated with continental rifts and grabens. They display excellent circular magnetic and radiometric signa-tures and may be associated with ring-shaped topographic breaks. Fenetization.
III	Mineralized pegmatites intrude fractures and joints of the cupola, at the intrusion/country rock contact or at the contact between two intrusive phases	Magmatic, low-temperature hydrothermal.	Karnasurt and Umbozero (Kola Peninsula, Russia), Strange Lake (Québec-Labrador), Kipawa (Québec).	Undeformed A-type (anorogenic) plutons. The radioactive alkaline granites and syenites are associa-ted with airborne radiometric ano-malies. Prospecting with a scintillo-meter can track down the source of radioactive boulders. Analyzing sediment and water samples from lakes and rivers can reveal REE, F, Th and Y anomalies.
IV	Marine: Heavy minerals concen-trate along shorelines in sediments reworked by waves and currents. Continental: In fluvial zones, placers concentrate in irregulari-ties within channels and surface depressions.	Sedimentary.	Ticor South Africa (South Africa), Tamil Nadu (India), Kwale (Kenya), Natashquan (Côte Nord [North Shore], Québec).	Anomalous concentrations of Ti, Zr, Fe, Cr, Au and Ag in stream sediments near the deposit. Heavy mineral separation by panning or by gravity (Wilfley table) can reveal the presence of native gold, ilmenite, zircon, magnetite or other heavy minerals.
V	Emplacement along faults and/or lithological contacts, particularly in small-scale grabens. Intense hydrothermal activity along faults associated with brecciation.	Magmatic and hydrothermal.	Bayan Obo (China), Olympic Dam (Australia), Kiruna (Sweden).	Rift zones and fault zones in Proterozoic cratons. Intrusive and volcanic A-type rocks displaying potassic or sodic alteration and intense brecciation. Iron oxides, particularly those in breccias, stoc-kworks and veins, produce positive gravimetric and aeromagnetic anomalies.
VI	Granite pegmatites and migmatites fill fractures and joints, and folia-tion planes in granitoids and their country rocks.	Magmatic. Hydrothermal alte-ration and remobilization during metamorphism may play a role.	Lac Turgeon granite showings (Basse Côte-Nord [Lower North Shore], Québec).	Radioactive minerals (uraninite, pitchblende, thorite, thorianite, pyrochlore, samarskite) in the granites and pegmatites produce excellent airborne radiometric anomalies. Radioactive minerali-zed zones can be identified and outlined by prospecting with a scintillometer.
VII	In calcareous and calcsilicate rocks forming thermal aureoles around intrusives.	Contact metamorphism and/or metasomatism of pure limestones and siliceous limestones.	Lataille showing (Minto Subprovince, Québec), Baie-Mercier showing (Grenville Province, Québec).	Radioactive minerals in the granites and skarns produce airborne radiometric anomalies. Radioactive mineralized zones can be identified and outlined in the field by pros-pecting with a scintillometer.

country rocks. On a larger scale, late tectonic to post-tectonic monzogranite intrusions and their accompanying pegmatitic intrusives are controlled by major faults and deformation corridors defining the boundaries of structural blocks.

Origin

Mineralization in granite pegmatites is essentially of magmatic origin. It is the result of extreme fractional crystallization of a parent peraluminous (S-type) granite enriched in Li, Be, Ta, Cs, Rb and volatile phases (H_2O, F, and B). The residual magmas enriched in rare metals and volatile phases are expulsed along fractures in the country rocks, in which pegmatitic bodies differentiate and form different mineralogical zones. Orthomagmatic fluids generally precipitate at the end of crystallization, sometimes causing autometasomatism and/or leaching accompanied by Ta mineralization. The expulsion of these fluids into the country rocks leads to the formation of an alteration halo enriched in Li, K, F and B (Jahns, 1982; Cerny *et al.,* 1985; Manning and Pichavant, 1985).

Important mine sites

International: Kings Mountains, North Carolina, USA: 70 Mt at 1.5% Li_2O; Greenbushes, Australia: 7.96 Mt at 3.96% Li_2O and 88.6 Mt at 222 ppm Ta_2O_5; Wodgina, Australia: 63.54 Mt at 366 ppm Ta_2O_5. Canada: Tanco mine, Bernic Lake, Manitoba: 1,500,000 lbs of Ta_2O_5; Québec Lithium mine (in production from 1954 to 1966), Barraute, Québec (reserves of 18.1 Mt at 1.30% Li_2O).

Information

Many sources, including Boily *et al.* (1989), Boily (1992 and 1995) and Cerny (1982).

Main Type I deposits in Québec

In Québec, occurrences of rare metal mineralization associated with peraluminous granitic complexes (Type I) have been found in the Abitibi, Pontiac, Opatica and Nemiscau subprovinces. One of the most explored regions for Type I of mineralization is the Preissac-Lacorne area in the Abitibi Subprovince. There, a large number of Li ± Ta ± Be occurrences are concentrated around the Preissac-Lacorne Complex (deposit nos. 198 to 212 and 215 to 231, Appendix 1, Figure 2), including the Québec Lithium mine (Figure 3). The complex was the subject of a detailed study by Boily (1992), who defined the spatial and mineralogical zonality of the granite pegmatite dykes and albitites (Figure 2). Barren pegmatites (Zone 1) are found in the cores of monzogranite plutons and display a similar paragenesis. Beryl (± Ta ± Li) pegmatites (Zone 2) crop out along the margins of these plutons, whereas albite-spodumene (± Ta ± Be ± Mo) pegmatites (Zone 3) occur in the country rocks (early intrusive phases of the Preissac-Lacorne Complex and volcano-sedimentary rocks) within a 1 km radius of the contact. Albitite dykes (Zone 4) rich in molybdenite and colombo-tantalite ± spodumene are found beyond the envelope containing albite + spodumene dykes. Finally, molybdenite mineralization occurs in pegmatites containing quartz + potassium feldspar + muscovite ± albite, and in quartz veins mineralized with Mo ± Bi ± Be (Zone 5). The main lithium deposits and prospects at Preissac-Lacorne are found within Zone 3. Among them, the Authier prospect (deposit no. 215, Figure 2) of Raymor Industries, with estimated reserves of 4.55 Mt at 1.05% Li_2O, and the former Québec Lithium mine (deposit no. 207), active from 1954 to 1966, with reserves of about 18.14 Mt at 1.30% Li_2O when it closed.

Significant lithium prospects and showings have been reported in the Opatica and Nemiscau subprovinces (deposit nos. 244 to 248,250 and 255 to 258, Appendix 1). The main ones are the Sirmac prospect (deposit no. 245, Figure 4) in the Frotet-Evans Volcano-sedimentary Belt (reserves of 318,000 t at 2.0% Li_2O), the Cyr-Lithium prospect (deposit no. 258, Figure 4), in the Lower and Middle Eastmain Belt (reserves of 12 Mt at 1.7% Li_2O) and the Lac des Montagnes showing, recently assessed for its tantalum potential and where two grab samples graded 207 and 317 g/t Ta_2O_5 (deposit no. 250). Origins: This large spodumene pegmatite (1,200 m long by 100 m wide) is oriented NE-SW and is associated with a swarm of differentiated pegmatites. These pegmatites may extend along a major brittle structure more than 110 km long, marking the boundary between the Nemiscau and Opatica subprovinces. (Figure 4).

The Pontiac Subprovince also contains a number of Li ± Ta showings in the Lac Simard area (Figure 1), south of Rouyn-Noranda (deposit nos. 188 to 193, Appendix 1). Particularly significant concentrations of tantalum were reported, generating interest among mining companies (press release of Osisko Exploration Ltd, 2002).

Québec Lithium mine

The Québec Lithium mine consists of 13 homogenous, spodumene-bearing granite pegmatite dykes measuring 0.3 to 50 metres thick (Figure 3). The dykes crosscut a hornblende monzonite belonging to the Preissac-Lacorne Complex, as well as metavolcanics and metasediments.

Pegmatites associated with the late monzogranitic suites of the complex were emplaced along the edges of the Manneville Deformation Corridor (Figure 2). The mineralogy consists of albite, quartz, spodumene, muscovite and spessartite, and accessory minerals that include beryl, lepidolite, colombo-tantalite, bismuthite, native bismuth, and petalite. Spodumene forms small prismatic crystals (1.2 to 1.5 cm) uniformly distributed and oriented perpendicular to the country rock contacts. In places, dykes have aplite margins and quartz cores (Figure 3). The country rocks are metasomatized up to 1 m from the contact, and holmquistite (a violet lithium amphibole) and biotite are present (Karpov, 1957; Boily, 1995).

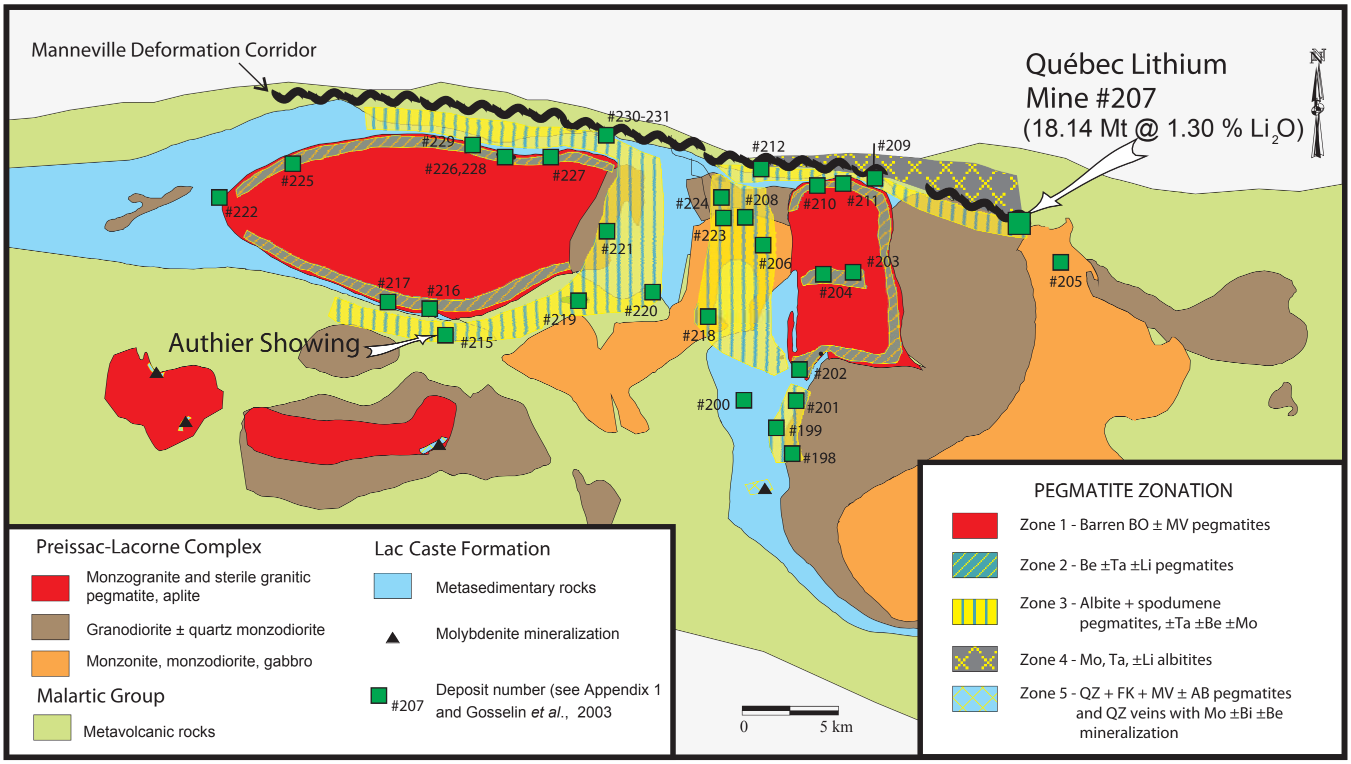

FIGURE 2 - Mineralogical zonation of mineralized pegmatites in the Preissac-Lacorne Plutonic Complex, Abitibi Subprovince, Québec (after Boily *et al.*, 1990). See Sharma, 1996 for an explanation of the mineralogical codes.

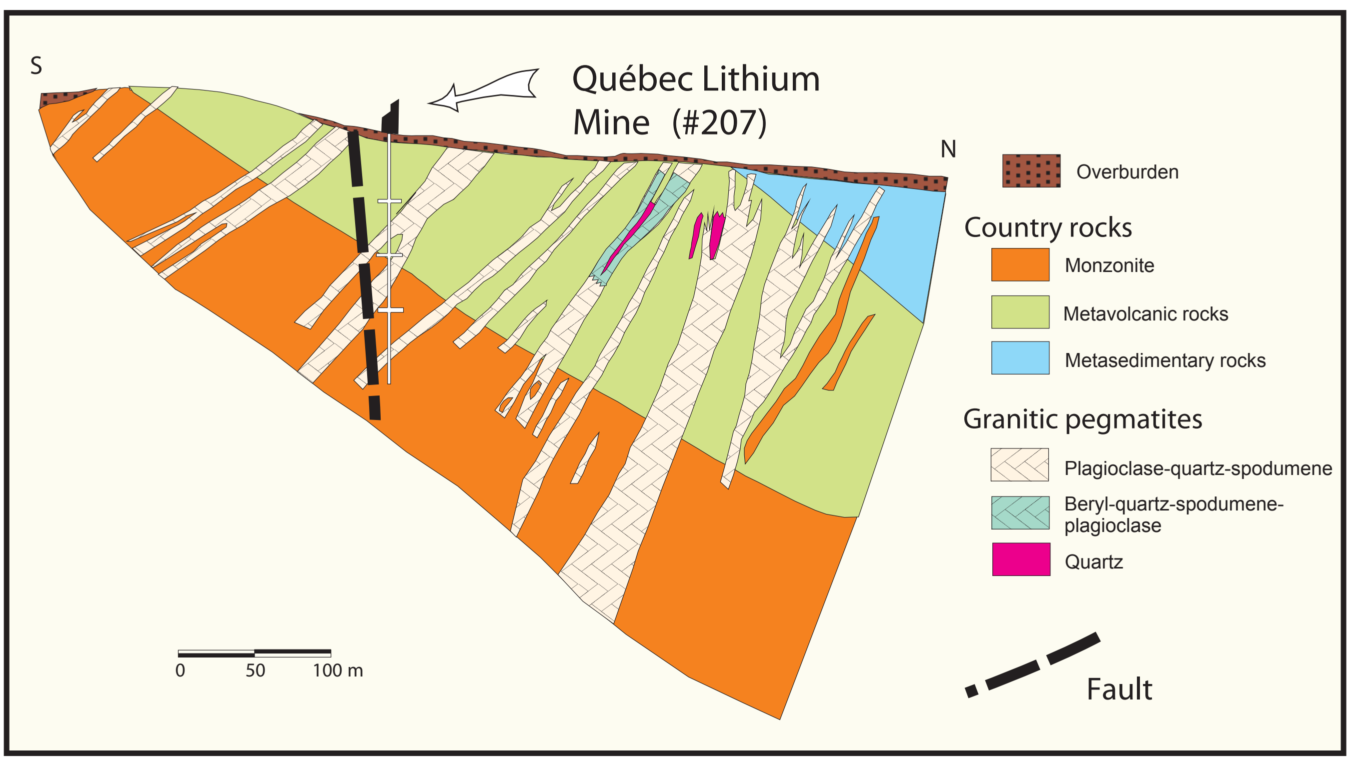

FIGURE 3 - Geology of the Québec Lithium mine, Barraute, Québec, Abitibi Subprovince (after Karpov, 1957; Boily, 1995).

Exploration criteria

- The presence of late tectonic to post-tectonic parent monzogranite complexes, with generally little deformation.

- Monzogranites emplaced along major deformation corridors marking the boundaries of structural blocks (e.g., Manneville Deformation Corridor, Abitibi Subprovince, Québec) or along the margins of contacts between subprovinces with different lithological assemblages (e.g., the Wabigoon–English River, English River–Uchi, and Quetico–Wabigoon subprovince boundaries in Ontario; Breaks *et al.*, 2002).

- The presence of a fine-grained leucogranite facies containing muscovite + biotite + garnet; pegmatitic leucogranite with megacrysts of potassium feldspar; aplite dykes; and potassic granite pegmatite containing beryl ± spodumene ± tantalite.

- Granite pegmatites mineralized in rare metals (Li, Ta, Be, Cs and Rb) crop out in metasedimentary and/or metavolcanic country rocks metamorphosed to greenschist to amphibolite facies, up to a distance of 1 to 2 km from the contact with the parent monzogranites.

- Pegmatites containing rare metals are often surrounded by a metasomatic aureole indicated by the appearance of indicator minerals in fractures, such as holmquistite (lithium amphibole), tourmaline and biotite. The presence of cleavelandite (albite) and silvery green muscovite are indicators of high Li potential (spodumene petalite). Internal metasomatism, characterized by albitization and the appearance of lepidolite, is generally an indicator of Ta and Li mineralization.

- The main geochemical characteristics of fertile granites are: SiO_2 = 72 to 76 wt%; peraluminosity index of A/CNK [$Al_2O_3/Na_2O + K_2O + CaO$ (molecular)] > 1, sometimes reaching 1.5; low concentrations of TiO_2 < 0.1 wt%), Fe_2O_3Total < 2 wt%), MgO < 0.2 wt%), Sr < 200 ppm), Ba < 400 ppm) and Zr (< 80 ppm); elevated values of Rb (> 300 ppm), Li (> 100 ppm), Be (> 3 ppm), Cs (> 10 ppm), Nb (> 15 ppm) and Ta (> 10 ppm); and ratios of Rb/Sr > 1, K/Rb < 250, Rb/Ba > 0.5 and K_2O/Na_2O > 1.

- With the exception of pegmatites containing radioactive U and Th minerals (e.g., petalite, apatite and monazite), geophysical methods are not particularly useful for detecting most mineralized granite pegmatites. However, if the pegmatitic body is large, on the scale of hectometres to kilometres, then the density contrast with the country rock may be great enough to detect it using gravimetric methods (e.g., the Tanco pegmatite, Winnipeg River Subprovince, Manitoba; Trueman and Cerny, 1982).

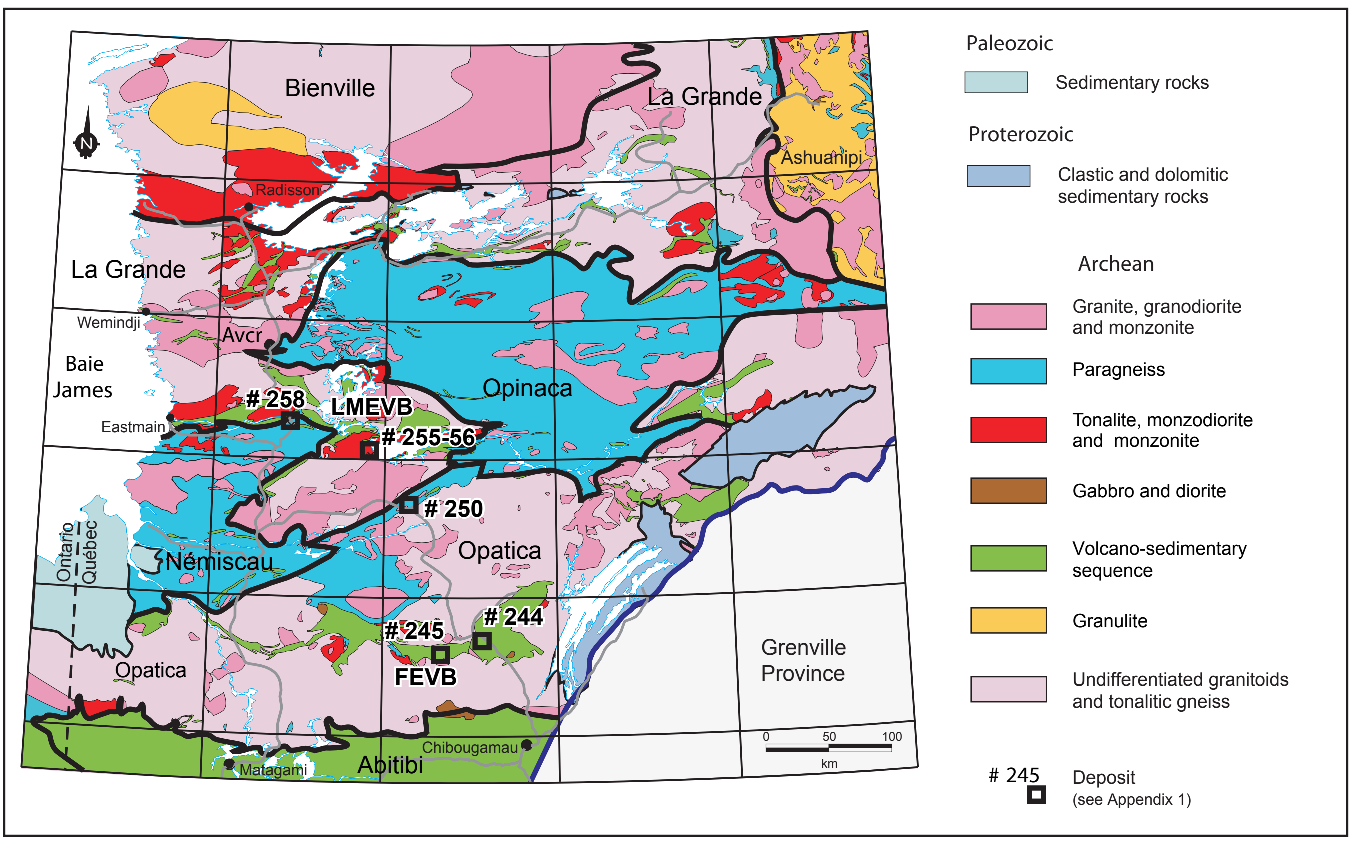

FIGURE 4 – Simplified geology of the Moyen-Nord region and the boundaries of the subprovinces within the Superior Province (modified from Perreault *et al.*, 2003). FEVB = Frotet-Evans Volcano-sedimentary Belt; LMEVB = Lower and Middle Eastmain Volcano-sedimentary Belt.

Type II: Nb, Ta, REE and P deposits associated with carbonatite complexes

Description

Occurrences of Nb, Ta, REE and P mineralization are concentred in carbonatite intrusions. Carbonatites are igneous rocks containing more than 50% carbonate minerals. Calcite carbonatites (sovites), dolomite carbonatites (beforsites) and ankerite carbonatites (rauhaugites) constitute the main types. Carbonatites are associated with alkaline intrusive complexes or form sills, dykes or isolated masses. Mineralization is mainly of magmatic, hydrothermal (replacement) or residual origin (erosion, dissolution and concentration of the valuable minerals). The principal ore minerals are pyrochlore (Nb), apatite (P) and bastnaesite (La, Ce).

Tectonic environment

Carbonatite intrusions are related to the formation of major continental structures, including grabens and rifts produced by rifting events or epeirogenic uplift.

Age of mineralization

Precambrian to recent.

Host rocks and associated rocks

Sovite, rauhaugite and beforsite intrusives containing magnetite + olivine + apatite ± phlogopite, nephelinite, syenite, pyroxenite, peridotite and phonolite.

Deposit form

Carbonatites form small circular masses (pipes of 3 to 4 km across), elliptical to irregular masses, dykes or sills. Mineralization in circular and elliptical bodies is crescent-shaped and steeply dipping. Metasomatic alteration produces veins and irregular veinlets. The forms of residual-type deposits produced by erosion are determined by topography, erosional depth, and the drainage pattern.

Mineralogy

Magmatic: bastnaesite, pyrochlore, apatite, anatase, zircon, baddeleyite, magnetite, monazite, parisite, fersmite. Hydrothermal/metasomatic: fluorite, vermiculite, chalcopyrite, bornite, hematite. Residual: anatase, pyrochlore, apatite, crandallite.

Alteration

A fenitization halo (alkali ± Fe metasomatism of country rocks accompanied by desilicification) surrounds the carbonatite. Typical alteration minerals are: sodic amphibole, wollastonite, nepheline, mesoperthite, antiperthite, aegirine-augite, biotite, phlogopite and albite.

Structural control

The form of the intrusive and its crystallization history are the controls on deposits of igneous origin (fractional crystallization). Tectonics and the local structure determine the form of hydrothermal/metasomatic mineralization, whereas erosion and drainage patterns control residual deposits of apatite and pyrochlore.

Origin

Different stages (syn- to post-intrusion) are involved: 1) magmatic mineralization related to fractional crystallization processes or the immiscibility of magmatic fluids (e.g., the intrusion of REE-rich sovite and beforsite containing magnetite, pyrochlore and apatite); 2) injection of fluorite and barite veins; 3) metasomatism/hydrothermalism: silicification and deposition of Th-V-minerals, calcite veins, and reprecipitation of hematite; 4) residual mineralization: alteration and erosion of carbonatite, accumulation of pyrochlore, anatase and apatite.

Information

Many sources, including Birkett and Simandl (1999).

Important mine sites

International: Mountain Pass, California, 36 Mt at 7.67% (REE_2O_3); Araxa, Brazil, 495 Mt at 2.5% Nb_2O_5 (residual mineralization). Québec: St-Lawrence Columbium (1961-1976), Oka, 25 Mt at 0.44% Nb_2O_5; Niobec mine, St-Honoré, Saguenay, 12.33 Mt at 0.66% Nb_2O_5; Niocan deposit, Oka, Québec, 12.3 Mt at 0.66% Nb_2O_5.

Main Type II deposits in Québec

Most occurrences of niobium (± Ta ± REE) mineralization associated with carbonatite complexes have been found along the Waswanipi-Saguenay and Ottawa-Bonnechère structural corridors (Figure 1). In the Waswanipi-Saguenay zone, the main deposits are the Niobec mine near Chicoutimi, and the Crevier prospect southeast of Chibougamau. Further west, the Lac Shortt and Montviel carbonatites (deposit nos. 241 and 237, Appendix 1) constitute other mineralized sites (REE ± Nb) related to this structure (Figure 1). In the Ottawa-Bonnechère graben, the main deposits are located in the Oka Complex, west of Montréal (Figure 1). This complex contains, among others, the former St-Lawrence Columbium mine and the Niocan deposit. Further west, the Saint-André Carbonatite contains the St-André-2 deposit (deposit no. 127, Figure 5), which also contains niobium and REE mineralization. Finally, other mineralized zones are associated with the Castignon and Lemoyne carbonatite complexes in the Labrador Trough (Figure 1; deposit nos. 95, 96 and 98 to 102, Appendix 1).

Niobec mine

The Niobec mine (deposit no. 48, Appendix 1) is the only niobium producer in North America and one of the world's top three producers. It is associated with the St-Honoré Complex, situated in the Saguenay region (Figure 1), and has reserves of 22.0 Mt at 0.67% Nb_2O_5. The complex consists of late Precambrian to early Cambrian (584-650 Ma) carbonatites and alkaline intrusive rocks related to the formation of the Saguenay Graben (Vallée and Dubuc, 1970; Fortin-Bélanger, 1977). It is a ring complex with units dipping steeply toward the centre, giving them the shape of an inverted cone. Intense fenitization of the country rocks preceded the emplacement of the early alkaline intrusions (ijolite, urtite, alkaline syenite and feldspathoid syenite), followed by the intrusion of a core composed of dolomitic (beforsite), ankeritic (rauhaugite), and calcitic carbonatite (sovite) (Figure 6). The Nb (pyrochlore) mineralized zone is concentrated in two sites forming lenticular bands (600 x 750 m) within sovite accompanied by beforsite, whereas the dolomitic part of the core is enriched in light REE (3 to 4% REE). The core of the carbonatite is brecciated and the rare earth minerals (monazite and bastnaesite) are contained in calcitic cement binding dolomitic fragments, suggesting a post-brecciation timing for the mineralization.

Crevier prospect

The Crevier prospect (deposit no. 242, Appendix 1) is associated with the Crevier Alkaline Complex (911 to 849 Ma) mainly composed of syenite, nepheline syenite, and minor carbonatite intrusions. The Nb-Ta mineralization is associated with albite and nepheline pegmatites. The deposit contains inferred resources of 33 Mt at 201 ppm Ta_2O_5 and 0.19% Nb_2O_5 (Fournier, 2002).

St-Lawrence Columbium mine

The St-Lawrence Columbium mine (deposit no. 121, Appendix 1, proven and probable reserves of 16.69 Mt at 0.44% Nb_2O_5 and 0.2 at 0.5% REE) is but one of the eight niobium-rich zones mined in carbonatites of the Oka Complex (Figure 5, deposit nos. 121 to 126, Appendix 1). This zone (100 ±15 Ma) consists of two central cores of carbonatite surrounded by numerous arc dykes, ring dykes and cone sheets composed of siliceous rocks and carbonatites that intercalate in a complex manner. The complex consists of carbonatite, intrusive rocks of the okaite-jacupirangite and ijolite-urtite series, fenite, and alnoite dykes and plugs. They intrude a Grenvillian basement consisting of gneiss and anorthosite. Nine types of carbonatites have been identified based on their mineralogy and texture. They are essentially sovites broadly divided into suites characterized by monticellite or pyrochlore. The Nb mineralization is found in pyrochlore and is concentrated in lenses within sovite/ijolite units.

The Niocan deposit

The Niocan deposit (Bond Zone, deposit no. 122, Appendix 1) is found along the margin of the Oka Complex (Figure 5). The main mineralized zone (S-60) is an endoskarn with pyrochlore and has an overall chimney shape (100 x 200 m). Reserves for the S-60 zone are 12.3 Mt at 0.66% Nb_2O_5. It also contains by-products in the form of apatite (10%), magnetite (10%) and REE (10% in the pyrochlore). The second mineralized zone (HWN-2) forms a band extending 600 m in length and measuring 25 m wide. Reserves are estimated at 2.2 Mt at 0.56% Nb_2O_5.

Exploration criteria

- The carbonatites are associated with vast fracture systems in continental environments (rifts, graben) but have a tendency to form small isolated intrusions.
- The carbonatite intrusives display excellent circular magnetic and radiometric signatures and may be associated with ring-like topographic breaks and features.
- Fenitization of the country rocks is a potential indicator of carbonatite intrusions and can be used to enlarge the target zone during regional exploration.
- The presence of radioactive minerals associated with fluorite and barite in the carbonatites is an indirect indicator of REE mineralization.

Type III: REE, Y, Zr and F deposits associated with peralkaline complexes

Description

Type III mineralization is found in peralkaline granite or syenite pegmatites, in the cupola of peralkaline intrusive complexes that may be either silica oversaturated (aegirine granite) or silica undersaturated (augite-aegirine syenite, sodic foyaite and lujavrite). The parent intrusives are A-type (anorogenic) and form ring complexes or massive subvolcanic bodies emplaced in Proterozoic post-orogenic extensional zones.

Tectonic environment

Major continental structures, including grabens and rifts associated with episodes of continental extension and mantel plumes.

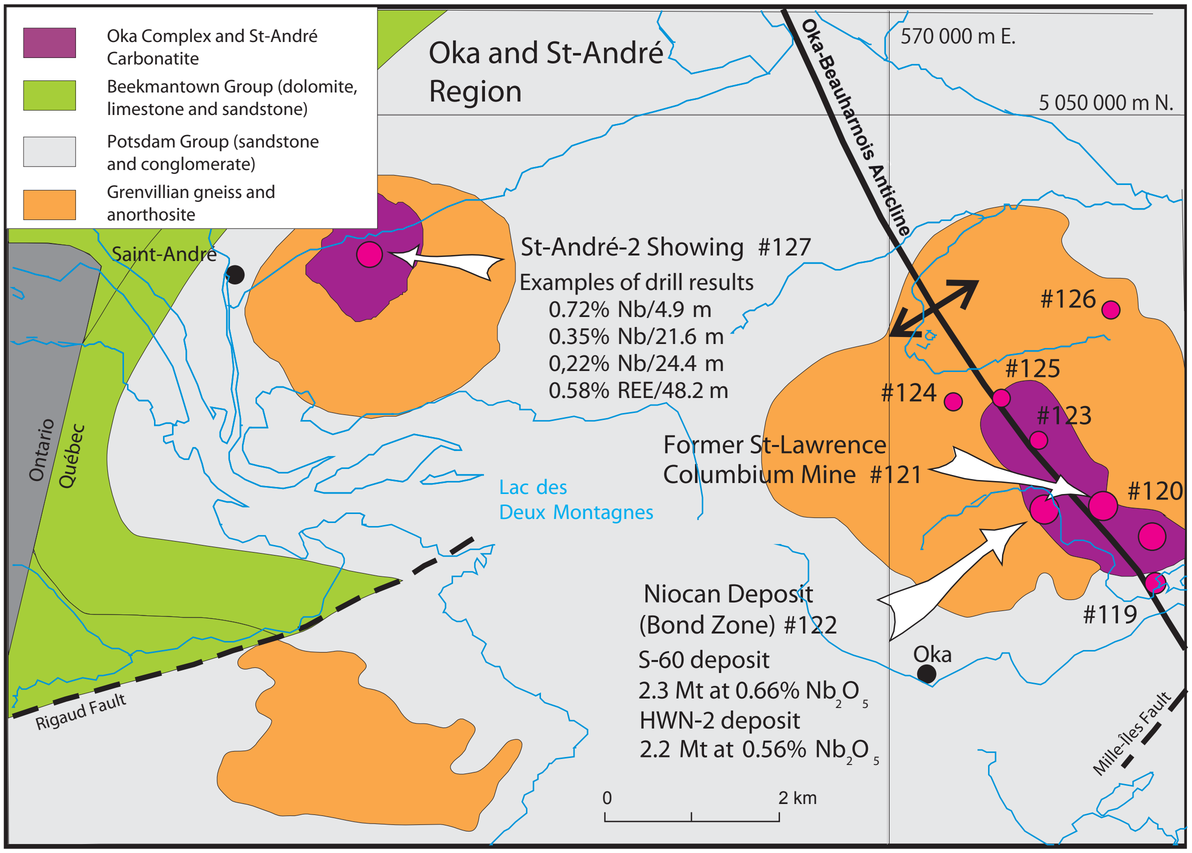

FIGURE 5 - Geology of the Oka and St-André region showing the locations of the former St-Lawrence Columbium mine, the Niocan deposit and the Saint-André-2 showing (see Appendix 1 for the names of the other deposits in the region).

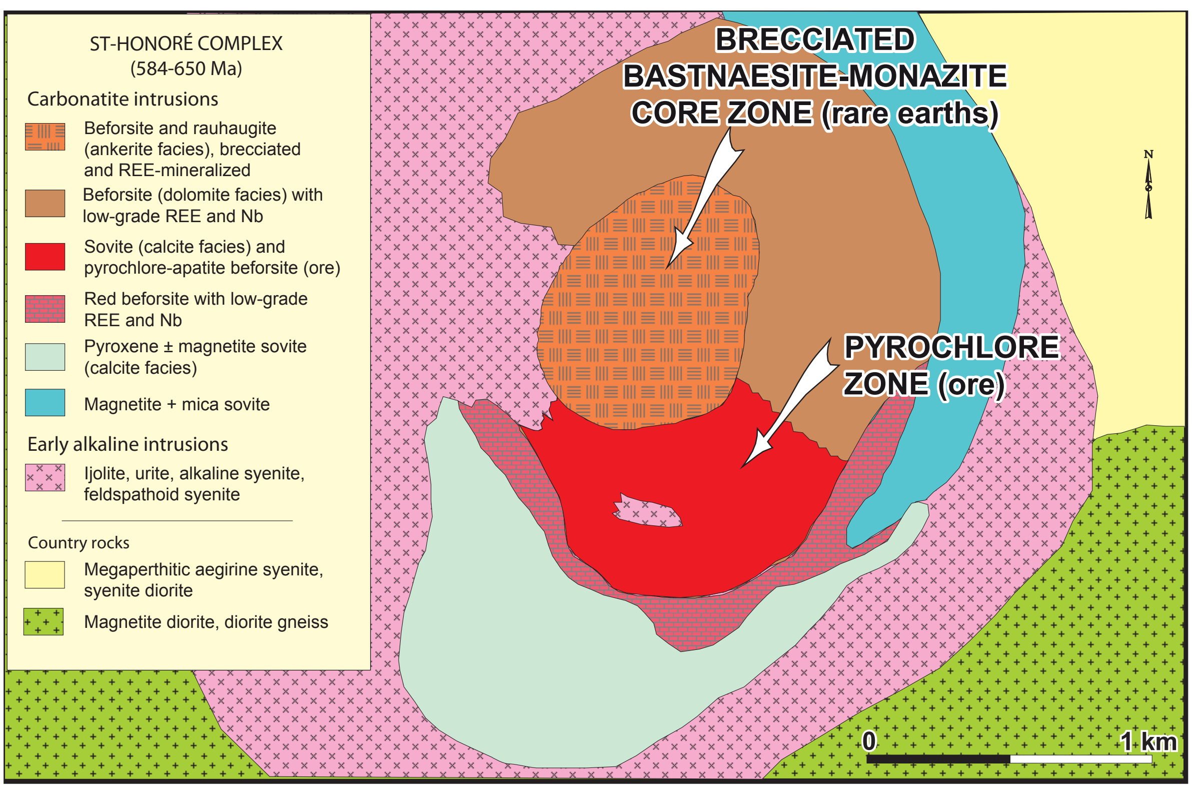

FIGURE 6 - Geology of the St-Honoré Carbonatite, Niobec mine, Saguenay region, Québec (simplified from Gauthier and Landry, 1980).

Age of mineralization

Proterozoic to Cenozoic.

Host rocks and associated rocks

Peralkaline pegmatites: silica oversaturated, perthite, albite, orthoclase, aegirine-riebeckite, fluorite; undersaturated, nepheline. Parent intrusives: augite-nepheline syenite, aegirine-arvfedsonite/riebeckite peralkaline granite, naujaite, sodalite, foyaite, lujavrite, kakortokite and biotite monzogranite. Volcanics: trachyte, commendite, pantellerite, hawaiite and phonolite.

Deposit form

Metre-scale to decametre-scale dykes and sills along cooling fractures at the summits of intrusives. Magmatic/hydrothermal disseminations at the summits of albitized intrusive cupolas.

Pegmatite mineralogy

Gangue: quartz, feldspathoid, albite, microcline, biotite, and sodic amphibole.

Ore: zircon, monazite, pyrochlore, bastnaesite, beryl, eudyalite, gittinsite, thorite, tantalite, hiortdahlite, armstrongite, elpidite, ilarite, bertrandite, yttrofluorite, gagarinite, britholite, kainosite, mosandrite and gadolinite.

Alteration

Parent granitoids are albitized in the summital parts of the intrusive. Orthomagmatic fluids released near the end of crystallization (600 to 500°C) can cause F leaching in the granite in the form of amphibole and feldspar destabilization and hematization. The circulation of Ca-rich low-temperature (< 200°C) meteoric fluids leads to the pseudomorphic replacement of sodic silicates by calcic silicates. Lastly, there is silicification.

Structural control

At the scale of the pluton, mineralized pegmatites are emplaced along fractures and joints produced by consolidation of the pluton. Mineralization can also occur at the contact between the intrusive and the country rocks, or at the contact between two phases or two facies. On a larger scale, the ring complexes are emplaced in continental rift zones.

Origin

Peralkaline A-type granites produced by the melting of residual crust following the release of felsic melt. High-temperature crustal melting under anhydrous conditions led to the destruction of residual amphibole, biotite and accessory minerals (e.g., zircon), and to halogen (F, Cl) and HFSE (Nb, Zr, REE, Y, U, Th) enrichment in the melt (Collins *et al.,* 1982). It is also likely that the residual crust was metasomatized by mantle-derived fluids/melts enriched in F, Cl and rare metals. The introduction of fluorine initiated melt depolymerization, a reduction in solidus temperature, and the formation of alkaline ionic compounds containing REE and HFSE. This delayed the crystallization of minerals carrying rare metals and caused extreme fractional crystallization, leading to the enrichment of residual melts/fluids that crystallized in the cupola of the intrusive and or invaded fractures as rare metal-rich pegmatites. Late hydrothermal fluids may have metasomatized parent granites and pegmatites (albitization, hematization and silicification) and precipitated REE-rich minerals (bastnaesite and fluorite).

Information

Many sources, including Pillet (1989), Miller (1986) and Boily and Williams-Jones (1994).

Important mine sites

International: Karnasurt and Umbozero mines in the nepheline syenite massif of the Lovozero Complex, Kola Peninsula, Russia; 25,000 tonnes of loparite concentrate ($(Ce, Na, K)_2(Ti, Nb, Ta)_2O_6$) are extracted annually for the REE, Nb and Ta content.

Main Type III deposits in Québec

There are only a few known occurrences of mineralization related to peralkaline complexes in Québec (deposit nos. 89, 92, 93, 128, 177, 183 to 186, Appendix 1). They are mostly minor showings except for two noteworthy exceptions: the Strange Lake deposit in the Rae Province (30 Mt at 2.4% Zr_2O_3, 1.1% REE_2O_3, 0.52% Y_2O_3 and 0.39% Nb_2O_5) and the Kipawa prospect in the Grenville Province (west zone: 786,000 t at 0.18% Y_2O_3 and 0.95% ZrO_2; east zone: 1 Mt at 0.14% Y_2O_3 and 1.17% ZrO_2; Figure 1).

Strange Lake deposit (Lac Brisson)

The Strange Lake Zr, REE, Y and Nb deposit (Lac Brisson, deposit no. 93, Appendix 1) is associated with the epizonal complex of peralkaline aegirine-arfvedsonite granite in the Rae Province, at the border between Québec and Labrador. The complex is Mesoproterozoic in age (1184 Ma; Pillet, 1989), with a diameter of 6 km, and is surrounded by a fluorite- and hematite-rich breccia. It is composed of three peralkaline granites (unaltered hypersolvus, unaltered subsolvus and altered subsolvus) emplaced as an intrusive ring complex (Figure 7a; Miller, 1986; Pillet, 1989; Boily and Williams-Jones, 1994). The complex was given its name due to the unusual abundance (up to 50%) of exotic

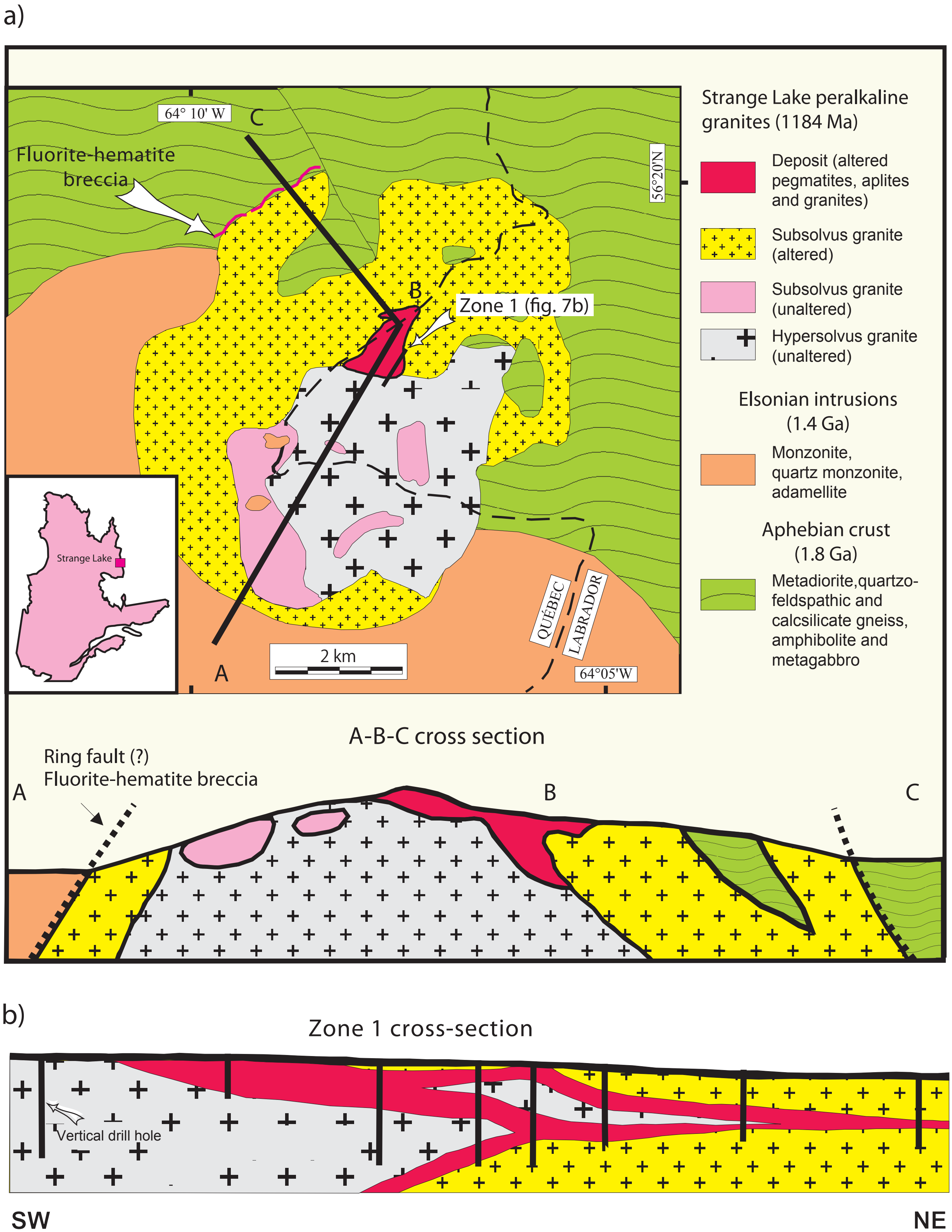

FIGURE 7 - a) Geology and schematic cross-section (A-B-C) of the Strange Lake Peralkaline Plutonic Complex (after Miller, 1986; Boily and Williams-Jones, 1994). **b)** Vertical cross-section of the Zone 1 lens (after Miller, 1990).

rare metal-rich minerals[1]. Alteration of the granites is characterized by: 1) the presence of hematite zones containing a variety of REE- and HFSE-rich calcic minerals; 2) the replacement of arfvedsonite by an assemblage of hematite ± aegirine ± quartz; 3) pseudomorphism of sodic phases by their calcic equivalents + quartz; 4) the appearance of secondary blue-violet fluorite.

The rare metal mineralization at Strange Lake is mainly concentrated in subhorizontal lenses and pegmatite/aplite veins genetically associated with the altered subsolvus granite facies. The Zone 1 lens (Figure 7b) contains all the mineralization. Located in the altered subsolvus granite cupola and crosscutting the unaltered subsolvus and hypersolvus granite facies, the lens has a surface area of 0.75 km^2 and is 6 to 10 metres thick on average. It is characterized by a well-developed textural zonality in which aplitic and pegmatitic phases respectively dominate the lower and upper parts of the lens. The aplites are composed of albite, pseudomorphs of narsarsukite and elpidite, aegirine, thorite, quartz, and potassium feldspar. The transition between the aplite and pegmatite zones is characterized by brownish-red and purplish-red aplite and pegmatite units, the colour reflecting the presence of hematized gittinsite and aegirine, thorite and fluorite. The highly heterogeneous nature of the pegmatitic zone is evident by variations in grain size (1-20 mm) and colour (beige to brown, to yellow, green or purple). In the aplite zone, aegirine is more abundant than riebeckite, and microperthite is more abundant than albite. The amount of fluorite appears to be greater in the pegmatite than in the aplite. The formation of mineralized pegmatite/aplite lenses began with the intrusion of the altered subsolvus granite unit initially enriched in REE and HFSE (Figure 8). During crystallization of the subsolvus granite, a residual apical zone, extremely enriched in rare metals, was formed by the circulation of fluorine-bearing orthomagmatic fluids generated by the formation of HFSE and REE fluoro-complexes in a highly differentiated and depolymerized peralkaline melt. These residual melts were then injected in fractures forming at the contact with the altered subsolvus granite and other units, to create subhorizontal lenses of pegmatite/aplite. Selective REE and HFSE enrichment accompanied the formation of the various aplitic and pegmatitic facies through crystallization processes or the migration of volatile phases (Miller, 1986).

1 Elpidite ($Na_2ZrSi_6O_{15}\cdot H_2O$), gittinsite ($CaZrSi_2O_7$), pyrochlore ($(Na,Ca,REELe)_2(Nb,Ta)_2O_6(OH,F)$), gadolinite ($Y_2Fe^{+2}Be_2Si_2O_{10}$+REE), kainosite ($(Ca_2(Ce,Y,REELo)_2Si_4O_{12}(CO_3))\cdot H_2O$), gagarinite ($Na(Y,Ca,Na,REE)_2F_6$), bastnaesite ($(REELe)CO_3F$) and thorite ($ThSiO_4$)

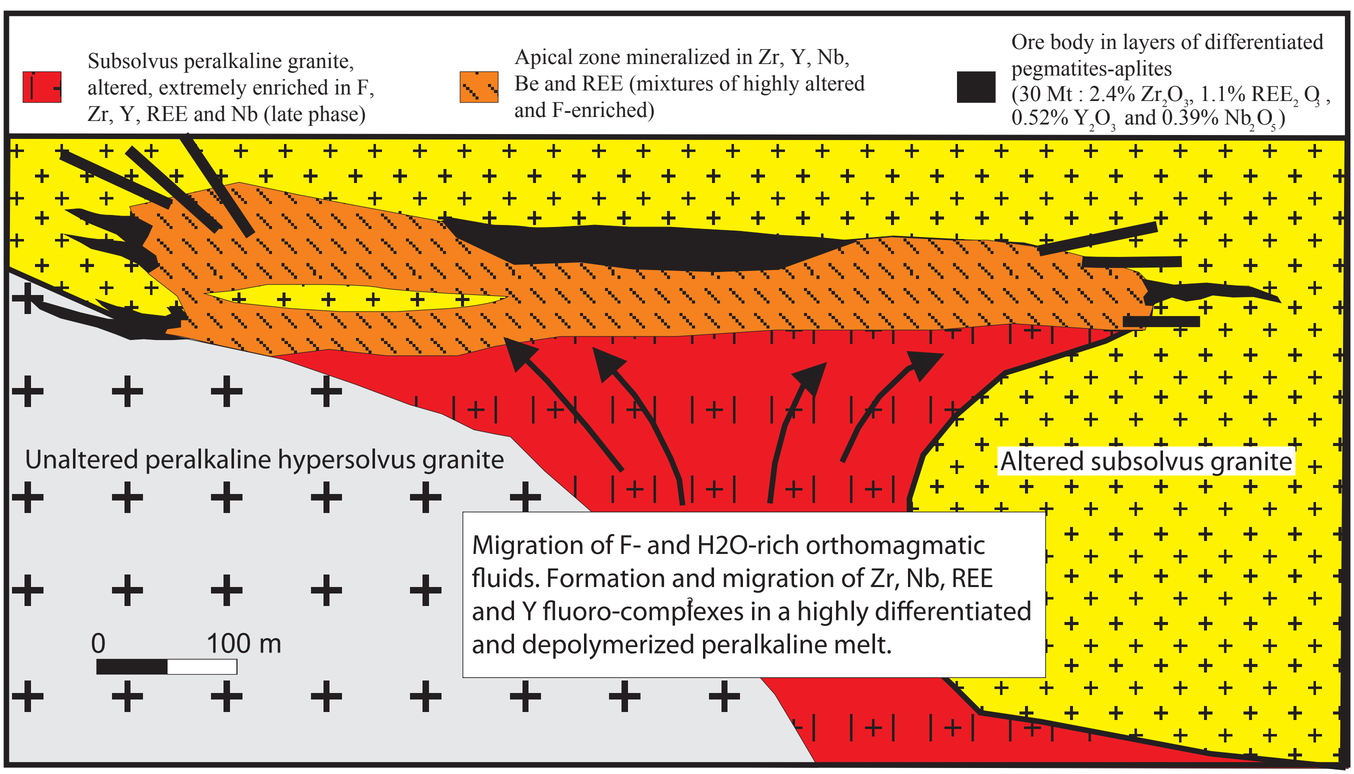

FIGURE 8 – Petrogenetic model for the formation of the Strange Lake Zr, REE, Y and Nb deposit, Québec-Labrador, Rae Province (adapted from Miller, 1990).

Kipawa prospect

The Kipawa Zr-Y ± REE prospect (Lac Sheffield-2, deposit no. 183, Appendix 1; Figure 1) and other examples of mineralization in this area (deposit nos. 184 to 186, Appendix 1) occur within the Grenville Province and are associated with the Kipawa Alkaline Complex, which has been assigned an approximate age of 1.0 Ga (Currie and Gittins, 1993). The complex is strongly metamorphosed and deformed. It consists of calcsilicate rocks (pyroxene-bearing rocks, marbles), syenite gneiss, and peralkaline granite gneiss. The work of Unocal Ltd (1985-1990) defined reserves in the west zone of 786,000 t at 0.18% Y_2O_3 and 0.95% ZrO_2, and reserves of 1 Mt at 0.14% Y_2O_3 and 1.17% ZrO_2 in the east zone.

Exploration criteria

- Undeformed A-type plutons (anorogenic) associated with a suite of alkaline intrusions emplaced in major continental extensional zones.
- Alkaline granites and syenites containing radioactive minerals (thorite, pyrochlore and gagarinite) are detectable as airborne radiometric anomalies. On the ground, glaciated regions can be prospected using a scintillometer, which has proven to be an effective tool for discovering radioactive boulder fields.
- The analysis of sediment and water samples from lakes and streams can reveal REE, F, U, Th and Y anomalies.
- In the field, granites and syenites have a particular mineralogy dominated by riebeckite-arfvedsonite, aegirine, fluorite, and a wide range of exotic rare metal-rich minerals.
- A common and intense alteration of mineralized granites manifests as a reddish hue for potassic feldspars, hematization of sodic amphiboles, fluorite-rich zones, and albitization.
- Mineralized granitic and syenitic intrusions often constitute the core of ring complexes comprising mafic to intermediate alkaline rocks (gabbros, monzodiorites), with ring dyke and cone sheet structures suggesting caldera subsidence.
- The granites and syenites intrude or are associated with alkaline felsic extrusive rocks, including trachytes and commendites-pantellerites.
- Mineralized pegmatite masses or dykes occur within granitic plutons, typically in the cupola.
- Fertile alkaline granites containing REE, Y, Zr, Be, Nb, Th and F mineralization display the following geochemical signatures: SiO_2 > 72 wt%; Fe_2O_3Total > 4 wt%; MgO < 0.1 wt%; Al2O3 < 12 wt%; Na_2O + K_2O > 10 wt%; F > 0.5%; Rb > 400 ppm; Sr < 50 ppm; La > 200 ppm; Zr > 300 ppm; Th > 50 ppm; U > 10 ppm; Rb/Sr = 5 to 160 and K/Rb = 27 to 120.
- For the syenitic intrusives, the criteria are the following: SiO_2= 55 to 65 wt%; Na_2O +K_2O > 10 wt%; F > 0.5 wt%; Rb> 400 ppm; Sr < 50 ppm; La > 200 ppm; Zr > 300 ppm; Th > 50 ppm; U > 10 ppm; Rb/Sr= 5 to 160 and K/Rb = 27 to 120.

Type IV: Fe, Ti, ± Zr and REE deposits associated with placers and paleoplacers

Description

Type IV comprises heavy mineral deposits (ilmenite, cassiterite, monazite, zircon and beryl) found in Holocene fluvial, glacial or fluvioglacial environments, as well as beach, dune, uplifted seafloor, and alluvial fan deposits.

Tectonic environment

The deposits are located along craton margins where clastic sediments are constantly reworked over long periods of time, and/or along the margins of Mesozoic to Cenozoic accretionary complexes and volcanic arcs.

Age of mineralization

Holocene to late Pleistocene in glaciated regions and Tertiary or younger in other regions.

Depositional environment

Marine placers form along or near shorelines where sediments are reworked by waves, coastal currents, and the tides. They are present along modern-day beaches, ancient submerged beaches, and uplifted shorelines during glaciation. Fluvial placers develop along the bottom of channels in high-energy rivers and on bedrock. Alluvial fans and delta fans are dominated by massive to sorted sand deposits. Glacial and fluvioglacial placers are restricted to regions where glaciers and meltwaters eroded pre-existing placers.

Host rocks and associated rocks

Marine: medium- to coarse-grained, well-sorted sand overlying finer-grained, shallow marine deposits. Continental: fine- to coarse-grained, well-sorted and rounded sand.

Deposit form

Marine: along shorelines, the deposit is thin (< 1 m), long (> 100 m) and narrow (< 50 m). Continental: laterally variable and discontinuous; thin deposits (< 2 m) occurring as lenses.

Mineralogy

Marine: Native gold, ilmenite, cassiterite, zircon, PGE, magnetite, monazite and garnet. Continental: Native gold, PGE, cassiterite and industrial minerals.

Control on mineralization

Marine: Heavy minerals are concentrated along stable shorelines where sediments are reworked by waves and where currents are present.

Continental: In fluvial environments, the placers are concentrated in channel irregularities, depressions in the bedrock, and spaces created by fractures, joints, cleavages and faults. Minerals in coarse-grained placers accumulate at the bottom of channels where reworking is extreme, along gravel bars, and/or around boulders. In alluvial fans, placers accumulate on steep slopes above the eroded zones.

Information

Many sources, including Levson (1995a, b).

Important mine sites

International: Ticor South Africa, South Africa, 16 Mt of heavy minerals. Tamil Nadu, India, 29.3 Mt of ore, including 9.45 Mt of heavy minerals, such as monazite, ilmenite, rutile and zircon. Kwale, Kenya, 222 Mt, including 3.8 Mt of ilmenite, 1.1 Mt of rutile and 0.6 Mt of zircon.

Main Type IV deposits in Québec

In Québec, Pleistocene sands enriched in Fe + Ti ± Zr ± REE are found along the Lower North Shore (Basse-Côte Nord), along the St-Lawrence River (deposit nos. 1 and 2), and along the edges of waterways and lakes (deposit nos. 148 and 243). The most important deposit is undoubtedly the Natashquan deposit on the North Shore. In the Eastern Townships, paleoplacers of sandstone containing titaniferous magnetite, rutile, zircon, and monazite have also been identified (deposit nos. 30 to 33 and 134 to 138).

Natashquan deposit

The Ti, Fe and Zr Natashquan deposit (deposit no. 2; Appendix 1) occurs on the north shore of the St. Lawrence River, near the village of Natashquan (Figure 1). It covers a surface area of 180 km^2. The deposit contains a great quantity of heavy minerals derived from the erosion of plutons and Fe-Ti-rich orthogneisses of the Grenville Province. The economically valuable heavy minerals are ilmenite (Ti), magnetite (Fe) and zircon (Zr). The sedimentary facies of the deposit form four groups. The first two, *pre-deltaic* and *pro-deltaic/deltaic*, constitute the basal sequence. The final two, *shoreface progradation* and *recent*, compose the upper sequence. The average thicknesses for the north and south heavy mineral zones are respectively 23 and 18 m. Reserves are estimated at 769 Mt at 9 wt% heavy minerals (north zone) and 890 Mt at 7.2 wt% heavy minerals (south zone). The Natashquan deposit contains at least 58 Mt of ilmenite, 22 Mt of magnetite, 0.995 Mt of zircon, and 35 Mt of garnet. The proportion of magnetite, ilmenite/hematite and zircon increases toward the basal sequence, whereas the garnet content is higher in the upper sequence.

Exploration criteria

- Anomalous concentrations of Ti, Zr, Fe, Cr, Au and Ag in stream sediments near the deposit.
- Surface-penetrating radar emissions can be used to define the geometry, structure and thickness of the placer deposits. Shallow seismic, electromagnetic and induced polarization methods, as well as resistivity measurements, can also be used
- Heavy mineral separation by panning or gravity (Wilfley table) can be used to determine whether native gold, ilmenite, zircon, magnetite and other heavy minerals are present.

Type V: Iron oxide, Cu, REE, Y and U deposits (Olympic Dam/Kiruna)

Description

Breccia zones and magnetite and/or hematite veins forming pipes or tabular bodies in volcanic rocks extruding in a continental environment, detrital sediments, and intrusive rocks. Mineralization ranges from monomineralic, such as Kiruna in Sweden (Fe ± P), to polymetallic, such as Olympic Dam in Australia (Fe ± Cu ± U ± Au ± REE).

Tectonic environment

Typically associated with grabens produced by intracratonic crustal extension, contemporaneous with the emplacement of the host rocks in the upper crust.

Age of mineralization

Proterozoic to Tertiary. Proterozoic polymetallic deposits formed between 1.2 and 1.9 Ga.

Host rocks

Veins and breccias hosted in a variety of extrusive and intrusive rocks, including felsic volcanic breccias, tuffs, clastic sedimentary rocks, and granites. The deposits are often associated with A-type (anorogenic) felsic alkaline suites, including “red granites”, granites with rapakivi textures, mangerites, and charnockites, as well as their volcanic equivalents. In several deposits, iron oxides (magnetite or hematite) constitute the matrix in heterogeneous breccias composed of lithic fragments, hematite clasts, hematite + quartz microbreccias, and massive fine-grained breccias.

Deposit form

Discordant masses, veins, dykes, tabular bodies and stockworks. The veins and tabular zones have kilometre-scale lateral extent and a vertical extent of several hundred metres.

Mineralogy

Ore: magnetite/hematite + apatite + actinolite or pyroxene deposits (type Kiruna) with variable amounts of Cu, Au and Ag sulphides, uranium minerals and REE. Major mineral constituents: hematite, magnetite, specularite, bornite, chalcopyrite, chalcocite and pyrite. Minor mineral constituents: digenite, covellite, native copper, carrolite, cobaltite, Cu-Ni-Co arsenides, pitchblende, coffinite, branerite, bastnaesite, monazite, xenotime, florencite, native silver, and Au and Ag tellurides. Gangue: associated with the ore in the form of veins and breccia fragments; it contains sericite, carbonates, chlorite, quartz, fluorite and barite.

Alteration

Olympic Dam: variable and intense sericite and hematite alteration at surface, and chlorite + potassium feldspar alteration at depth. Kiruna: scapolite and albite; actinolite + epidote in mafic country rocks.

Structural control

Significant. Emplacement along faults and/or lithological contacts, particularly in small-scale grabens. Intense hydrothermal activity in faults associated with brecciation.

Origin

Controversial. Some consider a hydrothermal origin, whereas others emphasize the magmatic nature of the deposits (Nystrom and Henriquez, 1994; Gow *et al.,* 1994).

Important mine sites

International: The Bayan Obo Fe-REE-Nb deposit in China; 1.500 Mt of iron oxides at 35% Fe, 48 Mt at 6% REE_2O_3 and 1 Mt at 0.13% Nb_2O_5. The Olympic Dam deposit, Australia; 2,000 Mt of ore at 1.6% Cu; a zone of 450 Mt containing 2.5% Cu, 0.08% U_2O_3, 6 g/t Ag, 0.6 g/t Au and 5,000 g/t REE.

Information

Various sources, including Lefebvre (1995) and Ray and Lefebvre (2000).

Main Type V showings and prospects in Québec

Type V mineralization (Fe, Cu, REE, Y, P, F and Ag; Olympic Dam - Kiruna) has been found in the Grenville Province but occurrences are limited to the Manitou region, northeast of Sept-Îles (deposit nos. 56 to 58 and 76 to 83, Appendix l, Figure 9). They are associated with brecciated or vein-type structures and characterized by an abundance of magnetite. The Kwyjibo area, north of Lac Manitou, is particularly interesting. A number of showings occur within three iron-rich en-echelon bands ranging from 5 to 50 m thick. The bands are concordant with the regional structural grain and enclosed in a porphyroid leucogranite (alaskite) belonging to the Canatiche Complex. Mineralized zones comprise magnetite, apatite, sulphides (chalcopyrite, pyrite, pyrrhotite, sphalerite), titanite, allanite and fluorite, present as disseminations, in massive form, or as veins. The main types of alteration are hematization, epidotization, silicification and calc-silicate alteration. The best grades for light REE (Ce, La, Nd and Sm) and yttrium are from the Josette showing (deposit no. 76; 1.83% Cu, 0.96% REE, 0.81% Y), the Fluorine showing (deposit no. 80; 1.95% REE, 0.41% Y, 0.69% Cu), the Andradite showing (deposit no. 81; 0.65% REE, 0.16% Y, 1.5-4.5% Cu), and the Rodrigue showing (deposit no. 82; 0.79% REE, 1.32% Cu). Post-Grenvillian in age (972 ± 5 Ma), the mineralization is associated with hydrothermal fluids related to the Canatiche Complex, focused along faults (Clark, 2003). The chemistry of the biotite ± hornblende granites and the leucogranites of the Canatiche Complex indicate an A-type intraplate affinity. The majority of these rocks are enriched in REE, Zr, Nb, Y and F.

Exploration criteria

- Regions with a potential for this type of deposit are narrow linear rift zones and deep ductile fault zones in cratonic environments. They are mostly of mid-Proterozoic age (1.9-1.2 Ga) and may extend for hundreds of kilometres.
- Although this type of deposit is associated with a wide variety of sedimentary, igneous and metamorphic rocks, the geochemical signature of the igneous rocks is clearly anorogenic (A-type).
- The associated intrusions display potassic or sodic alteration, the appearance of uranium oxides, and REE-rich alteration zones. Also noted is the presence of iron oxides, particularly in the breccias, stockworks and veins.
- The analytical results for stream and lake sediment samples define REE, Fe, Cu, Au-Ag ± F ± P anomalies.
- The presence of iron oxides in this type of deposit is reflected by very pronounced gravimetric anomalies. Strong regional aeromagnetic anomalies indicate the presence of magnetite. Radiometric anomalies are detected when the occurrence contains uranium mineralization or potassic alteration.

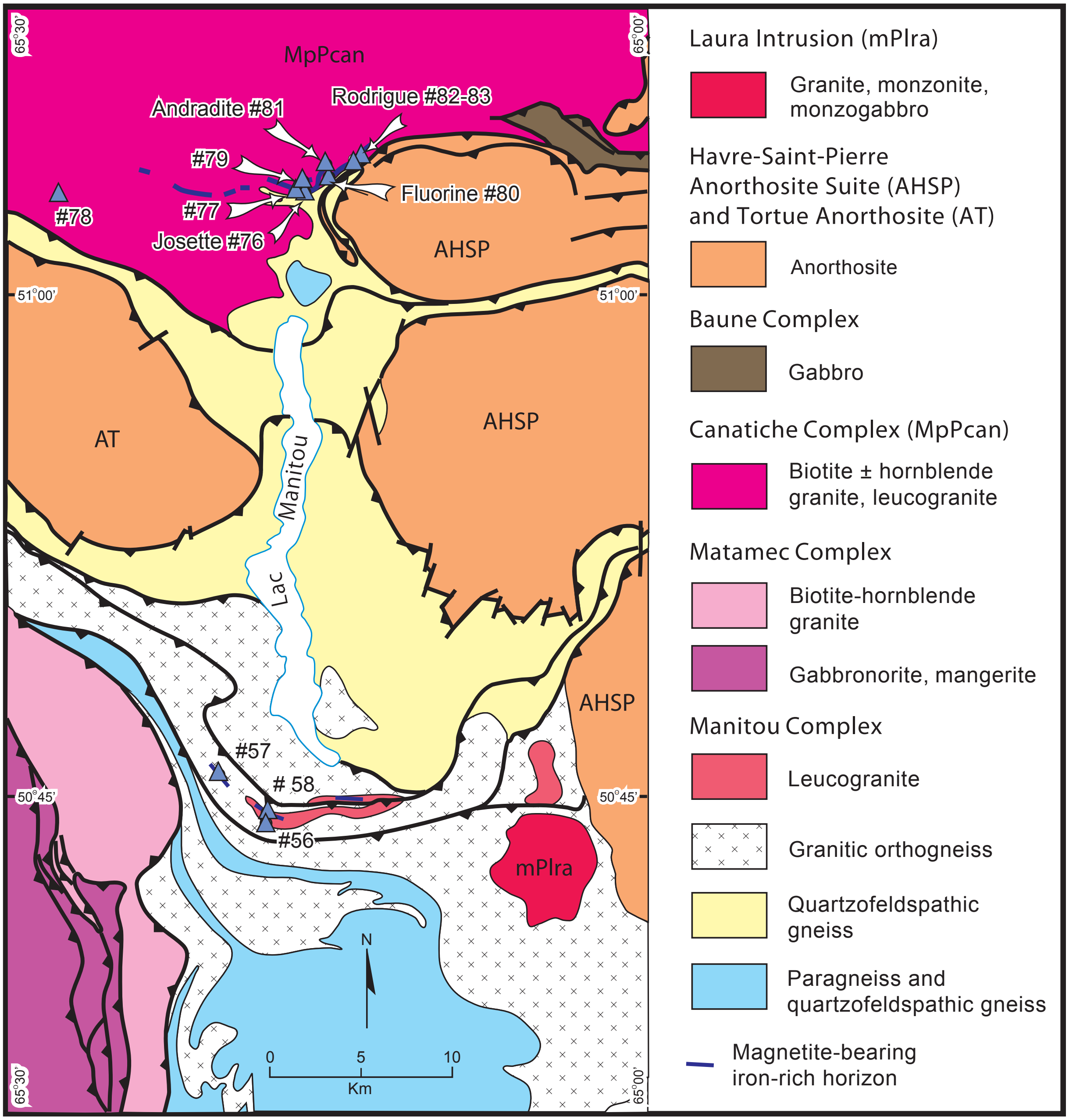

FIGURE 9 – Geology of the Lac Manitou region in the Grenville Province and its Fe, Cu, REE, Y, P, F and Ag showings (modified from Clark, 2003; see Appendix 1 for the names of the numbered showings).

Type VI: U, Th ± (REE, Nb, Zr and Y) mineralization in granite pegmatites, migmatites and peraluminous to metaluminous granites

Description

Uranium and thorium ± (REE, Nb, Zr and Y) mineralization is associated with granite pegmatite dykes, granites, and migmatites. Syn-tectonic to late tectonic pegmatites, granites and migmatites are metaluminous to peraluminous and contain essentially magmatic mineralization (zircon, monazite, uraninite, thorite and magnetite). However, the remobilization and concentration of rare metals during metamorphism and hydrothermal processes can play an important role.

Tectonic environment

Pegmatites, granites and migmatites are syn-tectonic to late tectonic and form in continental orogens, usually during intense metamorphism and crustal anatexis. Melting is initiated by crustal thickening caused by the collision of continental blocks or the underplating of the crustal base with mafic material.

Age of mineralization

Precambrian to Proterozoic, rare Mesozoic and Cenozoic occurrences.

Host rocks and associated rocks

Potassic granite pegmatite dykes, granite migmatites, biotite ± muscovite granites, TTG suite intrusives (tonalite-trondjhemite-granodiorite), metavolcanics (metabasalts, amphibolites), biotite schists (metagraywackes), orthogneiss and paragneiss, calcsilicate rocks.

Deposit form

1 – Swarms of granite pegmatite dykes, homogenous to broadly zoned, steeply dipping. Variable size: thicknesses ranging on the order of metres to decametres, lengths ranging from decametres to kilometres. 2 – Heterogeneous masses of granite migmatites and granites with a general foliation-parallel orientation. 3 – Disseminated mineralization in granites along joints and fractures.

Mineralogy

Pegmatites and migmatites: Quartz, orthoclase, microcline, perthite, biotite, muscovite and garnet. Ore: monazite, xenotime, allanite, zircon, magnetite, uraninite, pitchblende, thorite, thorianite, pyrochlore, samarskite, coffinite, uranophane, fergusonite, chevnickite, gadolinite and ferrocolombite.

Alteration

Pegmatite: Internal metasomatism of the pegmatites, albitization, chloritization, oxidation and hydrous alteration.

Structural control

Granite pegmatites fill fractures and joints in granitoids, or are emplaced along fractures and schistosity within host rocks. Migmatites inject along metamorphic foliation planes and contacts between different units.

Origin

Mineralization in granites, granite pegmatites and migmatites is mainly of magmatic origin. The migmatites and granites are the result of protolith melting (metasediments, ancient tonalitic crust) in the lower and mid-crust under moderate pH_2O and F conditions. They generally accompany major tectono-metamorphism, which leads to crustal anatexis following tectonic thickening of the continental crust or the introduction of mantle-derived mafic magmas at the base of the continental crust. Some pegmatites are derived directly from anatexis and are emplaced *in situ*. Granitoids may become differentiated to the point of generating mineralized pegmatites. Late hydrothermal alteration and metamorphism play a role in the remobilization and concentration of rare metals.

Main Type VI showings in Québec

Most reported Type VI showings (about 136, Gosselin *et al.,* 2003) were discovered during uranium exploration, and were not always tested to determine whether rare metals were present. Significant concentrations of REE ± (Nb, Zr, Y) were nevertheless detected in 26 mineralized zones, most of them within the Grenville Province. Notable examples are deposits 3, 4, 10, 12, 13, 18, 19 and 27 (Appendix l) to the east of Havre-Saint-Pierre on the Lower North Shore (NTS map sheet 12L, Figure 10), and the mineralized sites in the western part of the Grenville (Mont Laurier region, Figure 10; deposit nos. 139, 142 to 144, 154, 155 and 158, Appendix 1). Some uraniferous showings associated with a granitic complex in the Minto Subprovince also contain REE (NTS 34H, Figure 1; nos. 281,285,288 and 289, Appendix 1).

Exploration criteria

– The presence of radioactive minerals (uraninite, pitchblende, thorite, thorianite, pyrochlore, samarskite) in granites and pegmatites produce excellent airborne radiometric anomalies.

- On the ground, prospecting with a scintillometer has proven to be a very efficient tool for detecting and delineating radioactive mineralized zones.

- Analyzing sediment and water samples from lakes and rivers can reveal U and Th anomalies, and possibly F and REE anomalies as well.

Type VII: Th, U ± (Mo and REE) mineralization in calcsilicate and metasomatized rocks (skarns)

Description

Thorium and uranium (± Mo ± REE) mineralization can be genetically related to skarns (calcic and magnesian skarns) at the contacts of granitic intrusives or swarms of granite pegmatites.

Tectonic environment

Granites and granite pegmatites are syn-tectonic to late tectonic and form in continental orogens.

Age of mineralization

Precambrian.

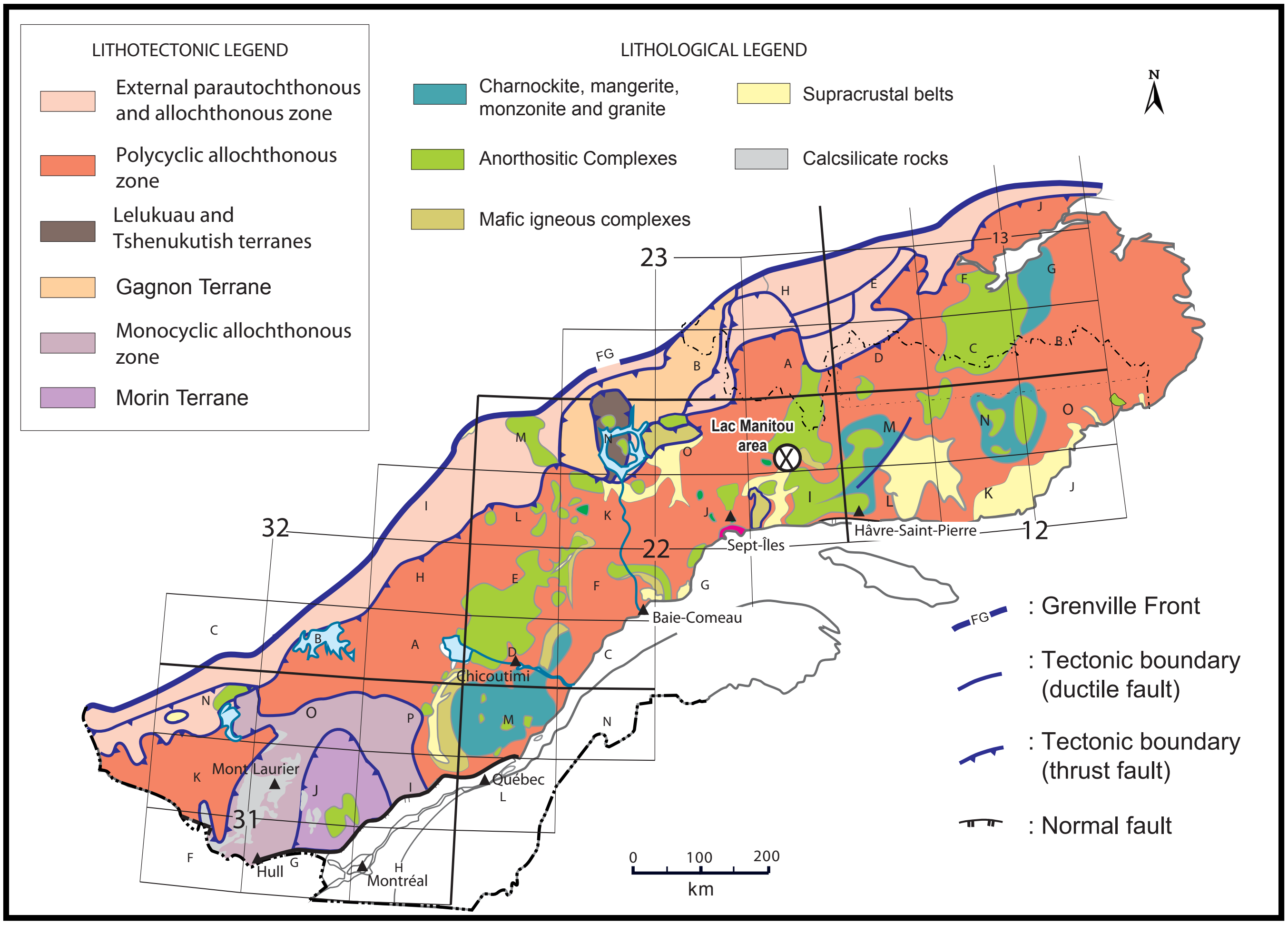

FIGURE 10 – Lithotectonic and lithological divisions of the Grenville Province and locations of NTS map sheets at 1:250,000 scale for the areas discussed in the text (modified from Perreault et al., 2003).

Host rocks and associated rocks

Granite pegmatites, granites, syenites, pyroxenites (pyroxene skarns), calcsilicate gneiss and marble.

Deposit form

Irregular zones along intrusive contacts.

Mineralogy

Ore: uraninite, monazite, xenotime, allanite, zircon, magnetite, uraninite, pitchblende, thorite, thorianite, pyrochlore and molybdenite. Skarn: clinopyroxene, garnet, wollastonite, hornblende, epidote, olivine, potassium feldspar, quartz, chlorite and muscovite.

Control on mineralization

In calcsilicate rocks forming contact (thermal) aureoles along intrusive margins.

Origin

This type of mineralization forms during contact metamorphism and/or metasomatism of pure or siliceous limestones. Metasomatic fluids derived from a granitic intrusion, or metamorphic fluids remobilized by the heat of the intrusion, penetrate and react with the calcareous rock, generally porous and fractured, introducing aluminium, silica and magnesium, as well as rare metals and molybdenum.

Main Type VII showings in Québec

Mineralization is mainly limited to the western part of the Grenville Province, near the boundary between the polycyclic and monocyclic allochthonous domains (map sheet 311, K and F; Figure 10). Most were discovered in the 1950s and 1960s during uranium exploration programs using scintillometers, and as was the case for Type VI mineralization (see above), there was no systematic testing for rare metals. Nevertheless, values of 0.48% REE were found in pyroxene skarns and marbles of the Baie Mercier showing (deposit no. 157). Calcsilicate rocks (deposit nos. 172, 174 and 176) also contain significant REE values between 0.18 and

0.29%, underscoring the rare metal potential of this type de mineralization. In the Minto Subprovince, two REE showings were reported in marbles associated in volcanic rocks of the Kimber Belt (deposit nos. 296 and 297, Appendix 1; NTS 35H02, Figure 1). Although the light REE enrichment in these marbles has not yet been accurately determined, the geological context suggests a significant metasomatic process associated with alkaline intrusions (Labbé *et al.,* 2003) and possibly related to a skarn-forming process.

Exploration criteria

- The presence of radioactive minerals in granites and skarns form radiometric anomalies that can be detected by airborne methods.
- Prospecting by scintillometer on the ground can detect and delineate mineralized radioactive zones.

RARE METAL MINERALIZATION IN QUÉBEC: A GEOCHEMICAL APPROACH

This section presents geological areas for which we have determined a rare metal potential. The Preissac-Lacorne region has been excluded because the mineralized (Li ± Be ± Ta) monzogranites and suite of pegmatites in this plutonic complex have already been the subject of numerous geochemical and metallogenic studies establishing the region's mineral potential (Boily *et al.,* 1989; Boily, 1995; Mulja *et al.,* 1995; Doucet and Ste-Croix, 2001). Since four of the more significant deposit types are associated with granitic and syenitic intrusions (i.e., Types l, III, V and VI), we retrieved all geochemical analyses for granitic and syenitic plutonic rocks from the SIGEOM database. Using these analyses and the analyses we already had for other complexes (Strange Lake and Preissac-Lacorne), it was possible to develop geochemical criteria relating to rare earth "fertility" for granitoids. The criteria are:

<u>For peralkaline granites</u> (Types III and V): SiO_2 > 72 wt%; Fe_2O_3Total > 4 wt%; MgO < 0.1 wt%, Al_2O_3< 12 wt%; Na_2O + K_2O > 10 wt%; F > 0.5 wt%; Rb > 400 ppm; Sr < 50 ppm; La > 200 ppm; Zr > 300 ppm; Th > 50 ppm; U > 10 ppm; Rb/Sr = 5-160 ppm and K/Rb = 27-120 ppm.

<u>For syenites</u> (Types III and V): SiO_2= 55-65 wt%; Na_2O + K_2O > 10 wt%; F > 0.5 wt%; Rb > 400 ppm; Sr < 50 ppm; La > 200 ppm; Zr > 300 ppm; Th > 50 ppm; U > 10 ppm; Rb/Sr = 5-160 ppm and K/Rb =27-120 ppm.

<u>For peraluminous monzogranites</u>: (Types 1 and VI): SiO_2 72-76 wt%; peraluminosity index of A/CNK [Al_2O_3(Na_2O + K_2O + CaO (molecular)] > 1 and up to 1.5; TiO_2 < 0.1 wt%; Fe_2O_3Total < 2 wt%; MgO < 0.2 wt%; Sr < 200 ppm; Ba < 400 ppm; Zr < 80 ppm; Rb > 300 ppm; Li > 100 ppm; Be > 3 ppm; Cs > 10 ppm; Nb > 15 ppm; Ta> 10 ppm; Rb/Sr> 1; K/Rb < 250; Rb/Ba > 0.5 and K_2O/Na_2O > 1.

These criteria may, however, be too restrictive since a number of granite and syenite analyses in the SIGEOM database do not include trace element values for Li, Cs, Be, Th, U, Nb and REE. We thus decided to ease the criteria by considering, at the outset, major element, Ba, Rb, Sr, Zr and Y contents, and REE concentrations when available. Plots of Rb vs Sr and Rb vs Ba were used in the preliminary sorting step to distinguish "fertile" granites from "infertile" granites as defined by Cerny and Meintzer (1988). These diagrams allow us to eliminate poorly differentiated monzogranites (that is, those with ratios of Rb/Sr < 0.5 and K/Rb > 200) containing relatively high amounts of MgO, Fe_2O_3Total and TiO_2 (wt%). However, since the compositions of several granites overlap the fertile field, we used more subjective criteria to further discern granites with significant potential. Concentration thresholds for rare metals were established as follows: Li > 20 ppm, Zr > 200 ppm, Be > 1 ppm, Ta > 0.5 ppm, Y > 50 ppm and La > 120 ppm. Moreover, chondrite-normalized REE profiles for fertile Type I peraluminous monzogranites show low to moderate fractionation (that is, $[La/Yb]_{NC}$ < 10) and negative Eu anomalies (Boily, 1995). When available, REE results can also be used as discriminating criteria. As is the case for fertile monzogranites, peralkaline syenites and granites associated with Types III and V have REE profiles that are flat or poorly fractionated with much higher REE concentrations (that is, 30-100x chondrite values) and the negative Eu anomalies are much more pronounced (Boily and Williams-Jones, 1994).

The application of our geochemical criteria identified 163 potentially fertile granitoid samples from a total population of 1,154. We ranked these samples into six groups according the major geological divisions to which they belong. Sample numbers for all potentially fertile granite and syenite samples are present in Appendix 2. The reader may consult the SIGEOM database for their major and trace element profiles.

Fertile granites in the Mont-Laurier region, Grenville Province

The large region of Mont-Laurier is covered by NTS map sheets 31J, 32K and 310 (Figure 10). Lacoste (2000) and Nantel and Pintson (2002) mapped several suites of fertile monzogranites (e.g., the porphyroid and augen-textured monzogranites of the intrusive Serpent Suite, the late monzogranites of the Notawassi Pluton, and the Brockaby monzogranite). These latter examples crop out mainly in the monocyclic allochthonous zone of the Grenville Province (Figure 10). This zone is formed of paragneiss, calcsilicate rocks, and dioritic to tonalitic orthogneiss.

Geochemistry

The fertility of monzogranites was established using a Rb vs Ba diagram (Figure 11f), even though sample compositions fall just outside the fertile field on a Rb vs

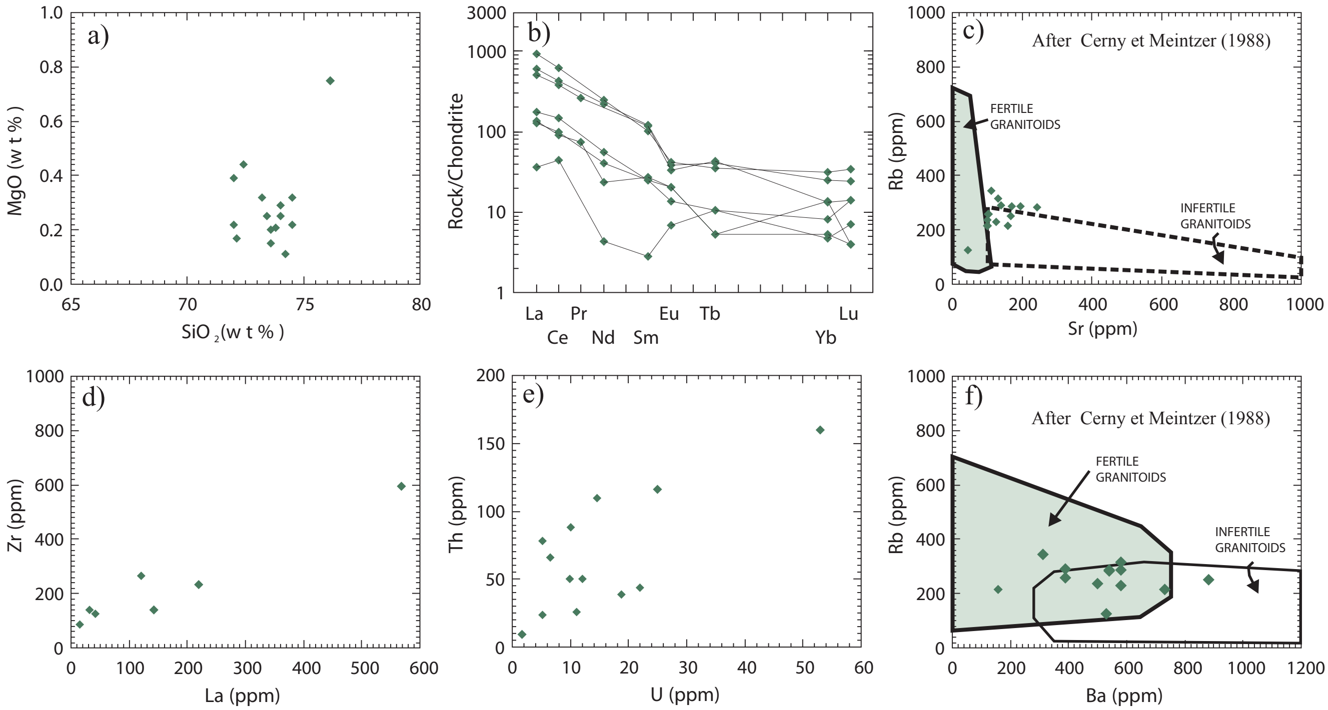

FIGURE 11 – Geochemical variations in fertile granites of the Mont-Laurier region, Grenville Province (NTS 31J/10, 11, 15; 31K/08; 31O/03).

Sr diagram (Figure 11c). The fertile granitic rocks are slightly to strongly peraluminous (A/CNK = 1.00-1.25) and moderately differentiated (Rb/Sr = 1.2-3.1), with low silica contents (SiO_2 = 72.0-76.2 wt%, Figure 11a). Some of the normalized REE profiles display light REE enrichment (La = 8.5-568 ppm, Figure 11b). Some samples have potentially interesting Zr values (88-656 ppm, Figure 11d), but not for other rare metals, like Y (12-109 ppm), Nb (8-66 ppm), Cs (1-10 ppm) and Li (12-21 ppm). Nevertheless, some monzogranites are enriched in Th (10-160 ppm) and U (2-53 ppm, Figure 11e), drawing attention to the uranium and thorium potential of the region. The compilation study by Gosselin *et al*. (2003) inventoried many **Type VI** showings (that is, U, Th ± (REE, Nb, Zr and Y) mineralization) in granite pegmatites and migmatites associated with peraluminous and metaluminous granites. Thorium and uranium enrichment in monzogranites suggests a genetic link with the small swarms of radioactive granite pegmatites containing mineralization generally limited to uraninite, thorite and monazite (Hébert, 1995).

The intraplate granites of the Manitou-Wakeham region

The Grenvillian intraplate granites of the Manitou-Wakeham region crop out over a vast area of land belonging to the polycyclic allochthonous zone, to the north and northwest of the cities of Sept-Îles and Havre-St-Pierre (Figure 10). The region covered by NTS map sheets 12K, 12L, 12M, 12N, 22I and 22P comprises anorthosite complexes (e.g., the Havre-Saint-Pierre, Fournier and Tortue suites), supracrustal rocks (e.g., the Wakeham Group) and several intrusive suites (e.g., the gabbroic intrusions of the Lillian Suite) (Madore *et al.,* 1997, 1999; Gobeil *et al.,* 2000, 1999; Verpaelst *et al.* 1999; Chevé *et al.,* 2001). The geochemistry for a number of felsic granitoids and mafic intrusives in the Manitou-Wakeham region reveals an A-type (anorogenic) affinity and an intraplate continental emplacement (Clark, 2003; Verpaelst *et al.,* 1999). The felsic Olomane Suite (1245-1239 Ma), the Canatiche and Manitou complexes, and the porphyritic granites of Kataht (1495-1510 Ma) are associated with showings and prospects mineralized with iron oxides, Cu, REE, Y, P, F, and Ag (Type V; Olympic Dam/Kiruna; Clark, 2003). In the Manitou region (Figure 9), Type V showings are hosted by a leucogranite (alaskite) body at least 3.5 km wide, located along the southern edge of the Canatiche Complex (Clark, 2003), whereas to the south, these types of showings are found within or near the foliated leucogranite body belonging to the Manitou Complex (Clark, 2003; Chevé *et al*., 2001).

Geochemistry

Figure 12 illustrates the geochemical variations in granitic rocks belonging to the Canatiche and Manitou complexes (Manitou region; Chevé *et al., 2001* and Clark, 2003). These leucogranites and biotite ± hornblende granites mostly fall within the field of fertile granites (Figures 12c and f). Metaluminous to strongly peraluminous (A/CNK = 0.95-1.10), they are highly differentiated (MgO = 0.66-0.05

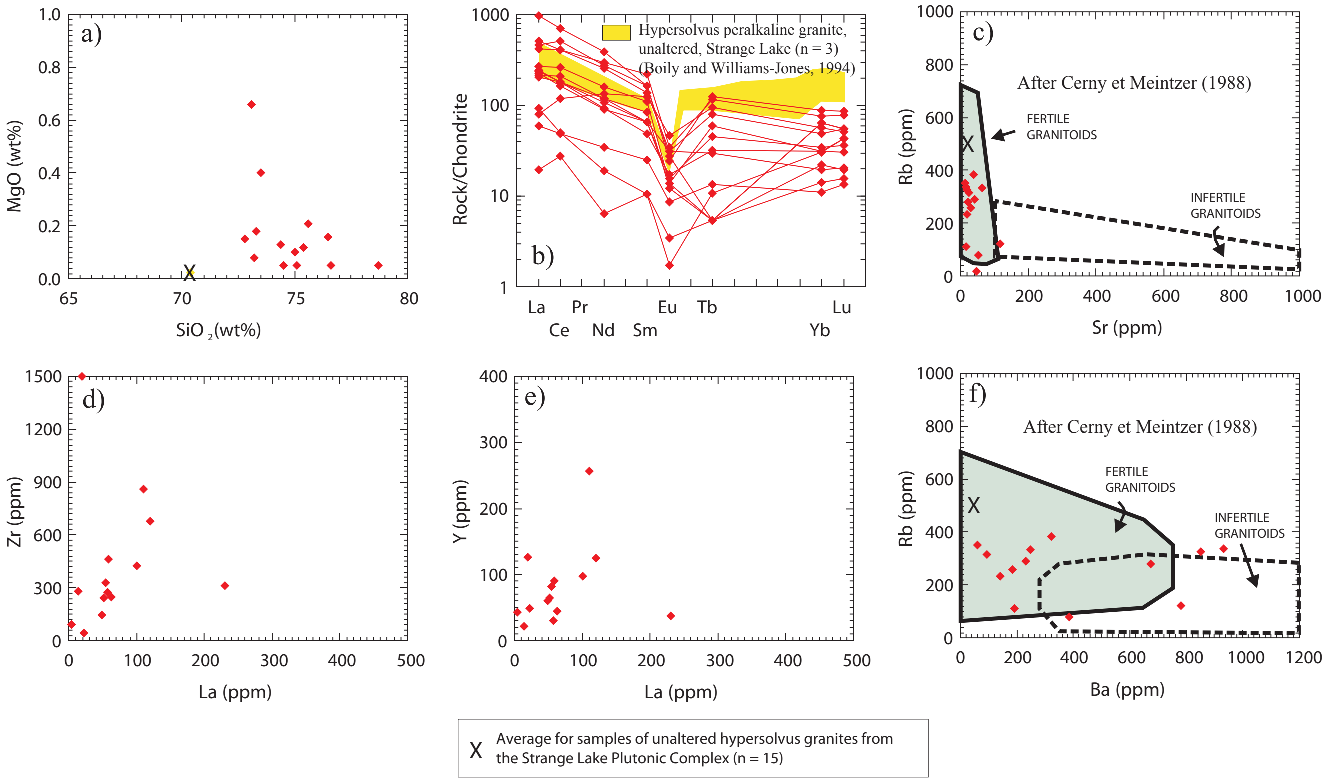

FIGURE 12 – Geochemical variations in granites mainly belonging to the Canatiche and Manitou complexes (NTS 22I/12, 13, 14; 22P/02, 03).

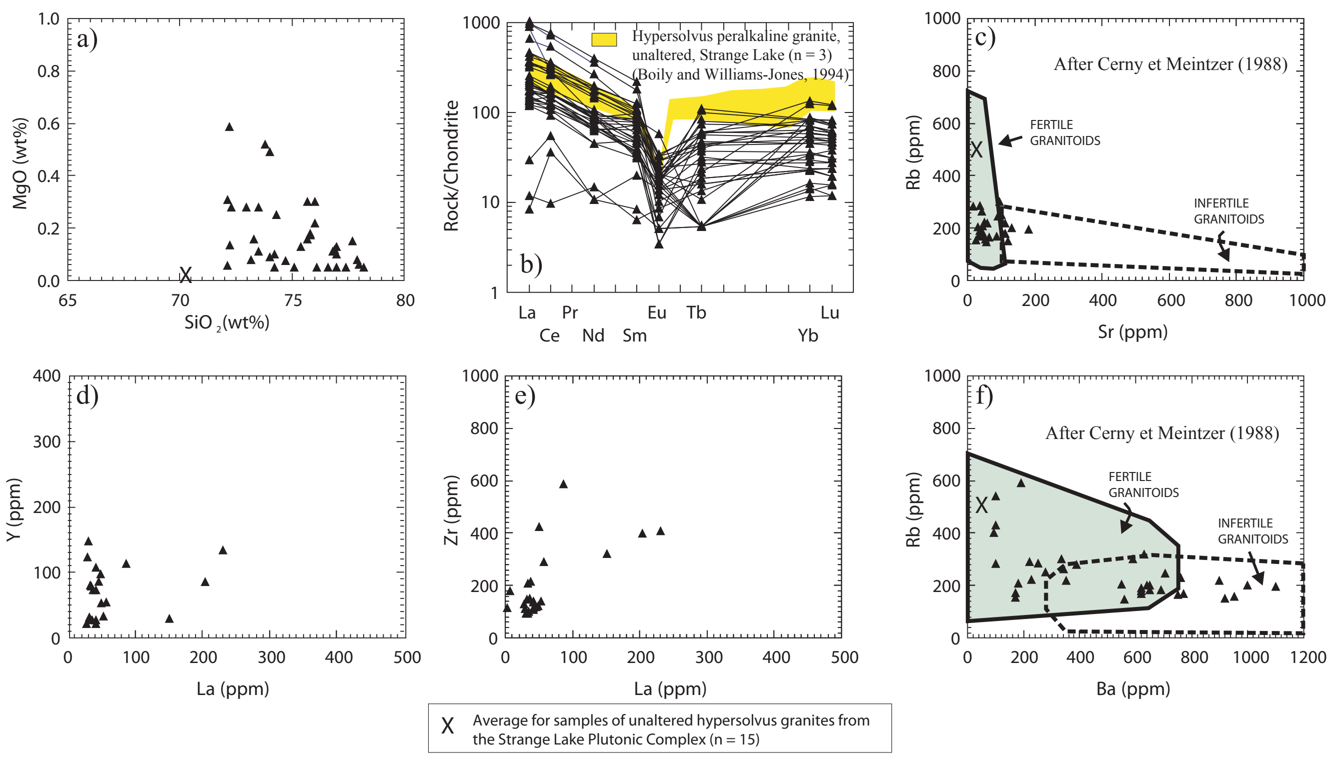

FIGURE 13 – Geochemical variations in granites mainly belonging to the Kataht and Olomane complexes (NTS 12L/07, 08, 11, 14; 12N/03 to 06).

wt% (Figure 12a) and Rb/Sr = 0.4-25) and enriched in iron (Fe_2O_3Total = 0.71-4.90), which is characteristic of A-type granites in contrast to Type I peraluminous monzogranite suites (e.g., the Preissac-Lacorne monzogranites; Fe_2O_3Total < 1.0 wt%; Boily, 1995). Enriched in Zr, Y and REE (Figures 12d and e), they display normalized REE profiles (Figure 12b) typically seen in granites with rare metal mineralization (e.g., Strange Lake deposit, Québec-Labrador (Boily and Williams-Jones, 1994) and Thor Lake deposit, Northwest Territories (Pinckston and Smith, 1991). Some granites contain elevated light REE (> 200x chondrite values) and heavy REE contents (> 100x chondrite values), and display pronounced negative Eu anomalies and moderate fractionation ($[La/Yb]_{NC}$ < 10; Figure 12b). Figure 13 illustrates the chemical variations for granitoids from the Kataht and Olomane complexes. These have very similar compositions to granites of the Canatiche Complex. Leucogranites from the Kataht and Olomane complexes (SiO_2= 72.1-78.2 wt%) are fertile based on Rb vs Sr and Rb vs Ba diagrams (Figures 12c and 12f), their iron contents (Fe_2O_3Total = 0.49-4.27 wt%), and their high degree of differentiation (Rb/Sr = 1-19 and MgO = 0.05-0.58%, Figure 13a). They are enriched in REE, Zr, Y, Nb and Th (and also fluorine for the granites from the Olomane Suite). Their normalized REE profiles are also similar to those of the leucogranites from the Canatiche Complex (Figures 12b and 13b).

These data emphasize the known association between fertile A-type leucogranites and Olympic Dam/Kiruna mineralization. The Manitou-Wakeham region possesses enormous rare metal potential due to the abundance of anorogenic granites enriched in F and rare metals that were emplaced in an extensional crustal environment between 1.1 and 1.2 Ga.

Anorogenic granites and syenites of the Rae Province

The Rae Province contains several suites of anorogenic (A-type) Granitoids. They comprise Aphebian orthogneiss and paragneiss, and metamorphosed granitoid and charnockite suites that were metamorphosed during the Hudsonian Orogeny (Danis, 1991; Taner, 1992). The Mistastin Batholith is composed of syenite, monzonite and biotite-hornblende granite. It belongs to a suite of bimodal anorogenic plutons (i.e., anorthosite-gabbro and adamellite-granite) that characterize Elsonian magmatism associated with continental rifting in the northeast part of the North American craton (Pillet, 1989). Also part of this suite is the peralkaline Strange Lake Plutonic Complex (1189 Ma; Miller, 1986; Boily and Williams-Jones, 1994), consisting of arfvedsonite-aegirine granites enriched in Zr, Y, Nb and REE. It has been associated with the final phase of Elsonian anorogenic

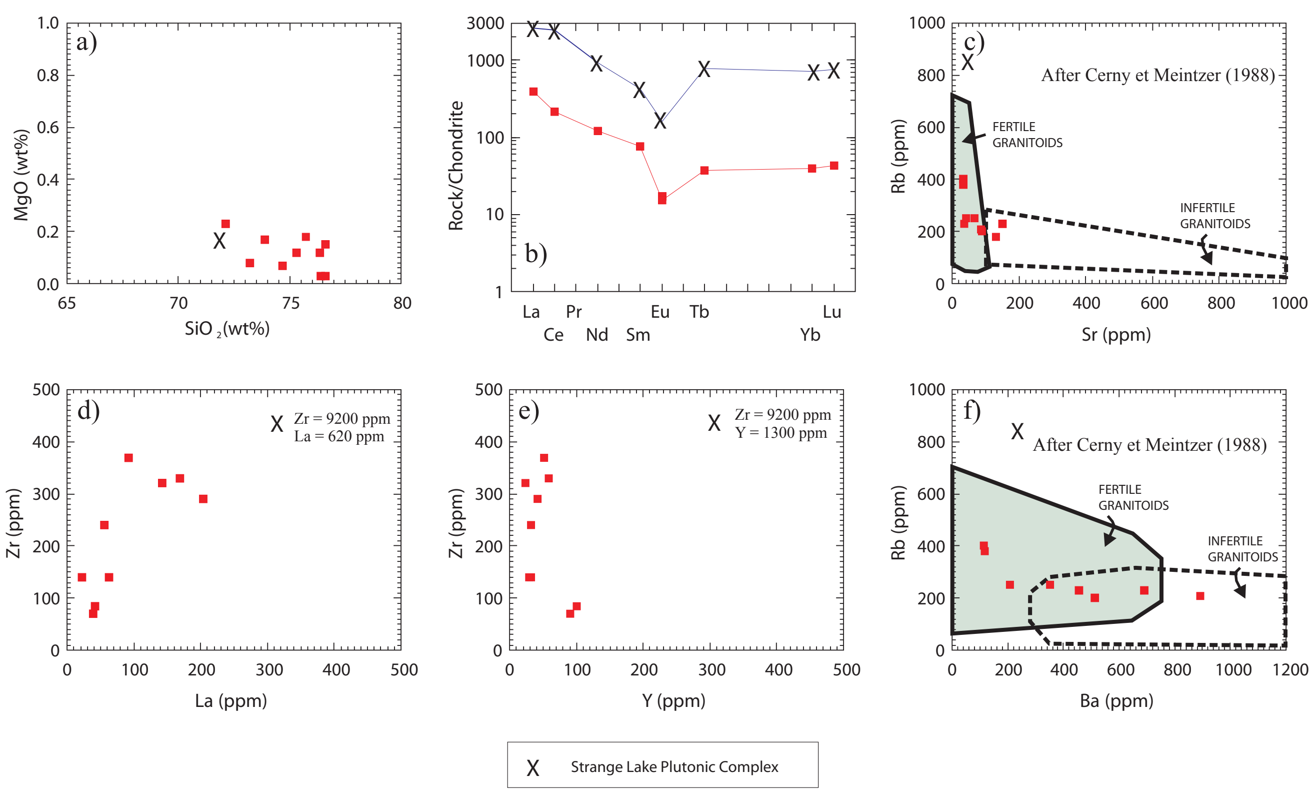

FIGURE 14 – Geochemical variations in anorogenic granites of the Rae Province (NTS 13L/13; 13M/05, 06, 13; 23P/08; 24A/01, 08).

activity characterized in Greenland by an assemblage of silica-saturated and silica-undersaturated alkaline intrusions forming the Gardar Province (Upton and Emeleus, 1987).

Geochemistry

The granite and syenite samples identified as fertile are from regions covered by NTS map sheets 13M, 13L, 231, 23P, 23N, 230 and 24A (Figure 1) that were mapped by Taner (1992) and Danis (1991). With the exception of a sample of peralkaline granite from the Strange Lake Complex, the fertile granites of the Rae Province are peraluminous (A/CNK = 1.0-1.12), fractionated (MgO = 0.23-0.03 wt% and Rb/Sr = 1-13) and display moderate enrichment of Zr (70-370 ppm), La (22-204 ppm) and Y (23-101 ppm, Figure 14). These contents are nonetheless much lower than the concentrations reported for unaltered peralkaline granites associated with the Strange Lake deposit (e.g., Y = 940-1,650 ppm; Zr = 3,700-6,300 ppm and La = 130-540 ppm; Boily and Williams-Jones, 1994). Without any chondrite-normalized REE profiles, it is difficult to determine whether the peraluminous granites of the Rae Province are typical of anorogenic suites. However, the Zr/Y ratios, which reflect LREE/HREE ratios, are low (1-14, and 6 on average), suggesting moderate fractionation typical of A-type granites (as determined by $[La/Yb]_{NC}$ ratios). Two samples of silica-rich and highly differentiated granites (SiO_2 = 76.4-76.6 wt% and Rb/Sr = 12-13) contain elevated concentrations of Li (103-119 ppm), Rb (380-400 ppm) and Be (3-4 ppm), indicating a potential for discovering granite pegmatites mineralized with these rare metals.

The syenites (SiO_2 = 59.47-65.69 wt% and K_2O = 4.87-6.47 wt%) (Figure 15a) have moderate to elevated amounts of La (9-623 ppm), Zr (94-1,300 ppm), Y (38-140 ppm) and Th (4-28 ppm) (Figures 15c and 15d). They are likely part of the anorogenic Mistastin Batholith. A syenite with 5,900 ppm F (the only available fluorine analysis) also contains 1,300 ppm Zr, but is depleted in REE, Nb and Y.

The presence of fluorine-enriched syenites and peralkaline granites confirms the potential of the region for Zr, Nb, Y and REE mineralization. Many fluorine-enriched peralkaline syenitic and granitic plutons, anorogenic and of Elsonian age, crop out in the Rae Province and Labrador (e.g., the peralkaline granites of Strange Lake and Flower River (Hill and Thomas, 1983) and the Red Wine Complex (Blaxand and Curtis, 1977).

Granites and syenites of the Ashuanipi Subprovince

The samples of fertile Archean granites were collected from a region lying mostly within the Ashuanipi and Opatica subprovinces, along the boundaries with the Archean La Grande and Opinaca subprovinces. They were taken from late tectonic felsic intrusive suites (e.g., the Ligneron and Gamart suites and the Dusterlo Batholith; approximately 2.64-2.65 Ga) and anorogenic granites (fluorite syenogranites of the Suite de Viau; ~2.57 Ga; Leclair *et al., 1998;* Lamothe *et al.,* 1998, 2000). The granites crosscut supracrustal rocks, diatexites and early tonalite and gabbro intrusions. The late alkaline syenites and nepheline syenites (2655 ± 3 Ma) are from the north part of the Ashuanipi Subprovince. They intrude supracrustal assemblages composed of metatexite-diatexite, amphibolite, tonalitic gneiss and paragneiss (Chevé and Brouillette, 1988 and 1989; Danis, 1991).

Geochemistry

The samples of granite were taken from regions represented by NTS map sheets 23C, 23E and 23F (Figure 1). They are all peraluminous (A/CNK = 1.00-1.17) and moderately differentiated (MgO = 0.0-1.03 wt%; Figure 16a) and Rb/Sr = 0.05-6.5). Although the analytical results for some granite samples fall outside the fertile granite field on Rb vs Sr and Rb vs Ba diagrams (Figures 16c and 16f), we have included them in this group due to their high light REE (La = 140-720 ppm) and Zr contents (62-400 ppm; Figures 16d and 16e). However, the fractionated REE profiles ($[La/Yb]_{NC}$= 24-235; Figure 16b), corroborated by low Y values (14-86 ppm), led us to conclude that their compositions are different from those attributed to A-type granites. Two monzogranites display low Zr/Y (1-7) and $[La/Yb]_{NC}$ ratios (0.7-1.4), accompanied by low REE values and pronounced negative Eu anomalies (Figure 16b), but these samples are not enriched in Li, Be, Cs or Th.

The syenitic samples (SiO_2 = 54.6-65.0 wt% and K_2O = 3.88-5.91 wt%) (Figure 15a) are from regions corresponding to NTS map sheets 13M and 23I. They are enriched in Zr (74-570 ppm), which is expected for syenites, but this enrichment is not accompanied by elevated values for light REE (La = 6-72 ppm), Y (316 ppm) or Th (0.2-7.8 ppm) (Figures 15c and 15d). Three chondrite-normalized REE profiles reveal significant fractionation ($[La/Yb]_{NC}$ ratio = 22-74; Figure 15b), confirmed by high Zr/Y values (5-190). However, we believe these late syenites are not of economic interest due to their low rare metal contents.

Monzogranites and granite pegmatites of the James Bay region

The intrusion of monzogranite plutons along the contact between volcano-plutonic and metasedimentary subprovinces constitutes one of the more favourable geotectonic contexts for rare metal mineralization. Two relatively unexplored areas with this type of geological environment have been identified in the James Bay region. Several mineralized areas were uncovered. The areas correspond to: 1) the Vieux-Comptoir Granite (Avcr) emplaced at the boundary between the volcano-plutonic La Grande Subprovince and the metasedimentary Opinaca Subprovince (Figure 4; NTS map sheets 33C14, 33F03 and 33F04; Goutier *et al.,* 1999b);

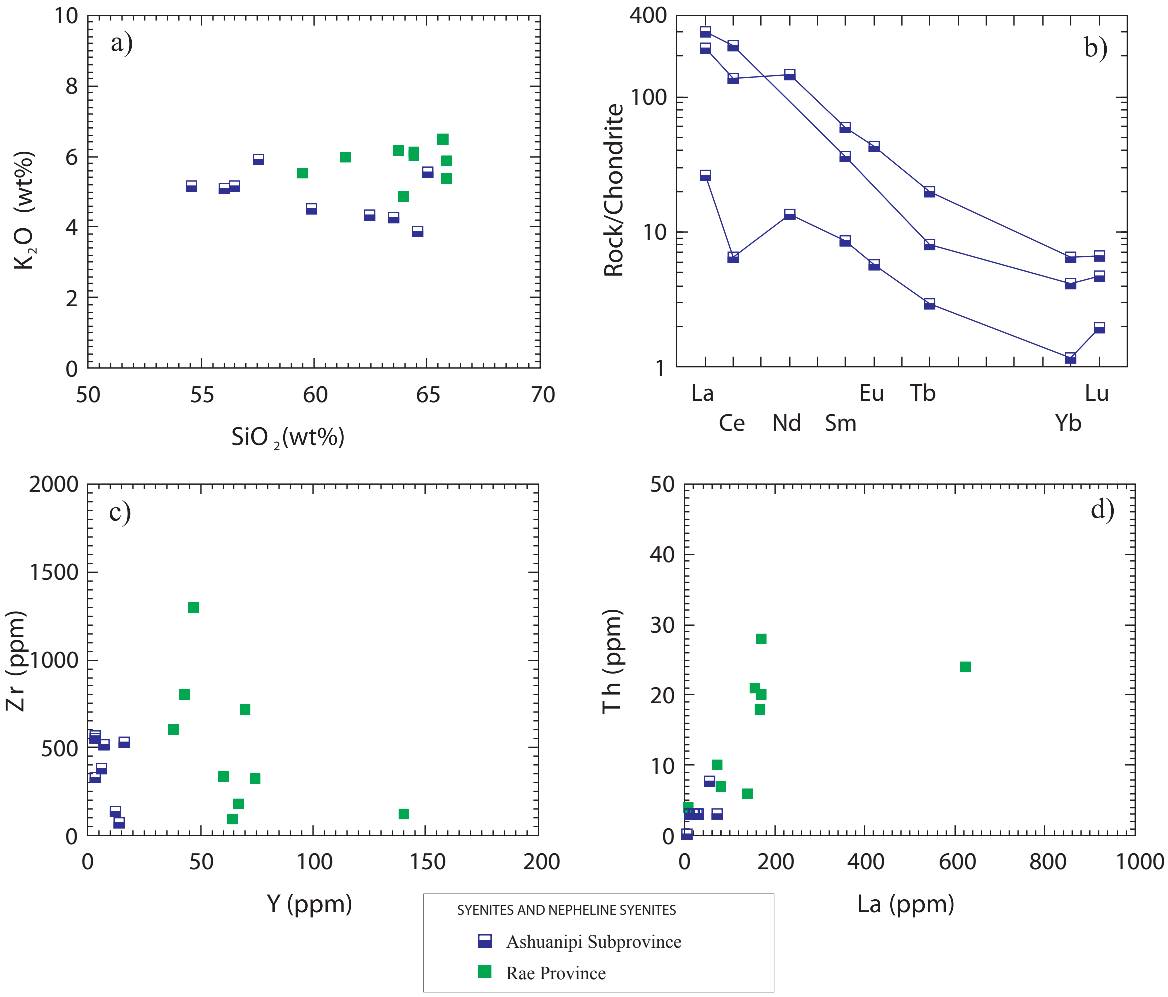

FIGURE 15 – Geochemical variations in syenites and nepheline syenites of the Ashuanipi Subprovince (NTS I3M/05, 06; 23I/09, 16) and the Rae Province (NTS 23N/08; 23O/04).

and 2) granitic masses near the contact between the metasediments of the Nemiscau Subprovince and the volcano-sedimentary rocks of the Lower and Middle Eastmain Belt (LMEVB; Figure 4; map sheets 33C01 to 08; Moukhsil *et al.,* 2003). These belts (2743-2703 Ma) and those of the La Grande Subprovince (2820-2736 Ma) comprise a platform of tholeiitic lavas and komatiitic flows, overlain by tuffs and intermediate calcalkaline lavas. The assemblage is discordantly overlain by detrital sediments. The La Grande Volcano-sedimentary Belt rests on ancient tonalitic basement (3360-2811 Ma) whereas no plutonic or orthogneissic rocks older than 2750 Ma crop out in the LMEVB.

In the La Grande region, the Vieux-Comptoir Granite (2657-2618 Ma; Goutier *et al.,* 1999a, 1999b) forms a vast, undeformed, late tectonic pluton. The pluton is composed of monzogranite with biotite ± muscovite and muscovite ± garnet phases, as well as granite pegmatite dykes and masses, some of which contain tourmaline and, more rarely, spodumene and beryl as accessory minerals. Goutier *et al.* (2002) also assigns other biotite monzogranite and pegmatitic granite plutons to the Vieux-Comptoir Granite (Avcr); these plutons crop out in the LG-3 Reservoir area. Further south, along the Eastmain River, Moukhsil (2000) and Moukhsil *et al.* (2001) mapped syn-tectonic to late tectonic plutons, including Kawachusi, Kapiwak, Mistumis, Ukawasis, Wapamisk, Akakanipanuch, Pawakis and Kasapawatish. They comprise monzogranitic phases and granite pegmatite dykes, some of which are mineralized with Li and Be.

Geochemistry

Vieux-Comptoir Granite

The few results we have for the Vieux-Comptoir Granite have typical silica-rich (SiO_2 = 72.8-76.9 wt%) and peraluminous compositions (A/CNK = 1.05-1.15), depleted in MgO (0.49-0.05 wt%; Figure 17a). Even though the compositions for three of the five samples fall within the fertile granite field (Figures 17c and 17f), the chondrite-

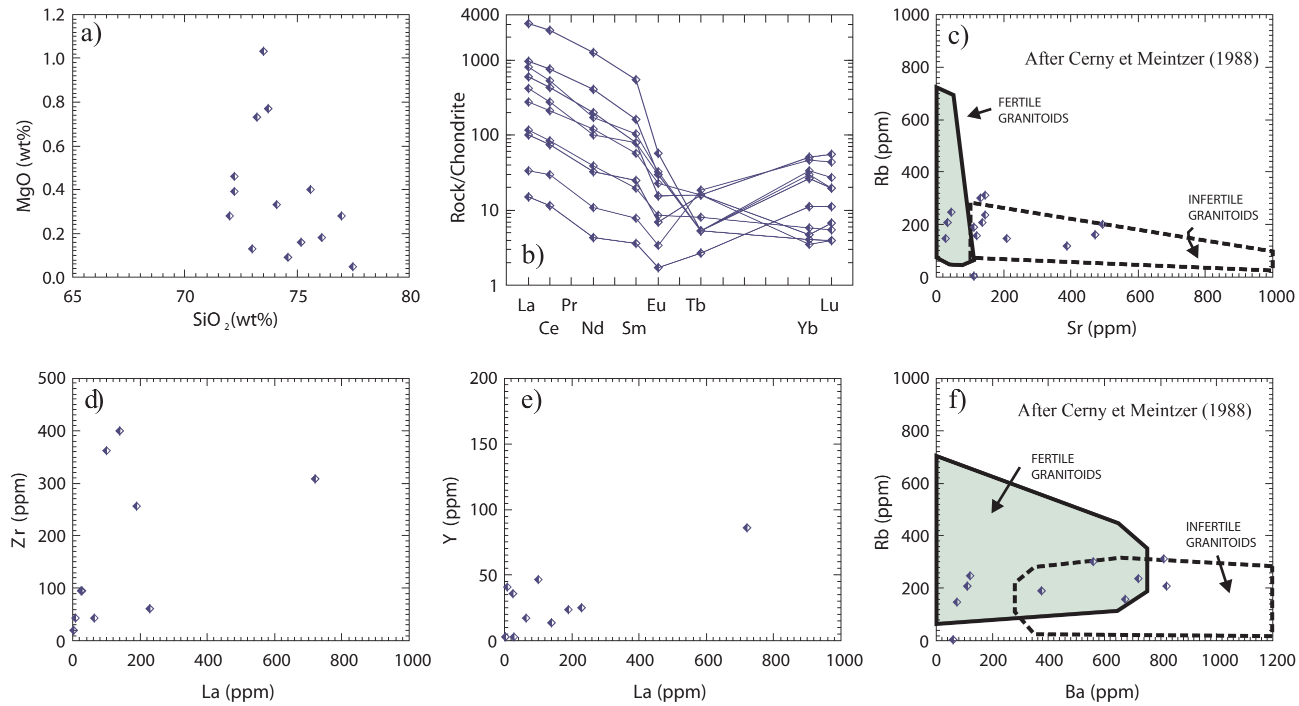

FIGURE 16 – Geochemical variations in granites of the Ashuanipi Subprovince (NTS 23C/11, 16; 23E/06, 07, 15, 16; 23F/01 to 04).

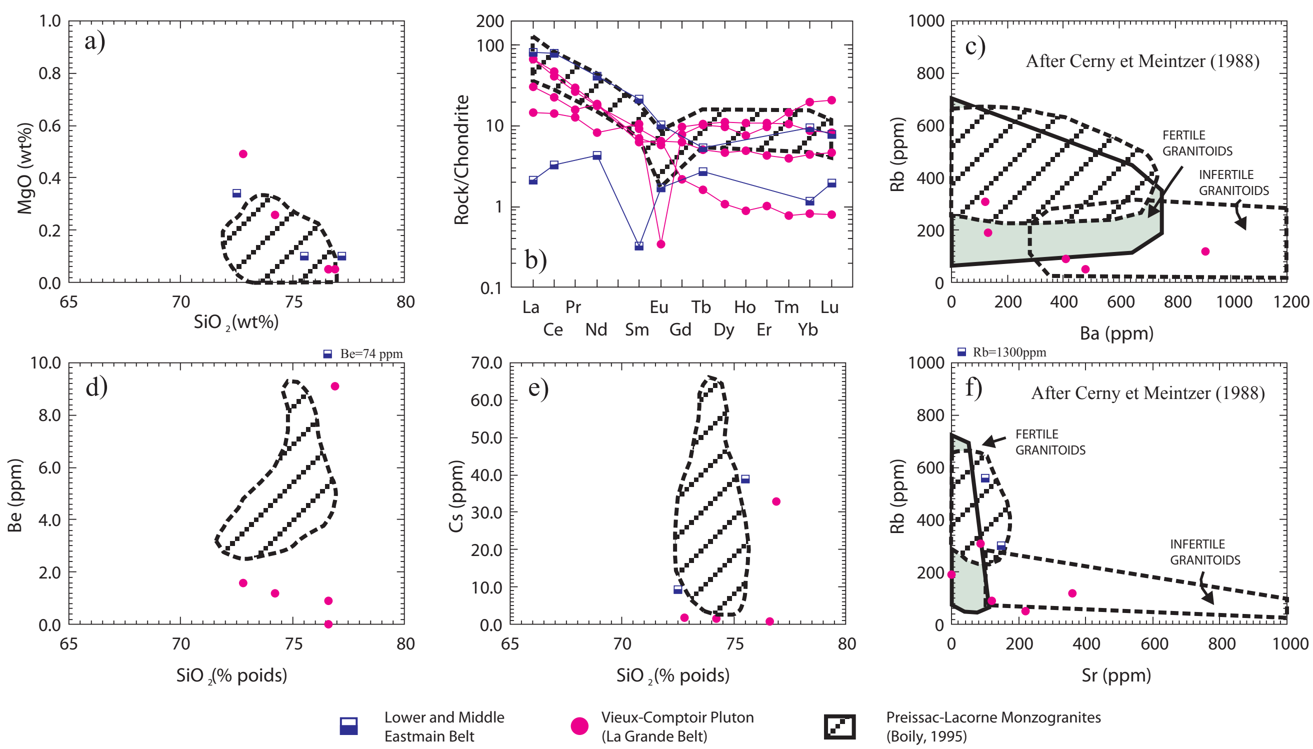

FIGURE 17 – Geochemical variations in monzogranites and granitic pegmatites of the Baie-James region (NTS 33C/01, 03, 07, 14; 33E/01; 33F/02, 03).

normalized REE profiles for three monzogranite samples display a similarity with the profile for Preissac-Lacorne monzogranites (Figure 17b). A sample of pegmatitic granite enriched in Be (9.1 ppm) and Cs (33 ppm) displays a very pronounced negative Eu anomaly, significant REE depletion (< 15x chondrite values), and a flat profile (e.g., $[La/Yb]_{NC} = 0.74$). This geochemical signature is typical of rare earth-fertile pegmatitic monzogranites (Cerny and Meintzer, 1988). It is difficult to assess the potential of the Vieux Comptoir Granite based on the analytical results of only four samples. However, the following considerations support the need for more thorough investigations into this granite: 1) the nature and the chemical and mineralogical composition of the pluton are, for the most part, poorly known since only its northern part was mapped in detail (Goutier *et al.*, 1999b); 2) several small Li and Be showings hosted in granite pegmatites were observed along the perimeter of the Vieux-Comptoir Granite (Remick, 1976; Goutier *et al.,* 1999a and b); and 3) the ages of the pluton and its satellite intrusives to the east (2657-2618 Ma) are comparable to those of the late tectonic to post-tectonic monzogranitic plutons that generated the set of granite pegmatites mineralized in Li, Be, Ta and Cs; e.g., the Lamotte pluton (2647-2639 Ma) in the Preissac-Lacorne Plutonic Complex; the granite pegmatite Tanco-Silverleaf Group in Manitoba (2640 Ma); the leucogranites and pegmatites of the Sioux Lookout Terrane (2684-2650 Ma) and the Separation Lake Volcano-sedimentary Belt of the English River Subprovince (2651-2635 Ma) (Baadsgaard, 1993; Ducharme *et al.,* 1997; Larbi *et al.,* 1999); 4). The Vieux Comptoir Granite and its satellite intrusives were emplaced in a similar geological context to that of the English River and Wabigoon subprovinces, where many fertile monzogranitic plutons have been found (Breaks *et al., 2002).*

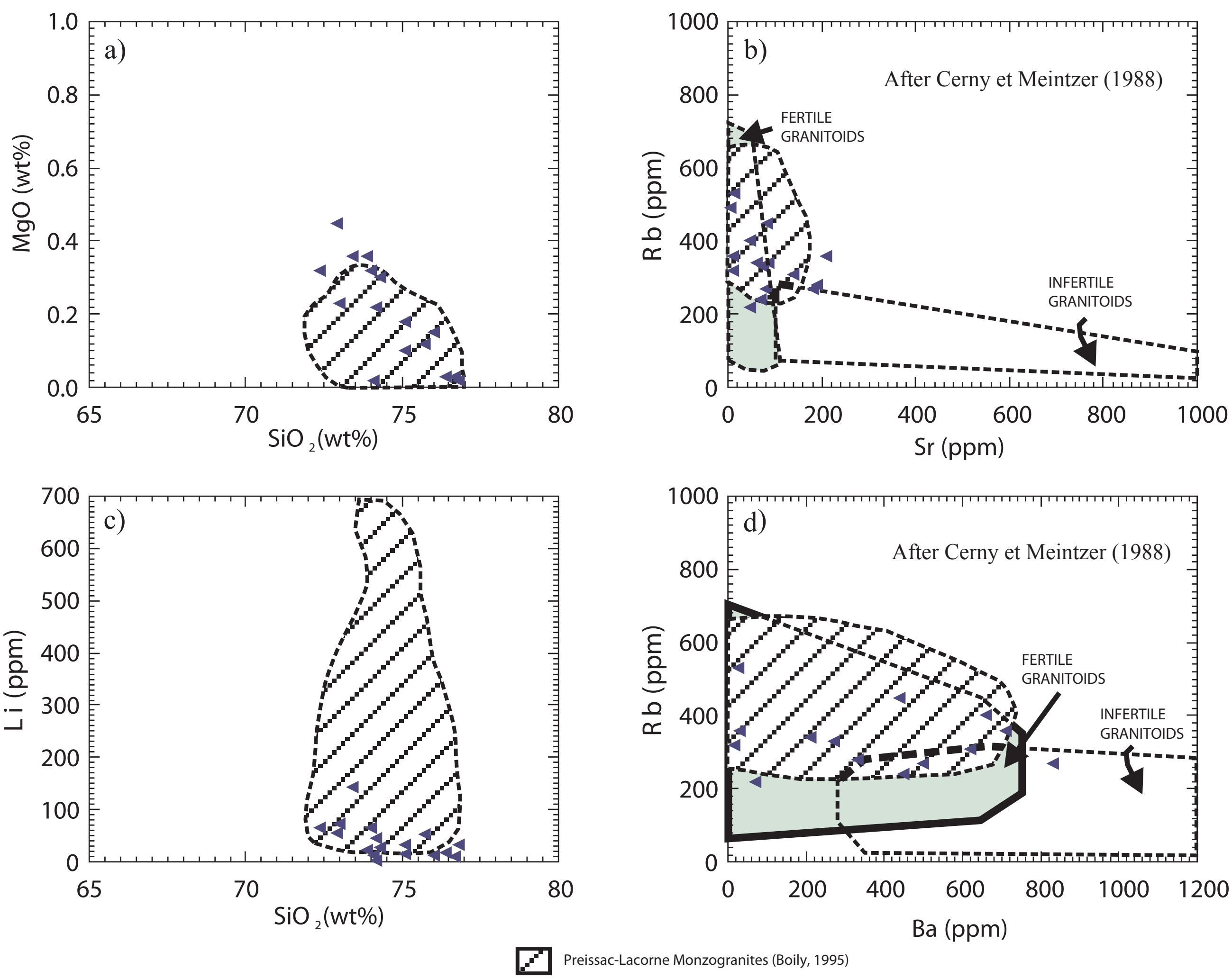

FIGURE 18 – Geochemical variations in monzogranites of the Frotet-Evans Volcano-sedimentary Belt (FEVB; NTS 32J/10, 15, 16).

Granitic masses of the Lower and Middle Eastmain Belt

In the Eastmain River region, one of the 16 samples of granite and pegmatite proved to be a fertile granite. Fairly silica-poor (SiO_2 = 72.5 wt%; Figure 17a) and moderately fractionated (MgO = 0.34 and Rb/Sr = 2.0), the sample produced a poorly fractionated chondrite-normalized REE profile ($[La/Yb]_{NC}$ = 8.5) (Figure 17b) and significant Cs (9.3 ppm) and Ta values (2.5 ppm). Two pegmatites mineralized with Li and Be were collected from known sites: the Lac Pivert showing and the Cyr-Lithium prospect (deposit nos. 256 and 258, Appendix 1 and Figure 4). As with the rare metal mineralized granite pegmatites, these pegmatites are very silica-rich (SiO_2 = 75.5-77.2 wt%; Figure 17a), with an unfractionated REE profile ($[La/Yb]_{NC}$ = 1.8) (Figure 17b) and light REE depletion (La = 0.5-2.0 ppm) and Zr (5-16 ppm).

Despite the insufficient number of granite and pegmatite analyses for the region, the contact between the Lower and Middle Eastmain Volcano-sedimentary Belt (LMEVB) and the Nemiscau Subprovince nonetheless remains a favourable geological contact for rare metal deposits (Figure 4). This is supported by the discovery of Li ± Be showings and prospects, some of which are of significant interest (Cyr-Lithium prospect; deposit no. 258). Others were only recently identified during mapping by Moukshil *et al.* (2001), including the Rose (deposit no. 255) and Lac Pivert showings (deposit no. 256). According to Moukshil *et al.* (2003), Be-, Nb- and Ta-rich pegmatites are likely present in the vicinity of the Cyr-Lithium prospect, along the perimeter of the fertile Kapiwak Pluton – an area that has seen little exploration. A similar scenario is proposed for the Lac Pivert and Rose showings, where the cogenetic intrusion that generated these dykes remains to be found. Also worth mentioning are the values of 207 g/t and 317 g/t Ta_2O_5 at the du Lac des Montagnes lithium showing (deposit no. 250) further to the south.

Monzogranites of the Frotet-Evans Volcano-sedimentary Belt

The Archean Frotet-Evans Volcano-sedimentary Belt (FEVB) (2793-2755 Ma) forms an immense thrust sheet overlying the summit of an assemblage of orthogneiss nappes that constitute, along with syn-tectonic to late tectonic plutons, the core of the Opatica Subprovince (Sawyer and Benn, 1993; Boily and Dion, 2002; Figure 4). The FEVB consists of assemblages of tholeiitic and calcalkaline lavas, intermediate to felsic calcalkaline tuffs, discordantly overlain by detrital sediments (Gosselin, 1996; Brisson *et al.*, 1998; Boily, 1999).

Geochemistry

Almost all the monzogranite analyses reported for the Frotet-Evans Belt are for samples from the eastern part of the belt. Fertile monzogranites are limited to the area covered by NTS map sheets 32J10, 15 and 16 where Simard (1987) mapped several syn-tectonic to post-tectonic granodiorites and monzogranites. The fertile peraluminous granites (A/CNK = 0.9-1.2) fall within the field of the Preissac-Lacorne monzogranites on Rb vs Sr and Rb vs Ba diagrams (Figures 18b and d). Depleted in MgO (0.01-0.22 wt%; Figure 18a), they do not have the pronounced Li enrichment of the Preissac-Lacorne monzogranites. However, the Li concentrations of the latter, like other fertile granites that give rise to lithium-bearing pegmatites, are highly variable (40-770 ppm; Figure 18c). The composition of monzogranites cropping out in the eastern FEVB is therefore suggestive of a potential for Li +Be ± Mo mineralization even though this region has been ignored since the discovery of the Moléon-Lithium showing in the 1950s (deposit no. 244, Figure 4). Elsewhere, Rondot (1972) noted the presence of numerous pegmatite dykes around Lac Moblan, near Lac Coulombe, where outcrops of fertile monzogranites have been identified. The potential of the FEVB for rare metal discoveries extends to the central part of the belt, where granite and pegmatite dykes containing spodumene and beryl have been found at the Sirmac prospect (deposit no. 245).

CONCLUSIONS

The growing interest in rare metal exploration in the Superior Province is largely due to the rising market price for Ta concentrate during the past few years. This new interest from the mining industry prompted the MRNFP to inventory all rare metal showings, prospects and deposits in the province of Québec (Gosselin *et al.,* 2003). This document, which complements the inventory, describes the main applications for rare metals in industrial and consumer products. It also provides a genetic classification for the main types of rare metal mineralization observed in Québec. They are: Type I - Li, Be, Ta, Cs, Rb, ± Mo, ± Nb, ± F mineralization in granite pegmatites associated with peraluminous granite plutonic complexes; Type II - Nb, Ta, REE and P mineralization associated with carbonatite complexes; Type III - REE, Y, Zr, F, ± (Be, Nb, Th) mineralization associated with pegmatites injected internally within intrusions of peralkaline granite and syenite; Type IV - Fe, Ti, ± (Zr, REE) mineralization associated with placers or paleoplacers; Type V - iron oxide mineralization with Cu, ± (Au, U, P, REE) (Olympic Dam/Kiruna); Type VI - Mo, U, Th, Zr and REE mineralization in granite pegmatites and migmatites associated with peraluminous to metaluminous granites; and Type VII - Th, U, ± (Mo, REE) mineralization in skarns (mineralized calcsilicate rocks).

Our study of the lithogeochemical analyses for granite and syenite samples collected in Québec and stored in the SIGEOM database was used to identify "fertile" granitoids, in the sense of being fertile for rare metal mineralization corresponding to types I, III, V and VI described above. For the most part, these granitoids demonstrate a spatial – if not genetic – association with granitic pegmatites or rare metal mineralized zones. The priority targets within little known regions should thus be any "fertile" granitic and syenitic intrusions considering the much greater volume they occupy compared to the associated pegmatites. Once the fertility of the granitoids has been established, in addition to their geochemical affinity (e.g., "anorogenic" peralkaline granite), it is then possible to define more specific targets. For example, in the search for Type I mineralization, granite pegmatites rich in Li, Ta, Be and Cs should occur along the margins of peraluminous granites or in the country rocks, within a radius rarely exceeding 1 to 2 km from the contact. On the other hand, peralkaline pegmatites and aplites mineralized in Zr, Y and REE (Type III) should outcrop in the apical zones of peralkaline granites and syenites.

Our work led to the following conclusions:

1- The Vieux-Comptoir Granite and the satellite monzogranites cropping out along the contact between the La Grande and Opinaca subprovinces are priority exploration targets based on: a) the scarcity of geological surveys carried out on these granites; b) their favourable chemical composition and their late tectonic to post-tectonic emplacement (2657-2618 Ma), which correspons to the emplacement ages of fertile monzogranites and granite pegmatites mineralized with Li, Be, Ta and Cs in the Superior Province of Ontario and Québec; c) the presence of associated potassic pegmatitic facies with beryl + tourmaline + spodumene; d) the existence of external pegmatites mineralized with beryl and spodumene; and e) the favourable tectonic context at the junction between a metasedimentary subprovince (Opinaca) and a volcano-plutonic/orthogneiss subprovince (La Grande).

Elsewhere, the region along the margin of the Lower and Middle Eastmain Volcano-sedimentary Belt (LMEVB) also warrants exploring for its rare metal potential. The favourable geological context is supported by the discovery of Li ± Be showings and prospects, some of which are long-known and considered significant (Cyr-Lithium prospect; deposit no. 258) and others more recently discovered during mapping by Moukshil et al. (2001) (Rose showing, deposit no. 255 and Lac Pivert showing, deposit no. 256).

2-We believe the Frotet-Evans Volcano-sedimentary Belt (FEVB) has potential for rare metal discoveries. In its central and eastern parts, several occurrences of lithium mineralization have been found (deposit nos. 244 to 248, Appendix I, including the Sirmac prospect), despite the sporadic exploration for this substance in the past. The few analyses for monzogranites from this region only cover the eastern part of the belt, but their results are comparable in some respects to results for the fertile Preissac-Lacorne Pluton. A more thorough assessment of the fertility of granitic masses within and along the boundaries of the belt, particularly in the central and western parts, is warranted.

3- Several A-type felsic plutons related to the formation of a pan-Proterozoic continental rift are present in the Rae Province. The peralkaline Strange Lake Pluton represents the culmination of anorogenic magmatism and likely forms the western extension of the Gardar Alkaline Province of southern Greenland (Upton and Emeleus, 1987). The Strange Lake Pluton, exceptional for its Zr, Y, REE and Nb enrichment, appears to constitute an isolated body embedded in Aphebian gneisses and other Elsonian intrusions. Nevertheless, if the example of the Gardar Province applies to the Rae Province, we should be able to find small peralkaline plutons (silica-saturated and silica-undersaturated) aligned along major breaks. This remote region of Québec has only been mapped at the regional scale. The Strange Lake Pluton, discovered by fluorine anomalies in lake water samples and by uranium anomalies in lake-bottom sediment samples, has a very small outcropping surface (< 5% based on our personal experience). Moreover, its diameter is 6 km at most, which makes it difficult to detect during regional-scale geological surveys. We therefore believe it is still possible to discover other small alkaline plutons in the Rae Province.

4- Clark (2003) recently published a document in which he reported on Olympic Dam/Kiruna-type Fe, Cu, REE, Y, P, F, Ag (Type V) mineralization in the Manitou-Wakeham region. Combining Clark's work with the results of our geochemical study led us to the following observations: a) the region contains several A-type felsic plutons of Mesoproterozoic age (Canatiche Complex, felsic Olomane and Kataht suites), b) these are moderately to strongly enriched in F, REE, Zr and Y; and c) the Olomane and Kataht suites intrude a sequence of clastic metasedimentary rocks, an association that is also found at the Olympic Dam and Bayan Obo deposits. Regional mapping programs and exploration for this type of deposit only began in the 1990s (Perry and Raymond, 1996; Verpaelst *et al.,* 1999). In our opinion, the potential for discovering world-class deposit in this region is one of the highest in Canada.

5- Although carbonatite complexes were not part of our geochemical study, they undoubtedly constitute first-order targets in the search for Nb, Ta and REE mineralization. Past, present and future mining at the Niobec, St-Lawrence Columbium and Niocan deposits reflect the relevance of exploring any complex identified in Québec. Also, some of the Nb, Ta ± REE prospects associated with the Crevier alkaline complex (deposit no. 245) in Lac St-Jean, and the Castillon (deposit nos. 94 and 95) and Lac Lemoyne alkaline complexes (deposit nos. 100 and 101) in the Labrador Trough, were the subject of recent prospecting work (Wright *et al.*, 1997; Fournier, 2002; and work by Osisko Mining).

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APPENDIX 1 - List of deposits mentioned in the present report and in DV2003-03 (common numbering system) and their corresponding COGITE database reference numbers. (* = chemical analysis with anomalous rare metal contents; x = new showing, no COGITE number).

Present report and DV 2003-03	Deposit name	COGITE number	Present report and DV 2003-03	Deposit name	COGITE number
1	Kegashka	12K03-02	184	Zone de la Riv. Kipawa	31L16-06
2	Natashquan-Sud	12K04-05	185	Zones PB & PS	31L16-2000
3	Lac Couillard	12K07-2000	186	Rapides Turner	31L16-04
4	Lac Couillard (Zone 3a)	12K07-1000	188	Vézina	31M10-05
10	Baie Quetachou	12L07-008	189	Île du Refuge	31M10-1000
12	Lac Turgeon (Zone 1)	12L07-1014	190	Claims Legault	31M10-04
13	Lac Petit	12L07-004	191	Lac Simard-Nord	31M10=03
18	Lac Turgeon	12L07-001	192	Dallaire	31M10-2000
27	Indice du Village Saint-Augustin	12O02-1001	193	Lac Simard	31M10-01
30	Wares	x	195	Lac Fourcet	31O06-03
31	Castor 300	21L07-18	196	Riv. Trenche Est	32A07-08
32	St-Charles	21L07-16	197	Lac Moore	32B04-02
33	Du Bloc	21L07-17	198	Chubb	32C05-48
48	Mine Niobec (Saint-Honoré)	22D11-07	199	Lac Baillarge-Est	32C05-35
89	1986016233*	x	200	Baillarge-Ouest	x
92	1983008599*	x	201	Baillarge-Nord	32C05-37
93	Lac Brisson	24A08-01	202	Baillarge-Sud	32C05-38
95	1986025449*	x	203	Valor Lithium	32C05-16
96	Lac Savigny-NE	24C07-01	204	Massberyl (Morono)	32C05-15
97	Lac Bishop	24C08-1008	205	Vallée Lithium	32C05-22
98	1990030908*	x	206	Buffalo Canadian-Abitibi	x
99	1990030913*	x	207	Mine Québec Lithium	32C05-21
100	1990030902*	x	208	La Motte-Est	32C05-13
101	Erlandson No, 2	24C16-04	209	Augustus Exploration	32C05-19
102	Erlandson No, 1	24C16-03	210	Canadian Lithium	32C05-17
119	Oka Columbium	31G08-02	211	Martin-McNeely	32C05-18
120	St-Lawrence Co.(Bloc D)	31G08-03	212	New Athona-2	32C05-01
121	Mine St-Lawrence Columbium	31G09-18	215	Authier	32D08-38
122	Zone Bond	31G09-14	216	La Motte VI-2	32D08-36
123	Zone Manny	31G09-15	217	Aldous	32D08-20
124	Bouscadillac (Zone A)	31G09-10	218	Lac La Motte	32D08-45
125	Advance	31G09-11	219	Duval-Lithium	32D08-22
126	Manoka	31G09-17	220	La Motte VII-47	32D08-25
127	St-André-2	31G09-21	221	Dumoulon	32D08-24
128	Lac Meach	31G12-92	222	Height of Land	32D08-16
134	1989022827*	x	223	Gaitwin	32D08-27
135	1989022809*	x	224	Lacorne Lithium	32D08-28
136	1989022811*	x	225	Lavandin-2	32D08-19
137	1984091409*	x	226	Tantalum	32D08-05
138	1986021286*	x	227	Boily-1	32D08-2000
139	Second Lac Roberge	31I15-008	228	Quebec Beryllium	32D08-06
142	Alleyn	x	229	Lac des Hauteurs	32D08-03
143	Lac des 31 Milles	x	230	International Lithium	32D08-09

APPENDIX 1 (Continued) - List of deposits mentioned in the present report and in DV2003-03 (common numbering system) and their corresponding COGITE database reference numbers. (* = chemical analysis with anomalous rare metal contents; x = new showing, no COGITE number).

Present report and DV 2003-03	Deposit name	COGITE number	Present report and DV 2003-03	Deposit name	COGITE number
144	Rapide-Tête-des-Six	x	231	Bouvier	32D08-08
154	Ragnar	x	241	Carbonatite du lac Shortt	x
155	Black Smoke Hill	x	242	Crevier	32H07-01
158	Rivière Petawawa	31J13-001	244	Moléon-Lithium	32J10-02
177	Gualillo	31K08-1004	245	Sirmac	32J11-03
183	Lac Sheffield-2	31L15-15	246	Lac Clapier-Nord	32J11-01
247	Lac Sirmac-Ouest	32J12-08	257	Cyr-2	x
248	Lac Gertrude-Sud	32J13-05	258	Cyr-Lithium	33C03-01
249	Lac Marcaut	32N04-02	281	Morrice-Carrier	x
250	Lac des Montagnes	32O12-04	285	Vernot-Dubé-1	x
255	Rose	x	287	Vernot-Larocque-18	x
256	Lac Pivert	33C01-05	289	Vernot-Quirion-4	x

APPENDIX 2 - List of the unique identification numbers for the lithogeochemical analyses of the granitic and syenitic intrusions presented on the diagrams in figures 11 to 18. (* see Sharma, 1996 for the lithological codes)

Identifi. number	NTS	Lithology*
Mont-Laurier region, Grenville Province		
1996009827	31J10	I1B
1996009830	31J10	I1B
1996009882	31J10	I1B
1997013317	31J11	I1B
1997013254	31J11	I1B
1997013274	31J11	I1M
1998018971	31J11	I1M
1998017085	31J14	I1M
1998017083	31J14	I1M
1991001369	31K08	I1G
2000030415	31O03	I1M
2000030417	31O03	I1M
2000030414	31O03	I1M
Manitou Wakeham region, Côte-Nord (Olomane and de Kataht complexes)		
1992007531	12L07	I1B
1997013386	12L11	I1B
1997013357	12L11	I1B
1997013354	12L11	I1B
1997013351	12L11	I1B
1997013352	12L11	I1B
1997013356	12L11	I1B
1997013380	12L11	I1B
1997013377	12L11	I1B
1997013378	12L11	I1B
1997013384	12L14	I1B
1997013448	12L14	I1B
1996009642	12N03	I1B
1996009684	12N03	I1B
1996009608	12N03	I1B
1996009629	12N03	I1B
1996008568	12N03	I1B
1995006517	12N05	I1F
1995006537	12N05	I1B
1995006532	12N05	I1B
1995006522	12N05	I1B
1995006635	12N05	I1G
1995006632	12N05	I1B
1995006535	12N06	I1B
1995006620	12N06	I1B
1995006629	12N06	I1B
1995006569	12N06	I1B
1995006586	12N06	I1B

Identifi. number	NTS	Lithology*
Granites, Rae Province		
1986023687	13L13	I1B
1986020767	13M05	I1B
1986020770	13M05	I1B
1986016984	13M06	I1B
1984020810	13M13	I1B
1984020810	13M13	I1B
1986020765	23P08	I1B
1983008597	24A01	I1B
1983008599	24A08	I1A
Syénites, Province de Rae		
1987032379	23N08	I2D
1987032379	23N08	I2B
1987032380	23N08	I2D
1987032382	23N08	I2D
1987032383	23N08	I2D
1988002491	23O04	I2B
1988002474	23O04	I2D
Granites, Ashuanipi Subprovince		
1997013711	23C11	I1G
1997013694	23C16	I1B
1997013695	23C16	I1B
1997013759	23C16	I1M
1998019974	23E06	I1M
1998021909	23E06	I1A
1998021903	23E07	I1M
1998017103	23E15	I1A
1998017104	23E15	I1A
1998017107	23E16	I1A
1996012294	23F01	I1M
1996012315	23F02	I1M
1996012312	23F03	I1A
1996012346	23F04	I1B
Syenites, Ashuanipi Subprovince		
1986023693	13M05	I2D
1986016963	13M05	I2C
1986020758	13M05	I2C
1986020761	13M05	I2C
1986016974	13M06	I2C
1986020771	13M06	I2C
1986020774	13M06	I2C
1986016233	23I09	I2D
1986016232	23I16	I2D

APPENDIX 2 (Continued) - List of the unique identification numbers for the lithogeochemical analyses of the granitic and syenitic intrusions presented on the diagrams in figures 1996 for the lithological codes)

Identifi. number	NTS	Lithology*
Baie-James region, Vieux-Comptoir Granite, La Grande Subprovince		
1998028930	33C14	I1B
1998028934	33F02	I1B
1998028912	33F03	I1B
1998028913	33F03	I1B
1998028916	33E01	I1B
Baie-James region, Lower and Middle Eastmain Volcano-sedimentary Belt		
2001038218	33C01	I1G
2000009774	33C03	I1G
1999023333	33C07	I1M
Manitou-Wakeham region, Côte-Nord (Canatiche and Manitou complexes)		
1998016623	22I12	I1B
1996012916	22I13	I1B
1996012156	22I13	I1B
1996012904	22I14	I1B
1997015594	22P02	I1B
1997015323	22P03	I1B
1997016981	22P03	I1B
1997015457	22P03	I1B
1998017807	22P03	I1B
1997016982	22P03	I1B
1997015326	22P03	I1B

Identifi. number	NTS	Lithology*
Frotet-Evans Volcano-sedimentary Belt, Opatica Subprovince		
1981006546	32J10	I1B
1981006547	32J10	I1B
1981006548	32J10	I1B
1981006549	32J10	I1B
1981006553	32J10	I1B
1981006554	32J10	I1F
1981006832	32J10	I1B
1981006560	32J10	I1A
1981006561	32J10	I1B
1981006562	32J10	I1B
1981006543	32J10	I1B
1981006886	32J10	I1F
1981006887	32J10	I1B
1981006887	32J10	I1B
1981006530	32J10	I1B
1981006531	32J10	I1B
1981006883	32J10	I1C
1981005682	32J15	I1C
1981006535	32J15	I1C
1981006889	32J15	I1C
1982003306	32J16	I1C
1982003311	32J16	I1C

Summary

This report is the result of a compilation of the main rare metal showings, prospects and deposits in the province of Québec. It presents the principal uses for these metals in industrial and consumer products, particularly in the high-tech fields of semiconductors, superconductors, electromagnets, ceramics and alloys.

A genetic classification was established for the main types of rare metal mineralization in Québec. These are: Type I – Li, Be, Ta, Cs, Rb, ± Mo, ± Nb, ± F mineralization in granite pegmatites associated with peraluminous granite plutonic complexes; Type II – Nb, Ta, REE and P mineralization associated with carbonatite complexes; Type III – REE, Y, Zr, F, ± Be, ± Nb, ± Th mineralization associated with pegmatites injected internally within intrusions of peralkaline granite and syenite; Type IV – Fe, Ti, ± Zr, ± REE mineralization associated with placers or paleoplacers; Type V – iron oxide mineralization with Cu, ± Au, ± U, ± P, ± REE (Olympic Dam/Kiruna); Type VI – Mo, U, Th, Zr and REE mineralization in granite pegmatites and migmatites associated with peraluminous to metaluminous granites; and Type VII – Th, U, ± Mo, ± REE mineralization in skarns (mineralized calc-silicate rocks). A list of the main world-class deposits for each type is presented, and mineralized sites in Québec are described, with an emphasis on the largest or otherwise most significant prospects and deposits. Exploration criteria are also proposed.

Analytical results for granites and syenites in Québec were taken from the SIGEOM database and the results used to identify fertile intrusives associated with, or likely to contain, zones of rare metal mineralization. These granitoids are found in six large regions of Québec. The four most significant groups are: 1) Grenvillian intraplate granites of the Manitou-Wakeham region associated with iron oxide, Cu, REE, Y, P, F, Ag mineralization (Type V; Olympic Dam/Kiruna); 2) anorogenic granitic and syenitic plutons of the Rae Province, related to the formation of a pan-continental Proterozoic rift and likely to contain REE, Y, Zr mineralization (Type III); 3) monzogranites and granite pegmatites of the James Bay region (Vieux-Comptoir Granite, Lower and Middle Eastmain Belt) containing Li, Be, Ta mineralization (Type I); and 4) Li- and Be-mineralized monzogranite intrusions and granite pegmatites of the Frotet-Evans Volcano-sedimentary Belt (Type I).

Ressources naturelles et Faune
Québec