INTERNATIONAL WORKSHOP GEOLOGY OF RARE METALS

NOVEMBER 9-10, 2010
HARBOUR TOWERS HOTEL
VICTORIA, BC, CANADA

George J. Simandl and David V. Lefebure, Editors

Niobium and Tantalum-bearing Carbonatite, Upper Fir Deposit, British Columbia.

Open File 2010-10 **BC Geological Survey**

International Workshop
Geology of Rare Metals

INTRODUCTION

The International Workshop on the Geology of Rare Metals was held at the Harbour Towers Hotel in Victoria, Canada on November 9-10, 2010. It was organized by the British Columbia Geological Survey in collaboration with the Geological Survey of Canada's Targeted Geoscience Initiative 4 and the Pacific Section of the Geological Association of Canada.

The Workshop focused on various aspects of rare earth elements (lanthanides, Y and Sc) and other rare metals (mainly Nb, Ta, Li, Be, Zr, Hf). The program consisted of 26 oral presentations and 6 poster displays. Extended abstracts are included in this volume for all the technical presentations. They are arranged in order that they were presented.

The Workshop is the first deliverable of the Rare Metals Project that is part of the renewed Targeted Geoscience Initiative. This Project is co-led by the Geological Survey of Canada and a number of Canadian provinces and territories. The Rare Metals Project will be implemented to:

- focus and coordinate research efforts across Canada that are designed to improve the understanding of the tectonic and depositional environments of this suite of deposit types, which in turn will lead to the development of better predictive models and more effective exploration methods and techniques; and
- facilitate greater interaction between interested provincial and territorial geological surveys, industry representatives and academics in order to generate sub-projects and foster greater Canadian expertise in the geoscience of rare metals through the staging of workshops and seminars.

Project activities will be carried out by federal, provincial and territorial geoscientists and academia. The research direction will be influenced by consultation with industry as to their present and future requirements for public geoscience data and knowledge. The Rare Metals Project will employ a number of geoscience methodologies including: geological, geophysical and geochemical mapping; geochronological and isotopic studies; and geometallurgical evaluations.

SPONSORS

The support of the following sponsors for the International Workshop on the Geology of Rare Metals is much appreciated:

- Acme Analytical Laboratories (Vancouver) Ltd.
- Aeroquest Surveys
- Canadian International Minerals Inc.
- Commerce Resources Corp.
- Great Western Minerals Group Ltd.
- Thermo Scientific Niton Handheld XRF Analyzers
- Zimtu Capital Corp.

RECOMMENDED CITATION STYLE

e.g. Simandl, G.J. (2010): Rare Metals and Their Importance – Potential Impact of the TGI-4 Initiative; in International Workshop on the Geology of Rare Metals, Simandl, G.J. and Lefebure, D.V., Editors, Extended Abstracts Volume, November 9-10, 2010 Victoria, Canada British Columbia Geological Survey, Open File 2010-10, pages 1-2.

ACKNOWLEDGMENTS

The support of both the Geological Survey of Canada and the Pacific Section of the Geological Association of Canada was instrumental to deciding to host the Workshop. In particular, Alan Galley of the Geological Survey of Canada was an early advocate and continuous supporter.

Staff of the British Columbia Geological Survey led by George Simandl organized the Workshop. The Survey team consisted of Katharine Benning, Patrick Desjardins, Kirk Hancock, David Lefebure, Ray Lett and Sarah Meredith-Jones.

TABLE OF CONTENTS

Rare Metals and Their Importance - Potential Impact of the Targeted Geoscience Initiative-4 (TGI-4)

by G.J. Simandl[1,2,3]

ABSTRACT

The Geology of Rare Metals Workshop will provide a state of the art update on a variety of mineralization types associated with peralkaline intrusions, carbonatites, peraluminous rocks, pegmatites, granites and lithium containing brines. Other papers will deal with selected exploration methods. This Workshop is associated with the national Rare Metals Program being carried out as part of Phase 4 of the Targeted Geoscience Initiative (TGI-4). Led by Natural Resources Canada, the Rare Metals Program will involve numerous provincial and territorial surveys and universities across the country.

The term “rare metals” is not strictly defined. It refers mainly to uncommon, nonferrous metals used in small quantities, typically <150 000 tonnes/year, or derived from geographically restricted areas. Examples of rare metals are tantalum (Ta), niobium (Nb), zirconium (Zr), hafnium (Hf), lithium (Li), beryllium (Be), gallium (Ga), germanium (Ge), Rare Earth Elements (REEs) and several other minerals. The term “rare earth elements” covers “lanthanides”, yttrium (Y) and scandium (Sc). The term “lanthanides” groups lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). Promethium is the only one of the lanthanides that does not occur in nature.

The external trade balances of many industrialized and developing countries depend on the availability of these metals. High technology industries cannot operate effectively without having a secure supply of rare metals at competitive prices. While other materials can be substituted for several of these metals by, they are either more expensive or do not perform as well. The United States government and a number of other countries consider several of the rare metals essential for national security and critical as “green minerals” for reducing greenhouse gas emissions. Several rare metals are highlighted in the 2010 “Review of Critical Raw Materials for Europe,” spearheaded by the European Commission. Current sources of some rare metals, such as REEs, are geographically and politically constrained. This situation can not last because their use is global and there is an intensive search for REE deposits (Simandl, 2010). Table 1 contains background information regarding selected rare metals of immediate interest.

Because many rare metal-bearing deposit types contain or are associated with other commodities, the final economic impact of new discoveries could be much broader. For example, carbonatites are known to be associated not only with economic concentrations of Nb (± Ta) and REEs but in specific situations also with Fe, Sr, Mo, Cu, U, Th, Ca and Mg carbonates, fluorite, barite, vermiculite, apatite (phosphate) and others (Mariano, 1989a,b; Richardson and Birkett, 1996a,b; Birkett and Simandl, 1999).

The Rare Metals TGI-4 Program will study ore deposits in terms of geological setting, mineralizing processes, applied mineralogy, exploration methods, and metallurgical constraints. The results will address some of the major knowledge gaps related to these deposits and are expected to help the Canadian mining industry tap domestic sources of rare metals. This will contribute directly to supporting the existing and newly developing segments of the high technology industry in North America and global supply.

REFERENCES

Birkett, T.C. and Simandl, G.J. (1999): Carbonatite-associated Deposits; *in* Selected British Columbia Mineral Deposit Profiles, Volume 3, Industrial Minerals and Gemstones, G.J. Simandl, Z.D. Hora and D.V. Lefebure, Editors, British Columbia Ministry of Energy and Mines, pages 73-76.

Mariano, A.N. (1989a): Nature of Economic Mineralization in Carbonatites and Related Rocks. *in* Carbonatites: Genesis and Evolution, K. Bell, Editor, Unwin Hyman, London, pages 149-176.

Mariano, A.N. (1989b): Economic Geology of Rare Earth Minerals. *in* Geochemistry and Mineralogy of Rare Earth Elements, B.R. Lipman and G.A. KcKay, Editors, Reviews in Mineralogy, Mineralogical Society of America, Volume 21, pages 303-337.

Richardson, D.G. and Birkett, T.C. (1996a): Carbonatite-associated Deposits; *in* Geology of Canadian Mineral

---

[1] *British Columbia Geological Survey, Ministry of Forests, Mines and Lands, Victoria, BC*

[2] *Science leader for the national Rare Metal Program, part of Phase 4 of the Targeted Geoscience Initiative (TGI-4) led by Natural Resources Canada, Ottawa, ON*

[3] *Adjunct professor, University of Victoria, Victoria, BC*

Deposit Types, O.R. Eckstrand, W.D. Sinclair and R.I. Thorpe, Editors, Geological Survey of Canada, Geology of Canada, Number 8, pages 541-558.

Richardson, D.G. and Birkett, T.C. (1996b): Residual Carbonatite-associated Deposits; *in* Geology of Canadian Mineral Deposit Types, O.R. Eckstrand, W.D. Sinclair and R.I. Thorpe, Editors, Geological Survey of Canada, Geology of Canada, Number 8, pages 108-119.

Simandl, G.J. (2010): Geological Constraints on Rare Earth Element Resources and their Availability – Canadian Perspective.; *in* Proceedings of the Twenty-First Canadian Conference on Markets for Industrial Minerals, Vancouver, BC, October 19-20, 2010, 12 pages.

USGS (2010): Mineral Commodity Summaries; US Department of the Interior, US Geological Survey, 193 pages.

Table 1. Background information on selected rare metals (Sources: USGS, 2010, Industrial Minerals - September 2010; Industry contacts).

Rare Metal	Production Estimate*	Representative Price	Main Producing Countries	Main Uses
Nb	62 000 tonnes	Ferroniobium (65% Nb) US$39/kg (USGS:2010)	Brazil - 57 000 tonnes, Canada 4300 tonnes of contained Nb.	Steel industry (76%, ferroniobium); Aerospatial/military applications (24% Supper alloys)
Ta	1160 tonnes	Tantalite concentrate, US$ 110/lb (of Ta_2O_5 content) -Sept. 2010; Ta_2O_5 $220/kg and $230/kg -July 2010; Depending on concentrations, Ta credits can be obtained from processing of Nb ores.	Historically Australia and Canada; recently Brazil, Congo, Rwanda	Ta capacitors 60% of total Ta use. Ta capacitors are essential for automotive electronics, pagers, personal computers, and portable telephones etc.
Zr, Hf, zircon, baddeleyite	Zr (metal)1300 tonnes; Zircon (industrial mineral) 1.1 -1.3 million tonnes.	baddeleyite concentrate; Zircon conc: FOB Australia US$830-980/ tonne; Fused ZrO_2 monoclinic, CIF European port: US$: 4400 - 5200/tonne (Industrial Minerals, 2010)	Australia, South Africa, China, Ukraine, Indonesia and Brazil	Zircon: ceramics, foundry, opacifier, and refractory products; baddeleyite: natural zirconia; Zr metal - noncorrosive applications in nuclear industry, oxygen sensors -combustion control, flue gas monitoring, condenser ceramics; cubic zirconia
Be	200- 250 tonnes	beryllium-copper master alloy, US$ 120/ lb of contained Be. (USGS:2010)	2008 production. USA (176 tonnes), China (20 tonnes), Mozambique (1 tonne) of contained Be. Information from Kazakhstan and Russia is not available.	Computer and telecommunications products (> 50%), remainder: aerospace / defence, appliances, automotive electronics, industrial components, medical and industrial x-ray equipment, and oil and gas
REE	124 000 tonnes of REO content	Bastnaesite con.: 70% leached, CIF Europe US$2.25/lb. REOs (FOB China; bulk, 99%) in US$ /kg Ce :22-38; Eu : 575-585; La: 20-23; Nd: 48-49;Pr:48-49	China (95%)	Catalytic converters, permanent magnets, rechargeable batteries for electric and hybrid vehicles. Glass additives, glass-polishing compounds; catalysts in oil refining; armaments, base-metal alloys, lighter flints, pyrophoric alloys, and super alloys; electronic thermometers, fibre optics, lasers, and oxygen sensors; and phosphors for color televisions and instrument monitors, electronic thermometers, fluorescent lighting, pigments, superconductors, x-ray-intensifying screens
Li	18 000 tonnes of Li content	Li carbonate (USA), large contracts $2.3-2.4/lb. Spodumene con.: > 7.25% LiO_2 (FOB West Virginia): US$ 700-770/tonne	Australia and Canada were historically principal producers (pegmatites). Recently Chile, Argentina, Australia, China, Portugal, Zimbabwe are assuming more prominent roles (brines).	Ceramics and glass (31%); batteries (23%); lubricants (10%);; continuous casting, 4%; aluminum production (3%); and other uses (>29%).
Cs	Not available	The main Cs ore mineral is pollucite historically produced at Bernic Lake (Tanco), Canada. The Cs formate is not for sale, it is rented to oil and gas drilling companies	Canada	Cs formate brines, a high-density, low-viscosity oil and gas drilling fluids, as an atomic resonance frequency standard in atomic clocks, in global positioning satellite, Internet, and cell phone transmissions and aircraft guidance systems. Other applications of cesium include biomedical research, infrared detectors, night vision devices, photoelectric cells, and traffic controls.

Tantalum & Niobium, The Sibling Metals

by D.L. Trueman[1]

ABSTRACT

Tantalum and niobium occur in several different mineral species; the most economically important of which are columbo-tantalite, wodginite, loparite, and pyrochlore. They are found in and mined from granitic rocks of subalkaline, alkaline or peralkaline kindred, and carbonatites. As these minerals are also resistates, placer deposits form important sources for them, and some tantalum is won from re-processing of Malaysian and Thai tin slags.

Columbo-tantalite forms an isomorphous series and the tantalum bearing end member, tantalite, commonly occurs with the Sn - Ta mineral wodginite. They occur in the LCT (Li-Cs-Ta) suite of granitic rocks. Columbite, the niobium bearing end member of the isomorphous series and loparite associate with the NYF (Nb-Y-F) alkaline and peralkaline suites of rocks. Pyrochlore, the principal ore mineral of niobium, is commonly associated with carbonatites.

The LCT suite is divisible twofold, and commercial deposits of tantalum and niobium are found in granitic pegmatites, and apogranites. Apogranites are peraluminous, two feldspar granites, chemically similar to highly fractionated S-type or ilmenite series granites, and are commonly Li, Sn, F and topaz bearing.

Historically, granitic pegmatites have been the principal producers of Ta, and less so for Nb. These *giant* pegmatites, of which the Tanco pegmatite in Manitoba is probably the best studied, are dimensionally large (1000s of metres), are, or were horizontally disposed during crystallization, display well developed but asymmetric internal zoning, and exhibit extremes in fractionation. Late stage albitization is common, associating with lepidolite and can be significant. At Tanco the albitization hosted approximately 40% of Tanco's tantalum ores.

Apogranite tantalum deposits are a relatively new source of Ta and are typified by the Yichun granite in China or the Abu Dabab in Egypt. They often have associated Sn mineralization and other valuable commodities. A typical apogranite displays extreme fractionation in which the tantaloan species are concentrated in solution with fluorine ligands while lithium, boron and H_2O depress their freezing temperatures. Accumulation of hydrothermal phases in an apogranite is upward and the Ta and Sn deposits commonly occupy cupolas in the domal facies or related, but rare, breccia pipes, veins and stockworks. Albite forms increasingly in the domal facies and lithium greisening is common.

Two examples of niobium deposits in the NYF suite are the Karnasurt loparite mine in the Lovozero massif in Russia's Kola Peninsula, and the Thor Lake deposits in Canada's NWT. The Karnasurt mine produces and concentrates the niobium-rare earth bearing mineral loparite which is essentially void of tantalum. The mineral deposits formed when loparite appeared as a cumulus phase. The deposits at Thor L. are of two types. One is marked by columbite void of tantalum and the other is marked by the Ta, Nb bearing species fergusonite formed during the hydrothermal breakdown of the cumulus mineral eudialyte.

Carbonatites are a significant source of Nb and approximately 85% of the world's niobium is mined from the Araxa carbonatite deposit in Brazil. The important ore mineral in this production is pyrochlore which is the Nb end member of an isomorphous series with Ta bearing microlite. Pyrochlore in carbonatites usually contain a few percent Ta, the recovery of which is problematic.

Processing of Ta and Nb minerals is largely done through gravity or electrostatic methods, but at about 35 micron grain size electrostatic charges build, overcoming the high specific gravities of the ore minerals and causes them to slime. At about 35 micron flotation becomes the effective route and English China Clays developed a flotation process capturing down to 1 -2 micron sizes.

Ta concentrates are usually sold on a contained Ta_2O_5 basis and in general, the lowest *sellite* grades are about 10-12%. These minimum grades reflect tin slag Ta_2O_5 contents and the minimum is dictated by the price of irrecoverable hydrofluoric acid used to dissolve the concentrates. It is this cost that precludes Ta recovery from pyrochlore and tin slags as the value of the HF may exceed that of the Ta recovered.

Nb in pyrochlore is usually recovered through gravity processes and the preponderance finished through pyrometallurgy to form NbFe master alloys.

The Russian loparite mine has a unique problem in that there are only two chlorination roast facilities that can treat the concentrates.

---

[1] *Geological Consultant, Richmond, BC*

Mineralogical-Genetic Classifications of Carbonatites: All Carbonatites are not Equivalent!

by R.H. Mitchell[1]

ABSTRACT

Carbonatites as defined by the IUGS system of classification are igneous rocks composed of more than 50 modal per cent primary (*i.e.* magmatic) carbonate *sensu lato*. Varieties of carbonatite are named on the basis of the dominant carbonate mineral, *e.g.* calcite carbonatite, dolomite carbonatite *etc.* The IUGS method of classification is *non-genetic* and typically is suitable for common rock types. However, this approach has been shown to be totally inadequate when applied to more exotic rock types such as kimberlites or lamproites. Currently, mineralogical-genetic classifications are employed for such rock types and classifications are based upon the observation that a spectrum of genetically-related rocks of diverse mode can be derived from a given magma type, *e.g.* the kimberlite or lamproite clans, and be recognized on the basis of the presence of typomorphic or characteristic assemblages of minerals, which include *major, minor AND accessory minerals*. Note that in this type of classification it is ***not*** necessary to know the actual origin of a particular magma type. Indeed genetic hypotheses advanced for a particular magma type will change depending upon the current petrological paradigm and/or how the empirical petrological and mineralogical data are interpreted. *One important aspect of mineralogical-genetic classifications is that they recognize that genetically-unrelated, but modally similar rocks can be derived from different parental magmas.* The IUGS approach to carbonatite classification leads initially to the grouping into one cohort carbonate-rich rocks of diverse origins, and ultimately to the formulation of misleading and incorrect petrogenetic hypotheses, or misdirected exploration efforts for strategic materials.

In mineralogical-genetic classifications, carbonatites *sensu lato* are defined as any rock containing greater than an *arbitrary* 30 vol.% primary igneous carbonate. The stress in this definition is on the presence of significant and variable amounts of primary magmatic carbonate rather than the precise modal content. This less restrictive approach to classification recognizes modal variations arising from the ubiquitous differentiation of carbonatite-forming magmas, and the formation of spatially- and genetically-related silicate-, apatite- and oxide-bearing-bearing rocks containing less than 50 vol.% carbonate. Wide modal variations are the rule rather than the exception in most plutonic carbonatite complexes, emphasizing the need for a mineralogical-genetic terminology. *Thus, a given "carbonatite" can be considered as a "package" of rocks that are of diverse modal character but common genesis.* For mapping or descriptive purposes, individual domains within the "package" can be given specific modal names, provided the size of these domains is specified.

Carbonatites (*sensu lato*) when considered in terms of mineralogical-genetic classifications can be divided into a group of *bona fide* carbonatites formed from diverse asthenospheric mantle-derived magmas, *i.e.* carbonatites associated with the melilitite, nephelinite and kimberlite clans, with the latter best being termed calcite kimberlites. Carbonatites associated with the melilitite and nephelinite clans have a multiplicity of origins and can be formed by partial melting, fractional crystallization and/or liquid immiscibility. A second group of carbonate-rich rocks associated with potassic and sodic peralkaline magmas derived from metasomatized lithospheric mantle, together with REE-carbonate-rich rocks of indeterminate genesis, are best termed carbohydrothermal residua rather than carbonatite (*sensu stricto*). There can be mineralogical convergence between these rocks and low pressure REE-rich derivatives of *bona fide* carbonatites derived from magmas of asthenospheric origin.

---

[1] *Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1*

Geological Constraints on Rare Earth Element Resources and Their Availability: A Non-Partisan View

by G.J. Simandl[1,2,3]

ABSTRACT

The term "rare earth elements" (REE) includes Y, Sc and the lanthanides (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu). Historically, REE were believed to occur only within uncommon mineral species and were very difficult to isolate, hence the name "rare". In fact, REE are nearly as abundant in the Earth's upper crust as the common industrial metals, such as Cu, Pb, Mo, and Zn. Even lutetium, the least abundant of the REE, is approximately 200 times as abundant as Au. The REE are traded mainly as rare earth oxides (REO), pure metals, mischmetal or in the form of chemicals. Anomalous concentrations of REE have been reported from a variety of mineral deposit-types including carbonatites and related deposits, peralkaline igneous complexes, peraluminous igneous complexes, pegmatites, metasomatic veins, Iron Oxide Cu-Au (IOCG) or "Olympic Dam" style deposits and weathered crusts overlying granitic rocks.

Currently, Bayan Obo (a carbonatite-associated deposit mined for Fe, Nb and REE), together with two carbonatite-hosted deposits in China, supply most of world's light rare earth elements (LREE), whereas ion adsorption clay deposits (weathered crusts overlying granites) supply a large proportion of the global heavy rare earth elements (HREE). Rare earth element-bearing minerals also may be obtained from the mining of placer and metasomatic vein deposits, and from the processing of uranium ores and phosphate fertilizers.

Rare earth element production in China started in the early 1980s and since then China has become the dominant producer of REE/REO supplier (> 95% of the world REE in 2009). During this same period, all of the REE mining and REE by-product recovery operations in the western world closed, including the venerable Mountain Pass (USA) deposit that dominated the global REE market from the early 1960s to the early 1980s. The rapid expansion of the Chinese economy during the past decade also has resulted in an increased internal demand for REE. To secure supply and provide a competitive edge for its domestic high technology industries, the Chinese government introduced export taxes and export quotas on REE. Not surprisingly, this resulted in rapid global price increases and created uncertainty of REE supply for industrial users outside of China. The United States government considers REE essential for the healthy development of its high technology industries, for its efforts to reduce greenhouse gas emissions, and for its national security. Similarly, REE are now highlighted within the 2010 "Review of Critical Raw Materials for Europe", spearheaded by the European Commission. In general, HREE are more expensive than LREE, although the market is also now experiencing short term price increases of LREE. This spectacular rise in LREE prices is due to a combination of factors including (1) increasing demand, and (2) attempts to stockpile REO by the users to avoid uncertainty and shrinking of the Chinese export quotas.

Over 100 grassroots exploration projects for rare metals are active across Canada. A number of these projects have been tested by diamond drilling. Some of deposits are considered as potential sources of LREE and HREE. Nb, Zr, phosphate, fluorite and/or Fe are potential co-products in some of the deposits. The stricter reporting guidelines for reserve/resource estimations in Canada compared with many other jurisdictions has resulted in fewer Canadian projects in the most recent worldwide REE market/REE resource assessments.

As is the case with most industrial minerals and rare metals, the size of the market, the growth-rate in the use of specific REE, and the prices will strongly influence which exploration stage projects will advance to the development stage. The discovery and development of a single giant and high-grade REE deposit, such as Bayan Obo in Inner Mongolia, would invalidate any of the recent medium to long-term supply/demand projections. Under normal conditions it takes approximately 10 years to move from grassroots exploration to mining. Consequently, short-term predictions would not be affected.

The REE market is global in nature and any new producer will have to be economically competitive on the world-scale. The most attractive primary REE development targets are located in politically stable jurisdictions such as Canada, are close to infrastructure,

---

[1] *British Columbia Geological Survey (Industrial Minerals and Specialty Metals), Ministry of Forests, Mines and Lands, Victoria, BC*

[2] *Adjunct professor, University of Victoria, Victoria, BC*

[3] *National Leader for the Rare Metals (High Technology Metals) Component of the Targeted Geoscience Initiative (TGI-4) on behalf of Natural Resources Canada*

and have acceptable grade and tonnage characteristics. The latter is important to allow the producer to survive periodic fluctuations in REE prices. Permissive metallurgy, simple coarse-grained homogeneous ores preferably consisting of REE carbonates (such as bastnaesite ± other REE carbonates and fluorocarbonates without Th), REE-bearing phosphates (such as monazite with low Th content), or ion adsorption clays (no breakdown of crystal structure required) is an important component of production cost. Complex REE-bearing silicates (*e.g.* allanite) are more difficult to crack using conventional, low-cost metallurgical methods. Some of the deposits containing eudialyte group minerals hosted by peralkaline igneous complexes , have been considered potential sources of Zr and HREE since the early 1980s. They still await metallurgical breakthroughs. Favourable market conditions, grade, and metallurgy of individual deposits could allow for REE to be derived as a byproduct of phosphate fertilizer production or uranium processing. It is also theoretically possible that some fluorspar deposits, Ti-Zr-bearing placers, and Olympic Dam-type (IOCG) deposits could enter into the supply-demand equation.

Rare-Metal Mineralization in Carbonatites: Challenges for Exploration and Mining

by A.R. Chakhmouradian[1]

ABSTRACT

Carbonatites, their associated rocks (*e.g.* phoscorites and fenites) and weathering products are an economically important source of Nb, rare-earth elements (REE), apatite, fluorite and Zr (Tolstov and Tyan, 1999; Pressacco, 2001; Boyarko and Khat'kov, 2004; Biondi, 2005; Castor, 2008; Hou *et al.*, 2009). Other potentially minable ore types associated with carbonatites include Ta-rich pyrochlore, thorite-rich veins (Th), crandallite-rich laterites (Sc), celestine (Sr) and barite (Anderson, 1961; Ontoev, 1988; Tolstov and Tyan, 1999; Reed, 2008).

Exploration for carbonatite-hosted mineral deposits routinely has to deal with challenges that require the involvement of experienced carbonatite petrologists. Presently, the exploration sector worldwide experiences shortage of this type of expertise, which provides an excellent foundation for mutually beneficial collaboration between explorationists and academics. This presentation focuses on some of the key challenges facing rare-metal exploration and mining.

(1) What criteria can be used to recognize carbonatites? Carbonatites cannot be identified on the basis of field or petrographic observations alone. Several other rock types, including marbles, contact metasomatic rocks and hydrothermalites, can exhibit the same structural and textural characteristics as carbonatites. Neither high modal contents of apatite and magnetite, nor the presence of exotic accessory minerals in the rock is a reliable identification criterion. Numerous examples of uneconomic rare-metal mineralization in hydrothermal and metasedimentary rocks (sensu lato) can be found in the literature (*e.g.* Gieré and Williams, 1992; Houzar and Novák, 2002). The best results are achieved with a combined trace-element and stable-isotope analysis of the rock-forming carbonate phase *(i.e.* calcite, dolomite or ankerite), which allows to discriminate easily between samples of igneous and non-igneous provenance (Figure 1). Although radiogenic isotope data can also be used for this purpose, their applicability to mineral exploration is hampered by the high cost of analysis.

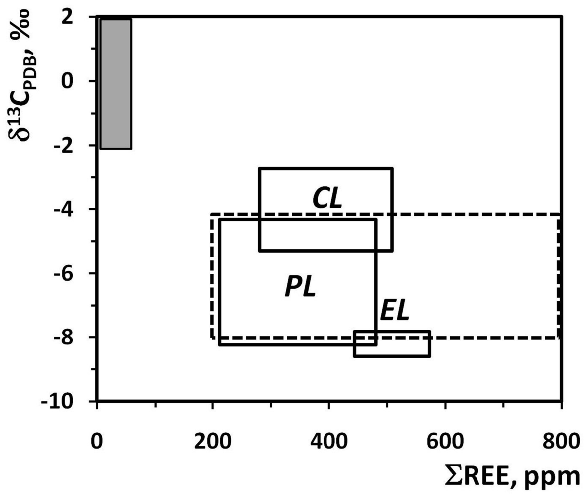

Figure 1. Geochemical discrimination diagram showing the range of $\delta^{13}C$ and REE values in carbonatites from Cinder Lake (CL), Paint Lake (PL) and Eden Lake (EL), all in Manitoba, in comparison with the typical compositional fields of calcite carbonatites (dashed) and metasedimentary rocks (shaded).

(2) What do carbonatite textures really show? It has been conventionally assumed that carbonatite textures result from igneous processes in the magma conduit (*e.g.* kinetic or gravitational separation), or post-emplacement grain coarsening. Recent studies of Precambrian carbonatites and younger occurrences in tectonically active settings (*e.g.* Chakhmouradian *et al.*, 2008; Chakhmouradian *et al.*, 2009) indicate that in many cases, the texture is a complex product of plastic flow, grain deformation, cataclasis, syn-deformational mineral reactions and post-deformational recovery (Figure 2). These processes have profound implications for both exploration and resource evaluation, which necessitates further studies of density-driven mineral separation in deformed carbonatites.

(3) How uniform is the distribution of a resource in carbonatite intrusions? The extremely low viscosity of carbonate melts (Treiman and Schedl, 1983; Dobson *et al.*, 1996) is conducive to episodic, small-volume tapping of the magma source, easy ascent through the lithosphere, and early segregation of heavy liquidus phases (principally magnetite, apatite, baddeleyite and pyrochlore). A significant proportion of REE is typically fractionated with apatite that can contain up to 12 wt.% REO and, in some cases, perovskite and early monazite. Subsequent crystallization of rock-forming carbonates removes a further 10-30% of the REE budget, contributing to enrichment of these elements in the most

---

[1] *Department of Geological Sciences, University of Manitoba, Winnipeg, MB*

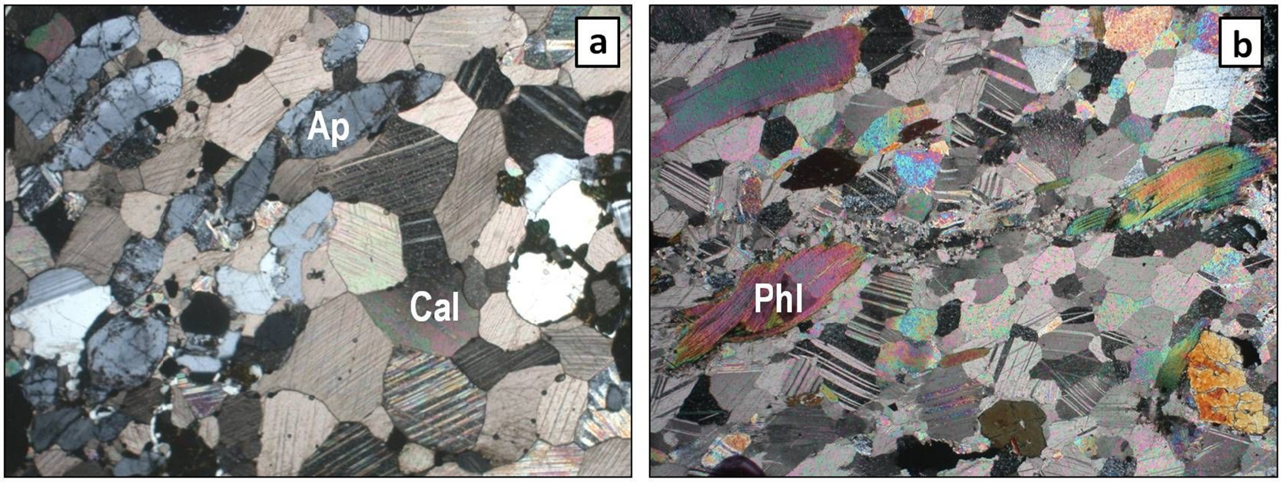

Figure 2. Alignment of apatite (Ap) and phlogopite (Phl) crystals in calcite carbonatites (Cal) from Eden Lake (a) and Paint Lake (b) caused by post-emplacement deformation rather than magma flow. Both images were taken in cross-polarized light; width of the field of view 5.5 mm.

evolved melt and fluid fractions and ultimately, development of subeconomic to economic REE mineralization in late-stage ankerite carbonatites and carbonate (± quartz ± fluorite ± barite) veins (*e.g.* Tolstov *et al.*, 1995; Wall and Mariano, 1996). The cumulative effect of these processes will be a structurally complex multiphase carbonatite body with a highly non-uniform distribution of rare metals.

(4) Does the grade improve or deteriorate with weathering? It is commonly assumed that decomposition of carbonates and ferromagnesian silicates followed by erosional concentration and low-temperature precipitation leads to enrichment of the weathering profile in Nb, REE and Sc (Figure 2). Examples from around the world (*e.g.* Tolstov and Tan, 1999; Freyssinet *et al.*, 2005), however, attest to the complexity of processes that control the remobilization and redeposition of rare metals in the lateritic environment. The distribution of rare-metal mineralization in the profile is controlled by modal heterogeneity of the precursor carbonatite, variations in the activity of $(PO_4)^{3-}$, CO_2, O_2 and silica in and below the vadose zone, and local hydrodynamic regime.

(5) Is rare-metal mineralization restricted to igneous units? In short, the answer is “No”. Rare earth elements, Nb and Zr are highly mobile in some types of fluids, especially where a variety of complexing ligands is available (*e.g.* Tromans, 2006; Korzhinskaya and Zaraisky, 2009), and can be deposited away from their source (typically, in proximal and distal fenites developed in the wallrock). Examples include pyrochlore-bearing microclinites of the Bol’shetagninskoye deposit (on average, 1 wt.% Nb_2O_5: Prokazina, 2009) and baddeleyite-zircon-bearing silicified dolostones of the Algama deposit in Far East (on average, 8.3 wt.% Zr, 0.22 wt.% Hf and 0.26 wt.% W: Bagdasarov, 1993). Enrichment in rare metals has also been noted in the vicinity of wall-rock xenoliths incorporated in carbonatite (*e.g.* at Aley in British Columbia and Afrikanda in Russia), but is commonly accompanied by an increase in the content of silicate minerals detrimental to the ore grade and generally not amenable to processing. A careful analysis of the carbonatite – wallrock structural relations and of the nature of chemical processes in the contact zone is required to assess the extent and economic value of rare-metal mineralization in the metasomatic envelope.

REFERENCES

Anderson, A.L. (1961): Thorium mineralization in the Lemhi Pass area, Lemhi County, Idaho; *Economic Geology*, Volume 56, pages 177–197.

Bagdasarov, Yu.A. (1993): Geochemical features of Upper Vendian Zr-bearing dolomites, a new type of Zr ore show; *Geochemistry International*, Volume 30 (7), pages 88–98.

Biondi, J.C. (2005): Brazilian mineral deposits associated with alkaline and alkaline-carbonatite complexes; *in*Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform (Comin-Chiaramonti, P. and Gomes, C.P., Editors), *EDUSP*, São Paulo, pages 707–750.

Boyarko, G.Yu. and Khat’kov, V.Yu. (2004): Mining of Nb in Russia; *Izvestiya Tomskogo Polytechnicheskogo Universiteta*, Volume 307, pages 149-153 (in Russian).

Castor, S.B. (2008): The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California; *Canadian Mineralogist*, Volume 46, pages 779–806.

Chakhmouradian, A.R., Couëslan, C., Reguir, E.P. (2009): Evidence for carbonatite magmatism at Paint Lake, Manitoba (parts of NTS 63O8, 63P5, 12); *Report of Activities, Manitoba Innovation, Energy and Mines*, Manitoba Geological Survey, pages 118–126.

Chakhmouradian, A.R., Mumin, A.H., Demény, A. and Elliott, B. (2008): Postorogenic carbonatites at Eden Lake, Trans-Hudson Orogen (northern Manitoba, Canada): Geological setting, mineralogy and geochemistry; *Lithos*, Volume 103, pages 503–526.

Dobson, D.P., Jones, A.P., Rabe, R., Sekine, T., Kurita, K., Taniguchi, T., Kondo, T., Kato, T., Shimomura, O. and Urakawa, S. (1996): In-situ measurements of viscosity and density of carbonate melts at high pressure; *Earth and Planetary Science Letters*, Volume 143, pages 207–215.

Freyssinet, P., Butt, C.R.M. and Morris, R.C. (2005): Ore-forming processes related to lateritic weathering; *Economic Geology*, Volume 100, pages 681–722.

Gieré, R. and Williams, C.T. (1992): REE-bearing minerals in a Ti-rich vein from the Adamello contact aureole (Italy); *Contributions to Mineralogy and Petrology*, Volume 112, pages 83-100.

Hou, Z., Tian, S., Xie, Y., Yang, Z., Yuan, Z., Yin, S., Yi, L., Fei, H., Zou, T., Bai, G. and Li, X. (2009): The Himalayan Mianning-Dechang REE belt associated with carbonatite-alkaline complexes, eastern Indo-Asian collision zone, SW China; *Ore Geology Review*s, Volume 36, pages 65-89.

Houzar, S. and Novák, M. (2002): Marbles with carbonatite-like geochemical signature from variegated units of the Bohemian Massif, Czech Republic, and their geological significance; *Journal of the Czech Geological Society*, Volume 47 (3-4), pages 103-110.

Korzhinskaya, V.S. and Zaraisky, G.P. (2009): Experimental study of concentration dependence of pyrochlore and columbite solubility in NaOH solutions at T=550^{o}C and P=1000 bar. *Vestnik Otdeleniya Nauk o Zemle RAN*, Volume 27 (1), pages 1–3.

Ontoyev, D.O. (1988): Complex rare-earth deposits as a new source of barium, strontium and fluorine; *International Geology Review*, Volume 30, pages 444–452.

Pressacco, R. (2001): Geology of the Cargill Township residual carbonatite-associated phosphate deposit, Kapuskasing, Ontario; *Exploration and Mining Geology*, Volume 10, pages 77–84.

Prokazina, A.A. (2009): Characteristics of ore-bearing rocks from the Bol'shetagninskoye deposit; *in* New Ideas i Earth Sciences, *Proceedings of the IX International Conference*, Moscow, page 223 (in Russian).

Reed, R. (2008): Thorium and rare earth reserves and resources of Thorium Energy, Inc., Lemhi Pass, Idaho and Montana; *Unpublished report to Thorium Energy, Inc.*, available online at www.thoriumenergy.com.

Tolstov, A.V., Entin, A.R., Tyan, O.A. and Orlov, A.N. (1995): Industrial Mineral Deposits in Carbonatite Complexes of Yakutia; *Russian Academy of Sciences, Siberian Branch*, Yakutsk (in Russian), 168 pages (in Russian).

Tolstov, A.V. and Tyan, O.A. (1999): Geology and ore potential of the Tomtor massif; *Russian Academy of Sciences, Siberian Branch*, Yakutsk, 164 pages (in Russian).

Treiman, A.H. and Schedl, A. (1983): Properties of carbonatite magma and processes in carbonatite magma chambers; *Journal of Geology*, Volume 91, pages 437–447.

Tromans, D. (2006): Solubility of crystalline and metamict zircon: A thermodynamic analysis; *Journal of Nuclear Materials*, Volume 357, pages 221-233.

Wall, F. And Mariano, A.N. (1996): Rare earth minerals in carbonatites: a discussion centred on the Kangankunde Carbonatite, Malawi; *in* Rare Earth Minerals: Chemistry, Origin and Ore Deposits (Jones, A.P., Wall, F. And Williams, C.T., Editors), *Chapman & Hall*, London, pages 193-225.

Niobium Mineralization in Carbonatites: Parageneses and Origins

by R.H. Mitchell[1]

ABSTRACT

Economic concentrations of niobium are typically associated with carbonatites. In such deposits (Fen; Oka; Fir-Verity; St. Honoré; Prairie Lake; Newania; Qaqarssuk *etc.*) primary Nb mineralization is represented by a wide variety of oxide (pyrochlore group minerals; perovskite group minerals; ferrocolumbite; niobian rutile *etc.*) and silicate (wöhlerite-niocalite-marianoite; niobian titanite) minerals. In some instances (Araxa; Lueshe; Bolshetaginskoye) significant concentrations of secondary Nb-bearing pyrochlore group minerals (kalipyrochlore; bariopyrochlore *etc.*) form by the sub-aerial weathering of primary deposits. Typically, carbonatites exhibit wide variations in macroscopic modal mineralogy commonly expressed as decimetre/centimetre-scale modal layering in which concentrations of oxides and silicates grade into carbonate-dominated layers. Because of these extreme modal variations coupled with significant mineralogical diversity it is extremely difficult to establish an ore-grade for a given Nb-bearing carbonatite. Petrological studies of carbonatites show that each Nb-deposit is unique with respect to the assemblage of Nb-bearing minerals present. For example, Nb mineralization occurring at Oka, St. Honoré, and Prairie Lake differs with respect to the proportions and varieties of minerals present within, and between, individual carbonatites. Thus, the Oka (Bond Zone) calcite carbonatites contain pyrochlore, perovskite and niocalite, whereas the St. Honoré dolomite carbonatites lack perovskite and niobium silicates and, in addition to pyrochlore, contains abundant ferrocolumbite and magnetite together with minor Nb-rutile. Typically, pyrochlore is an early crystallizing phase that coexists with apatite and/or magnetite and more rarely phlogopite-tetraferriphlogopite. Experimental studies of pyrochlore formation indicate that pyrochlore is an initial liquidus phase in F-bearing haplocarbonatite melts, and that Ta-bearing types such as niobian microlite and tantalian pyrochlore form before Nb-rich varieties. In the absence of F, lueshite ($NaNbO_3$) or other perovskite-structured phases ($Ca_2Nb_2O_7$) are the primary liquidus phases. The low viscosity of carbonatite melts promotes segregation and accumulation of pyrochlore. Thus, high grade Nb deposits (up to c.60 wt.% Nb_2O_5), relative to the typical grade of 1000-7000 g/t Nb_2O_5 (0.1 - 0.7 wt.% Nb_2O_5) of many carbonatite-hosted Nb-occurrences can conceivably be produced where pyrochlores (together with apatite and other dense oxides) can form sequences of cumulates. Typically, such cumulates have apparently been disrupted and remobilised by subsequent batches of magma. Early formed pyrochlores (or perovskites) can act as nuclei for several cycles of additional crystallization in the hybrid magmas. Consequently, pyrochlores in carbonatites commonly exhibit discrete cores and mantles of widely differing composition with, or without, discontinuous epitaxial compositional zoning. Euhedral zonation-free pyrochlores can co-exist with complexly mantled pyrochlores and resorbed pyrochlores in the same rock and are clearly non-equilibrium assemblages. It is considered that the assemblage of Nb-bearing minerals observed in any given carbonatite results principally from magma differentiation, rheological factors and magma mixing. In some instances late stage primary pyrochlores can crystallise from the hybrid melts and are mixed with the earlier-formed pyrochlores. The relationship of Nb-silicates to Nb-oxides remains enigmatic but it seems probable that many (but not all) Nb-silicates form prior to Na-Ca pyrochlore in the relatively silica-rich fractions of carbonatite-forming magma and are incorporated along with later-formed pyrochlores in the hybrid melts. However, many Nb-silicates show no petrographic evidence for resorption in carbonatite melts. U-and Th-bearing pyrochlores are common in some carbonatites and on textural evidence appear to occur as both early- or late-forming varieties.

---

[1] *Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1*

An Overview of Geology, Mineralogy and Genesis of the Giant REE-Fe-Nb Deposit Bayan Obo, Inner Mongolia, China

by E. Reguir[1], A. Chakhmouradian[1], C. Xu[2] and J. Kynicky[3]

INTRODUCTION

Bayan Obo or Baiyunebo is the world's largest deposit of rare-earth elements (REE), representing, according to some sources, as much as 75% of the global measured REE resources, and is the largest Nb deposit in China. In addition to REE and Nb, it contains significant reserves of Fe (ca. 1.5 Gt of proven reserves at an average grade of 35 wt.% Fe) and Sc, both of which are currently extracted from the Bayan Obo ores (Smith and Chengyu, 2000). According to the published estimates (Drew *et al.*, 1990; Yuan *et al.*, 1992), the deposit has reserves of at least 48 Mt of REE (average grade 6 wt.% REE_2O_3 or REO) and 1.0 Mt of Nb (average grade 0.19 wt.% Nb_2O_5), although some sources cite up to 100 Mt REE and 2.2 Mt of Nb. The Bayan Obo deposit was discovered in 1927 by the Chinese geologist Ding Daoheng and went into production in the 1950s, initially as an iron mine. Today, the mine contributes 95-97% of the global REE production (ca. 120 000 tonnes annually).

GEOLOGICAL SETTING

The deposit is located in Inner Mongolia, northern China, approximately 80 km south of the border with Mongolia, and is situated in the transitional zone between the margin of the North China block (Sino-Korean craton) and the Late-Paleozoic Mongolian fold belt (Smith and Chengyu, 2000). It consists of two large orebodies (Main and Eastern) and a group of smaller bodies to the west (Western group). The orebodies are confined to the Proterozoic sediments of Lower Bayan Obo group subdivided into nine lithological units (H1-H9), represented predominantly by sandstones and slates (H1-H7). The lens-like orebodies are hosted by dolomite marble (H8), and to a lesser extent, by slates and biotite schists (H9) conformably overlying the marble (Xu *et al.*, 2008). The Bayan Obo group forms a broad syncline separated from the less metamorphosed sedimentary sequence to the north by the Kuanggou fault. The sediments of the Bayan Obo group were probably deposited on the margin of the North China block during a Mesoproterozoic rifting episode (1350-1650 Ma) (Ren *et al.*, 1994). On and around the mine property, the Bayan Obo group and underlying basement rocks are crosscut by numerous carbonatite dikes, which do not appear to be associated with any voluminous alkaline magmatism. To the south and north of the orebodies, the Bayan Obo group is intruded by Carboniferous (?) gabbros, which are in turn intruded by Permian granites (Smith and Chengyu, 2000).

HOST ROCKS

The dolomite marble hosting the orebodies occurs as a concordant stratiform body with distinct lamination and extensive fenite-type alteration along its margins. It extends latitudinally for about 18 km reaching up to 540 m in thickness and 2-3 km in width (Smith *et al.*, 1999; Yang *et al.*, 2009). So far there is no convincing evidence of carbonatite intrusion into the H8 marble. The origin of this rock unit is still a matter of debate, and has been interpreted as sedimentary, carbonatitic or volcano-sedimentary on the basis of textural, paleontological, isotopic and trace-element evidence (Yuan *et al.*, 1992; Chao *et al.*, 1992; Le Bas *et al.*, 1997). Involvement of magmatic fluids interacting with the dolomite protolith and leading to recrystallization of the carbonate matrix has also been suggested (Le Bas *et al.*, 1997; Meng and Drew, 1992). Some compositional and textural features of the H8 marble have also been explained by intrusion of carbonatites into metasedimentary dolomite (Campbell, 1999). The Bayan Obo deposit is extremely complex paragenetically, with at least eleven stages of mineralization and more than 190 mineral species recognized (Chao *et al.*, 1992). On the basis of $^{40}Ar/^{39}Ar$ geochronology of alkali amphiboles, three episodes of metamorphism and metasomatism have been identified: (i) Proterozoic, approaching the age of the H8 marble; (ii) Caledonian, possibly correlating with the main ore-forming event; and (iii) Hercynian, coinciding with the emplacement of granitoids to the south of the orebodies (Chao *et al.*, 1997).

---

[1] *University of Manitoba, Winnipeg, MN, Canada*

[2] *Peking University, Beijing, China*

[3] *Mendel University, Brno, Czech Republic*

ECONOMICALLY IMPORTANT MINERALIZATION AND ORE TYPES

REE mineralization

There are three major types of REE ore: disseminated (ranging in grade from 3 to 6 wt.% REO), banded (6-12 wt.% REO) and massive (< 3 wt.% REO) (Chao, 1992). The major ore minerals also exhibit significant variations in REE distribution (Zhang, 1990). The earliest ore assemblage to crystallize is developed along fractures and grain boundaries in relatively unaltered marble, and includes disseminated monazite-(Ce) (555-470 Ma; Wang *et al.*, 1994), Fe-rich dolomite or ankerite, with minor magnetite and bastnäsite. This mineralization is overprinted by banded ores (430-420 Ma; Wang *et al.*, 1994) comprising monazite-, bastnäsite- and apatite-rich bands. The formation of banded ores is associated with several episodes of Fe mineralization (magnetite ± hematite). Subsequently, the H8 dolomite underwent alkali metasomatism producing aegirine(-augite), which was followed by fluoritization and another episode of REE- and Fe-mineralization at ca. 310-220 Ma; Wang *et al.*, 1994]. The final stages involved deposition of Ca-REE and Ba-REE fluorocarbonates in veins cross-cutting the banded ores. These veins are composed largely of aegirine-augite, calcite, fluorite, apatite, alkali amphibole and barite.

Nb mineralization

Niobium mineralization is mainly restricted to the western orebodies. Here, Nb-rich rutile occurs in association with granular hematite, and ferrocolumbite is found in association with magnetite in disseminated ores (Zhang, 1990). The Main and Eastern orebodies are cut by veins containing (niobo-)aeschynite and pyrochlore associated with alkali amphiboles. Pyrochlore has also been reported from skarns related to the intrusion of Permian granites. In addition, a number of other Nb minerals have been identified at Bayan Obo, including fergusonite, fersmite and baotite.

Sc mineralization

Scandim-bearing minerals at Bayan Obo have recently been recognized as important by-products of Fe-REE-Nb mining. Various ore types contain 40-169 ppm Sc, and the REE-ore tailings are reported to contain 250 ppm Sc (Shimazaki, 2008). The highest levels of Sc are found in chevkinite-perrierite group minerals (2.8-3.6 wt.% Sc_2O_3), followed by ferrocolumbite (0.2-1.0 wt.% Sc_2O_3) and rutile (< 1540 ppm Sc_2O_3). Other ore constituents (magnetite, hematite, bastnäsite, etc.) contain 100-500 ppm Sc_2O_3 (Shimazaki, 2008), whereas the silicate minerals magbasite and aegirine may contain as much as 2.1 and 3.5 wt.% Sc_2O_3, respectively, but have no commercial value.

Fe-oxide mineralization

The most important Fe minerals at Bayan Obo are magnetite and hematite. Early euhedral magnetite in the host marble was replaced by hematite ("martitized"), which is scattered throughout the disseminated ore (Yang, 2009). This was followed by the deposition of granular hematite in disseminated ores, magnetite in banded ores and, subsequently, crystallization of massive magnetite. The latest generation of hematite is related to late-stage alteration of the ores (Yang, 2009).

GENESIS OF THE DEPOSIT

The genesis of the Bayan Obo deposit remains controversial. The models proposed thus far include syngenetic sedimentary deposition, metasomatism associated with granitic magmatism, deposition from exhalative hydrothermal fluids, and multisource metasomatism of the metasediments (Smith and Chenhyu, 2000; Yuan *et al.*, 1992; Chao *et al.*, 1992; Wang *et al.*, 1994). It has been suggested that the fluids responsible for the transport and deposition of ore metals could have been related to subduction (Chao *et al.*, 1992; Wang *et al.*, 1994), emplacement of anorogenic granites (Chao *et al.*, 1997), carbonatite or alkaline magmatism (Drew *et al.*, 1990). The arguments for the involvement of carbonatites in the formation of the deposit include enrichment of the H8 marble in REE, Sr and Mn, fenite-type alteration along its margins, evidence of carbonatite magmatism elsewhere in the Bayan Obo series, isotopic and trace-element similarities between the marble and carbonatites, and the composition of fluid inclusions in the ore-forming minerals (Drew *et al.*, 1990; Yang *et al.*, 2009). Several studies agree, at least in general, that the most probable petrogenetic scenario involved multistage metasomatism of metasedimentary marbles by Cl- and F-rich orthomagmatic fluids (possibly of mantle or carbonatitic provenance), followed by tectonic deformation of the orebodies during the Caledonian continent-continent collision and their subsequent reworking by hydrothermal fluids and eventually, low-temperature meteoric waters (Smith and Chengyu 2000; Chao *et al.*, 1997).

REFERENCES

Campbell, L.S. (1999): Discussion on Le Bas *et al.* (1997) Oxygen, carbon and strontium isotope study of the carbonatitic dolomite host of the Bayan Obo Fe-Nb-REE deposit, Inner Mongolia, N China; *Mineralogical Magazine*, Volume 61, pages 531-541.

Chao, E.C.T., Back, J.M, Minkin, J.A. and Ren, Y. (1992): Host-rock controlled epigenetic, hydrothermal and metasomatic origin of the Bayan Obo REE-Fe-Nb ore deposit, Inner Mongolia, P.R.C.; *Applied Geochemistry*, Volume 7, pages 443-58.

Chao, E.C.T., Back, J.M, Minkin, J.A., Tasumoto, M., Wang, J., Conrad, J.E., Mackee, E.H., Hou, Z.L., Meng, Q.R. and Huang, S.G. (1997): The sedimentary carbonate-hosted giant Bayan Obo REE-Fe-Nb ore deposit of Inner Mongolia, China: a cornerstone example of for giant polymetallic ore deposits of hydrothermal origin; *USGS Bulletin*, 2143, pages 1- 65.

Drew, L.J., Meng, Q. and Sun, W. (1990): The Bayan Obo iron-rare-earth-niobium deposit, Inner Mongolia, China; *Lithos*, Volume 26, pages 43-65.

Le Bas, M.J., Spiro, B. and Yang, X.M. (1997): Oxygen, carbon and strontium isotope study of the carbonatitic dolomite hostof the Bayan Obo Fe-Nb-REE deposit, Inner Mongolia, N China; *Mineralogical Magazine*, Volume 61, pages 531-541.

Meng, Q. and Drew, L.J. (1992): Study on oxygen and carbon isotopes and the implication for genesis of Bayan Obo ore-bearing H8 dolomite; *Contributions to Geology and Mineral Resources Research*, Volume 7, pages 46-54.

Ren, Y., Zhang, Y. and Zhang, Z. (1994): Study on heat events of ore forming in the Bayan Obo deposit; *Scientia Geologica Sinica*, Volume 29, pages 95-101.

Shimazaki, H., Yang, Z., Miyawaki, R. and Shigeoka, M. (2008): Scandium-bearing minerals in the Bayan Obo Nb-REE-Fe deposit, Inner Mongolia, China; *Resource Geology*, Volume 58, pages 80-86.

Smith, M.P., Henderson, P. and Zhang, P.S. (1999): Reaction relationships in the Bayan Obo Fe-REE-Nb deposit, Inner Mongolia, China: implications for the relative stability of rare-earth element phosphates and fluorcarbonates; *Contributions to Mineralogy and Petrology*, Volume 134, pages 294-310.

Smith, M. and Chengyu, W. (2000): The geology and genesis of the Bayan Obo Fe-REE-Nb deposit: a review; *in* Hydrothermal Iron Oxide Copper-Gold & Related Deposits, Australian Mineral Foundation, pages 271-281.

Wang, J., Tatsumoto, M., Li, X., Premo, W.R. and Chao, E.C.T. (1994): A precise ^{232}Th-^{208}Pb chronology of fine-grained monazite: age of the Bayan Obo REE-Fe-Nb ore deposit, China; *Geochimica Cosmochimica Acta*, Volume 58, pages 3155-3169.

Xu, C., Campbell, I.H., Kynicky, J., Charlotte, M.A., Chen, Y., Huang, Z. and Qi, L. (2008): Comparison of the Daluxiang and Maoniuping carbonatitic REE deposits with Bayan Obo REE deposit, China; *Lithos*, Volume 106, pages 12-24.

Yang, X.-Y., Sun, W.-D., Zhang, Y.-X. and Zheng, Y.-F. (2009):Geochemical constrainson the genesis of the Bayan Obo Fe-Nb-REE deposit in Inner Mongolia, China; *Geochimica et Cosmochimica Acta*, Volume 73, pages 1417-1435.

Yuan, Z., Bai, G., Wu, C.Y., Zhang, Z.Q. and Ye, X. (1992): *Applied Geochemistry*, Volume 7, pages 429-442.

Zhang, P. (1990): Mineralogical research of the Bayan Obo rare-earth-niobium-iron ore deposit; *Journal of Rare Earths*, Volume 9, pages 221-225.

Mountain Pass Carbonatite Project

by J.O. Landreth[1] and P.J. Dockweiler[2]

ABSTRACT

The rare earth-bearing carbonatite at Mountain Pass, California was discovered in 1949. It became world famous for its high-grade content of rare earth elements (REE) and remains as the premier rare earth property in the Western Hemisphere. This world-class bastnaesite deposit produced REE for nearly five decades, until permits to operate the tailings storage facility expired in 2002. During the period from 2002 to present, Molycorp has produced rare earth products from stockpiled materials. After a hiatus of about 10 years, mining and milling operations will restart under Molycorp Minerals LLC in 2012, along with new RE separation facilities. The alkaline complex is unique in its character. It consists of ultrapotassic, silicate, alkaline igneous rocks that include seven shonkinite and syenite stocks, and hundreds of dikes that compositionally vary from shonkinite to syenite to alkali-rich granite. The final intrusive sequence includes several varieties of RE-bearing carbonatites (sovite to beforesite) that have formed a roughly tabular, sill-like body. Fenitization is the major alteration, which usually accompanies alkaline carbonatite intrusions. The alkaline complex was structurally controlled by pre-existing zones of weakness and foliation in the host Precambrian metamorphic basement. The complex is bound on three sides by post-alkaline intrusive faulting.

---

[1] *Chief Geologist, Mountain Pass Mine, CA, United States of America*

[2] *Geologist, Mountain Pass Mine, CA, United States of America*

The Aley Carbonatite Complex - Part I
Structural Evolution of a Cordilleran Niobium Deposit

by D.F. McLeish[1,2], R. Kressall[1,3], A. Chakhmouradian[3], J. Crozier[1], S.T. Johnston[2] and J.K. Mortensen[4]

ABSTRACT

The Aley carbonatite complex, a property belonging to Taseko Mines Ltd., is a 3 km wide niobium-bearing carbonatite sill in the Rocky Mountain Muskwa Ranges of northeast British Columbia. Located approximately 135 km north-northeast of Mackenzie, it is the largest of five known occurrences of carbonatite in the Foreland Belt of the Canadian Cordillera. Despite enrichment in rare earth elements (REEs) and niobium, tantalum, yttrium, and zirconium, the Foreland Belt carbonatites have been subject to limited study beyond reconnaissance-scale mapping and early-stage mineral exploration. Many aspects of carbonatite petrogenesis in the Cordillera remain enigmatic and knowledge gaps – spanning structure, petrology, and tectonics – have challenged efforts to successfully evaluate and model their resource potential. Addressing these challenges, Taseko Mines Ltd. initiated a collaborative academic/industry study of its Aley property in summer 2010 to better understand the structural and petrological controls on niobium mineralization. This work helped in the determination of optimal locations for exploration holes for a recently completed diamond drilling-program in the central area of the Aley complex and is the subject of this two-part talk.

Detailed, 1:5,000 scale mapping of the carbonatite, fenite aureole, and Paleozoic host stratigraphy reveals a complex poly-phase deformation record preserved within the ellipse-shaped complex. Deformation is manifested by early isoclinal folding and associated shearing (D1) of mineralized apatite and magnetite-rich laminations. Based on field and petrographic evidence, it is most likely that the mineral laminations developed as a result of large rheological variations between carbonate, phosphate, and oxide mineral phases during stress-induced plastic flow and kinematic differentiation associated with the D1 event. Fabrics generated by this event have been transposed by asymmetric, large-amplitude cascading and chevron-style folds of the Rocky Mountain orogeny (D2); fold interference between these two deformation events has led locally to the development of mineral fabrics trending approximately E-W, orthogonal to the regional Rock Mountain trend.

A detailed study of peripheral parts of the complex and adjacent hostrock carried out during mapping has shed further light on the structure of the deposit (Figure 1). Key findings include: (*1*) way-up structures in the host stratigraphy (Cambrian Kechika Formation, Ordovician Skoki Formation, and Siluro-Devonian Road River Group) indicate that the hostrock is uniformly overturned in the map area; (*2*) the carbonatite/host-rock contact is always found in a strongly fenitized volcaniclastic unit at the base of the Kechika Formation and mineral fabrics within the bordering carbonatite are parallel with the contact; (*3*) south-verging isoclinal folds and an associated bedding-parallel cleavage are pervasively developed throughout the host stratigraphy; and (*4*) early-phase dolomite carbonatite dykes are concordant with D1 isoclinal folds in hostrock whereas late-phase calcite carbonatite dykes cross-cut the D1 fabric. We interpret these findings to indicate that the entire host Kechika-Road River stratigraphic sequence is part of the lower, overturned limb of a major south-verging nappe, cored by the carbonatite complex, and emplaced synchronously with the D1 deformation event. Intrusion of the carbonatite into the base of the Kechika Formation was temporally related to nappe formation (Figures 2a and 2b) as suggested by (*4*). Subsequent Rocky Mountain deformation has folded the nappe (Figure 2c), and erosion has removed its upper limb leaving the carbonatite as a deformed sill-like body coring two Rocky Mountain synclines (Figure 2d).

The age of Rocky Mountain deformation affecting the Aley area (D2) is inferred from published regional geological syntheses (*e.g.* Thompson, 1989) to be Late Cretaceous. Two K-Ar dates on phlogopite from the carbonatite by Cominco Ltd. (Pride *et al.*, 1986) yielded ages of 349±12 Ma and 339±12 Ma. Our attempts to date zircons from the carbonatite have failed due to the very low U/Pb content of the samples. Although fabrics related to the D1 event have been mapped regionally, attempts to constrain D1 age have previously not been made. In 2009, the discovery of D1 fabrics in clasts of the Kechika

---

[1] *Taseko Mines Ltd., 300-905 West Pender Street, Vancouver, BC, V6C 1L6*

[2] *School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, V8W 3V6*

[3] *Department of Geological Sciences, University of Manitoba, Winnipeg, MB, R3T 2N2*

[4] *Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC, V6T 1Z4*

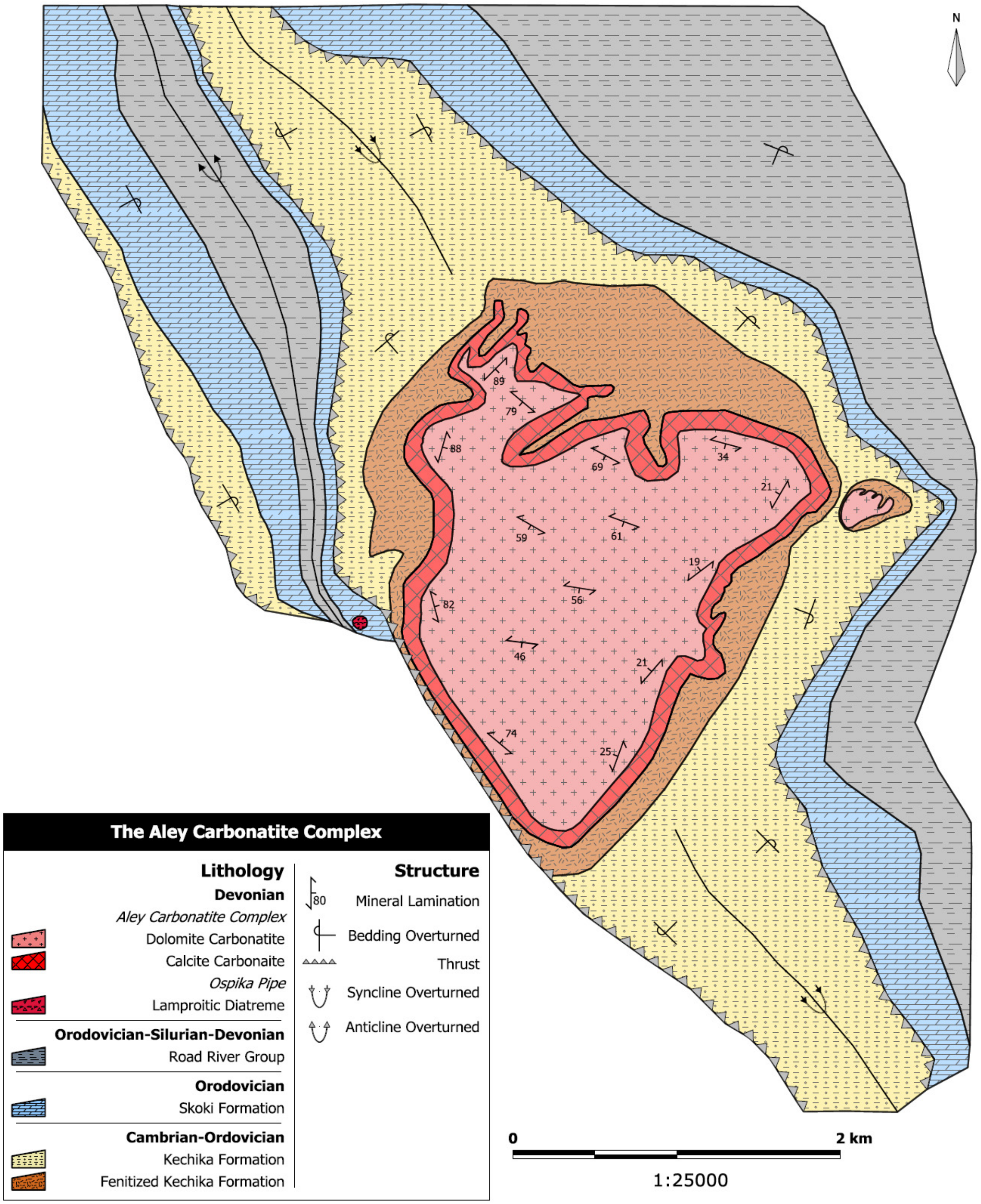

Figure 1. Map of the Aley Carbonatite Complex.

Formation in the nearby Ospika diatreme prompted U-Pb dating of the pipe to constrain a minimum D1 age. Recent results from four titanite grains sampled from the pipe and dated by chemical-abrasion thermal-ionization mass-spectrometry yield an age of 365.9±2.1 Ma. Given that the carbonatite has been involved in D1 deformation and is likely to be a product of the same magmatic event as the diatreme, the timing of carbonatite emplacement and D1 are inferred to be Late Devonian. The slightly younger K-Ar ages of phlogopites from the carbonatite would therefore be interpreted as cooling ages.

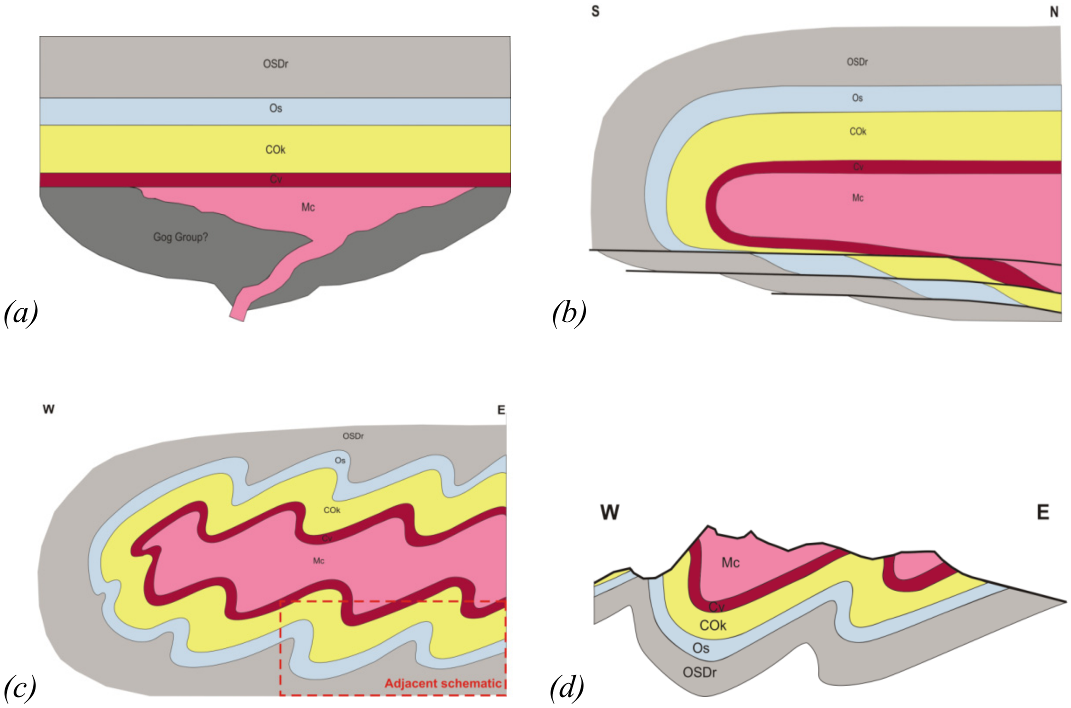

Figure 2. Schematic depiction of the evolution of the Aley carbonatite complex. Units coded via the same colour scheme as map in Figure 1.

In summary, poly-phase deformation of the Aley carbonatite complex has first-order control on the distribution of niobium mineralization. A Late Devonian D1 event, temporally related to carbonatite magmatism, involved isoclinal folding and synkinematic differentiation of carbonatite into carbonate laminae and foliation-defined bands of mineralized apatite and magnetite-rich material. A Cretaceous D2 event transposed the D1 fabric along axial planes of Rocky Mountain folds and gave rise to an E-W trending fold interference pattern within the core of the carbonatite. Notwithstanding the possibility that the apatite and magnetite bands represent primary cumulates reworked during D1 and D2, primary igneous characteristics of the carbonatite have been largely obliterated or reworked beyond recognition during deformation.

Lessons from Aley for advancing carbonatite exploration and resource definition in the Cordilleran Foreland Belt are that: (1) structural mapping and analyses focused on understanding the structural controls on mineralization must form an integral part of any exploration program – attempting to model Foreland carbonatites from aspects of igneous petrogenesis alone is inadequate given the structural complexities of the western Foreland Belt; and (2) structural interpretations need to be reconciled with petrography as deformation events have the potential to alter mineralization through metasomatism, metamorphism, and carbonate remobilization.

REFERENCES

Thompson, R.I. (1989): Stratigraphy, tectonic evolution and structural analysis of the Halfway River map area (94B), northern Rocky Mountains, British Columbia; Geological Survey of Canada, Memoir 425, 119 pages.

Pride, K.R., LeCouteur, P.C., Mawer, A.B. (1986): Geology and Mineralogy of the Aley Carbonatite, Ospika River Area, British Columbia. Conference Abstract. Canadian Institute of Mining and Metallurgy Tenth District 6 meeting. Montreal, PQ, Canada.

The Aley Carbonatite Complex - Part II
Petrogenesis of a Cordilleran Niobium Deposit

by R. Kressall[1,2], A. Chakhmouradian[2], D.F. McLeish[1,3] and J. Crozier[1]

ABSTRACT

As part of the recent exploration project of the Aley Carbonatite Complex, north-eastern British Columbia, a detailed petrological study was conducted on behalf of Taseko Mines Limited at the University of Manitoba to better understand and constrain Nb-mineralization at Aley. Due to the fine-grained texture of the Aley Carbonatite Complex, detailed petrographical work was conducted in thin-section using optical microscopy, energy-dispersive x-ray spectroscopy (EDS) and back-scatter electron imaging (BSE). Eighty samples, collected from drill-core and surface, representing the three major Nb-bearing units of the complex were studied in detail. The Nb-bearing units consist of: 1) dolomite carbonatite; 2) calcite carbonatite; and 3) a magnetite-apatite carbonatitic cumulate unit.

1) Dolomite carbonatite is by far the most abundant phase found within the complex, occurring towards the core of the body. The unit consists dominantly of dolomite (75-99%), apatite (1-20%), pyrite (1-5%), calcite (0-5%) and niobates (1-2%). Rutile inclusions along rhombohedral cleavage give some larger (up to 1.5 cm across) dolomite grains a dark grey metallic luster. Black phenocrystic pseudomorphs of chlorite, silica, dolomite, monazite and Fe-oxides after phlogopite compose up to 5% of dolomite carbonatite locally. The unit is locally observed to be replaced up to 25% by chlorite and silica, likely associated with the low-grade metamorphism of the complex. 2) Calcite carbonatite, occurring along the fringes of the complex is composed of calcite (65-95%), apatite (2-10%), magnetite (0-15%), phlogopite (0-10%), Na-amphibole (0-5%), oxidized pyrite (<1%) and niobates (0-2 %). Both dolomite and calcite carbonatites are texturally variable ranging from fine-grained laminated to inequigranular massive with common porphyritic (phlogopite phenocrysts) and brecciated variants. 3) Magnetite-apatite cumulate layers occur conformable to local fabric and as clasts within dolomite carbonatite. The unit consists dominantly of magnetite (35-45 %), apatite (25-35%), phlogopite (0-15%), niobates (0-5%) and zircon (<1.5%) with interstitial dolomite and calcite comprising up to 10 % of the unit.

The three dominant niobate phases identified at Aley are: 1) pyrochlore ($NaCaNb_2O_6F$); 2) columbite ($(Fe, Mn)Nb_2O_6$); and 3) fersmite ($CaNb_2O_6$). 1) Pyrochlore occurs as pale yellow to dark brown octahedral crystals up to 4 mm across within laminated to massive fine-grained calcite carbonatite. Pyrochlore composition is near ideal formula with a significant proportion of Ti^{4+} substitution (2.5-4.5 TiO_2 wt. %). Other substitutional elements (rare earth elements, Ta, Th and U) never exceed 0.5 wt. %. 2) Columbite occurs as black pseudohexagonal crystals up to 1.5 mm in diameter in close association with magnetite in cumulate layers and less commonly within calcite carbonatite. Columbite at Aley is poor in Mn (< 0.8 MnO wt. %) but shows appreciable variation with respect to Ti (1.4 to 6.1 wt. % TiO_4) and Ta (0.2 to 5.1 wt. % Ta_2O_5). 3) Fersmite, most commonly found in dolomite carbonatite, occurs as anhedral, octahedral and hexagonal polycrystalline pseudomorphs up to 4 mm after pyrochlore and columbite. Fersmite shows the most chemical and morphological variation of the three phases. At least two varieties of fersmite occur as Aley. The most common morphology is pseudomorphs comprised of acicular yellow crystals typically less than 50 µm in length and enriched in Ti (3.13-4.53 TiO_2 wt. %) and rare earth elements (1.53-5.48 REE_2O_3 wt. %). Less commonly are pseudomorphs composed of subplatey lamellar Th-rich (3.32-7.20 ThO_2 wt. %) fersmite embedded in Th-poor (0.38-1.58 ThO_2 wt. %) fersmite. Rare discrete and aggregated acicular fersmite is observed with chlorite in chloritized and silicified carbonatites. Monazite commonly accompanies fersmite in pseudomorphs. In addition to the magnetite-columbite association, all three niobate phases are observed to occur within zircon-bearing apatite laminae observed in dolomite and calcite carbonatite; an observation that is reflected in whole-rock geochemistry. Correlations are observed to occur between Nb_2O_5 and P_2O_5/Zr. Randomly oriented apatite inclusions are common within niobates, suggesting the lamination of the carbonatite occurred postemplacement of carbonatite. Although it is interpreted that most of the fersmite is secondary after pyrochlore and columbite, replacement rims of the later minerals around the former indicate that

---

[1] *Taseko Mines Ltd., 300-905 West Pender Street, Vancouver, BC, V6C 1L6*

[2] *Department of Geological Sciences, University of Manitoba, Winnipeg, MB, R3T 2N2*

[3] *School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, V8W 3V6*

there are likely multiple crystallization phases of Nb-mineralization at Aley.

Few of the textural characteristics observed in the Aley Carbonatite Complex are interpreted as being of primary igneous origin. These include heavy-mineral (magnetite, apatite, zircon and columbite) cumulate layers, porphyritic textures, enrichment of mafic silicates (phlogopite, aegirine and riebeckite) in calcite carbonatite near fenite contact, and occurrence of sedimentary dolomite and fenite xenoliths in carbonatite. Brecciation of carbonatite, observed in outcrop and drillhole cannot be unambiguously interpreted as synemplacement or postemplacement. Most of the primary characteristics of the carbonatites have been modified or obliviated by the postemplacement history of the complex that includes at least two deformational events, low-metamorphic grade overprint and re-equilibration of carbonatite with ground water. Deformation of the complex involved the stress-induced plastic flow of carbonate material resulting in grain-size reduction thereof and development of lamination and folds within the carbonatite observed in the alignment of apatite crystals. Low-grade metamorphism involved the replacement of phlogopite by chlorite, dolomite and muscovite; chloritization and silicification of carbonatite; deposition of low-temperature carbonates (zoned rhombohedral dolomite) and pyrite; resorption of apatite and niobates; and crystallization of monazite and secondary fersmite in association with chlorite. Reequilibration of carbonatites with groundwater resulted in the oxidation of pyrite and decomposition of carbonatite into incompetent decalcified material.

Nb-mineralization appears to have been concentrated initially in the heavy mineral cumulate layers. During the deformation of the carbonatite, the cumulate layers likely acted as coherent units resisting plastic flow due to the low carbonate and high apatite content of the unit. Complex deformation of the carbonatite resulted in the disaggregation of the cumulate unit and the dispersal of apatite and niobates into the carbonatite.

A major application of this study in the 2010 exploration program at Aley was the use of accessory minerals to help identify potential mineralized zones. Owing to the fine-grained nature of the Aley carbonatites, macroscopic recognition of niobates is not always possible. Alternatively accessory magnetite, apatite and zircon found commonly associated with niobates can be easily identified due to their magnetism or fluorescence behaviour under ultraviolet light. Important implications of this study include the importance of differentiating primary igneous textures from postemplacement fabrics when modeling mineralization and the significance of structural controls on the redistribution of Nb-mineralization at Aley. The results of this study stresses the importance of detailed petrographical work to better understanding and modeling a complex rare metal deposit, such as a Cordilleran Foreland Belt carbonatite.

Polyphase Rare-Earth Mineralization at the Bear Lodge Alkaline Complex, Wyoming

by M. Moore[1,3], A. Chakhmouradian[1] and J. Clark[2]

ABSTRACT

The Bear Lodge Alkaline Complex (BLAC) has been known since 1949 to host potentially economic levels of rare-earth elements (REE) concentrated in late-stage intrusive carbonatite dikes, veins and stockwork associated with post-magmatic metasomatic/hydrothermal processes. The focus of the current research is REE mineralization in the Bull Hill diatreme in the BLAC, which is currently being examined for economic viability by Rare Element Resources, Ltd. Materials for this study include drill core supplied by Rare Element Resources, Ltd. from the 2004, 2007 and 2008 exploration program and surface samples collected by M. Moore.

The deposit exhibits zonation consisting of (from surface downward): oxidized (FMR; FeOx-MnOx-REE), transitional and unoxidized zones. The REE mineral assemblage is composed predominately of parisite [$CaREE_2(CO_3)F_2$], synchysite [$CaREE(CO_3)F$], ancylite and calcioancylite [ideally, $(Sr,Ca)REE(CO_3)_2(OH)\bullet H_2O$] and cerianite [$CeO_2$], with subordinate bastnaesite [$REE(CO)_3$], monazite [$REE(PO)_3$], carbocernaite [$(Ca,Na)(Sr,REE,Ba(CO_3)_2$] and burbankite [$(Na,Ca)_3(Sr,Ba,REE)_3(CO_3)_5$], which are variably present in different zones of the deposit. This study examines the petrographic, mineralogical and geochemical characteristics of distinct carbonatite paragenesis in order to constrain the paragenetic sequence of events and resultant REE enrichment in the BLAC. Processes that may have been involved in the transport, concentration, and deposition of the REE are investigated and compared to other similar deposits elsewhere in the world.

---

[1] *University of Manitoba, Winnipeg, MN, R2M 2R7*

[2] *Rare Element Resources, Ltd., Vancouver, BC*

[3] *corresponding author: e-mail, mamarsters@gmail.com*

Rare Metal Li-Cs-Ta-(Sn-Nb) Mineralization: What Do We Know And Where Are We Going?

by R.L. Linnen[1]

KEYWORDS: Pegmatite, lithium, cesium, tantalum

INTRODUCTION

Pegmatites are one of the most important sources of the rare-metals Li, Cs and Ta. They are the traditional source of Li, primarily as spodumene or petalite, for the ceramics industry as well as for processing into Li carbonate for batteries, *e.g.* the Greenbushes pegmatite in Australia. Cesium production is primarily as pollucite from the Tanco mine in Manitoba, where it is dominantly used as Cs formate, which is used in a high-density, low-viscosity fluid used for high-pressure/high-temperature oil and gas drilling. Finally tantalum is also derived primarily from pegmatites and is used in wireless technology. The dominant ore minerals of tantalum are columbite-tantalite and wodginite

The association of these three metals has long been recognized and is one of the criteria for classifying pegmatites. Cerny and Ercit (2005) classify pegmatites based on their petrogenetic characteristics and trace-element associations; the LCT family contains economic concentrations of Li-Cs-Ta, as well as high abundances of Rb, Be, Sn and fluxing elements B, P and F. These pegmatites are typically syn to late-orogenic and are associated with S-type granites. Most 'world-class' LCT pegmatites are associated with shear zones and the host is typically a metabasite, which may be important as it is a more competent host that result in the formation of thicker pegmatite bodies.

TANTALUM MINERALIZATION

Two styles of Ta mineralization are recognized, notably at the Tanco pegmatite (*e.g.* Van Lichtervelde *et al.*, 2007). Magmatic mineralization consists of columbite-tantalite crystals that display oscillatory zoning and skeletal shapes, which indicate rapid growth. This is consistent with current theories on pegmatite formation by undercooling (London, 2008). The second style of mineralization is metasomatic. At the Tanco pegmatite this has been termed 'MQM' (muscovite-quartz after microcline) by Tanco geologists. However, replacement does not exclusively mean that hydrothermal fluids are involved and in this case can be interpreted to represent magmatic replacement. One argument in favour of magmatic replacement is that highly fluxed silicate melts are a very effective transport medium for tantalum and other high field strength elements (Bartels *et al.*, 2010).

EXPLORATION FOR RARE-ELEMENT PEGMATITES

One of the traditional exploration techniques for rare-element pegmatites is lithogeochemistry (Trueman and Cerny, 1982). Lithium anomalies around pegmatites can be quite extensive, with Rb and Cs anomalies being progressively more restricted. Another method is the use of mineral chemistry (Selway *et al.*, 2005). In particular the chemistry of K-feldspar, mica, beryl, and columbite-tantalite can be applied to locating mineralized pegmatites. Most recently enzyme leach techniques have been applied to pegmatite exploration (Galeschuk and Vanstone, 2005) as well as the use of fracture minerals as indicator minerals.

REFERENCES

Cerny, P. and Ercit, T.S. (2005) The classification of granitic pegmatites revisited. *Canadian Mineralogist*, Volume 43, pages 2005-2026.

Bartels, A., Holtz, F. and Linnen, R.L. (2010) Solubility of manganotantalite and manganocolumbite in pegmatitic melts. *American Mineralogist*, Volume 95, pages 537-544.

Galeschuk, C. R., Vanstone, P. J. 2005, Exploration for Buried Rare-element Pegmatites in the Bernic Lake Area of Southeastern Manitoba. In: Linnen, R.L., and Samson, I.M. (Eds) *Rare-Element Geochemistry and Mineral Deposits, Geological Association of Canada Short Course Notes* Volume 17, pages 153-167.

London, D. (2008) Pegmatites. Canadian Mineralogist, Special Publication 10, 345 pp.

Selway, J.B., Breaks, F.W. and Tindle, A.G. (2005) A Review of Rare-Element (Li-Cs-Ta) Pegmatite Exploration Techniques for the Superior Province, Canada, and Large Worldwide Tantalum Deposits. *Exploration and Mining Geology*, Volume 14, pages 1-30.

Trueman, D.L. and Cerny, P. (1982) Exploration and processing. In Granitic Pegmatites in Science and Industry, Mineralogical Association of Canada Short Course Volume 8, pages 463-493.

---

[1] *Department of Earth Sciences, University of Western Ontario, London, ON, N6A 5B7*

Van Lichtervelde, M., Linnen, R.L., Salvi, S. and Didier, B. (2007) Textures and chemical evolutions in tantalum oxides: a discussion of magmatic versus metasomatic origins for Ta mineralization in the Tanco Lower Pegmatite, Manitoba, Canada. *Economic Geology*, Volume 102, pages 257-276.

Exploring for a Tanco Type Pegmatite

by D.L. Trueman[1]

ABSTRACT

Granitic pegmatites such as the Archean Tanco pegmatite at Bernic Lake, Manitoba have been significant sources of many lithophile elements. At Tanco these elements have included Ta, Li, Rb and Cs. In other pegmatites, economic elements have also included Be, Nb and Sn and many pegmatites have been mined or studied as potential sources of quartz, feldspars, micas, ceramic clays, and gemstock.

The Tanco pegmatite, which is a member of the LCT (Li-Cs-Ta) type of pegmatite according to classification of Cerny (2002), has been studied extensively and the Bernic Lake area serves as a model for the exploration for mineral deposit counterparts, globally. The Tanco pegmatite is essentially horizontally disposed, approximately 1990 metres long, 1060 metres wide and 100 metres thick. Its attitude, structurally controlled during implacement, fits well with its occurrence in the zonation common to fields of pegmatites. It is at the high end of fractionation of suites of other progressively fractionated pegmatites and is strongly internally zoned and overprinted by late metasomatic assemblages of albite and lepidolite.

The Tanco Mine area has served as a testing ground for many geophysical and geochemical methods. The following exploration guidelines are based on 34 years of personal rare metal exploration experience, 9 of which were in the Tanco area.

Granitic pegmatites occur in large fields, swarms, or clusters and the objective in exploration is to find the reduced area most likely to host the target element(s). A pegmatite field will display a regional pattern of progressive fractionation which can be mapped out by simple accessory mineral identification, determinative mineralogy, or chemical analysis of fractionating pairs in major minerals. This is essential and early work that will reduce the search area and can be greatly facilitated by interrogation of local or artisanal miners who know what minerals have been produced from which pegmatites. In this regard mineral typomorphism is useful and may be as simple as mapping colour of polychrome tourmalines or transition of beryllium minerals from beryl to gem forms. Beryl also changes colour to white and its c-axis shortens with increasing Cs contents. Muscovite will turn green and yellow coloured (sericite or 'tin mica') in highly fractionated pegmatites and purple or mauve coloured spodumene is a good indicator of Cs and pollucite, its ore mineral.

The minerals containing lithophile elements and granitic pegmatites themselves are not, in general, good geophysical responders. Magnetics and electromagnetic methods cannot be ruled out completely as they may be useful tools for outlining hostrocks or favourable structures. Gravity surveys have been shown to work at Tanco where they delineated the high density contrast between the essentially granitic host (s.g. 2.7) and spodumene (s.g. 3.2). Radioactivity is at best minimal in LCT pegmatites where U and Th are very rare. Ground penetrating radar is now being used to map pocket lines in gemstone pegmatites and to assist in production.

As many of the targeted elements in a highly fractionated pegmatite occur in resistate minerals, stream sediment sampling can narrow a search field. Lithogeochemistry, soil geochemistry and MMI are useful geochemical tools. Lithium is a highly mobile element and lithium geochemistry can detect a blind lithium pegmatite target by hundreds of metres relative to the outline of pegmatite body. Rubidium and cesium are progressively less mobile and simple contouring of Li-Rb-Cs geochemical data can help position a drillhole.

There are other thumb rules useful in prospecting for rare metal deposits in a granitic pegmatite area. One is that spodumene will not occur inside of the sillimanite isograd and this can considerably reduce a search area. Another is determination of the mineral in which the element is occurring. For example, a pegmatite will not generate spodumene or petalite until the phosphorous in the system has been consumed, usually by crystallization of amblygonite-montebrasite.

---

[1] *Geological Consultant, Richmond, BC*

Rare Metal Peraluminous Granites: Similarities and Contrasts with Pegmatite Deposits

by R.L. Linnen[1]

KEYWORDS: Granite, tantalum, peraluminous, peralkaline, pegmatite, LCT, NYF

INTRODUCTION

The most important source of tantalum is pegmatites, however granite-hosted deposits are also exploited for tantalum, both as a primary resource and as a byproduct. Rare-metal granites are enriched in large-ion-lithophile elements (LILE) such as Rb and Cs. Because of their large ionic radii they are incompatible in silicate melts, but they are also mobile in aqueous fluids. Other mobile elements include Li, F, B and Be. Rare-metal granites are also characterized by high concentrations of high field strength elements (HFSE), notably Ta, Nb, Sn, REE, U and Th. Many of the HFSE are immobile in aqueous fluids (particularly Ta-Nb-Zr-Hf), thus these elements are better-suited to monitor magmatic processes compared to the LILE. There have been a number of classification scheme of rare-metal granites, but essentially there are three main types (Linnen and Cuney, 2005): i) peralkaline rare-metal granites are characterized by very high abundances of F, REE, Y, Zr and Nb and high concentrations of Th, Sn, Be, Rb and U, a high Nb/Ta ratio and low P contents. These granites are typically rich in Fe and contain sodic amphiboles and pyroxenes. Li contents generally are only moderate, but some granites contain Li-F micas, zinnwaldite or polylithionite. They are typically emplaced in anorogenic settings; ii) metaluminous rare-metal granites typically have intermediate REE, Y, Zr, Hf and Th. These granites are associated with high K, calcalkaline magma series and occur in post-orogenic and anorogenic settings. iii) peraluminous rare-metal granites. These can in turn be subdivided into high and low phosphorous types. The high P subtype is characterized by very low REE, Y, Zr, Hf and Th. By contrast Li, F, Rb and Cs contents are very high. Peraluminous rare-metal granites are generally associated with two-mica S-type granites but have highly variable mineralogy which results in variable geochemical characteristics, although one consistent characteristic is low Zr/Hf and Nb/Ta ratios. The typical tectonic setting of these granites is as post-orogenic plutons in continental collision belts. Overall, peraluminous rare-metal granites share many of the characteristics of LCT rare-metal pegmatites, whereas peralkaline rare-metal granites are analogous to NYF pegmatites.

GRANITE-HOSTED TANTALUM MINERALIZATION

There are several examples of granite-hosted Ta deposits around the world. Notable deposits are Orlovka in Russia (Badanina *et al.*, 2004), Yichun in China (Yin *et al.*, 1995), Beauvoir in France (Raimbault *et al.*, 1995) and Abu Dabbab in Egypt (Kuster, 2009). In most of these examples the granite bodies are comprised of multiple intrusions, with highly evolved compositions. In fact the compositions are so highly evolved that many authors (*e.g.* Bandanina *et al.*, 2004) have invoked additional processes such as salt melt immiscibility to explain these high concentrations of the LILE and HFSE. However, the style of mineralization at granite-hosted deposits provides a key constraint on their origin. Virtually all of the Ta mineralization occurs as disseminations of Ta oxide minerals (primarily columbite-tantalite) in the granite, whereas Sn-W mineralization (primarily as cassiterite-wolframite) is vein-hosted both within and external to the granite and may be associated with greisens alteration. This indicates that the Ta-Nb mineralization is dominantly magmatic in origin whereas Sn-W originates from hydrothermal fluids

REFERENCES

Badanina, E.V., Veksler, I.V., Thomas, R., Syritso, L.F., and Trumbull, R.B., 2010, Magmatic evolution of Li-F, rare metal granites: a case study of melt inclusions in the Khangilay complex, Eastern Transbaikalia (Russia). *Chemical Geology*, Volume 210, pages 113-133.

Kuster, D., 2009, Granitoid-hosted Ta mineralization in the Arabian–Nubian Shield: Ore deposit types, tectono-metallogenetic setting and petrogenetic framework. *Ore Geology Reviews*, Volume 35, pages 68-86.

Linnen, R.L., and Cuney, M., 2005, Granite-related rare-element deposits and experimental constraints on Ta-Nb-W-Sn-Zr-Hf mineralization: *in* Linnen, R.L., and Samson, I.M., eds., *Rare-Element Geochemistry and Mineral Deposits, Geological Association of Canada Short Course Notes* Volume 17, pages 45-68.

Raimbault, L., Cuney, M., Azencott, C., Duthou, J.L., and Joron, J.-L., 1995. Multistage magmatic genesis of a Ta-Sn-Li

---

[1] *Department of Earth Sciences, University of Western Ontario, London, ON, N6A 5B7*

mineralized granite at Beauvoir, French Massif Central: A geochemical study: *Economic Geology*, Volume 90, pages 548-576.

Yin, L., Pollard, P.J., Shouxi, H., and Taylor R.G., 1995,Geological and geochemical characteristics of the Yichun Ta-Nb-Li deposit, Jiangxi Province, south China: *Economic Geology*, Volume 90, pages 577-585.

The Geology and Geochemistry of REE Deposits – A Primer

by A.E. (Willy) Williams-Jones[1]

ABSTRACT

Deposits of the Rare Earth Elements (REE) and associated high field strength elements (HFSE; *e.g.* Zr and Nb) form predominantly in or in close proximity to peralkaline intrusive rocks and carbonatites that originate as a result of mantle upwelling (mantle plume?) in regions of subsequent continental rifting. They occur in aulacogens or failed rifts. Magmas enriched in the REE, Zr and Nb are the products of very low degrees of partial melting of mantle and owe this enrichment to a combination of volatile fluxing (notably by fluorine) and a high proportion of alkalis relative to aluminium. Deposits associated with carbonatites tend to be enriched preferentially in the light REE, whereas those associated with peralkaline igneous rocks are richer in the heavy REE. The nature of the association between peralkaline silicate and carbonatitic magmas is still a matter of some debate. However, whether they are associated by slightly different degrees of partial melting of the same mantle plume, fractional crystallization or liquid immiscibility, it seems likely that the LREE prefer carbonatite liquids because of the similarity of their ionic radii to that of Ca. The ionic radii of the heavy REE are substantially smaller. Further magmatic concentration of REE, Zr and Nb in silicate magmas occurs due to fractional crystallization either because of the incompatible nature of these elements, which causes them to be concentrated in the most evolved magmas, *e.g.* granitic pegmatites, or because changes in the environment lead to a mineral rich in them being the only phase on the liquidus. This could occur because of contamination of the magma by stoping of the surrounding rocks or magma mixing, both of which might lead to displacement of the magma from a cotectic involving a major rock-forming mineral into the field of stability of a REE-HFSE mineral (*e.g.* eudyalite). Hydrothermal processes play a major role in the concentration of the REE to economic levels. As the REE are hard metals, *i.e.* they have a high charge/radius ratio, they form strong complexes with hard ligands, *e.g.* F^-. However, recent experimental data show that they also form moderately stable complexes with the borderline ligand, Cl^-. Both F- and Cl- are likely to play important roles in the hydrothermal transport of the REE, F-, because of the great strength of its complexes and Cl- because of the high concentration of Cl- in REE ore fluids. These experimental data also show that the LREE form more stable complexes with these ligands than do the HREE. Thus deposits forming distally to the magmatic source are likely to be concentrated in the LREE, whereas those forming proximally will be more enriched in the HREE. Transport of the REE as fluoride complexes is only effective in the near absence of Ca, because of the very low solubility of fluorite. Thus mixing of a magmatic hydrothermal REE-fluoride-bearing ore fluid with an external Ca-bearing fluid (*e.g.* formational water) would be a very effective mechanism for ore deposition. The mixing would lead to precipitation of fluorite, thereby destabilizing the REE-fluoride species and causing precipitation of REE minerals. Fluid phase separation-induced cooling and fluid mixing-induced cooling and ligand dilution are additional mechanisms for the formation of REE minerals from chloride- or fluoride REE species.

---

[1] *Department of Earth and Planetary Sciences, McGill University, Montreal, QC*

Ilímaussaq Alkaline Complex, A Unique Rare Element Deposit

by H. Friis[1] and J.L. Mair[2]

ABSTRACT

The Ilímaussaq alkaline complex is situated in South Greenland and is one of several alkaline complexes related to Mesoproterozoic NE-SW continental rifting. The complex forms a layered, ellipsoid body measuring 17 by 8 km and covering an area of 85 km^2. The Ilímaussaq complex is the type locality for agpaitic nepheline syenites and for 33 minerals, and represents an enormous concentration of rare elements, particularly REEs, Y, Zr, U, Nb, Th, Li and Be (Sørensen, 2006). Historical exploration in the Ilímaussaq complex was conducted by the Danish government in the 1950s, 60s and 70s, and largely focussed on identifying uranium resources at an area known as Kvanefjeld. More recent exploration has identified vast polymetallic resources that are strongly enriched in REEs, U and Zn at Kvanefjeld. Resources defined to date in accordance with the Australian Joint Ore Reserves Committee (JORC) code include 250 Mt @ 1.22% REO+Y, 350 ppm U_3O_8 within an overall resource of 457 Mt @ 1.07% REO+Y, 280 ppm U_3O_8 (Greenland Minerals and Energy Limited, Company Report).

The three main rock types found in Ilímaussaq, in volume and from a resource point of view, are:

Lujavrite: Aegirine or arfvedsonite dominated rock, with nepheline and alkali feldspar, if dominated by aegirine it is often called green lujavrite and black lujavrite if arfvedsonite is the dominating mafic mineral. The average grain size is a few mm, but it can increase to a pegmatoidal type often referred to as m-c lujavrite.

Naujaite: The main minerals are sodalite, nepheline, aegirine, alkali feldspar, arfvedsonite and sometimes eudialyte, where the latter three can be found enclosing the sodalites giving a characteristic poikilitic texture. The poikilitic texture results in some grains being up to decimetre in size.

Karkortokite: A layered part of the intrusion consisting of black (arfvedsonite), red (eudialyte) and dominated by a white (feldspar) layer. Karkortokite is restricted to the southern part of the complex.

The layered nature of the complex is attributed to four successive pulses of magma. The first produced an augite syenite, which now forms a marginal shell. This was followed by intrusion of a sheet of peralkaline granite that is mostly preserved in the roof of the complex. The third batch of magma differentiated to produce pulaskite, foyaite and naujaite that form the roof series. Stage four produced the agpaitic lujavrites and kakortokites. These rock types formed from volatile-rich alkaline magmas that were extremely enriched in incompatible elements, *e.g.* REE, Li, Be, U and Nb. It is interpreted that roof series had crystallized prior to injection of the fourth batch of magma, which was emplaced across the complex and integrated with the overlying roof series via a process of piecemeal stoping. The result is a that the lujavrite body is a heterogeneous unit entwined with naujaite (Figure 1).

Multi-element mineralization at Kvanefjeld is dominated by orthomagmatic mineralization hosted within black and m-c lujavrite. Rocks adjacent to mineralized lujavrite commonly contain pegmatites and hydrothermal veins rich in REEs and uranium but are of less significance overall. However, naujaite rich in eudialyte are found in several drill cores. The black lujavrite is pervasively mineralized; however economic grades generally occur in the upper part of lujavrite sections. At Kvanefjeld, the steenstrupine-rich black lujavrite is dominant from surface to depths of 200-300 metres, where the eudialyte-REE phosphate assemblage becomes more dominant. This corresponds to a decrease in REE and uranium concentrations with depth. There is also a narrow zone along the western margin of the deposit that is eudialyte-bearing. Eudialyte is most concentrated in the basal kakortokite units, but is commonly enriched at the base of individual lujavrite lenses throughout the complex.

Historically, the focus of research into Kvanefjeld has been on uranium but in Ilímaussaq 26 REE minerals have been indentified of which 10 were described from here for the first time and six have only been found here. In addition to these REE minerals several minerals will contain REE in significant amounts, *e.g.* eudialyte and rinkite. The main focus of the exploration is the mineral steenstrupine, a complex phospho-silicate. Due to high levels of U and Th steenstrupine is almost always metamict and the structure and chemistry of the mineral is therefore not well constrained but one idealised formula is $Na_{14}Mn^{2+}_2(Fe^{3+},Mn^{3+})_2Ce_6(Zr,Th)[(OH)_2|HPO_4|(PO_4)_6|(Si_6O_{18})_2]*2H_2O$. Steenstrupine can be found distributed throughout the black lujavrite as micro crystals but crystals up to 5 cm have been found (Figure 2).

---

[1] *Mineral Deposit Research Unit, University of British Columbia, Vancouver, BC*

[2] *Greenland Minerals & Energy Limited, West Perth, Australia*

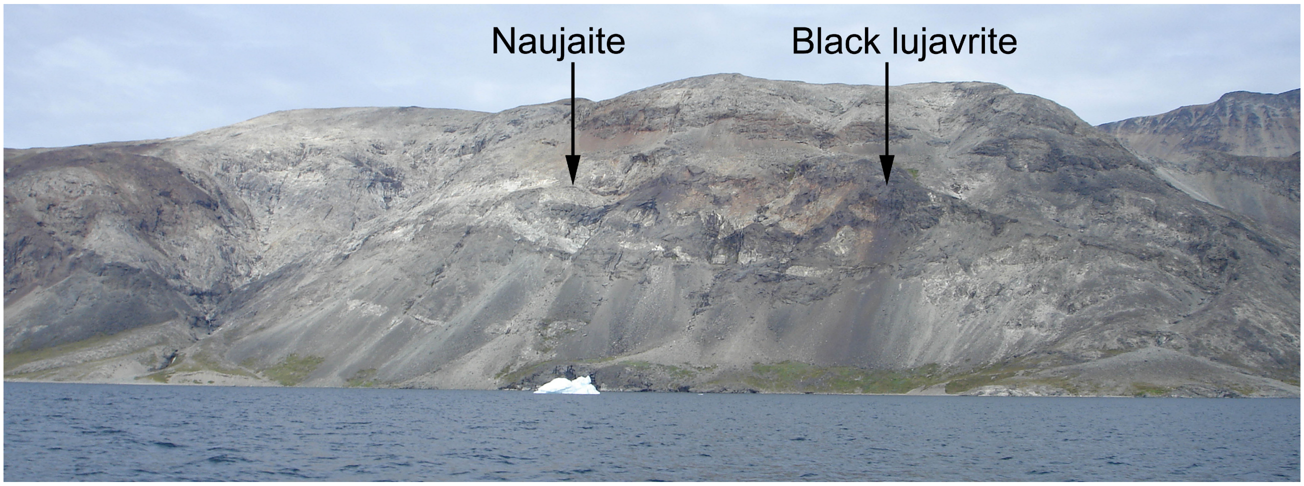

Figure 1. Cliff face showing black lujavrite outcrops on the northern shore of the Tungdliarfik Fjord. The slope is approximately 700 m from the ridge crest to sea level.

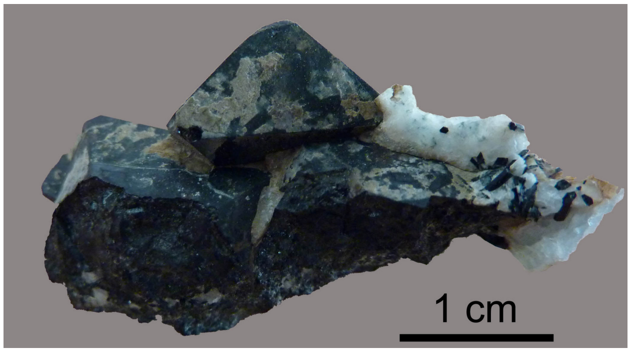

Figure 2. Euhedral steenstrupine from Ilímaussaq alkaline complex, South Greenland.

Mineralogical studies suggest that it commonly contains between 0.2 and 1% U_3O_8, and likely hosts >70% of the uranium overall (Makovicky *et al.*, 1980).The metamict nature of steenstrupine results in different degrees of replacement often into other REE minerals (Sørensen, 1962; Pekov *et al.*, 1997).

Although steenstrupine has conventionally been thought to be the main host for both U and REE the uniqueness of Ilímaussaq means that areas of lujavrite will contain economically viable amounts of minerals only known from here or few places in the world. Pekov and Ekimenkova (2001) describes a type of mineralisation based on the two REE minerals nacareniobsite ($Na_3Ca_3(REE)Nb[F_3|O|(Si_2O_7)_2]$) and vitusite ($Na_3REE(PO_4)_2$). These studies are based on samples collected from a 1000 m test adit from 1980, but recent field studies of the Kvanefjeld plateau revealed nacareniobsite to be more abundant then previously though. The new discoveries are often associates with fracture systems indicating REE mobility within the lujavrite unit, which is currently not understood.

The mineralogical variations of Ilímaussaq (approximately 220 minerals have been found) have great significance to metallurgical studies and process development. Variations include primary mineralogical variation, variation relating to hydrothermal alteration events, and variation as a result of leaching in the near-surface environment. The REE and uranium bearing minerals typically occur in certain groups, or associations, that account for primary variation. Overall the steenstrupine-rich rocks behaved favourably with uranium extraction commonly exceeding 80%, whereas for rocks that feature the eudialyte-REE phosphate association uranium extraction was lower than %. For samples that contained strongly-altered steenstrupine, which had been replaced with an alteration assemblage, uranium recoveries were also poor (Makovicky *et al.*, 1980).

The black lujavrite also contains a series of other phospho-silicates than steenstrupine, *e.g.* lomonosovite and vuonnemite, which will have similar chemical properties in the processing of the ore. With the mineral diversity elements like Zr, Nb, Be, Li and Zn can contribute as valuable side products. It is therefore important to understand the distribution and paragenesis of these minerals in order to establish the best processing strategy and be able to classify the ore based on whole rock analyses.

This project will examine the different associations of ore minerals and their geochemical characteristics. The aim is to develop a method whereby the resources can be domained into areas of common ore minerals, using whole rock geochemistry. Understanding the different mineralogical associations is critical to metallurgical process development, and will ultimately allow a reliable method to predict metallurgical response and recovery.

REFERENCES

Pekov, I.V. and Ekimenkova, I.A. (2001): Two new rare-earth-rich mineral associations in the Ilímaussaq alkaline complex, South Greenland. In H. Sørensen, Ed. The Ilímaussaq alkaline complex, South Greenland: Status of mineralogical research with new results, *Geology of Greenland Survey,* Bulletin 190, pages 143-144.

Pekov, I.V., Petersen, O.V. and Voloshin, A.V. (1997): Calcio-ancylite-(Ce) from Ilímaussaq and Narssarssuk, Greenland, Kola peninsula and Polar Urals, Russia; Ancylite-(Ce) calcio-ancylite-(Ce), an isomorphous series. *Neues Jahrbuch für Mineralogie-Abhandlungen*, volume 171, pages 309-322.

Makovicky, M., Makovicky, E., Nielsen, B.L., Karup-Møller, S. and Sørensen, E. (1980): Mineralogical, Radiographic and Uranium Leaching Studies on the Uranium Ore from Kvanefjeld, Ilímaussaq Complex, South Greenland. *RISØ*, Rapport R-416, 187 pages.

Sørensen, H. (1962): On the occurrences of steenstrupine in the Ilímaussaq massif, Southwest Greenland. *Meddelelser Om Grønland*, volume 167, pages 1-251.

Sørensen, H. (2006): The Ilímaussaq Alkaline Complex, South Greenland – an overview of 200 years of research and an outlook. *Geoscience*, volume 45, 70 pages.

The Nechalacho Rare Earth Deposit, Thor Lake, Northwest Territories

by A.E. (Willy) Williams-Jones[1]

ABSTRACT

The Nechalacho REE deposit is a large resource containing some 175 million tons with 1.43 TREO (inferred) located in rocks of the Aphebian Blachford Lake complex (2.1 Ga), a suite of alkaline intrusions located in the Athapuscow aulacogen. The bulk of the REE mineralization is hosted by the youngest unit of the complex, the Nechalacho Layered Alkaline Complex, which is largely unexposed at surface and is currently being drilled by Avalon Rare Metals Inc. This body is open on all sides but is > 2 km in diameter and > 1.1 km in thickness. Rocks of the Nechalacho Layered Complex range in composition from agpaitic at depth to miaskitic? in its upper part. The principal rocks units are a sodalite cumulate roof syenite underlain by a thick unit of porphyritic nepheline aegirine syenite, comprising layers of cumulate aegirine and layers with a pronounced trachytic texture (lujavrite).

The ore zone, which has been subdivided into a LREE enriched upper part and a HREE enriched lower part, forms two layers each 15 to 30 m thick and locally a single layer that occur within the aegirine nepheline syenite. The primary mineralogy of the ore zone and the overlying rocks has been largely obscured by alteration and was reconstructed from relicts. Upper ore zone rocks are characterised by high concentrations of zircon, locally up to 30 volume percent, some of which displays a primary cumulate texture. The principal ore minerals are zircon, allanite-(Ce), fergusonite-(Y) and bastnaesite-(Ce). Lower ore zone rocks also contain high concentrations of zircon. However, this mineral occurs almost exclusively in pseudomorphs that form cumulate layers and are tentatively interpreted to represent former eudyalite phenocrysts. The zircon is accompanied in these pseudomorphs by fergusonite-(Ce), allanite (Ce), bastnaesite-(Ce), biotite, albite, quartz and fluorite. Early hydrothermal alteration, represented mainly by biotite and magnetite, locally remobilized REE and Zr. Later fluids leached the rocks, altered the primary mineralogy, including ore minerals, to albite and left vugs which were filled by cleavelandite (acicular albite), fluorite and bastnaesite-(Ce).

A preliminary model for the deposit envisages multiple injection of peralkaline magmas of miaskitic composition in the upper part and agpaitic composition in the lower part. Mixing of these magmas resulted in displacement of the liquidus from a cotectic along which crystallization of aegirine was accompanied by minor crystallization of zircon or eudyalite to the field of zircon (upper ore zone) or eudyalite (lower ore zone). Near mono-mineralic crystallization of these phases and gravitational settling resulted in accumulation of zircon and eudyalite and eventual return of the magma composition to the cotectic. The REE were concentrated dominantly in zircon and eudyalite. Subsequent alteration by hydrothermal fluids (autometasomatism) partially released the REE from the zircon in the upper ore zone and re-deposited them proximally as fergusonite-(Y) and allanite-(Ce) and more distally as bastnaesite-(Ce). The Zr was partially remobilised and re-deposited as zircon. In the lower ore zone, these fluids converted the eudyalite to the minerals listed above. Subsequent albitization by late fluids locally dispersed the REE mineralization.

---

[1] *Department of Earth and Planetary Sciences, McGill University, Montreal, QC*

The Petrology and Petrogenesis of One of the World's Biggest Ta Deposits – the Motzfeldt Centre, South Greenland

by J.A. McCreath[1], A.A. Finch[1,*], C.H. Donaldson[1] and A. Armour-Brown[2]

ABSTRACT

The Motzfeldt centre is one of five major alkaline centres and several satellites that together form the Igaliko complex of South Greenland. This centre contains syenogabbro, nepheline syenites and peralkaline agpaitic units. Within the East of the complex, an exceptional Ta, Nb and REE-rich unit, one the earliest parts of the complex, is the subject of commercial interest.

We have examined the petrology and petrogenesis of the centre, paying particular attention to the processes that formed the enriched zone. The enriched zone comprises a pink, highly altered syenite that is texturally highly heterogeneous. Grain sizes vary from microsyenite to nepheline syenite, pegmatitic syenites and aplites. The highest Ta contents are found within a particular microsyenite suite that cross-cuts and pervades the centre. The Ta is hosted by pyrochlore but the textures within pyrochlore are complex, reflecting very pervasive late-stage alteration.

Rift-related magmatism produced rare-element enriched magmas by partial melting of an enriched mantle source. U-Pb isotopic measurements on preserved magmatic zones in zircon define a strongly concordant age of 1273 ± 8 Ma, demonstrating that Motzfeldt is the earliest preserved magmatic episode in the region. Magmatism was followed by hydrothermal alteration that substantially altered nepheline and feldspar producing a characteristic pink colour in hand specimen. Analysis of F contents of biotite shows that this late-stage fluid had an exceptionally high HF fugacity, the highest in the Gardar province (with the possible exception of the agpaitic Ilímaussaq complex to the south). Textural analysis of the mineralogy provides evidence for late-stage mobility in many traditionally 'immobile' elements such as U, Zr, Nb and REE. For example, pyrochlore crystals show complex internal textures indicative of alteration and have experienced compositional changes associated with element mobility and redistribution during the sub-solidus. RE are present in pyrochlore and unidentified RE-fluorcarbonates. However, despite the mobility of many elements in this geochemical environment, we find no evidence for remobilisation of Ta. U-Pb isotopic analysis of secondary pyrochlore defines an isochron age of 1267 ± 6 Ma, slightly younger but within error of the U-Pb zircon age. We therefore infer that alteration in eastern Motzfeldt occurred during, or shortly after, the late-magmatic stage and is not a later hydrothermal event associated with neighbouring younger magmatism.

The rare-element-enriched nature of the centre results from the fact that it is the earliest magmatism in the region and one of the earliest in the province. The Motzfeldt magmas tapped a relatively enriched mantle source which generated rare-element-enriched magmas associated with high volatile contents. This combination of exceptional magma and exceptional hydrothermal phase accounts for the geochemistry of the enriched zones. Although rifting and magmatism at Igaliko continued by similar mechanisms over a further ~150 Ma, these tapped a now relatively depleted mantle producing rocks without such enrichment. The extraordinary late-stage hydrothermal activity at Motzfeldt was essentially contemporaneous with magmatism, mobilising U, Zr, Nb and REE, but not Ta.

---

[1] Centre for Earth Resources St Andrews (CERSA), Department of Earth Sciences, University of St Andrews, St Andrews, Scotland (Adrian.finch@st-andrews.ac.uk)

[2] Angus and Ross plc, York, England (ashlyn.armour-brown@ntlworld.com)

[*] contact author

The Characteristics and Origin of Great Western Minerals Group Ltd.'s Hoidas Lake REE Deposit, Rae Province, Northwestern Saskatchewan

by K. Halpin[1], K. Ansdell[2] and J. Pearson[1]

ABSTRACT

The Hoidas Lake REE Deposit is one of several REE showings situated along the Hoidas-Nisikkatch fault, Rae Province, northwestern Saskatchewan. Hosted predominantly by Paleoproterozoic(?) felsic orthogneisses of the Zemlak Domain the most significant of these showings is the JAK Zone, which consists of multiple northeast trending, steeply east dipping anastomosing veins. The combined measured and indicated resource of the JAK Zone is 2.56 Mt grading 2.4% total rare earth oxide (TREO), with the vein system open both along strike and at depth. The deposit is LREE (Nd, Ce, La) dominant, with the REE hosted by allanite(Ce) and fluoroapatite, with minor amounts of monazite, bastnaesite and chevkinite-perrierite. The veins of the JAK Zone are undeformed, and crosscut fabrics associated with the peak upper amphibolite regional metamorphism. Spatially associated with the deposit are undeformed lamprophyres and peralkaline pegmatites, although crosscutting relationships are lacking. U-Pb geochronology of these rocks and vein minerals is currently in progress, but a published monazite age suggests the mineralization occurred at 1.87 Ga.

The mineralization at Hoidas Lake is complex, with the earliest vein generation consisting of REE-bearing allanite and chevkinite-perrierite in association with diopside, hyalophane and titanite. The allanite-rich veins are followed by several vein generations which are dominated by REE-bearing apatite. The earliest of the apatite vein generations is a red apatite breccia, followed by a less common green apatite breccia. Finally, there is a late, coarse red apatite which crosscuts all previous vein generations. The majority of the apatite and allanite crystals are internally complex, with the earliest veins displaying the significant alteration, reflecting chemical changes in the mineralizing system. The oldest apatite generations contain monazite inclusions, whereas the younger apatites are inclusion-free. The green apatites are the most REE-rich (5.5% TREO), whereas those with the lowest REE values are the coarse red apatites (>1.5% TREO). Allanites typically have REE-poor rims and are altered to bastnaesite.

There is no mineralogical or textural evidence to support the replacement of a primary igneous rock. The complex alteration, and brecciation, of older vein minerals suggests that the veins were deposited from an evolving (magmatic)-hydrothermal fluid focused along an active fault structure. The presence of lamprophyres in the region is indicative of metasomatized mantle, from which an appropriate magmatic source for F-Cl-REE-Ba-Sr-P-bearing fluids may have been derived.

---

[1] *Great Western Minerals Group Ltd., Saskatoon, SK*

[2] *University of Saskatchewan, Saskatoon, SK*

Rare Earth Mineralization at the True Blue Property, Southern Yukon

by D. Turner[1] and L.A. Groat[1]

ABSTRACT

The True Blue property is located in the Ketza-Seagull District of the southern Yukon (NTS Sheets 105F/8, 9, and 10). The name refers to the unusual dark blue aquamarine crystals that were discovered on the western Shark claims in 2003. These crystals are found in quartz veins that fill sigmoidal tension gashes within a syenite of Mississippian age (362.7 Ma ± 3.6). Accessory minerals in the veins include siderite, ankerite, allanite-(Ce), fluorite, and minor albite, sulfides, and Fe-Ti-Nb oxides. Fluorite from several veins has been dated using Sm-Nd geochronology at 171.4 ± 4.8 Ma. Evidence points to a metamorphic origin for beryl mineralization and a local derivation of vein constituents. One sample of an allanite-bearing vein returned 0.14% TREO. Bastnaesite and monazite also occur on the Shark claims.

The Guano prospect is 2.8 km east of the Shark claims. Exploration and academic studies in the 1970s outlined a Th-U target along Guano Ridge. Fieldwork was undertaken in 2009 to reevaluate the area for REE potential, which prompted further exploration in 2010. The occurrence consists of hornfels and diopside-calcite-phlogopite skarn located in the metamorphic aureole of the syenite intrusion. The skarn is also intruded by dark coloured, altered zircon-enriched felsic dikes interpreted to be related to the syenite. Assays of 44 samples from the Guano prospect showed up to 6.02 wt.% TREO, Nb 2.52 wt.% Nb_2O_5, and 0.51 wt.% Ta_2O_5; the arithmetic average was 0.90% TREO and 0.55% Nb_2O_5, and the average proportion of HREE was 10%. Rietveld refinements of 6 rock pulps show allanite-(Ce) (up to 16.6%), zircon (up to 10.8%), fersmite (up to 1.9%), baddeleyite (up to 1.3%), hydroxylapatite (up to 1.2%), columbite (up to 0.6%), monazite-(Ce) (up to 0.5%), tazheranite (up to 0.4%), and xenotime-(Y) (up to 0.3%) as the REE-bearing minerals.

At the Camp Skarn, 1.2 km northwest of the Guano prospect, a coarse grained garnet-allanite skarn zone occurs over 150 m within altered syenite. Assays of seven rock samples showed up to 1.99% TREO. The average percentage of HREE in all of the Camp Skarn samples is 12%. Lower levels of Nb, Zr, and Th suggest this prospect has a different genetic history.

---

[1] *Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC, V6T 1Z4*

Lithium Resources

by D.L. Trueman[1]

ABSTRACT

Lithium (Li) deposits are found in a variety of geological environments but can be grouped into two categories: *endogenous* for those formed *in situ*, such as in granitic pegmatites, or *exogenous* for those deposits such as salars and brines formed away from their source rocks. Both types contributed to the some 22 500 tonnes of lithium produced globally in 2008. With the advent of Li production from brines however, the role of pegmatite Li production has been in decline. At present, several pegmatite Li projects are testing the viability of production of *battery grade* lithium.

Endogenous Deposits: Historically, and at present, Li production has come from granitic pegmatites. The best known of these are the Tanco pegmatite in Manitoba, the Greenbushes pegmatite in Australia, and the Bikita pegmatite in Zimbabwe. These pegmatites form a class by themselves in that they display well developed internal zoning and are distinct from primary spodumene pegmatites. The former group hosts Li in the form of lithiophosphates such as amblygonite-montebrasite, lepidolite, petalite and *squi*, an acronym for spodumene-quartz intergrowth formed from the breakdown of their primary lithium mineral petalite. Lithiophosphates are no longer produced, but squi and petalite are prized by the glass and ceramics industries for having very low iron content. Lepidolite is also used in Europe in the manufacture of glass and ceramics.

Primary spodumene pegmatites such as those at Kings Mountain, North Carolina and which occur abundantly in the Canadian Shield, are being touted as potential Li sources to satisfy the anticipated demand for lithium batteries in electric and hybrid electric vehicles. These pegmatites are characterized by poor internal zoning, and their Li mineralization extends essentially homogenously from the footwall to the hanging wall border zones. The high iron content of spodumene precludes its use in the glass industry but does not seem to be an issue in production of battery grade lithium carbonate. Spodumene contains nearly twice the amount of Li found in petalite and hence has a significant economic advantage as a source material outside of the glass industry.

Should global Li supplies become depleted, other endogenous sources of Li such as apogranites (Li-containing, F-rich, commonly topaz bearing, peraluminous granites which contain variable concentrations of Li micas or muscovite) may become viable resources.

Exogenous Deposits: These types of deposits include brines, salars formed from brines, and lithium bearing clays. At present, brines and associated salars in Chile and Argentina produce the preponderance of Li consumed globally. The cost of such production is very low and it is this economic aspect that has caused the near cessation of lithium pegmatite production. These economies must also be matched in the production of lithium from clays (hectorite) such as those for example, at McDermitt, Nevada or the Borate Hills clays near Silver Peak, Nevada. There are other large but unquantified lithium deposits in Tibet and a new, large jadarite bearing Li-B deposit is being investigated in Serbia.

The origins of exogenous deposits are somewhat speculative. In the case of clay deposits, it has been considered that lithium was derived from devitrication of volcanic glasses from topaz rhyolites, the effusive equivalents of apogranites. In the present speaker's experience some are clearly epithermal in origin.

Oilfield and geothermal brines found at depth may be well documented but little has been published on their grades, processing or economics. Lithium is highly mobile and these brines may have derived their lithium contents from deeper seated magmatism and hydrothermal systems.

---

[1] *Geological Consultant, Richmond, BC*

Geological Considerations for Lithium-Rich Devonian Oilfield Waters in the Swan Hills Area of West-Central Alberta

by D.R. Eccles[1], H. Berhane[1], C. McAleenan[2], L. Long[3] and G.F. Huff[1]

KEYWORDS: West-central Alberta, Devonian formation water, lithium, geochemistry, paragenesis

INTRODUCTION

Economic concentrations of lithium are known to form in lithium pegmatite and high-lithium brine and clay. In addition, some oilfield waters have medium to high lithium content including Devonian formations in North Dakota, the Jurassic Smackover Formation in the US Gulf Coast, and Cretaceous reservoirs in Texas. Exploration companies have recently expressed interest in the lithium potential of Alberta's oilfield waters. The awareness is largely due to a 1993 government study that reviewed nearly 130 000 chemical analyses of Cambrian to Triassic Alberta formation waters for economic industrial mineral potential (Hitchon *et al.*, 1993). These authors reported anomalous lithium concentrations of up to 140 mg/L in the Devonian carbonate build-ups of the Swan Hills area in west-central Alberta (Figure 1). The Li-rich oilfield waters occur in the Leduc (Woodbend Group) and Swan Hills (Beaverhill Lake Group) formations at depths of approximately 2500-3500 m below surface. Bachu *et al.*, (1995) estimated that the total lithium resource in the Leduc and Beaverhill Lake formation waters in the Swan Hills area is 515 000 tonnes over an area of 4000 km^2.

During 2009, at least three exploration companies verified the lithium potential of the Swan Hills formation waters when they reported compositions of up to 112 mg/L Li from brine-sampling programs of producing wells in the area. In addition to lithium, these companies also reported elevated boron (223 mg/L), potassium (5870 mg/L) and therefore the potential for a multi-element separation plant. Duplicate splits of industry collected water samples were donated to the Alberta Geological Survey for analytical procedures attempting to elucidate the origin and history of the Li-rich Swan Hills formation water.

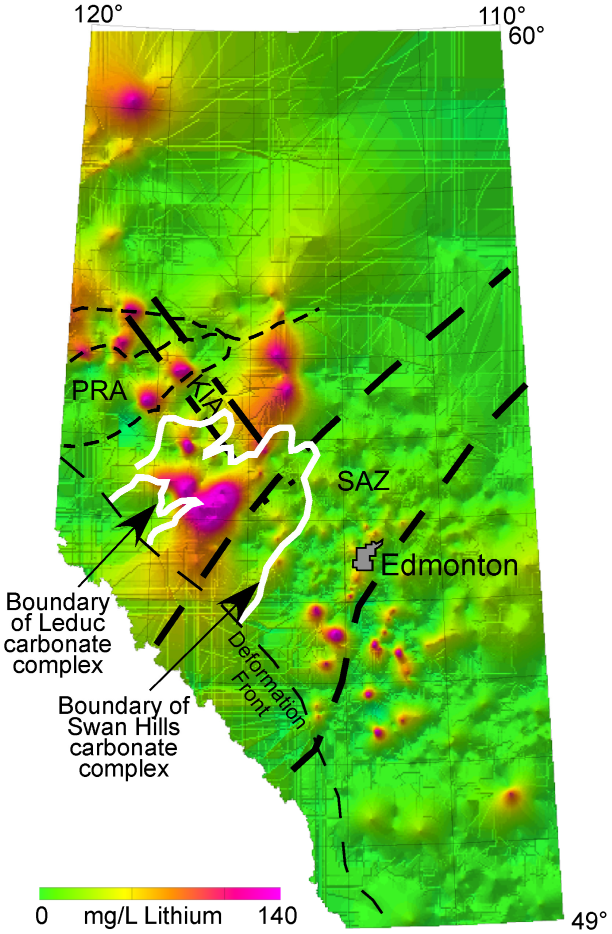

Figure 1. Shaded contour map of lithium-bearing formation waters in Alberta. The map is generated from a dataset totalling 1511 analyses (Eccles and Jean, 2010). Nineteen analyses with >100 mg/L Li (up to 140 mg/L) occur within the Middle to Upper Devonian Leduc (Woodbend Group) and Swan Hills (Beaverhill Lake Group) carbonate complexes in west-central Alberta. Abbreviations for selected west-central Alberta tectonic features: KIA - Kimiwan Isotopic Anomaly; PRA – boundary of the Devonian Peace River Arch; SAZ - Snowbird Anomaly Zone.

MAJOR-ION GEOCHEMICAL RESULTS

Lithium-rich (80-112 mg/L) and Li-poor (10-43 mg/L) water samples were analyzed for major-ion chemistry (n=13 and 5, respectively) and Li, Pb and Sr isotopes (n=7 and 5, respectively). These data are compared with 195 geochemical analyses from Li-bearing

---

[1] *ERCB, Alberta Geological Survey, Edmonton, AB*

[2] *Channel Resources Ltd., Vancouver, BC*

[3] *Headwater Mineral Exploration & Development Ltd., Red Deer, AB*

Devonian formation waters throughout Alberta (Eccles and Jean, 2010; Alberta Geological Survey data holdings). We also obtained three regional basement rock powders (variations of biot-plag-micro-hbld-gneiss) for isotopic comparison.

The majority (92%) of the data are hypersaline Na-Ca-Cl type water typical of Devonian aquifer systems. In Cl-Br space, there is not much deviation from the seawater evaporation trajectory (SET; Fontes and Matray, 1993; Figure 2a). Starting as seawater, the brine has evaporated up to the point of halite formation with little evidence of halite dissolution or dilution with meteoric water. A small cluster of >100 mg/L Li waters from the Cooking Lake carbonate platform located ~275 km southeast of the Swan Hills has evaporated past halite precipitation; possibly as a product of advanced evaporation similar to processes responsible for potash precipitation.

Based on an evaluation of Devonian to Tertiary formation waters in west-central Alberta, Michael and Bachu (2001) suggested highly saline, low Na/Cl ratio Devonian waters are partly the product of albitization of feldspar as waters refluxed through the crystalline basement. When sodium of Li-bearing Devonian water is evaluated against SET, however, there is only slight evidence of Ca-Na exchange and albitization. Rather, Figure 2b shows Li-rich brine experienced significant potassium enrichment suggestive of water-rock interaction involving silicate alteration. In addition, Mg and Ca are far removed from the SET suggesting these brines were highly influenced by dolomitization (Figures 2c, d). As dolomitization requires Mg and expels Ca, these elements were either subtracted or added to the resulting brine relative to seawater.

ISOTOPIC GEOCHEMICAL RESULTS

Radiogenic ^{87}Sr/^{86}Sr (0.720465-0.725840) characterizes the high-Li formation water while the low-Li water approaches the Sr isotopic composition of Devonian seawater (Figure 3a). This defines two end-members in our dataset where normal seawater trends towards radiogenic ^{87}Sr/^{86}Sr associated with water-silicate interaction. The Pb-isotope data are generally scattered, but radiogenic such that they mimic basement, or plot between basement and the Swan Hills carbonate Pb-isotope values (Duggan, 1997). The δ^7Li isotope values range between +6‰ and +16‰, forming a tight cluster between +10‰ and +13‰ (Figure 3b). These δ^7Li values are substantially lighter than seawater and the Heletz-Kokhav, Israel oilfield brines (Chan *et al.*, 2002), providing further evidence that the Swan Hills Devonian formation waters experienced significant silicate interaction, and possibly, are associated with marine hydrothermal vent fluids.

SUMMARY AND PARAGENETIC CONSIDERATIONS

Geological processes in the Swan Hills area have effectively shed their impurities (Li, K, B) to create Li-rich brines in the Beaverhill Lake-Woodbend-Winterburn aquifer systems. The source of these impurities is ultimately unknown, but they preclude halite precipitation, involve alteration of silicate (particularly Li- and K-bearing minerals), and correlate with dolomitization. As tempting as it is to consider Li^+-Mg^{2+} substitution and expulsion during dolomitization (due to their similar ionic ratios and charge imbalance, respectively) temporal and even spatial association between silicate-leachate and dolomitization is not required to produce Li-rich brine. It is unlikely that even the dirtiest carbonate could have sequestered enough monovalent cations of Li^+ and K^+ prior to, or during dolomitization, to produce potentially economic Li-bearing brine. A more viable scenario involves direct contact between Devonian waters and basement, or mobilization of silicate-bearing fluids to the aquifer.

At least two Swan Hills carbonate complex dolomitization models are applicable, the squeegee flow model (Machel *et al.*, 2001), and the fault-controlled dolomitization model (Duggan *et al.*, 2001). Both models advocate silicate interaction, either directly through reflux with the Precambrian basement, or with immature siliciclastics deposited above the basement (*e.g.*, Cambrian basal sandstone and/or Devonian Gilwood and Watt Mountain formations). The squeegee model contends that ^{87}Sr/^{86}Sr-isotope values are unusually high adjacent to the deformation front and decrease into the foreland basin. The fault-controlled dolomitization model contends that dolomitization is plume-like, confined to laterally confined flow systems associated with faults, and that at least some of the dolomitizing fluids were hydrothermal. The fault-controlled dolomitization model seems more appropriate to form the relatively isolated Li-rich formation waters in the Swan Hills; however, fluids emanating from both models could have contributed Li, K, and B. In addition, we propose spatial association between the Swan Hills and west-central Alberta basement tectonic features. Any model of Li-accumulation of these formation waters must consider the Peace River Arch, Kimiwan Isotopic Anomaly and Snowbird Tectonic Anomaly.

ACKNOWLEDGMENTS

We thank R. Burwash, emeritus professor with the University of Alberta, for donating basement rock powders. Water geochemistry was completed at Exova in Edmonton, Alberta. We are also grateful to K. Kyser of Queen's University and his laboratory staff for completing Sr, Pb and Li isotope analyses.

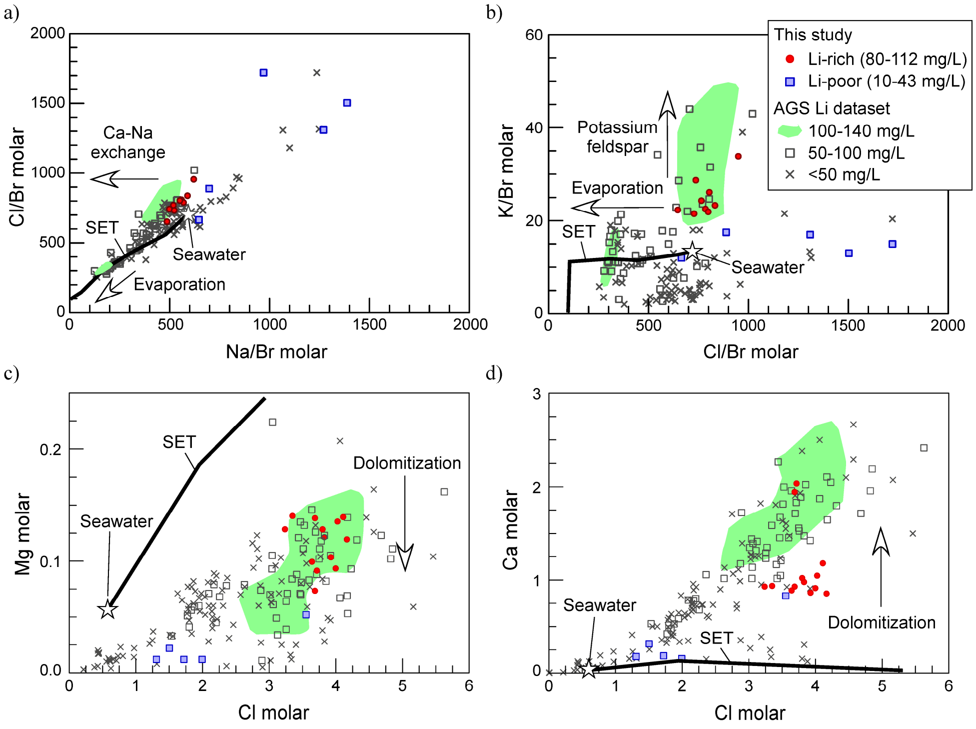

Figure 2. Na-Cl-Br, K-Cl-Br, Mg-Cl and Ca-Cl systematics of lithium-bearing formation waters in the Swan Hills (this study; solid symbols) and Alberta Devonian formation waters (grouped according to Li values). Heavy solid line represents the modern day seawater evaporation trajectory (SET) from Fontes and Matray (1993).

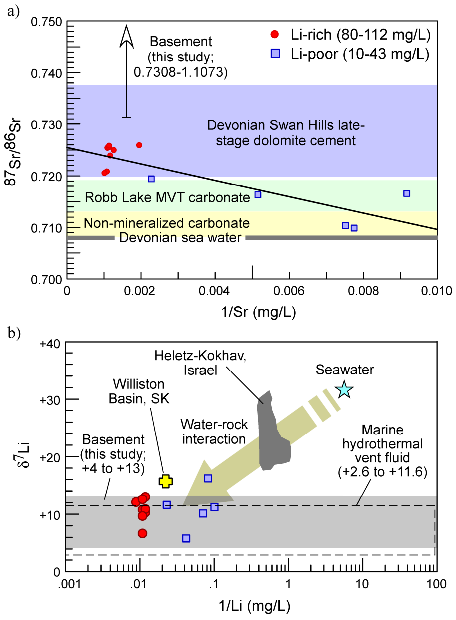

Figure 3. Plot of $^{87}Sr/^{86}Sr$ and δ^7Li ratios versus their inverse Sr and Li concentrations for lithium-bearing formation waters in the Swan Hills. A) For comparison: Devonian sea water, Devonian Manetoe facies, Presqu'ile Barrier Reef, and Western Canada Sedimentary Basin Cambrian non-mineralized carbonate, mineralized dolomite and saddle dolomite from the Robb Lake Mississippi Valley Type (MVT) deposit (Pana, 2006 and references therein); and late-stage "pure" calcite and dolomite cement from burial dolomite at the Swan Hills Simonette Reef (Duggan et al., 2001). B) For comparison: Heletz-Kokhav, Israel oilfield brine, Williston Basin brine, and marine hydrothermal vent fluid (Tomascak, 2004 and references therein).

REFERENCES

Bachu, S. Yuan, L.P. and Brulotte, M. (1995): Resource estimates of industrial mineral in Alberta formation waters; Alberta Research Council, Alberta Geological Survey, Open File Report 1995-01, 59 pages.

Chan, L-H., Starinsky, A. and Katz, A. (2002): The behavior of lithium and its isotopes in oilfield brines: Evidence from the Heletz-Kokhav field, Israel; Geochimica et Cosmochimica Acta, Volume 66, pages 615-623.

Duggan, J.P. (1997): Sedimentology and diagenesis of Swan Hills Simonette oilfield, west-central Alberta basin; M.Sc. Thesis, McGill University, Montreal, 177 pages.

Duggan, J.P., Mountjoy, E.W. and Stasiuk, L.D. (2001): Fault-controlled dolomitization at Swan Hills Simonette oilfield (Devonian), deep basin west-central Alberta, Canada; Sedimentrology, Volume 48, pages 301-323.

Eccles, D.R. and Jean, G.M. (2010): Lithium ground- and formation-water geochemical data; Energy Resources Conservation Board, Alberta Geological Survey, Digital Data 2010-0001.

Fontes, J.Ch. and Matray, J.M. (1993): Geochemistry and origin of formation brines from the Paris Basin, France; Chemical Geology, Volume 109, pages 149-175.

Hitchon, B., Underschultz, J.R. and Bachu, S. (1993): Industrial mineral potential of Alberta formation waters; Alberta Research Council, Alberta Geological Survey, Open File Report 1993-15, 85 pages.

Machel, H.G., Buschkuehle, B.E. and Michael, K. (2001): Squeegee flow in Devonian carbonate aquifers in Alberta, Canada; In: R. Cidu (ed.), Water-Rock Interaction, Vol. 1. Proceedings of the 10th International Symposium on Water-Rock-Interaction, Villasimius, Italy, pages 631-634.

Michael, K. and Bachu, S. (2001): Origin and evolution of formation waters in the west-central part of the Alberta basin; Rock the Foundation Convention, Canadian Society of Petroleum Geologists, June 18-22, 2001, pages 004-1 to 004-5.

Pana, D. (2006): Unravelling the structural control of Mississippi Valley-type deposits and prospects in carbonate sequences of the Western Canada Sedimentary Basin; In: P.K. Hannigan (ed.), Potential for carbonate-hosted lead-zinc Mississippi Valley-type mineralization in northern Alberta and southern northwest Territories. Geological Survey of Canada, Bulletin 591, pages 255-304.

Tomascak, P.B. (2004): Developments in the understanding and application of lithium isotopes in the earth and planetary sciences; Reviews in Mineralogy and Geochemistry, Volume 55, pages 153-195.

The Whabouchi Lithium/Beryllium Deposit, Quebec, Canada Geology, Resource Estimates and Mineralogical Characteristic

by G. Bourassa[1]

ABSTRACT

The Whabouchi property is located in the southeastern portion of the Archean Superior Province, more specifically in the Lac des Montagnes volcano-sedimentary formation, which is principally composed of metasediments and mafic-ultramafic amphibolites. Geographically, it is located in the James Bay region, about 300 km North of Chibougamau.

The Whabouchi spodumene-bearing pegmatite swarm is composed of a series of subparallel and generally subvertical pegmatites. The mineralised pegmatite swarm have a general NE-SW orientation, it is up to 130 metres wide, extends to more than 1.3 km along strike and reaches a depth of more than 300 metres below surface. The lithium mineralisation is hosted by the spodumene-bearing pegmatite phase which corresponds to most of the pegmatite swarm material. The mineralisation observed at Whabouchi consists principally of spodumene crystals (up to 30 centimetres in length), finer grained petalite and beryl.

Nemaska completed a total of 37 surface channels and 67 drillholes for 12 755 m. From these channels and drillholes, 5161 samples were collected and sent for analysis. The results allowed *Nemaska Exploration* to delineate a lithium-beryllium mineral deposit with mineral resource estimate, of 9.8 million tonnes grading 1.63% Li_2O and 449 ppm BeO in the Measured and Indicated resources categories, and an additional 15.4 million tonnes grading 1.57% Li_2O and 420 ppm BeO in the Inferred resources category (Laferriere, 2010). The cutoff used to obtain these estimates was 0.5% Li_2O.

A high definition mineralogical study was performed on six composite drill core samples. X-ray diffraction analysis indicates that all samples consist mainly of quartz, albite and microcline, and muscovite. The Li-bearing phase in two of these samples was spodumene in proportions ranging between ~14% and ~16%, while three others had both spodumene and petalite in proportions ranging from 10% to 20% and 3% to 13%, respectively.

REFERENCES

Laferrière, A. (2010): NI 43-101 Technical Report, Mineral Resource Estimation, Whabouchi lithium deposit, Nemaska Exploration,SGS Canada inc., 73 pages.

---

[1] *Nemaska Exploration, Québec, QC*

Yttrium and HREE – Real and Potential Economic Sources

by A.N. Mariano[1]

ABSTRACT

Currently the major source for Y and HREE is from the ion-adsorbed REE clays of South China. Small, unsustained concentrates of xenotime (YPO_4) are periodically derived as byproducts from tin and titanium mining of beach sands.

For a short period of time Y and HREE were extracted from fluids (rafinates) resulting from the chemical processing of uraninite from the Blind River-Elliot Lake deposit of Ontario, Canada.

At this time a number of exploration programs are being conducted both in the field and in processing laboratories directed to the acquisition of Y and HREE from alkali-zirconosilicates (AZS) with special attention to the mineral eudialyte.

This presentation reviews the apparent major sources of Y and HREE.

---

[1] *Consulting Geologist, Carlisle, MA, United States*

Exploration Geophysics for Intrusion-Hosted Rare Earth Metals

by M.D. Thomas[1], K.L. Ford[2] and P. Keating[3]

ABSTRACT

Alkaline and carbonatitic intrusions feature prominently as hosts for rare earth metals. Pegmatites and intrusive veins are also recognized as sources for such metals, but deposits are characteristically much smaller. Historically, intrusion-related rare earth metals have been discovered using a variety of exploration techniques and occasionally by chance. Examples of geological serendipity are the discoveries of the Kipawa alkaline complex, Quebec, when rare earth minerals were identified while drilling for uranium, and the Oka alkaline complex, Quebec, when thorium and a pyrochlore-microlite series mineral were noted in magnetite-bearing rocks collected by a farmer. A case of serendipitous geophysical discovery is that of the Mountain Pass carbonatite, California, where ground exploration for uranium using a Geiger counter located a radioactive outcrop yielding bastnaesite. More conventional techniques leading to discovery of rare earth metals are geochemical surveys (anomalous F and Pb in lake water and sediment targeted the Strange Lake alkaline complex, Quebec/Newfoundland-Labrador), airborne radiometric surveys (the St-Honoré carbonatite complex, Quebec was discovered when high thorium values and presence of rare earths were determined by ground follow-up within the area of an intense anomaly) and aeromagnetic surveys (a prominent circular magnetic anomaly located the Mount Weld carbonatite, Western Australia under alluvial cover).

Geophysical successes depend not so much on the physical properties of the rare earth metals and minerals as on the physical properties of the host rocks. This is true for several other economic minerals, which are discovered geophysically by association rather than directly. Diamond-hosting kimberlite pipes producing circular anomalies are a classic example of "discover the host, discover the commodity". Rare earth oxide minerals have relatively high densities ranging generally from 3.5 to 7.2 g/cm^3, and most lanthanide rare earth compounds are stated to be strongly paramagnetic. A significant direct magnetic expression would not therefore be expected, whereas a gravity response might be generated depending on the grade, size, attitude and depth of rare earth mineralization. One property of rare earth minerals that does translate into a more directly linked signature is radioactivity, which may be significant in some minerals, *e.g.*, pyrochlore, monazite, zircon.

For both alkaline and carbonatite intrusions it is apparent the principal gravity and magnetic signatures relate to the intrusions, and not to rare earth mineralization. For carbonatites significant positive gravity anomalies may be expected consequent on comparatively higher densities of carbonatitic and any accompanying mafic intrusive varieties. The Oka carbonatitic and alkaline complex is associated with a gravity high attaining 15 mGal above background, and attributed to rocks of the complex that have densities ranging typically from 2.84 – 3.41 g/cm^3 in comparison to country rock densities that are generally < 2.75 g/cm^3 (Gold *et al.*, 1967). The St-Honoré carbonatite complex likewise is accompanied by a strong gravity expression (Vallée and Dubuc, 1970). Mafic and ultramafic components of alkaline complexes may also produce positive gravity signatures. Until fairly recently gravity surveying has been used as a follow-up technique to assess host intrusions discovered by other means. In Canada, for land areas, the national gravity data base comprises ground measurements made several kilometres apart (typically 6-15 km), which generally lack the resolution to identify the described intrusive targets. This situation is likely to change with airborne gravity surveys yielding increased resolution and accuracy.

The aeromagnetic technique has an advantage in that the greater part of Canada is covered by surveys flown at 805 m line-spacing, and in the last decade an increasing number of areas have been reflown at 400 m line spacing. At these resolutions aeromagnetic data are capable of outlining magnetic anomalies associated with carbonatitic and alkaline intrusions. Some forty years ago Satterly (1970), using principally maps published as a result of the national aeromagnetic program, compiled the geophysical expression of 34 carbonatitic-alkalic complexes in Ontario, commenting on their potential for rare earths among other types of mineralization, yet recognizing that little was known about the geology in some cases. Satterly (1970) noted that many of the complexes had been found by "aeromagnetic or aeroradiometric" surveys by mining companies and government agencies. It was observed that in the simplest complexes carbonatite cores coincide with magnetic lows, whereas surrounding highs might be associated with magnetite-bearing carbonatite or a ring of alkalic rocks. Diameters of the most circular anomalies range from about 3–16 km, and amplitudes commonly

---

[1] *Geological Survey of Canada, Ottawa, ON*

[2] *Geological Survey of Canada, Ottawa, ON*

[3] *Geological Survey of Canada, Ottawa, ON*

attain several thousand nT. Such a circular anomaly (Figure 1) led to the discovery in 2007 of Quest Uranium Corporation's Misery Lake rare earth alkali intrusive complex, which is a 6 km diameter compositionally zoned ultramafic to granitic intrusion in northeastern Quebec. Mineralization is associated with magnetite-rich magmatic segregation layers.

Widespread magnetic coverage and strong circular signatures make the magnetic method one of the prime choices for exploration of rare earth minerals. The magnetic technique benefits from availability of cospatial radiometric data, which help discriminate between circular magnetic anomalies related to favourable alkaline intrusions and other magnetic intrusions barren of rare earth minerals, based on the presence or absence of a strong radioactive signature. And the radiometric approach is a powerful means of targeting favourable host intrusions in its own right. An example of its effectiveness is the discovery of the Allan Lake carbonatite, Ontario. It was discovered by a reconnaissance (5 km line-spacing) airborne gamma-ray spectrometric survey in 1977 under the Geological Survey of Canada's Uranium Reconnaissance Program (Ford *et al.*, 1988). Ground follow-up investigations detected a glacial dispersal train composed of Th-rich till containing Th-bearing carbonatite boulders. A refined radiometric-magnetic survey flown at 1 km and 0.5 km line-spacing along with various ground geophysical, geochemical and geological studies led to eventual drilling of a small (~800 m diameter) unexposed carbonatite under a small lake. The equivalent thorium signature outlining the glacial dispersal train from the Allan Lake carbonatite is displayed in Figure 2. The example of the Allan Lake carbonatite demonstrates the utility of the radiometric method in Canada's glaciated environment, where glaciation offers a larger fingerprint of potential mineralization than would be observed in a non-glaciated environment. A case in point is a radiometric signature extending at least 50 km down ice from the Strange Lake alkaline complex.

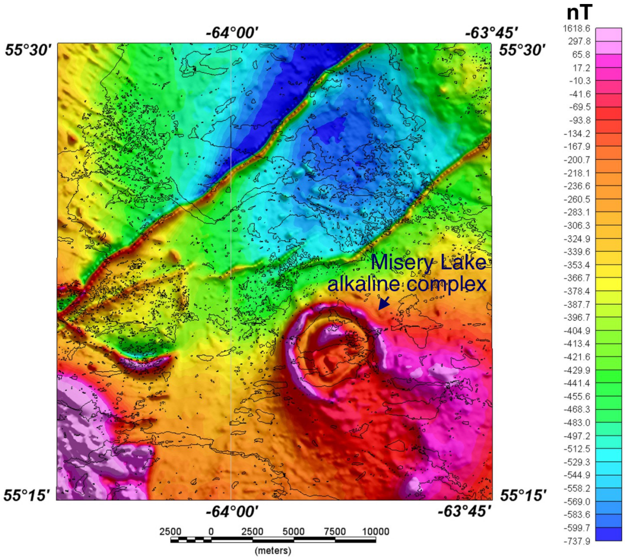

Figure 1. Residual total magnetic field map of the area of the Misery Lake alkaline complex hosting rare earth mineralization, Quebec.

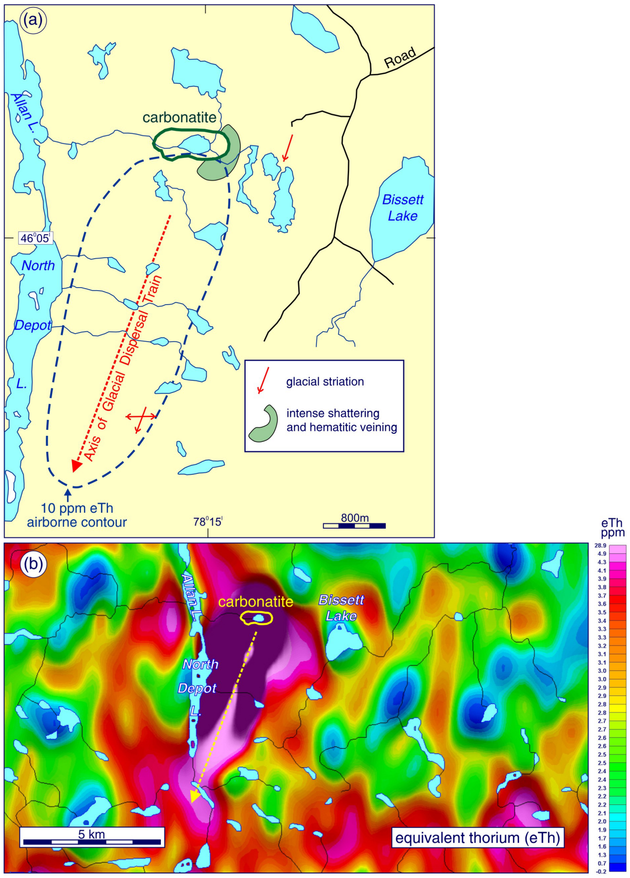

Figure 2. (a) Outline of equivalent thorium concentration signature outlining the thorium-rich glacial till in a dispersal train originating at the Allan Lake carbonatite, Ontario (Modified from Ford *et al.*, 1988). (b) Colour image of equivalent thorium concentrations measured by an airborne survey in the area of the Allan Lake carbonatite highlighting the prominent anomaly associated with the glacial dispersion train.

The magnetic and radiometric methods, besides targeting hosts of rare earth mineralization, along with the gravity technique, have a role to play in more focused exploration investigations once the target has been located. Modelling of anomalies provides structural and geometric information and a glimpse into the third dimension. Modern airborne surveys now offer concurrent acquisition of magnetic, radiometric, electromagnetic and gravity data. Access to a suite of such data holds considerable promise for future discovery of rare earth deposits.

REFERENCES

Ford, K.L., Dilabio, R.N.W. and Rencz, A.N. 1988. Geological, geophysical and geochemical studies around the Allan Lake carbonatite, Algonquin Park, Ontario. Journal of Geochemical Exploration, Volume 30, pages 99-121.

Gold, D.P., Vallée, M. and Charette, J-P. 1967. Economic geology and geophysics of the Oka alkaline complex, Quebec. Transactions of the Canadian Institute of Mining, Volume LXX, pages 245-258.

Satterly, J. 1970. Aeromagnetic maps of carbonatite-alkalic complexes in Ontario. Ontario Department of Mines and Northern Affairs, Preliminary Map No. 152 (Revised).

Vallee, M. and Dubuc, F. 1970. The St-Honoré carbonatite complex, Québec. Transactions of the Canadian Institute of Mining, Volume LXXIII, pages 346-356.

Remote Sensing in the Search for Rare Metals

by W.E. Kilby[1] and D.N. Riley[2]

ABSTRACT

Minerals and rocks hosting Rare Earth Element (REE) deposits have electromagnetic spectral signatures that can be identified and spatially located with airborne and space based sensors. The spectral characteristics of these materials have been known for many years but it has only been in the last decade or so that suitable sensors have become widely available to the mineral exploration community. Remote sensing systems are now available that can measure the reflected and emitted electromagnetic radiation (EMR) with wavelengths between .45 and 14 µm passing through several atmospheric windows. Figure 1 locates the positions of these atmospheric windows and the potential measurable EMR available. Figure 2 illustrates the energy pathway from source to sensor. Reflectivity measurements require an unobstructed path from the sun to the surface material and back to the sensor. A high sun angle and no obstructing clouds are required to provide adequate energy to measure spectral details. Emissivity measurements only require a clear path from the surface material to the sensor. This allows collections to be made in any lighting conditions, day or night, and below cloud cover.

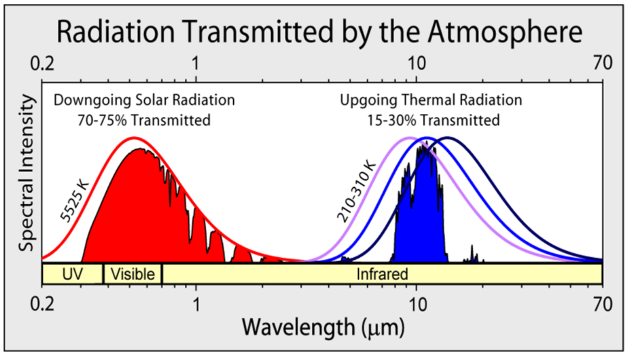

Figure 1. Red and blue areas denote the regions of the electromagnetic spectrum that can be measured. The red and blue curves represent the total energy input across the spectrum and the difference between the curves and areas represents the energy blocked by the atmosphere (www.Globalwarmingart.com, 2010).

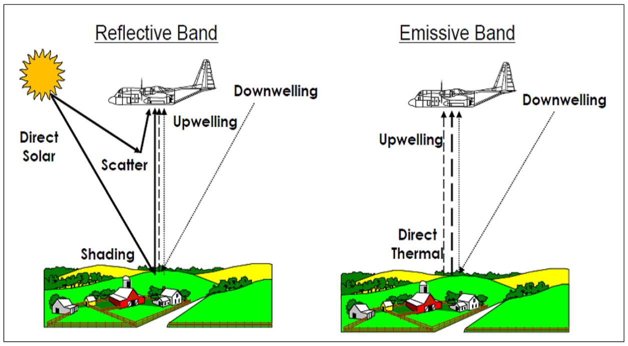

Figure 2. Energy pathways for reflective and emissive energy (Schulenburg, 2009).

REE oxides of elements such as neodymium, samarium and europium have spectral features in the visible to near infrared (VNIR, .45 - 1.0 µm) and short-wave infrared (SWIR, 1.0 - 2.5 µm) range (Figure 3). Minerals such as bastnaesite and monazite containing lanthanum and cerium can be identified and mapped using these spectral features. Potential carbonatite host rocks have spectral features in the SWIR and long-wave infrared (LWIR, 7.5 - 14.0 µm) range that are sensitive to the relative portions of Ca, Mg and Fe (Figure 4). Potential silicate host rocks such as syenite, nepheline syenite, trachyte and quartz monzonite have spectral features best defined in the LWIR range (Figure 5).

Spaceborne multispectral systems such as ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and the new WorldView-2 (WV-2) systems provide limited but useful first look capabilities. The eight VNIR bands and 4 metre spatial resolution of WV-2

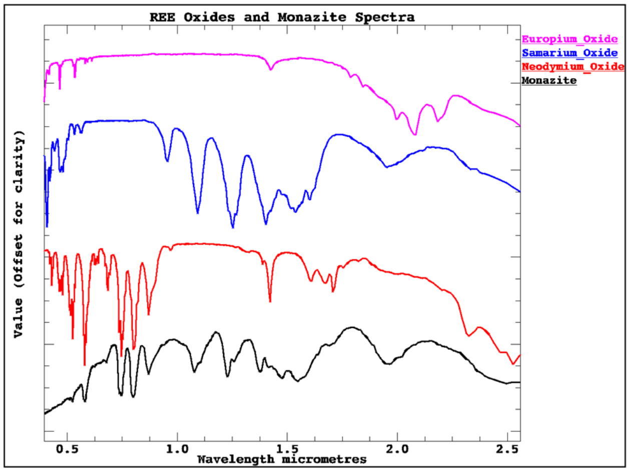

Figure 3. Reflectance spectra from USGS Spectral Library. See Figure 8 for an example of a Bastnaesite spectrum. Note strong Nd features in Monazite and Bastnaesite.

---

[1] *Cal Data Limited*

[2] *The Aerospace Corporation*

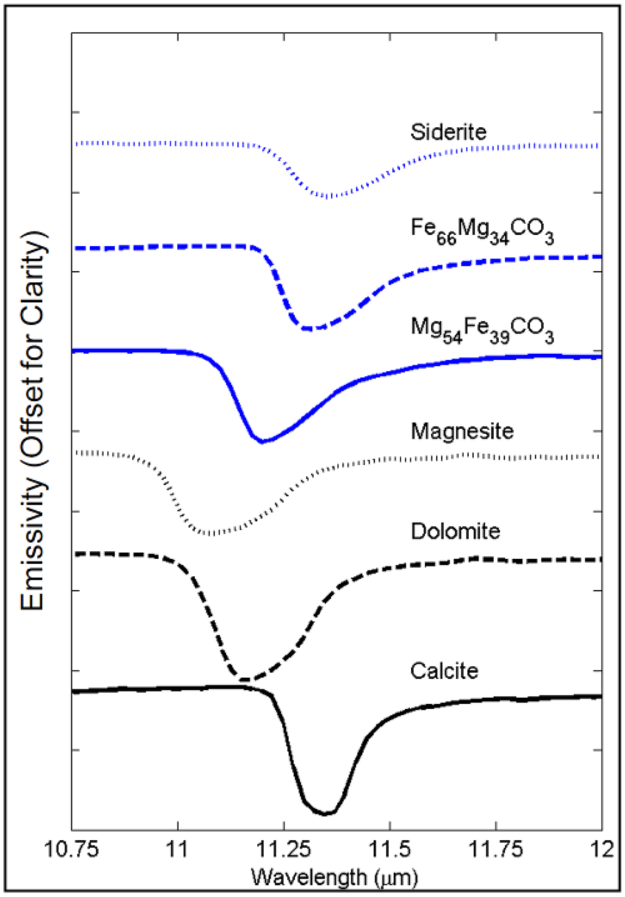

Figure 4. Emissivity spectra of carbonate minerals showing the migration of the feature with variable element content (Schulenburg, 2009).

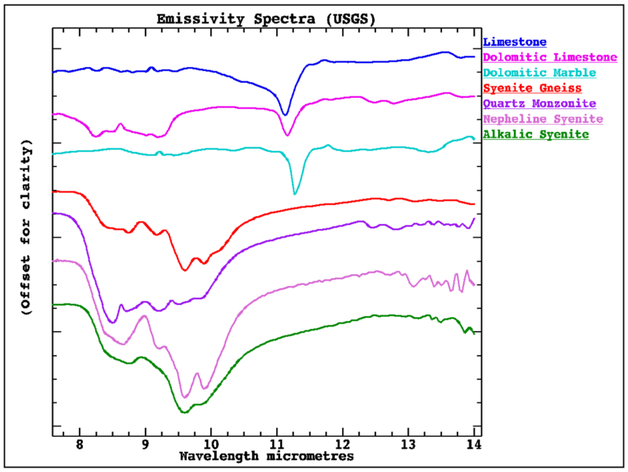

Figure 5. Emissivity spectra from USGS Spectral Library for common rocks found in association with carbonatite deposits.

should prove useful in identifying Nd spectral features (Figure 6). ASTER has proven useful in identifying and mapping known REE deposits but its 15-90 metre spatial resolution is a limiting factor (Figure 7).

Airborne hyperspectral systems are capable of sampling the available EMR in sufficient detail to identify most spectral features that can be identified in a laboratory environment. Image spatial resolution can be controlled by instrument to ground distance, with 1 metre resolutions commonly available. Systems such as AVIRIS, HYMAP, CASI-SASI and ProSpecTIR (AISA) map the VNIR and SWIR regions of the spectrum with up to 227 discrete bands. Figure 8 is an example of AVIRIS mapping of bastnaesite at Mountain Pass. The relative abundance of Nd can be inferred by feature depth. The LWIR region of the spectrum can be mapped with SEBASS (Spatially Enhanced Broadband Array Spectrograph System) and TASI-600. Each system has different capabilities and availability. These two classes

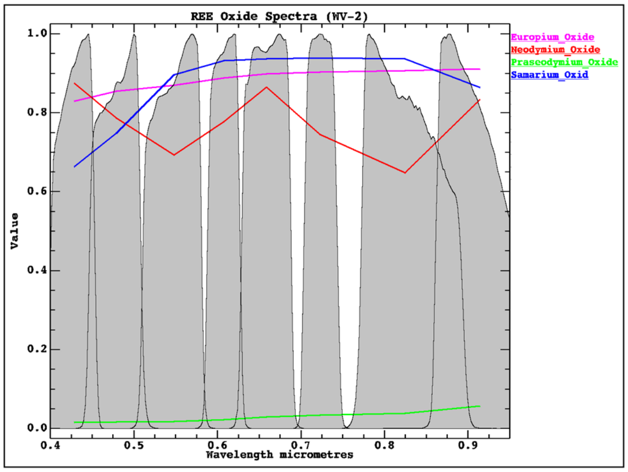

Figure 6. Expected WorldView-2 spectra for some REE. The Neodymium spectra will be the most distinctive. The grey response curves illustrate the portion of the EMR spectrum sampled by each of the eight bands.

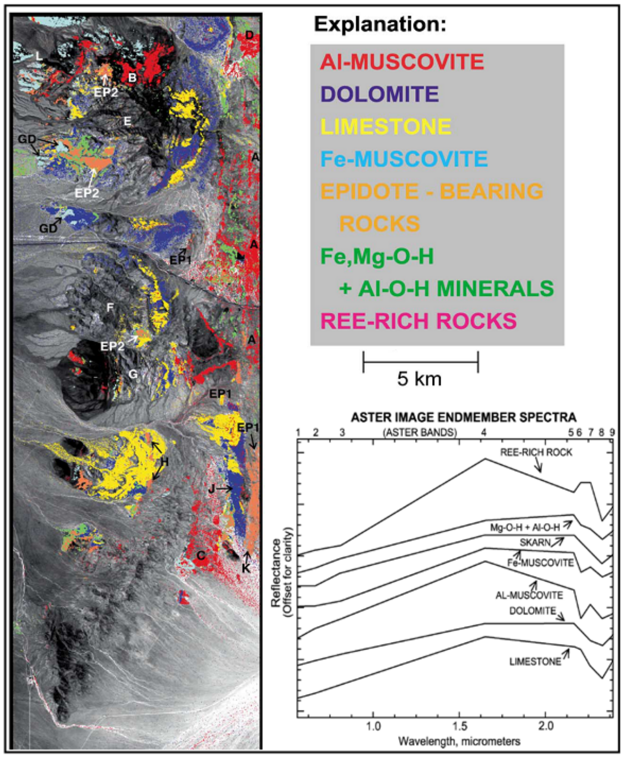

Figure 7. ASTER mapping of the region surrounding Mountain Pass carbonatite (Rowan and Mars, 2003).

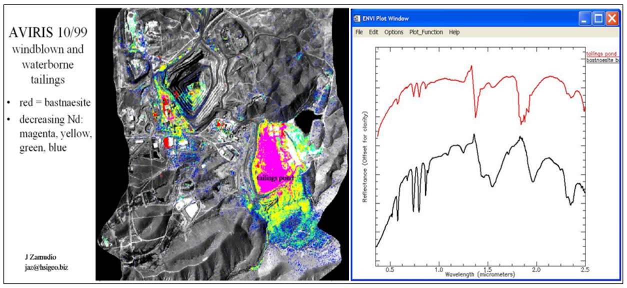

Figure 8. AVIRIS image overlain with relative abundance of Nd obtained by image spectral analysis. Two spectra on the right were collected in the field with an ASD field spectrometer (Zamudio, 2010).

of instruments (reflectance and emissivity) and their uniquely different collection characteristics now provide complete spectral mapping capabilities. Surveys designed around both reflectivity and emissivity provide significant collection flexibility, increased mineral species identifiable and more robust identification of many minerals. SpecTIR LLC is currently flying the ProSpecTIR (VNIR-SWIR) instrument along with SEBASS (MWIR-LWIR) on a single platform providing 613 spectral channels (Figure 9).

Figure 9. An example of VNIR, SWIR and LWIR sensors mounted on a single platform (Twin Otter). SEBASS - left red arrow, high resolution camera – middle arrow and ProSpecTIR – right red arrow (Riley, *et al.*, 2008).

REFERENCES

Globalwarmingart.com (2010): Radiation Transmitted by the Atmosphere; URL http://WWW.Globalwarmingart.com, {Oct 2010}.

Riley, D.N., Peppin, W.A., Bryant, G.P., Wright, C., Schulenburg, N.W., and Landers, M. (2008): Airborne Collection of Hyperspectral Systems: Mineral Mapping Cuprite in VNIR-SWIR and MWIR-LWIR with 613 Spectral Channels; Annual General Meeting of the Geological Remote Sensing Group, Geological Society of London, December 2008.

Rowan, L.C. and Mars, J.C. (2003): Lithologic mapping in the Mountain Pass, California area using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data; Remote Sensing of Environment 84. pp 250-266.

Schulemburg, N.W. (2009): On Using SEBASS as a Mineral Exploration Tool; Annual General Meeting of the Geological Remote Sensing Group, Geological Society of London, December 2009.

Zamudio, J.A., (2010) pers communication, Oct 2010.

Rare Metal Occurrences and Exploration Potential in Québec

by C. Maurice[1]

ABSTRACT

Rare metals (Nb, Ta, Li, Be, Zr, Hf, rare earths, Y and Sc) are elements that are considered as essential strategic substances in the high tech sector (energy, transport, telecommunications, ceramics). Québec contains several geological environments favourable to the discovery of rare metal mineralization. A detailed compilation of showings, prospects and deposits at the scale of the province has led to a genetic classification comprising seven main types of mineralization (Gosselin *et al*., 2003; Boily and Gosselin, 2004). This classification now needs to be updated in light of the recent interest in rare metal exploration. Several new discoveries made by the industry and the Québec government will thus be compiled and then possibly integrated into a national database as part of a Targeted Geoscience Initiative project (TGI-4).

Regional work in the Churchill Province recently led to a better documentation of prospective signatures for rare metals associated with anorogenic alkaline plutonic rocks (rare earths, Y, Zr ±Be, ±Nb). New aeromagnetic data (Dumont *et al.*, 2010) improved the delineation of magmatic phases within these plutons, some of which contain rare earth mineralization. In addition, the reanalysis of lake sediments by the ICP-MS method (Maurice and Labbé, 2009) now makes possible to identify concentrations of elements that were previously unavailable or undetectable, including beryllium (Be) which serves as an excellent tracer for targeting alkaline intrusions. The application of these findings to the remaining of Québec, notably in the Grenville Province, may eventually lead to the discovery of new rare metal mineralization.

REFERENCES

Boily, M. and Gosselin, C. (2004): Les principaux types de minéralisations en métaux rares (Y-Zr-Nb-Ta-Be-Li-ETR) du Québec. Ministère des Ressources naturelles et de la Faune du Québec; ET 2004-01, 46 pages.

Dumont, R., Fortin, R., Hefford, S. and Dostaler, F. (2010): Série des cartes géophysiques, parties des SNRC 13L, 13M, 23I et 23P, levé géophysique lac Ramusio, région de Schefferville. Ministère des Ressources naturelles et de la Faune du Québec; DP 2010-01, 6 pages.

Gosselin, C., Boily, M., Beaumier, M., Leduc, M., Dion, D.J., Garneau, C. and Thériault, R. (2003): Les minéralisations en métaux rares (Y-Zr-Nb-Ta-Be-Li-ETR) au Québec. Ministère des Ressources naturelles et de la Faune du Québec, DV 2003-03, 1 poster, 1 CD-ROM.

Maurice, C. and Labbé, J.Y. (2009): Réanalyse de sédiments de fond de lac dans la partie nord-est du Québec (Sous-province d'Ashuanipi, Orogène du Nouveau-Québec et Province de Churchill Sud-Est). Ministère des Ressources naturelles et de la Faune du Québec; PRO2009-09, 8 pages.

---

[1] *Bureau de l'exploration géologique du Québec, Ministère des Ressources naturelles et de la Faune*

Rare-Earth Element Mineralization in Labrador and Newfoundland: An Overview of the Geological Context, Mineralization and Exploration Potential

by A. Kerr[1]

ABSTRACT

Since 2007, increased interest in exploration for deposits of Rare-Earth Elements (REE, *i.e.* La, Ce, Pr, Nd, Sm, Nd, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) and associated rare metals (RM, *e.g.* Zr, Y, Nb, Be) has been driven by commodity price increases linked to demand-supply imbalance. In Labrador and adjacent Québec, this has led to renewed evaluation of previously-defined deposits, and to grass-roots activity in prospective but unexplored regions. REE deposits in this region are all associated with peralkaline igneous suites of known or presumed Mesoproterozoic age, which in part represent the extension of the well-known Gardar igneous province in Greenland. The island of Newfoundland has not seen the same level of exploration activity, but it contains numerous peralkaline igneous suites, and REE mineralization is known in several areas.

The largest resource sits near the Québec-Labrador border at Strange Lake, hosted by a ~1240 Ma peralkaline ring complex. Previous exploration outlined 56 Mt of 2.9% ZrO_2, 0.38% Y_2O_3, 0.31% Nb_2O_5, 0.08% BeO and ~0.54% total REE oxides (TREO; Y_2O_3 excluded), including a smaller high-grade near-surface zone containing up to 1% Y_2O_3 and 1.3% TREO. Development of this deposit was proposed in the 1980s, but faltered due to the remote location and poor market conditions. The deposit is presently exempt mineral lands (EML), but similar mineralization a few kilometres inside Québec is now part of an advanced exploration project, where substantial resources of similar grade are defined. Strange Lake is enriched in the more valuable "heavy" REE, which make up about 30% of total REE oxides (excluding Y_2O_3). The potential for definition of large bulk-tonnage resources in this complex is good. Mineralization is associated with a the youngest unit in the host peralkaline complex, which is strongly enriched in Zr, Y, Nb and REE; the highest grade mineralization is hosted by complex aplite-pegmatite zones near the roof of this body. REE-Nb-Be deposits also occur in central Labrador, in the ~1330 Ma volcanic rocks of the Letitia Lake Group and the coeval Red Wine Intrusive Suite. The original geological relationships here are locally obscured by mineralization in undersaturated metasyenites is entirely different, consisting of disseminated to semi-massive eudialyte (Na-Ca-Zr silicate). This style of mineralization is enriched in Zr and heavy REE, and could be the locally intense Grenvillian deformation, but mineralization is still viewed as broadly syngenetic with respect to host peralkaline suites. Volcanic-related mineralization is enriched in Be and light REE, but cumulate counterpart to the incompatible-element-enriched association seen at inferred higher levels. Outside these previously-defined areas, other early-stage exploration programs have given encouraging results. In southeastern Labrador, at least two styles of mineralization are defined in the Port Hope Simpson area, and these also represent contrasting light-REE- and heavy-REE-enriched signatures, hosted by felsic gneisses and later pegmatites, respectively. Drilling of these prospects commenced in the fall of 2010. Prospecting discoveries in correlative areas of central Labrador suggest that the Grenville Province as a whole demands evaluation. A remote stretch of territory near the border, within the largely unmapped Mistastin batholith, is now known to contain smaller (later?) bodies of compositionally-evolved granite, associated with locally high-grade REE mineralization. In conjunction with other discoveries in Québec, exploration results indicate that this entire region of the Canadian Shield represents an important target area for deposits of this type.

On the island of Newfoundland, REE mineralization is associated with late Precambrian peralkaline complexes in two areas; western Newfoundland, and southeastern Newfoundland. Minor Zr-Y-Nb-REE mineralization in these areas was discovered in the 1980s, and these prospects are now under renewed investigation. There are also reports of REE mineralization in peralkaline granites of mid-Paleozoic (Silurian-Devonian) age.

---

[1] *Geological Survey of Newfoundland and Labrador, Department of Natural Resources, PO Box 8700, St. John's, NL, A1B 4J6*

BRITISH COLUMBIA GEOLOGICAL SURVEY

TGI 4
Ore Systems

Pacific Section
Geological Association of Canada

CANADA
1842
GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

COMMERCE RESOURCES CORP.

zimtu
CAPITAL CORP.

GreatWestern
MINERALS GROUP LTD

AcmeLabs

Canadian
INTERNATIONAL MINERALS INC

AEROQUEST
SURVEYS

Thermo
SCIENTIFIC