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

Michel Boily, Charles Gosselin

Nioibium (Niobec) mine in the Saint-Honoré Alkaline Complex, Saguenay region.
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Michel Boily and Charles Gosselin

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).
TABLE OF CONTENTS

SUMMARY .......................................................................................................................... 1

INTRODUCTION ......................................................................................................................... 5
   Methodology ......................................................................................................................... 5

MAIN USES FOR RARE METALS ............................................................................................... 5
   Lithium (Li) ............................................................................................................................. 5
   Rubidium (Rb) and Cesium (Cs) ......................................................................................... 7
   Tantalum (Ta) ......................................................................................................................... 7
   Zirconium (Zr) and Hafnium (Hf) ....................................................................................... 7
   Rare earth elements (REE) .................................................................................................... 7
   Beryllium (Be) ....................................................................................................................... 7
   Niobium (Nb) ......................................................................................................................... 7
   Thorium (Th) ........................................................................................................................ 8

CLASSIFICATION OF RARE METAL DEPOSITS ......................................................................... 8
   Type I: Li, Be, Ta, Cs and Rb deposits associated with peraluminous granite complexes ........ 8
      Description .......................................................................................................................... 8
      Tectonic Environment ...................................................................................................... 8
      Age of mineralization ....................................................................................................... 8
      Host rocks and associated rocks ...................................................................................... 8
      Deposit form ....................................................................................................................... 8
      Zonation and type of pegmatite ....................................................................................... 8
      Pegmatite mineralogy ....................................................................................................... 8
      Alteration .......................................................................................................................... 8
      Structural control ............................................................................................................. 8
      Origin ............................................................................................................................... 11
      Important mine sites ....................................................................................................... 11
      Information ....................................................................................................................... 11
      Main Type I deposits in Québec ..................................................................................... 11
         Québec Lithium mine .................................................................................................... 11
      Exploration criteria .......................................................................................................... 13

   Type II: Nb, Ta, REE and P deposits associated with carbonatite complexes ......................... 14
      Idem and
         Niobec mine .................................................................................................................. 15
         Crevier prospect ........................................................................................................... 15
         St-Lawrence Columbium mine .................................................................................... 15
         The Niocan deposit ....................................................................................................... 15
      Exploration criteria .......................................................................................................... 15

   Type III: REE, Y, Zr and F deposits associated with peralkaline complexes ............................. 15
      Idem and
         Main Type III deposits in Québec ................................................................................ 17
            Strange Lake deposit (Lac Brisson) ........................................................................... 17
            Kipawa prospect ........................................................................................................ 20
      Exploration criteria .......................................................................................................... 20
Type IV: Fe, Ti, ± Zr and REE deposits associated with placers and paleoplacers ........................................... 20
Idem and
Main Type IV deposits in Québec .................................................................................................................. 21
Natashquan deposit ........................................................................................................................................ 21
Exploration criteria ........................................................................................................................................ 21

Type V: Iron oxide, Cu, REE, Y and U deposits (Olympic Dam/Kiruna) ................................................................. 21
Idem and
Main Type V showings and prospects in Québec ............................................................................................... 22
Exploration criteria ........................................................................................................................................ 22

Type VI: U, Th ± (REE, Nb, Zr and Y) mineralization in granite pegmatites, migmatites and peraluminous
to metaluminous granites .................................................................................................................................. 23
Idem and
Main Type VI showings in Québec ................................................................................................................. 24
Exploration criteria ........................................................................................................................................ 24

Type VII: Th, U ± (Mo and REE) mineralization in calcsilicate and metasomatized rocks (skarns) ............... 24
Idem and
Main Type VII showings in Québec .................................................................................................................. 25
Exploration criteria ........................................................................................................................................ 26

RARE METAL MINERALIZATION IN QUÉBEC: A GEOCHEMICAL APPROACH ......................................................... 26
Fertile granites in the Mont-Laurier region, Grenville Province ........................................................................... 26
Geochemistry .................................................................................................................................................... 26
The intraplate granites of the Manitou-Wakeham region ...................................................................................... 27
Geochemistry .................................................................................................................................................... 27
Anorogenic granites and syenites of the Rae Province ......................................................................................... 29
Geochemistry .................................................................................................................................................... 30
Granites and syenites of the Ashuanipi Subprovince ............................................................................................. 30
Geochemistry .................................................................................................................................................... 30
Monzogranites and granite pegmatites of the James Bay region ......................................................................... 30
Geochemistry .................................................................................................................................................... 31
Monzogranites of the Frotet-Evans Volcano-sedimentary Belt ........................................................................... 34
Geochemistry .................................................................................................................................................... 34

CONCLUSIONS .................................................................................................................................................... 34

REFERENCES ...................................................................................................................................................... 36

APPENDIX 1 - List of deposits mentioned in the present report and in DV2003-03 ............................................. 39

APPENDIX 2 - List of the unique identification numbers for the lithogeochemical analyses.......................... 41
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-Lacorne 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 Niobe, 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, 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:


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.

Batteries: The ionic properties of Li are favourable for its use in long-lasting rechargeable batteries. Metallurgy: 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 refractive 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 metallic 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 magnets (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 LnNbO3 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-Al-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 concen-
trated 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
albite, albite, fine-grained or porphyroblastic biotite monzo-
granite, fine-grained monzogranite containing biotite, mus-
covite, ± garnet, and pegmatitic monzogranite. Associated
rocks: TTG suite intrusives (tonalite-trondhjemite-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 mono-
mineralic zones or layers (e.g., albite, tantalite, petalite).

Zonation and type of pegmatite

The granite pegmatites become increasingly differenti-
ated moving away from the parent monzogranite. An ideal-
ized sequence based on the paragenesis proposes 7 zones:
1) barren biotite-magnetite pegmatites; 2) barren plagio-
clase-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-lithio-
philite, amblygonite-montebasite), tantalum (colombo-
tantalite, wodginite, microlite), beryllium (beryl) and
cesium (pollucite).

Alteration

Pegmatite: Internal metasomatism within the pegmatites:
albitization (often associated with Ta mineralization), tour-
malinization, 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 granit-
oids, and are emplaced along fractures and foliation planes in
<table>
<thead>
<tr>
<th>Type</th>
<th>Mineralization</th>
<th>Host rocks and associated rocks</th>
<th>Form</th>
<th>Mineralogy</th>
<th>Alteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Li, Be, Ta, Cs, Nb, ±Mo, ±F</td>
<td>Pegmatite dykes, apitites, albitites, biotite + muscovite ± garnet monzogranites, monzogranite pegmatites. Associated rocks: TTG intrusions, metavolcanics, biotite schists.</td>
<td>Swarms of granite pegmatite dykes, homogenous to broadly zoned. Pegmatic masses of variable forms (moderately to highly differentiated).</td>
<td>Li: spodumene, petalite, lepidolite, tryphile-titiphylite, amblygonite-montebasite. Ta: colombo-tantalite, wodginite, microlite. Be: beryl, Cs: pollucite.</td>
<td>Pegmatite: albitionization, tourmalinization, leaching of Li from spodumenes. Country rock: tourmalinization (B); biotitization (biotite-zinnwaldite; Li, K); holmiumsite (Li); fluorite.</td>
</tr>
<tr>
<td>III</td>
<td>REE, Y, Zr, ±Be, ±Nb, ±Th</td>
<td>Peralkaline pegmatites, silica-oversaturated: aegirine-nepheline, fluorite; silica-underosaturated: nepheline. Associated rocks: augite-nepheline syenites, peralkaline aegirine-ardotite, albitite, biotite monzogranites.</td>
<td>Dykes and sills filling cooling fractures and/or magmatic/hydrothermal disseminations at the summits of albition intrusive cupolas.</td>
<td>Zircon, monazite, pyrochlore, bastnaesite, beryl, eudyalite (Zr), gittinsite (Zr), thorite, tantaite, elpidite (Zr), gagarinite (REE, Y), thorthite, kainosite (REE, Y), mosandrite (REE), gadolinite (Y, Be, REE), loparite (REE, Nb, Ta).</td>
<td>Albition 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.</td>
</tr>
<tr>
<td>IV</td>
<td>Fe, Ti, ±Zr, ±REE (Placers and palaeoplacers)</td>
<td>Marine: coarse- to medium-grained sand, well sorted, overlying finer-grained shallow marine deposits. Continental: fine- to coarse-grained sand, well sorted, rounded.</td>
<td>Marine: along coastlines, thin (&lt;1 m thick), long (&gt;100 m) and narrow (&gt;50 m). Continental: discontinuous lenses (&lt;2 m).</td>
<td>Native gold, ilmenite, cassiterite, zircon, PGE, magnetite, monazite, garnet.</td>
<td>Olympic Dam: intense sericitization and hematite at surface and chlorite + potassium feldspar at depth. Kiruna: scapolite and albite; actinolite + epidote in mafic host rocks.</td>
</tr>
<tr>
<td>V</td>
<td>Iron oxide, Cu, REE, Y and U (Olympic Dam/ Kiruna)</td>
<td>Veins and breccias, discordant or concordant, in felsic volcanic breccias, tuffs, clastic sedimentary rocks, and A-type alkaline granites.</td>
<td>Discordant masses, veins, dykes, tabular bodies, and stockworks.</td>
<td>Hematite, magnetite, specularite, bornite, chalcopyrite, chalcolite, pyrite, pitchblende, coffinite (U), bertrandite (U), bastnaesite, monazite, xenotime. Gangue (breccias or veins): sericite, carbonato, chlorite, quartz, fluorite, barite.</td>
<td>Olympic Dam: intense sericitization and hematite at surface and chlorite + potassium feldspar at depth. Kiruna: scapolite and albite; actinolite + epidote in mafic host rocks.</td>
</tr>
<tr>
<td>VI</td>
<td>U, Th, ±REE, ±Nb, ±Zr and ±Y</td>
<td>Potassic granite dykes, granite migmatises, biotite ± muscovite granites, TTG sills intrusive. Associated rocks: metavolcanics, biotite schists, orthogneiss and paragneiss, calcisilicate rocks.</td>
<td>Swarms of granite pegmatite dykes, homogenous to broadly zoned. Heterogeneous masses of granite migmatites and granites.</td>
<td>Monazite, xenotime, allanite, zircon, magnetite, uraninite, pitchblende, thorite, thorianite, pyrochlore, samarskite (Nb, Ta, U), coffinite (U), uranophane, fergusonite (Y, Nb, Ta), gadolinite, ferrocolumbite.</td>
<td>Pegmatite: albitionization, chloritization, oxidation and hydrous alteration.</td>
</tr>
</tbody>
</table>
| VII  | Th, U, ±Mo and ±REE (skarn) | Associated rocks: granite pegmatites, granites, syenites, pyroxenites (pyroxene skarn), calcisilicate gneisses, 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).

<table>
<thead>
<tr>
<th>Type</th>
<th>Structural Control</th>
<th>Origin</th>
<th>Examples</th>
<th>Exploration Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>The pegmatites fill fractures, joints, and foliation planes in granitoids and country rocks. The monzogranite intrusions are controlled by major faults and deformation corridors that mark the boundaries of structural blocks.</td>
<td>Magmatic.</td>
<td>Greenbushes and Wodgina mines (Australia), Tanco mine (Canada), Québec Lithium mine (Québec)</td>
<td>Late to post-tectonic peraluminous monzogranite complexes. Deformation corridors marking the boundaries of major structural blocks. Mineralized granite pegmatites crop out in metasedimentary and/or metavolcanic country rocks within a 1-2 km radius from the contact with the parent monzogranites.</td>
</tr>
<tr>
<td>II</td>
<td>Magmatic: the shape of the intrusion and its crystallization history. Hydrothermal/metasomatic: tectonics and structures. Residual: erosion and the drainage pattern.</td>
<td>Magmatic, metasomatic/hydrothermal, residual.</td>
<td>Mountain Pass (California), St-Lawrence Columbium and Niocan (Oka, Québec), Niobec mine (St-Honoré, Québec).</td>
<td>The carbonatites are associated with continental rifts and grabens. They display excellent circular magnetic and radiometric signatures and may be associated with ring-shaped topographic breaks. Fenitization.</td>
</tr>
<tr>
<td>III</td>
<td>Mineralized pegmatites intrude fractures and joints of the cupola, at the intrusion/country rock contact or at the contact between two intrusive phases</td>
<td>Magmatic, low-temperature hydrothermal.</td>
<td>Karnasurt and Umbozero (Kola Peninsula, Russia), Strange Lake (Québec-Labrador), Kipawa (Québec).</td>
<td>Undeformed A-type (anorogenic) plutons. The radioactive alkaline granites and syenites are associated with airborne radiometric anomalies. Prospecting with a scintillometer 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.</td>
</tr>
<tr>
<td>IV</td>
<td>Marine: Heavy minerals concentrate along shorelines in sediments reworked by waves and currents. Continental: In fluvial zones, placers concentrate in irregularities within channels and surface depressions.</td>
<td>Sedimentary.</td>
<td>Ticor South Africa (South Africa), Tamil Nadu (India), Kwale (Kenya), Natashaquon (Côte Nord [North Shore], Québec).</td>
<td>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.</td>
</tr>
<tr>
<td>V</td>
<td>Emplacement along faults and/or lithological contacts, particularly in small-scale grabens. Intense hydrothermal activity along faults associated with brecciation.</td>
<td>Magmatic and hydrothermal.</td>
<td>Bayan Obo (China), Olympic Dam (Australia), Kiruna (Sweden).</td>
<td>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, stockworks and veins, produce positive gravimetric and aeromagnetic anomalies.</td>
</tr>
<tr>
<td>VI</td>
<td>Granite pegmatites and migmatites fill fractures and joints, and foliation planes in granitoids and their country rocks.</td>
<td>Magmatic. Hydrothermal alteration and remobilization during metamorphism may play a role.</td>
<td>Lac Tourgeon granite showings (Basse Côte-Nord [Lower North Shore], Québec).</td>
<td>Radioactive minerals (uraninite, pitchblende, thorite, thorianite, pyrochlore, samarskite) in the granites and pegmatites produce excellent airborne radiometric anomalies. Radioactive mineralized zones can be identified and outlined by prospecting with a scintillometer.</td>
</tr>
<tr>
<td>VII</td>
<td>In calcareous and calcsilicate rocks forming thermal aureoles around intrusives.</td>
<td>Contact metamorphism and/or metasomatism of pure limestones and siliceous limestones.</td>
<td>Lataille showing (Minto Subprovince, Québec), Baie-Mercier showing (Grenville Province, Québec).</td>
<td>Radioactive minerals in the granites and skarns produce airborne radiometric anomalies. Radioactive mineralized zones can be identified and outlined in the field by prospecting with a scintillometer.</td>
</tr>
</tbody>
</table>
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 (H₂O, F, and B). The residual magmas enriched in rare metals and volatile phases are expelled 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% Li₂O; Greenbushes, Australia: 7.96 Mt at 3.96% Li₂O and 88.6 Mt at 222 ppm Ta₂O₅; Wodgina, Australia: 63.54 Mt at 366 ppm Ta₂O₅. Canada: Tanco mine, Bernic Lake, Manitoba: 1,500,000 lbs of Ta₂O₅; Québec Lithium mine (in production from 1954 to 1966), Barraute, Québec (reserves of 18.1 Mt at 1.30% Li₂O).

**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 50 cm) uniformly distributed and oriented perpendicular to the country rock contacts. In places, dykes have aplitic 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 Québéc Lithium mine, Barrera, 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 sub-provinces 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 holmiquistite (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 albition and the appearance of lepidolite, is generally an indicator of Ta and Li mineralization.
- The main geochemical characteristics of fertile granites are: SiO₂ = 72 to 76 wt%; peraluminosity index of A/CKN (Al₂O₃/Na₂O + K₂O + CaO (molecular)) > 1, sometimes reaching 1.5; low concentrations of TiO₂ < 0.1 wt%, Fe₂O₃Total < 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 K₂O/Na₂O > 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 concentrated 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, nepheline, sycnite, 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


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: silification 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% (REE₂O₃); Araxa, Brazil, 495 Mt at 2.5% Nb₂O₅ (residual mineralization). Québec: St-Lawrence Columbium (1961-1976), Oka, 25 Mt at 0.44% Nb₂O₅; Niobec mine, St-Honoré, Saguenay, 12.33 Mt at 0.66% Nb₂O₅; Niocan deposit, Oka, Québec, 12.3 Mt at 0.66% Nb₂O₅.

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% Nb₂O₅. 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 (iulite, 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 Ta₂O₅ and 0.19% Nb₂O₅ (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% Nb₂O₅ 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 endokarst 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% Nb₂O₅. 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% Nb₂O₅.

**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.
Oka Complex and St-André Carbonatite
Beekmantown Group (dolomite, limestone and sandstone)
Potsdam Group (sandstone and conglomerate)
Grenvillian gneiss and anorthosite

570 000 m E.
5 050 000 m N.

Examples of drill results
0.72% Nb/4.9 m
0.35% Nb/21.6 m
0.22% Nb/24.4 m
0.58% REE/48.2 m

Niobec Deposit (Bond Zone) #122
S-60 deposit
2.3 Mt at 0.66% Nb₂O₅
HWN-2 deposit
2.2 Mt at 0.56% Nb₂O₅

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


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, epidote, ilarite, bertrandite, yttrofluorite, gagarinite, britholite, kainosite, mosandrite and gadolinite.

Alteration

Parent granitoids are albitized in the summits 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/liquids 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)₂O₆) 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 (deposits 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% Zr₂O₃, 1.1% REE₂O₃, 0.52% Y₂O₃ and 0.39% Nb₂O₅) and the Kipawa prospect in the Grenville Province (west zone: 786,000 t at 0.18% Y₂O₃ and 0.95% ZrO₂; east zone: 1 Mt at 0.14% Y₂O₃ and 1.17% ZrO₂; 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. 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) pseudomorphosis 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 km² and is 6 to 10 metres thick on average. It is characterized by a well-developed textural zonality in which aplite 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).

*Elpidite (Na₂ZrSi₆O₁₉·H₂O), gittinsite (CaZrSi₄O₁₀), pyrochlore ((Na, Ca, REE)₂(Nb, Ta)₂O₆(OH, F)), gadolinite (Y₂Fe²⁺Be₂Si₆O₁₆·REE), kainosite (Ca₂(Y,REE)₂Si₄O₁₀(CO₃)₂)·H₂O, gagarinite (Na(Y, Ca, Na, REE)₂F₆), bastnaesite (REE₂CO₃F) and thorite (ThSiO₄)*

1 Elpidite (Na₂ZrSi₆O₁₉·H₂O), gittinsite (CaZrSi₄O₁₀), pyrochlore ((Na, Ca, REE)₂(Nb, Ta)₂O₆(OH, F)), gadolinite (Y₂Fe²⁺Be₂Si₆O₁₆·REE), kainosite (Ca₂(Y,REE)₂Si₄O₁₀(CO₃)₂)·H₂O, gagarinite (Na(Y, Ca, Na, REE)₂F₆), bastnaesite (REE₂CO₃F) and thorite (ThSiO₄)

**FIGURE 8** - Petrogenetic model for the formation of the Strange Lake Zr, REE, Y and Nb deposit, Quebec-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 calcisilicate 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$_2$O$_3$ and 0.95% ZrO$_2$, and reserves of 1 Mt at 0.14% Y$_2$O$_3$ 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 albitionization.
- 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 comendites-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$_2$O$_3$/Total > 4 wt%; MgO < 0.1 wt%; Al$_2$O$_3$ < 12 wt%; Na$_2$O + K$_2$O > 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.

**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**

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 km². 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% REE2O3 and 1 Mt at 0.13% Nb2O5. 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% U3O8, 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 1, 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.
**Type VI: U, Th ± (REE, Nb, Zr and Y) mineralization in granite pegmatites, migmatises and peraluminous to metaluminous granites**

**Description**

Uranium and thorium ± (REE, Nb, Zr and Y) mineralization is associated with granite pegmatite dykes, granites, and migmatises. Syn-tectonic to late tectonic pegmatites, granites and migmatises 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 migmatises 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-trondhjemite-granodiorite), metavolcanics (metabasalts, amphibolites), biotite schists (metagraywackes), orthogneiss and paragneiss, calcisilicate 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, chevrickite, 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 pH₂O 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 1) 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 calcisilicate 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.
Host rocks and associated rocks

Granite pegmatites, granites, syenites, pyroxenites (pyroxene skarns), calcisilicate 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 calcisilicate 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). Calcisilicate rocks (deposit nos. 172, 174 and 176) also contain significant REE values between 0.18 and
possible to develop geochemical criteria relating to rare 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.

**Explanation 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 I, 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 rare earth “fertility” for granitoids. The criteria are:

**For peralkaline granites (Types III and V):** SiO₂ > 72 wt%; Fe₂O₃Total > 4 wt%; MgO < 0.1 wt%; Al₂O₃ < 12 wt%; Na₂O + K₂O > 10 wt%; F > 0.5 wt%; Nb > 15 ppm; TiO₂ < 0.1 wt%; Ta > 10 ppm; Zr > 300 ppm; Th > 50 ppm; Sr > 1; K/Rb > 250; Rb/Ba > 0.5 and K₂O/Na₂O > 1.

**For syenites (Types III and V):** SiO₂ = 55-65 wt%; Na₂O + K₂O > 10 wt%; F > 0.5 wt%; Nb > 15 ppm; TiO₂ < 0.1 wt%; Ta > 10 ppm; Zr > 300 ppm; Th > 50 ppm; Sr > 1; K/Rb > 250; Rb/Ba > 0.5 and K₂O/Na₂O > 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, Fe₂O₃Total and TiO₂ (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 to 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, calcisilicate rocks, and diorite to tonalite 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
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 (SiO₂ = 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 221/12, 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 (Fe₂O₃Total = 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; Fe₂O₃Total < 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 (SiO₂ = 72.1-78.2 wt%) are fertile based on Rb vs Sr and Rb vs Ba diagrams (Figures 12c and 12f), their iron contents (Fe₂O₃Total = 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 AþPhebian 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 granitoids.
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 (SiO2 = 76.4-76.6 wt% and Rb/Sr = 12-13) contain elevated concentrations of Li (103-22-74; Figure 15b), confirmed by high Zr/Y values (5-190). Although the analytical results for some granites lack sufficient information to define their compositions accurately, we believe these late syenites are not of economic interest due to their low rare metal contents.

The syenites (SiO2 = 59.47-65.69 wt% and K2O = 4.87-6.47 wt%) (Figure 15a) have moderate to elevated amounts of La (9-623 ppm), Zr (94-1,300 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 Vieu; ~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 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 (SiO2 = 76.4-76.6 wt% and Rb/Sr = 12-13) contain elevated concentrations of Li (103-22-74; Figure 15b), confirmed by high Zr/Y values (5-190). Although the analytical results for some granites lack sufficient information to define their compositions accurately, 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);
and 2) granitic masses near the contact between the metasediments of the Nemiscou 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 over lain 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 pegmatitic 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 Kasapawatis. 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 ($A/\text{CNK} = 1.05-1.15$), depleted in MgO (0.49-0.05 \, wt\%; Figure 17). 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 Froto-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]$_{\text{NC}}$ = 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]$_{\text{NC}}$ = 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 coherent intrusion that generated these dykes remains to be found. Also worth mentioning are the values of 207 g/t and 317 g/t Ta$_2$O$_5$ 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 migmatises associated with peraluminous to metaluminous granites; and Type VII - Th, U, ± (Mo, REE) mineralization in skarns (mineralized calcisilicate 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 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 Lemoine 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).
KARPOV, B.S., 1957 - The Quebec Lithium deposit, Barraute.


KARPOV, B.S., 1957 - The Quebec Lithium deposit, Barraute, Abitibi, Québec. Internal report of the Quebec Lithium Mining Company, 26 pages.


MOUKHSIL, A., 2000 - Géologie de la région des lacs Pivert, Anatacau, Kauputauchechun et Wapamisk (SNRC 33C/01, 33C/02, 33C/07 et 33C/08). Ministère des Ressources naturelles, Québec; RG 2000-04, 47 pages.
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).

<table>
<thead>
<tr>
<th>Present report and DV 2003-03</th>
<th>Deposit name</th>
<th>COGITE number</th>
<th>Present report and DV 2003-03</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kegashka</td>
<td>12K03-02</td>
<td>184</td>
<td>Zone de la Riv. Kipawa</td>
<td>31L16-06</td>
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<tr>
<td>2</td>
<td>Natashquan-Sud</td>
<td>12K04-05</td>
<td>185</td>
<td>Zones PB &amp; PS</td>
<td>31L16-2000</td>
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<td>Lac Couillard</td>
<td>12K07-2000</td>
<td>186</td>
<td>Rapides Turner</td>
<td>31L16-04</td>
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<td>188</td>
<td>Vézina</td>
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<td>Baie Quetachou</td>
<td>12L07-008</td>
<td>189</td>
<td>Île du Refuge</td>
<td>31M10-1000</td>
</tr>
<tr>
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<td>12L07-1014</td>
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<td>Claims Legault</td>
<td>31M10-04</td>
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<td>Lac Simard-Nord</td>
<td>31M10-03</td>
</tr>
<tr>
<td>18</td>
<td>Lac Turgeon</td>
<td>12L07-001</td>
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<td>Dallaire</td>
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<tr>
<td>27</td>
<td>Indice du Village Saint-Augustin</td>
<td>12O02-1001</td>
<td>193</td>
<td>Lac Simard</td>
<td>31M10-01</td>
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<tr>
<td>30</td>
<td>Wares</td>
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<td>195</td>
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<td>31</td>
<td>Castor 300</td>
<td>21L07-18</td>
<td>196</td>
<td>Riv. Trenche Est</td>
<td>32A07-08</td>
</tr>
<tr>
<td>32</td>
<td>St-Charles</td>
<td>21L07-16</td>
<td>197</td>
<td>Lac Moore</td>
<td>32B04-02</td>
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<td>33</td>
<td>Du Bloc</td>
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<td>198</td>
<td>Chubb</td>
<td>32C05-48</td>
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<td>48</td>
<td>Mine Niobec (Saint-Honoré)</td>
<td>22D11-07</td>
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<td>Massberyl (Morono)</td>
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<td>Lac Bishop</td>
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<td>Augustus Exploration</td>
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<td>119</td>
<td>Oka Columbium</td>
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<td>211</td>
<td>Martin-McNeely</td>
<td>32C05-18</td>
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<td>St-Lawrence Co.(Bloc D)</td>
<td>31G08-03</td>
<td>212</td>
<td>New Athona-2</td>
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<tr>
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<td>Mine St-Lawrence Colombium</td>
<td>31G09-18</td>
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<td>Zone Bond</td>
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<td>216</td>
<td>La Motte VI-2</td>
<td>32D08-36</td>
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<td>Zone Manny</td>
<td>31G09-15</td>
<td>217</td>
<td>Aldous</td>
<td>32D08-20</td>
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<td>Bouscadillac (Zone A)</td>
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<td>Lac La Motte</td>
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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 migmatises 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, 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).