RARE-EARTH ELEMENT (REE) GEOCHEMISTRY OF THE STRANGE LAKE DEPOSITS: IMPLICATIONS FOR RESOURCE ESTIMATION AND METALLOGENIC MODELS

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ABSTRACT

The Strange Lake intrusion (SLI) hosts potentially large Zr–Y–Nb–REE deposits that are currently attracting much exploration interest. The Main Zone, located in Labrador, is currently Exempt Mineral Land (EML), pending finalization of landuse plans with the Nunatsiavut Government. A physically discrete deposit in adjacent Québec, known as the B-Zone, is also considered to have economic potential. Mineralization in both deposits is hosted by compositionally evolved peralkaline granites, and by associated high-grade pegmatite and aplite. Although REE have long been know to occur in the Main Zone deposit, they were not analyzed on a routine basis during earlier exploration.

Archived (reject) samples from drillcores from 1980s exploration were re-analyzed to document REE patterns, and to evaluate methods for the prediction of REE grades and profiles from previous Y, Zr, Nb and Be data. Historical Y data and the new Y analyses correlate well, although the latter are generally some 18% lower. However, the new REE analyses are generally higher than the few results available from the 1980s. The REE are poorly correlated with Zr and Nb, but show much better correlation with Be and particularly with Y. In the case of the heavy REE (HREE; Gd to Lu), these correlations with Y are very strong, but the light REE (LREE; La to Eu) show less predictable behaviour. Linear regression provides equations for prediction of REE abundances from historical Y data, and two methods were investigated. Further testing is in progress with additional analyses, but the methods seem to work in practice, and could be of value in resource estimation.

The new REE data are also of geological interest. Chondrite-normalized REE profiles for mineralized granites are remarkably similar and do not show disturbance suggestive of pervasive hydrothermal alteration. High-grade pegmatites and aplites have distinct REE patterns that are relatively LREE depleted; such variations could reflect loss of LREE to hydrothermal fluids, or igneous fractionation processes involving LREE-enriched minerals. The observed patterns of high-grade samples are consistent with previous mineralogical studies indicating that the Ca–Y–REE silicate gerenite and the Ca–Y–Be silicate gadolinite are the principal hosts for the REE in such rocks. However, these minerals cannot fully account for the observed profiles, especially for the LREE, nor can they fully explain REE patterns seen in the granites. A preliminary comparison between data from the Main Zone and the B-Zone data suggests that the latter contains a higher proportion of LREE, and a lower proportion of HREE.

INTRODUCTION

Rare-earth elements (REE) became the focus of renewed exploration efforts during 2008, in response to increased prices for these commodities. Labrador and adjacent Québec are targets for REE exploration in Canada, because both Provinces contain previously known deposits. The best-known examples are the Strange Lake deposits, located on the Labrador–Québec border, some 125 km west of Nain and 250 km northeast of Schefferville (Figure 1). Exploration from 1980 to 1985 outlined a significant resource in Labrador, and several areas of interest on both sides of the border (IOC, 1985). In the 1980s, interest was mostly in zirconium (Zr), yttrium (Y) and niobium (Nb), but enrichment in REE was also noted, with the largest deposit estimated to contain 57 Mt at 0.54% total REE oxides (0.92% including yttrium). However, these estimates were based only on limited direct analyses, because the REE were of little value at the time.

The first deposit discovered in this area (called the Main Zone) has not been re-evaluated by industry, because it currently lies within Exempt Mineral Lands (EML) pending finalization of land-use plans with the Nunatsiavut Gov-



Figure 1. Location of the Strange Lake area on the Labrador-Québec border, west of Nain and northeast of Schefferville.

ernment. However, since 2008, exploration in adjacent Québec has defined a discrete deposit of possible economic importance located about 2–3 km west of the border (Figure 1). This deposit, called the B-Zone, is now estimated to contain over 100 Mt of material at grades broadly similar to those previously estimated for the Main Zone (Collins, 2011; *see* also the Quest Rare Minerals website information).

In 2008, the Geological Survey of Newfoundland and Labrador (GSNL) commenced an appraisal of the REE potential of the Main Zone deposit, and other prospects that might host additional resources. This work was largely conducted using information from assessment files and feasibility studies from the 1980s, and through selective re-analysis of archived sample material held in the Departmental corestorage facility. Limited field work was completed at Strange Lake in 2010 and 2011, and there is an ongoing study of archived drillcore. The main objective of this work is to investigate the REE abundances and distributions within the Main Zone deposit, and evaluate methods that might facilitate an updated resource estimate. However, the results are also of interest from the perspective of genetic models for the deposits. This article provides a progress report on this work, and brief discussion of new results from both pragmatic and scientific viewpoints.

GEOLOGY AND MINERALIZATION

REGIONAL AND LOCAL GEOLOGY

The Strange Lake deposits lie within the Churchill Province of Labrador (Figure 1). The host rocks to Zr-Y-Nb-REE mineralization, here termed the Strange Lake intrusion (SLI), form a small circular peralkaline granite ring-complex, that was dated at 1240 ± 2 Ma (U–Pb zircon, Miller et al., 1997). The country rocks to the SLI include orthogneisses of unknown age, and a quartz-monzonite to monzogranite intrusion believed to be linked to the nearby Mistastin batholith. The features of the SLI and associated mineralization were outlined by Miller (1986, 1988, 1996), Salvi and Williams-Jones (1990, 1992, 2006), Birkett and Miller (1991), Boily and Williams-Jones (1994) and Miller et al. (1997). Kerr (2011) provides an overview in a recent review paper. The following account is condensed from these sources, and illustrated by maps and cross-sections in Figure 2. Outcrop is poor in most of this area, especially in Labrador, and knowledge of the SLI comes largely from drillcores.

The SLI is a complex body, but contains three main units of peralkaline granite composition. An inner core to the intrusion is formed by a hypersolvus granite (*i.e.*, containing just one perthitic K-feldspar) that is generally fresh and unaltered, and has the least-evolved composition in terms of incompatible elements and REE. This was termed the 'exotic-poor' granite by Miller (1986), based on terminology used in exploration. The most areally extensive unit is a subsolvus (i.e., containing discrete K-feldspar and albite crystals) granite that forms an outer shell around most of the complex, and typically is more enriched in incompatible elements and REE than the hypersolvus granite. This outer unit is widely characterized by the presence of rounded, dark inclusions, some of which contain lath-like phenocrysts that superficially resemble feldspars but are more likely pseudomorphs after alkali-zirconosilicates. This unit was termed the 'exotic granite' by Miller (1986). The third unit of the SLI occupies a small area in the centre of the complex, and is spatially linked to the Main Zone mineralization. It is an equigranular, fine- to medium-grained, subsolvus granite that shows very strong enrichment in incompatible elements and REE; it was termed the 'exotic-rich' granite by Miller (1986). There was - and still is - a divergence of opinion about the significance of this unit, as Salvi and Williams-Jones (1990) contended that it was simply a strongly altered variant of the more abundant outer subsolvus granite. However, this highly evolved granite is texturally distinct, and no inclusions are observed within it, suggesting that it does indeed represent a discrete intrusive unit. In this report, the term 'exotic-rich subsolvus granite' is used for this unit, but other unit designations proposed by Miller (1986) are aban-



Provincial Border (not surveyed)



Figure 2. Simplified geological map of the Strange Lake intrusion, with schematic cross-sections for the Main Zone and B-Zone. After Miller (1986, 1990), IOC (1985) and information on the Quest Rare Minerals website.

doned in favour of the simpler 'hypersolvus granite' and 'subsolvus granite'. The previous designations remain useful as exploration terms, but are not fully correct, as even the 'exotic-poor' granite is strongly enriched in incompatible elements and REE compared to most granites.

Previous accounts (*e.g.*, Miller, 1986) suggested that the hypersolvus granite is the oldest unit, followed by the subsolvus granite and then the exotic-rich subsolvus granite. Crosscutting relationships observed at a bulk sample trench located on the interprovincial border show that aplitic-pegmatite zones, which resemble the exotic-rich subsolvus granite, intrude the inclusion-bearing subsolvus granite; drillcore from this area also suggests this relationship. However, unequivocal evidence for the relative age of the hypersolvus granite unit is hard to resolve in outcrops or archived drillcore.

MINERALIZATION

Main Zone Deposit

Mineralization at Strange Lake is largely of interest for Zr, Nb, Y and REE, but it also has significant enrichment in Be, Hf and Th. There are two styles of mineralization. Lower grade mineralization is disseminated in form, and simply dispersed in fine- to medium-grained subsolvus granite. The Zr-, Nb- Y- and REE-bearing minerals occur as important modal constituents, in part of primary igneous origin, and are most abundant in the exotic-rich subsolvus unit. Mineralization of this type is extensive on the Labrador side of the border, but was only partly included in resource estimates developed in the 1980s; generally, it is defined only by very shallow drilling (<50 m). The full depth extent and geometry of the exotic-rich subsolvus granite remain undefined, although a few deeper holes suggest that it is continuous to depths of 250 m or so in some areas. Generally, the exotic-rich subsolvus granite appears little-altered, although there is variable replacement of early Na-Zr-silicates (such as elpidite) by later Ca-Zr-silicates (such as gittinsite), and replacement of amphibole by aegirine. Higher grade mineralization is of more restricted extent, and is largely concentrated within an area termed the Zone 1 Lens, located at the northeastern end of the exotic-rich unit. The mineralization here is associated with a high density of pegmatitic, aplitic and composite aplite-pegmatite veins and sheets, which appear to occupy the contact region between the outer subsolvus granite and the exotic-rich unit (Figure 2). The pegmatites and aplites have variable compositions, but typically are more strongly enriched in Zr, Nb or REE than any of the granites, but not necessarily in all of these elements on a sample scale. The thickest part of the Zone 1 Lens is a composite aplite-pegmatite zone within which well-developed textural and chemical zonation is described, suggesting insitu crystallization from a volatile-rich silicate magma

greatest density of highly enriched pegmatite and aplite on the Labrador side of the border, thinner zones of such material occur in many other areas, and occur commonly on a centimetre-scale in numerous drillholes. The overall resource defined by the Iron Ore Company of Canada (IOC) in the 1980s represents a mixture of these two styles of mineralization, but it is not clear from available documents exactly which sections of the deposit were included in resource calculations. Similarly, no precise tonnage estimate seems to be recorded for the Zone 1 Lens, although it was the only area proposed for small-scale mining in the feasibility study (IOC, 1985). Given that the total output proposed for a 20-year seasonal mining operation was some 5 million tonnes (IOC, 1985), the Zone 1 Lens is assumed to represent about that tonnage at an average grade of 3.25% ZrO₂, 0.66% Y₂O₃, 0.56% Nb₂O₅, 0.12% BeO and 1.3% REE oxides (about 2% if Y is included with the REE). The overall estimate for the Main Zone deposit was 57 million tonnes at 2.93% ZrO2, 0.38% Y2O3, 0.31% Nb2O5, 0.08% BeO and 0.54% REE oxides (IOC, 1985). None of these figures are compliant with current (NI 43-101) standards for the estimation of mineral resources.

(Miller, 1996). Although the Zone 1 Lens represents the

Mineralogical investigations of the Main Zone deposit including the Zone 1 Lens, indicate that the principal host mineral for Zr is gittinsite (Ca-Zr-silicate), and that most Nb is hosted in pyrochlore (Ca-Nb-oxide). The principal host for Y in the Zone 1 Lens is a hydrated Ca-Y-silicate that for years remained unnamed, but was eventually named gerenite (Jambor et al., 1998) after the president of the Iron Ore Company during the time of the exploration, Richard "Dick" Geren. This mineral was stated to also be the host for most of the REE, but several other potential REE-bearing minerals were also identified through metallurgical studies (IOC, 1985; Jambor et al., 1998). The most abundant are kainosite (Ca-Y-silicate also containing CO₂) and a Y-rich variety of gadolinite (a hydrated REE-Be-silicate). The formulae of unusual and unique minerals at Strange Lake that are relevant to this article are listed in Table 1.

B-Zone Deposit

The B-Zone deposit is a physically discrete mineralized zone within Québec (Figure 2) that was originally detected by IOC in the 1980s, but never explored in detail (Miller, 1984). Subsequent drilling by Quest Rare Minerals has established that mineralization is extensive. Information on the mineralization is confined to public-domain sources such as websites and NI 43-101 reports, but a brief visit to the site was made in 2011, and a small amount of archived IOC drillcore is retained in Goose Bay. In many respects, the B-Zone resembles the Main Zone in that the overall resource is a mixture of enriched pegmatites and less-enriched peral-

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Mineral Name	Formula
Silicates	
allanite (Ce-rich)	$(Ce,Ca)_2(Al, Fe^{3+})_3(SiO_3)_3 (OH)$
armstrongite	CaZrSi ₆ O ₁₅ ·3H ₂ O
astrophyllite	$(K,Na)_{3}Fe^{2+}_{7}Ti(Si_{8}O_{24})(O,OH,F)_{7}$
catapleiite	CaZrSi ₃ 0 ₉ ·2H ₂ O
dalyite	$K_2 Zr Si_6 O_{15}$
elpidite	Na ₂ ZrSi ₆ O ₁₅ ·3H ₂ O
gadolinite (Ca-rich)	Be_2 (Ca,Y, REE,Fe) $_3Si_2O_{10}$
gerenite	$(Ca, Na)_{2} (Y, REE)_{3}Si_{6}O_{18} 2H_{2}O$
gittinsite	$CaZrSi_2O_7$
kainosite	Ca_{2} (Y,Ce) $_{2}Si_{4}O_{12}$ (CO ₂)·H ₂ O
leifite	Na ₂ (Si,Al,Be) 7 (O,OH,F) 14
milarite	$K_2Ca_4Al_2Be_4Si_{24}O_{60}$ · H_2O
narsarsukite	$Na_{2} (TiFe^{3+})Si_{4} (O,F)_{11}$
thorite	(Th,Fe,Y,P,Ca)SiO ₄
titanite	CaTiSiO ₅
vlasovite	$Na_2ZrSi_4O_{11}$
zircon	$ZrSiO_4$
Oxides	
pyrochlore	$(Na,Ca)_2Nb_2O_6$ (OH,F)
Carbonates/fluorides	
bastnaesite (Ce-rich)	(Ca,La)(CO ₃)F
gagarinite (Y-rich)	NaCaY(F,Cl) 6
Phosphates	
monazite (Ce-rich)	(La,Ce,Nd,Th)PO ₄

Table 1. The names and generalized chemical formulae of unusual Zr-, Y- and REE-bearing minerals known in the Strange Lake intrusion and associated mineral deposits

kaline granite country rocks. Aplitic rocks also occur in association with the pegmatites, but are reported to be less common than in the Zone 1 Lens (Collins, 2011). The pegmatites form multiple sheets, with a flat to gently inclined attitude; some of the thicker pegmatites can be correlated laterally from hole to hole on at least a local basis (Figure 2). The country rocks to the pegmatite sheets belong to the subsolvus granite unit, and the dark phenocryst-bearing inclusions characteristic of this rock type are ubiquitous in drillcore. The host granites of the B-Zone display more obvious and pervasive alteration than equivalent rocks in the vicinity of the Main Zone. In particular, the country rocks at the B-Zone exhibit strong hematite alteration, which gives them a red cast, and leads to pervasive replacement of primary mafic silicates (notably sodic amphibole) by hematite.

Geochemical data for the B-Zone mineralization are confined to material available in press releases by Quest Rare Minerals, and emphasize overall averages for mineralized intervals, which represent a mixture of pegmatite and country rock, and analyses from shorter high-grade intervals representing individual pegmatite zones. No data representing the granitic host to the pegmatites have been released to date.

GEOCHEMISTRY

PREVIOUS WORK AND DATA SOURCES

Research studies completed on the Strange Lake intrusion and its mineral deposits include little discussion of geochemical trends or inter-element relationships. Miller (1986) and Boily and Williams-Jones (1994) touch upon these issues, and present the only previously published REE data. Salvi and Williams-Jones (1990, 1992, 2006) focus upon fluid-inclusion studies, and other papers (e.g., Birkett et al., 1992; Miller, 1996; Jambor et al., 1998) largely emphasize mineralogy. Additional REE data for selected drillcore samples are contained in an unpublished company report (Miller, 1985) but most other assessment reports for the project list only a few determinations of 'Total REE oxides'. The elements Zr, Y, Nb and Be were analyzed at internal IOC laboratories for almost all samples throughout the exploration program; Th, U, Ce, F, Sn, Mo, Zn and Pb data were analyzed externally for much smaller subsets of samples. According to company reports, the total REE oxides for many samples were estimated on the basis of Y and Ce contents, but this is not discussed in detail (IOC, 1985). Estimates of precision for Y, Nb and Be were stated to be \pm 5%, with worse precision $(\pm 10\%)$ for Zr (IOC, 1985); aside from Be, these data were reported in oxide form as weight percent, to 2 decimal places, and are thus rounded to the nearest 100 ppm.

Miller (1986) showed that Al₂O₃ is a useful index of differentiation, as it decreases systematically from the hypersolvus granite to the exotic-rich subsolvus granite. The abundances of REE and many trace elements of interest increase as Al₂O₃ decreases, and other oxides and elements that are normally considered 'compatible' (e.g., CaO, Sr) are also inversely correlated with Al2O3. Rare-earth element data quoted by Miller (1985, 1986) were obtained using the thin-film XRF method, which at that time was a popular low-cost analytical method for samples that have elevated REE contents. The REE data reported by Boily and Williams-Jones (1994) were acquired by instrumental neutron-activation analysis (INAA), then considered a more accurate method for scientific research. Inductively-coupled plasma mass spectrometry (ICP-MS) methods have now replaced these earlier methods as standard techniques, and REE analyses are now routine rather than specialized procedures. The early REE data presented by Miller (1985, 1986) do show mutual similarities in the REE patterns of various granite units, and indicate strong REE enrichment, with the exotic-rich subsolvus granite containing about 0.5% total REE oxides (excluding Y) and some pegmatites and aplites containing up to 3.0% total REE oxides. These earlier data have not been assessed in detail, but they appear to be more scattered in plots than the ICP-MS data from the 2010 analyses.

SAMPLING AND RARE-EARTH ELEMENT ANALYSIS

Sampling Strategy

The data discussed in this report come largely from selective re-analysis of archived reject samples (i.e., crushed drillcore left over from earlier IOC analyses), retrieved from the Department of Natural Resources core-storage facility in Goose Bay. These are supplemented by analyses of field samples collected in 2010 from the bulk sample trench on the interprovincial border and other outcrops in Labrador. The archived samples are stored in durable sealed plastic bottles and are thus immune from cross-sample contamination; the sample material generally has a grain size of less than 4 mm, and shows no sign of oxidation. Only one of several large storage crates in Goose Bay was unpacked. This contained about 300 samples, from which 100 were selected for reanalysis on a semi-random basis. Fortuitously, the crate contained material from a range of drillholes distributed across the deposit area. The final selection of samples was designed to cover a wide range of previous assay values for Y, Zr, Nb and Be, whilst maintaining representative geographic coverage. The batch of 100 samples analyses also included 10 sample duplicates, representing cases where a given sample was stored in two separate bottles; material from both was analyzed separately to monitor precision and reproducibility. The samples selected for re-analysis did not include any high-grade material (defined as >0.8% Y₂O₃), which is difficult to locate, possibly because much of it was used for testing purposes in the 1980s. For this reason, several field samples from the bulk sample trench excavated in the high-grade Zone 1 Lens were analyzed and incorporated into the database to provide information on the high-grade end of the compositional spectrum. There are no equivalent IOC data for these high-grade samples.

Analysis Details

Samples were processed at the ActLabs facility in Goose Bay, Labrador and were then analyzed by ActLabs for major elements, trace elements and REE. The processing and analysis using inductively-coupled plasma mass spectrometry (ICP-MS) essentially duplicate the methods currently used in REE exploration. The current discussion is focused largely on the REE and associated elements such as Zr, Y, Nb, Be and Hf, but the complete dataset will be released as an Open File in 2012. In this section, the acronym REE refers to elements of the lanthanide series (La to Lu), and excludes yttrium (Y), although this element has many similar properties, and is included with the REE in exploration reports. The REE are further divided for discussion purposes into the light REE (LREE; La to Eu) and the heavy REE (HREE; Gd to Lu). Accuracy is assessed by internal standards used by Act-Labs for REE analysis, but these generally have lower REE contents than typical material from Strange Lake, even where the latter is unmineralized. Estimates of precision based on the 10 duplicate samples indicate acceptable reproducibility ($\leq \pm 5\%$) for the REE and Y.

Correlation with Previous Analytical Data

The correspondence between the IOC analyses for Y, Zr, Nb and Be and new analyses of the same materials was assessed from simple charts and statistical analysis (Figure 3). Bivariate plots show a good correspondence between the two datasets for Y ($R^2 = 0.95$), but the 2010 data for Y are consistently lower than the IOC results, by some 18% (Figure 3a). The data for Zr are not as well correlated ($R^2 =$ 0.67), and 2010 values also tend to be lower than those obtained by IOC (Figure 3b). For both Nb and Be (Figures 3c, d), the 2010 values are generally higher than those reported by IOC, and correlations are reasonable ($R^2 = 0.93$ and 0.84, respectively). However, correlation is significantly poorer for Nb where values fall below 1000 ppm (not shown in the chart). The results suggest that the earlier IOC Zr values might be less reliable, but it should be remembered that Zr abundances are an order of magnitude greater than for Y or Nb, and were acknowledged by IOC to have poorer precision at $\pm 10\%$. The good correspondences of the other elements, notably Y, suggest that the older IOC data can be reliably used as a basis for calculation. However, the IOC data for Y need to be corrected to better match values obtained in 2010 if they are to be used as to estimate REE concentrations. The conversion expression (from linear regression of data in Figure 3b) is:

$$Y_{(2010 \text{ data, ppm})} = Y_{(IOC, \text{ ppm})} * 0.82 + 15$$
 (R² = 0.95)

Note that the IOC analyses are reported as weight % Y_2O_3 , and thus require conversion to ppm as a preliminary step, using the expression:

$$Y_{(ppm)} = (Y_2O_3_{(\%)} / 1.27) * 10^4$$

INTERELEMENT CORRELATIONS AND TRENDS

The relationship between the REE and other elements commonly associated with them (*e.g.*, Zr, Nb, Be, Hf) was investigated statistically by the calculation of Spearman correlation coefficients using SPSS for Windows. The choice of this parameter over Pearson correlation coefficients was based on the observation that most of elements under consideration showed negatively skewed frequency distributions, although the Pearson coefficients do illustrate essentially the same patterns. Selected bivariate scatter plots are also used to visually illustrate specific relationships for dis-



Figure 3. Bivariate plots showing the relationship of 2010 data and IOC data from the 1980s for Y, Zr, Nb and Be. The IOC data are derived from several different assessment reports dated between 1980 and 1985, and are converted to ppm from wt% oxide, except for Be. (a) Y comparison, (b) Zr comparison, (c) Nb comparison, (d) Be comparison.

cussion. The samples analyzed in this study have high concentrations of REE and related elements, well above the detection limits for the analysis method.

Analysis of Correlations

Correlation coefficients for the 2010 analyses are represented graphically using a colour block matrix, in which the REE are ordered according to their position in the periodic table (Figure 4). Correlations below 0.5 are left uncoloured, as such low values indicate very weak associations between elements. Figure 4 shows strong to very strong correlation between individual REE, notably where they are adjacent in the periodic table. This strong linkage is predictable, as the REE have similar properties, and adjacent REE have almost identical ionic radii. However, correlation amongst REE elements from different parts of the series is not as strong; for example, La has moderate to strong correlations (R > 0.7)



Figure 4. Spearman correlation coeffcients for the 2010 database, indicated by colour codes.

with the other LREE (Ce, Pr, Nd, Sm, Eu), but correlation coefficients with most HREE (Tb to Lu) are generally less than 0.5. Conversely, Lu is moderately to strongly correlated (R > 0.7) with most other HREE (Yb, Tm, Er, Ho, Dy and Tb), but poorly correlated with the LREE. As a group, the REE mostly show moderate to strong correlations with Y, and these are strongest for the HREE, but La, Ce, Pr and Nd have coefficients below 0.5 with Y. These patterns show that the REE behave as a group, which is to be expected, but also indicate some degree of "decoupling" between LREE and HREE.

Correlations between the REE and Zr or Nb are weaker than between REE and Y, but there are some moderate to strong correlations (R = 0.7 to 0.9) between Zr, Nb and the HREE (Dy to Lu). Correlations between the REE and Be are generally weak to moderate, aside from those of Tb and Dy, for which R values are >0.8. There is, as expected, a very strong correlation between Zr and the geochemically similar element Hf. The patterns shown in Figure 4 indicate that the strongest association for the entire REE group is with Y, but also that the behaviour of light and heavy REE is decoupled to some extent.

Geochemical Trends for REE against Y, Zr, Nb and Be

The relationship between the five major commodities of interest was further assessed using bivariate plots of total REE content (excluding Y) against Y, Zr, Nb and Be (Figure 5). There is no evidence of a linear relationship in plots of total REE against Zr (Figure 5a) and Nb (Figure 5b) sug-

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gesting that any attempt to calculate REE contents from Zr or Nb would be futile. The correlation between total REE and Be (Figure 5c) is better, but the closest relationship is between total REE and Y (Figure 5d). The correlation matrix (Figure 4) suggests that the light and heavy REE need to be considered separately, so this was investigated using individual elements from each grouping (Figure 6). Individual HREE (e.g., Dy, Yb; Figure 6c, d) show a closer correlation and less scatter when plotted against Zr and Nb than do individual LREE (e.g., Ce, La; Figure 6a, b). The same approach was used to investigate correlations between REE and Y (Figure 7). Individual LREE (e.g., Ce, Nd; Figure 7a, b) show some positive correlation with Y, but the relationship is extremely close and almost linear for individual HREE (e.g., Dy, Yb; Figure 7c, d). The relationship between individual light and heavy REE with Be is not illustrated, but it broadly resembles the pattern shown for Y (Figure 7) albeit with slightly weaker correlations overall. The patterns illustrated in Figures 5, 6 and 7 confirm that there are only limited associations between the REE and Zr or Nb, but indicate that a much stronger association exists between the REE and Y. The nearly linear trends shown in Figure 7 suggest that this relationship could be used to accurately predict some individual REE abundances from Y data. As indicated by the correlation matrix (Figure 4) there is strong correlations between individual REE within the light and heavy groups, which are also of potential use in such prediction (see later discussion).

Rare-Earth Element (REE) Profiles

Rare-earth element geochemistry is commonly assessed using REE profiles, in which raw concentration data are normalized to (i.e., divided by) standardized abundances for chondritic meteorites, considered representative of the bulk Earth composition. This produces smooth patterns by suppressing differences in absolute abundances, and such profiles have distinctive shapes that may be indicative of compositional groupings or processes. This section assesses the REE profiles from the 2010 analyses, and compares them to other data reported from the SLI and the B-Zone deposit in Québec. The data are divided on the basis of geological units, as recorded in the IOC drill logs. This creates three groups of analyses, representing the subsolvus granite unit, the exotic-rich subsolvus granite unit, and pegmatite-aplite zones, respectively. Pegmatites and aplites are typically closely associated and difficult to sample separately. The IOC drill logs indicate that some samples within the database represent more than one unit, most commonly a mixture of subsolvus granite and exotic-rich granite and/or pegmatite. These mixed analyses are excluded from the following discussion. The 2010 data do not include any samples from the hypersolvus granite unit, because this does not occur in the main mineralized area. However, Miller (1985)



Figure 5. *Bivariate plots illustrating the relationship between the total REE content of samples (expressed as ppm, excluding Y) and other elements. (a) REE vs Zr; (b) REE vs Nb; (c) REE vs Be; (d) REE vs Y. Based on 2010 re-analysis data.*

does report some REE data from this unit, which are discussed briefly below.

The REE profiles from the three main granite units are displayed in Figure 8, including the data from the hypersolvus granite listed by Miller (1985). The most obvious feature of the REE profiles for the subsolvus granite (Figure 8a) and exotic-rich subsolvus granite (Figure 8b) is that they are closely similar in shape, although the REE abundances differ slightly according to unit. All profiles are characterized by a steeply sloping LREE subprofile, and a much flatter HREE profile, separated by a prominent negative Eu anomaly. There is considerable overlap between the profiles for the subsolvus granite and the exotic-rich subsolvus granite, but the latter is relatively enriched in REE. There is a more complete separation between these units and the hypersolvus granite (Figure 8a, shaded field), which has lower REE abundances, but the patterns are closely similar.

The REE profiles for pegmatites and aplites show very strong overall REE enrichment, and have more variable shapes (Figure 9). Some of these samples overlap with the exotic-rich subsolvus granite, but most have much higher REE contents. The REE profiles for pegmatites and aplites



Figure 6. Bivariate plots illustrating relationships between individual light and heavy REE and Zr or Nb. (a) Ce vs Zr; (b) La vs Nb; (c) Dy vs Zr; (d) Yb vs Nb.

retain prominent negative Eu anomalies, but in most cases their normalized LREE profiles are less-enriched than their HREE profiles. Note that this does not mean that HREE are more abundant than LREE in *absolute* terms, because the latter are far more abundant.

Rare-earth element profiles for the B-Zone deposit in Québec cannot be examined in the same detail, because the data reported, from shorter intervals, all represent pegmatite (\pm aplite) zones that have high overall REE grades. Nevertheless, the REE profiles for several such intervals broadly resemble those shown in Figure 9 for equivalent rocks in the Main Zone. The REE profile for the resource estimate (54 million tonnes) proposed for the B-Zone deposit (Ramsay *et al.*, 2010) is similar in shape to profiles from the two subsolvus granite units (as shown in Figure 8), but slightly more enriched in the LREE. The profiles for individual pegmatite analyses from the B-Zone are likewise enriched in LREE relative to equivalent rocks in the Main Zone.

REE Grades and Proportions

From an exploration perspective, the three most important parameters in assessing a rare-earth element deposit are



Figure 7. *Bivariate plots illustrating relationships between individual light and heavy REE and Y. (a) Ce vs Y; (b) Nd vs Y; (c) Dy vs Y; (d) Yb vs Y.*

total REE content, the proportions of the various REE and the mineralogical habitat of the REE. The information from the re-analysis program is directly relevant to the first two parameters, and indirectly relevant to the third. The grades of REE deposits are conventionally reported in exploration as total REE oxides, including Y_2O_3 ; the notation TREO* is used here for this composite variable.

Original IOC estimates of the REE content at Strange Lake were $\sim 0.54\%$ REE oxides (not including Y), or 0.92% TREO*. The average value for all the re-analyzed samples is 0.58% REE oxides (not including Y), but the overall

TREO* value is slightly lower at 0.87%. This difference reflects the slightly lower Y values reported in 2010 compared to those quoted by IOC, so the 2010 average closely resembles earlier projections. Average TREO* grades are 0.66% for the subsolvus granite, and 0.76% for the exoticrich subsolvus granite. Pegmatites and aplites have significantly higher average TREO* grades of 1.73%, but are also compositionally variable, as indicated by Figure 9. These values compare well with those suggested by earlier exploration work, and also with the averages from previous REE analyses presented by Miller (1985). It is difficult to directly assess the relationship between the 2010 data and earlier



Figure 8. Chondrite-normalized REE profiles for the three main granite units in the Strange Lake intrusion, including the exotic-rich subsolvus granite that in part defines the mineralized zone. (a) "Exotic granite" of IOC, and data from the hypersolvus granite (Miller, 1985, 1986). (b) Exotic-rich subsolvus granite unit.

IOC total rare-earth oxide analyses, because only a small number of the IOC samples were actually analyzed for REE in the 1980s.

The proportions of different groups of REE are indicated by pie charts showing the relative contributions of the LREE (La to Eu), HREE (Gd to Lu) and Y (Figure 10). The average value for the Main Zone contains some 22% HREE, and 52% LREE, with the balance accounted for by Y. Individual units have HREE proportions from about 15% (subsolvus granite) to 24% (pegmatites and aplites). The latter also have significantly higher proportions of Y, consistent with the relative LREE depletion as indicated by some REE profiles (Figure 9). The results for the B-Zone deposit in Québec suggest that it has a slightly lower proportion of HREE (about 16%) compared to the Main Zone (about 22%). Overall, both the bulk average and data from individual pegmatite zones indicate a higher proportion of LREE in the B-Zone compared to the Main Zone.

Amongst Canadian REE deposits currently under advanced exploration, Strange Lake stands out by virtue of its high relative content of HREE. Other deposits cited as potential sources of HREE, such as Kipawa (Québec) and Nechalacho (Northwest Territories, also known as Thor Lake) contain only 10% to 14% HREE, and are also lower in Y (~20%) compared to Strange Lake (data from Matamec Explorations and Avalon Ventures websites). In Labrador, only the eudialyte-rich rocks from the Red Wine Mountains area (*see* Kerr, 2011, and the Search Minerals website information) have proportions of HREE approaching those of the Main Zone deposit at Strange Lake.



Figure 9. Chondrite-normalized REE profiles for the aplitic and pegmatitic samples from the Main Zone, compared to the fields of profiles for granite units illustrated in Figure 8.

Other Trace-Element Abundances and Trends

The REE mineralization at Strange Lake is commonly associated with elevated radioactivity, and both Th and U are enriched in samples that have high Y and REE contents. Uranium ranges from about 20–30 ppm in samples containing ~1000 ppm Y, to about 100–200 ppm in high-grade material. Thorium is an order of magnitude more abundant, and high-grade samples contain up to 8000 ppm Th. Based on this information, it is unlikely that Strange Lake contains a significant recoverable uranium resource. As indicated by



Figure 10. *Pie charts illustrating the proportions of Y, HREE (Gd to Lu) and LREE (La to Sm) in various units of the Strange Lake intrusion, including the B-Zone deposit.*

correlation coefficients (Figure 4), there is a very strong Hf–Zr correlation, and Hf abundances range from about 200 ppm to over 1000 ppm; based on regression of the data (not illustrated), the average Hf content for the deposit is estimated at about 500 ppm. Hafnium is currently used only in small quantities, but has important applications in the nuclear industry. Other elements that are variably enriched in mineralized samples include Ta (30 to 200 ppm), Sn (200 to 1000 ppm), Pb (100 to 8000 ppm) and Zn (700 to 3000 ppm). The higher values for all these elements resemble those reported from the bulk sample collected from the Zone 1 Lens in the 1980s (IOC, 1985). For all of these elements, higher values are correlated with elevated Y, but the correlations are generally weaker than those between the REE and Y.

REGRESSION ANALYSIS AND PREDICTION OF REE VALUES

Principles

The strong correlations between the REE, and between REE and Y suggest that regression methods could provide predictions of REE contents from historical IOC analyses. The very strong correlations shown by individual HREE with Y indicate that these elements (Gd to Lu) could be predicted accurately. The more abundant but less valuable LREE (La to Eu) are also correlated with Y, but show significantly more scatter, indicating that they will be harder to predict. Two approaches to prediction of REE values from the IOC data were investigated and partially tested; further testing is now in progress. The first method uses linear regression to directly derive equations for calculation of REE from Y. The second method is an indirect technique in which selected light and heavy REE (those for which correlation with Y is strongest) are first calculated, and the remaining REE are predicted based upon their linear regression against these elements. During testing, it became apparent that the relationships between elements may not be completely linear, as the results of regressions including highgrade samples differ from those derived from the bulk of the data. This necessitated the modification of both methods to use slightly different regression equations for lower and higher grade material, so as not to overestimate the REE contents of the latter. The dataset used for regression analysis included all samples except the duplicate analyses used to estimate reproducibility. Outlying samples with high or low concentrations were retained as part of the dataset.

Direct Linear Regression Methods using REE-Y Relationships

The relationships between REE and Y were quantified using linear regression (least-squares fit method) performed by the Grapher package of Golden Software, Inc. The results are shown in Table 2, which includes three sets of results. Parts 1 and 2 list equations derived from regression against Y (2010 data) and Y (uncorrected IOC data) for the archived sample analyses only (n=87). The results for Parts 1 and 2 are similar in terms of slopes. Y-intercepts and fit statistics (R²), but differ because the IOC data for Y are generally higher than those obtained for the same samples in 2010. Part 3 shows regressions against Y (2010 data) for the full dataset including both archived samples and high-grade samples from the bulk sample site on the Zone 1 Lens. There are significant differences in the regression equations when the larger dataset is used; specifically, slopes tend to be smaller, and Y-axis intercepts greater (and always positive), compared to results from the archived samples alone. These differences are most marked for the LREE, but there are lesser differences for most HREE. The best-fitted regressions are for the HREE (Tb, Dy, Er and Ho), but most of the regressions for the LREE exhibit poor fitting statistics, aside from Sm. The negative Y-axis intercept values for some regressions are obviously unrealistic, but these are not considered significant because the measured values for Y in all samples are vastly greater than zero.

Limited testing completed to date suggests that the best predictions come from using equations in Parts 1 or 2 for samples that have <4000 ppm Y and equations in Part 3 for samples that have >4000 ppm Y. The latter are a small fraction of the overall sample population reported by IOC, but are obviously important in terms of their contribution to the mineral resource. The procedure for calculating REE abun**Table 2.** Summary of linear regression analysis of REE data

 from the Strange Lake Intrusion

Part 1	:]	Yttrium	(2010	Data)	as ind	ependent	variable
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Element	Slope	Y Intercept	R ² Value
La	0.1582	417	0.24
Ce	0.4417	850	0.27
Pr	0.0447	99	0.21
Nd	0.1526	400	0.17
Sm	0.0531	66	0.44
Eu	0.0036	3.1	0.63
Gd	0.062	51	0.74
Tb	0.0178	4.7	0.92
Dy	0.1518	6.8	0.97
Но	0.0389	3.6	0.97
Er	0.1375	-24	0.95
Tm	0.0178	4.7	0.89
Yb	0.1556	-32	0.81
Lu	0.0241	-4	0.73

Part 2: Yttrium (IOC Data) as independent variable

Slope	Y Intercept	R ² Value
0.1183	448	0.20
0.3384	920	0.24
0.0345	106	0.18
0.1157	427	0.15
0.0417	72	0.41
0.0029	3.5	0.59
0.0489	58	0.69
0.0142	6.4	0.88
0.1211	20	0.93
0.0311	-0.3	0.94
0.1098	-12	0.92
0.0183	-3.1	0.86
0.1243	-18	0.78
0.0192	-1.8	0.71
	Slope 0.1183 0.3384 0.0345 0.1157 0.0417 0.0029 0.0489 0.0142 0.1211 0.0311 0.1098 0.0183 0.1243 0.0192	SlopeY Intercept 0.1183 448 0.3384 920 0.0345 106 0.1157 427 0.0417 72 0.0029 3.5 0.0489 58 0.0142 6.4 0.1211 20 0.0311 -0.3 0.1098 -12 0.0183 -3.1 0.1243 -18 0.0192 -1.8

Part 3: Yttrium (2010 Data) as independent variable using larger dataset including high-grade field samples

Element	Slope	Y Intercept	R ² Value
La	0.0816	556	0.46
Ce	0.2188	1250	0.47
Pr	0.0197	143	0.34
Nd	0.069	546	0.3
Sm	0.0353	97	0.77
Eu	0.0029	4	0.89
Gd	0.0599	53	0.95
Tb	0.0188	2.5	0.98
Dy	0.1512	6.5	0.99
Но	0.0359	2.1	0.99
Er	0.1082	32	0.98
Tm	0.0155	9.2	0.93
Yb	0.0872	100	0.84
Lu	0.0108	21	0.69

	Dataset wit	h high-grade samp	les	Re-analyzed	l core only	
Element	Slope	Y Intercept	R ² Value	Slope	Y Intercept	R ² Value
La	2.6529	270	0.78	3.6710	107	0.83
Ce	7.1933	470	0.83	10.0123	23	0.89
Pr	0.7335	57	0.76	1.1532	-7.6	0.88
Nd	2.6971	221	0.74	4.3257	-28	0.86
Eu	0.0735	-2.1	0.95	0.0551	0.8	0.93

Table 3. Summary of linear regression analysis of rare-earth elements

Part 1: Regressions of light REE using Samarium as independent variable

Part 2: Regressions of heavy REE using Dysprosium as independent variable

	Dataset wit	h high-grade samp	les	Re-analyze	d core only	
Element	Slope	Y Intercept	R ² Value	Slope	Y Intercept	R ² Value
Gd	0.3984	49	0.97	0.4219	44	0.82
Tb	0.1247	1.6	0.99	0.1189	3.4	0.98
Но	0.2365	0.8	0.99	0.2351	-4.4	0.98
Er	0.7106	29	0.97	0.8792	-23	0.92
Tm	0.1011	9	0.91	0.1438	-4.1	0.84
Yb	0.5669	100	0.81	0.9659	-22	0.74
Lu	0.0696	22	0.66	0.1478	-1.9	0.65

dances is straightforward, but the IOC data for Y must first be corrected downward if the equations based on the 2010 Y analyses are employed.

Indirect Linear Regression Methods using REE Profiles

A second method for predicting REE abundances was also tested, with particular reference to the problem of estimating the LREE. Amongst these elements, only Sm exhibits a fit for regression with Y that is comparable to those of the HREE (R²=0.77). The strong correlations amongst LREE (Figure 4) imply that estimation from their regression against Sm might provide slightly more accurate estimates. Table 3 shows regression equations for the LREE (La, Ce, Pr, Nd, Eu) against Sm, and shows that they have better fits than equivalent regressions against Y (Table 2). The same approach can be used for the HREE (Table 3), for which the element Dy provides the best anchor, as it provides an excellent regression against Y (Table 2). As in the case of regressions against Y, slightly different results are obtained for the larger dataset including high-grade samples. The procedure for indirect regression is a three-stage process.

First, the IOC analysis for Y is corrected to account for the observed differences between the two datasets; second, values for Sm and Dy are calculated using the appropriate regression equations against Y (*see* Table 2); and third, the remaining LREE and HREE are calculated using the appropriate regression equations that link them to Sm and Dy, respectively (*see* Table 3).

The indirect method still *ultimately* results in prediction of all REE abundances from the Y data, and the question of its statistical validity was considered at length. Calculations show that predicted REE abundances from the direct and indirect methods are essentially identical for the HREE, which is to be expected, given the strong correlations between HREE and Y. However, the two methods do produce slightly different predicted abundances for the LREE, which suggests that the indirect approach is a valid concept, although not necessarily a better method. Further evaluation of its validity and usefulness requires testing using a second batch of analyses, discussed in the next section.

Assessment of Precision and Reliability for Calculation Methods

The most rigorous approach for testing prediction methods is to complete further analyses on a second group of samples using the same analytical methods, so that predictions based on the IOC data *before* re-analysis can be compared with measured values. This work is currently in progress using another 50 archived samples. However, two other assessment methods provide encouraging preliminary results.



Figure 11. Preliminary tests of prediction methods using three field samples from the Main Zone area, and also the 54 Mt resource estimate for the B-Zone deposit. The four model solutions shown represent direct and indirect estimation methods for low-grade (<4000 ppm Y) and high-grade (>4000 ppm Y) compositions. (a) low-grade mineralized granite, (b) medium-grade mineralized granite, (c) bulk (composite) sample from exploration trench on the Zone 1 Lens, (d) 54 Mt resource estimate for the B-Zone. See text for discussion.

Tests on a sample level were performed using data from three other samples that were not part of the dataset used for regressions. These were two field samples collected from outcrops near the southern edge of the exotic-rich subsolvus granite, and a composite sample representing the bulk metallurgical sample, collected from a metal storage drum left at the site. The predictive methods were also tested against the information released from the B-Zone deposit in Québec. Figure 11 shows chondrite-normalized REE profiles for observed values, and calculated results from the two regression methods for all three samples, and also the B-Zone average resource estimate quoted by Ramsay *et al.* (2010). For both direct and indirect methods, separate results were derived from expressions for lower grade (< 4000 ppm Y) and higher grade (> 4000 ppm Y) samples. The greatest discrepancy between observed and calculated values is in the lowest grade sample (359 ppm Y), for which the LREE are overestimated and the HREE are variably underestimated; the pattern for the HREE is also markedly different from the observed profile (Figure 11a). This feature is to a large extent is a function of the negative Y-intercept values for some HREE (Table 2), which have proportionally greater impact wherever Y concentrations are low, and it is also exaggerated somewhat by the logarithmic scaling (Figure 11a). All four methods provide a good fit to observed values for a medium-grade sample (1078 ppm Y), and the indirect technique for low-grade samples again provides the closest match (Figure 11b). Results for the higher grade bulk sample (5033 ppm Y) show that all methods overestimate the LREE content, but provide a good fit for the HREE profile (Figure 11c). In this example, methods intended for higher grade samples provide the best overall prediction for the LREE, but those intended for lower grade samples actually yield a better match for the HREE. The methods were also tested using the 54-million-tonne resource estimate for the B-Zone (Ramsay *et al.*, 2010), for which a Y value of 2589 ppm was calculated. In contrast to the other tests, the predicted LREE abundances are underestimates, but all methods provide a close fit for the HREE (Figure 11d). As discussed above, and shown also in Figure 10, there may be a real difference in the proportions of light and heavy REE between the Main Zone and the B-Zone, so the underestimation of the LREE does not necessarily indicate any problem with the techniques.

The differences between results from the direct and indirect regression methods are very small, especially for the higher grade expressions. The indirect methods generally provide slightly better fits to the observed values for the LREE, but it is not yet clear if this more complex approach has real advantages over simpler direct regression of all REE against Y. The results of preliminary testing do suggest that the use of separate regression equations for lower and higher grade samples is a valid approach with respect to the LREE, but may not necessarily offer advantages in estimation of the HREE. It would also appear that the least reliable results are those from the lowest grade material, much of which would likely not be included in any resource calculations. The best matches in Figure 11 come from medium- to high-grade material.

The regression equations were used to estimate total REE abundances for the overall Main Zone resource, using the value of 0.38% Y₂O₃ (~2900 ppm Y) reported by IOC (1985) as a starting point. Results suggest a total REE content of ~5400 ppm, corresponding to about 0.63% total REE oxides, higher than the original IOC estimates.

It is important to emphasize that these methods are not intended to provide information on a sample level, but rather to provide information on larger groups of results, to facilitate some sort of central measure, such as average grades for resource estimation. The ultimate test for this application will come from blind prediction using a second batch of reanalyzed samples, but it can also be assessed by evaluating the precision statistics for the present database. Table 4 summarizes precision values obtained by comparing measured and predicted REE abundances, with separate results provided for grade intervals based on Y abundances. The REE abundances were calculated from the 1980s IOC data for Y, rather than from the 2010 analyses. The mean values suggest that the calculated values are precise to $\pm 20\%$ or so for most elements, with the best mean precision (around $\pm 10\%$) for some of the HREE. However, the median values listed in Table 4 likely provide a better assessment parameter, and in most cases these suggest a higher degree of overall precision. Finally, in assessing any large group of samples, there would be both overestimation and underestimation of sample-level REE values, such that these uncertainties should tend to self-neutralize, and overall averages would be more precise than any measure based on individual cases. The next step in testing is to see if our predictions for samples yet to be analyzed provide essentially the same mean results as the eventual measured data.

DISCUSSION

The information presented in this report is of interest from two viewpoints. First, it allows assessment of earlier data from 1980s exploration programs, and development of methods to further evaluate the potential resource of REE at Strange Lake without additional drilling, sampling or analysis. Second, the REE profiles and inter-element correlations are relevant in the context of mineralogical studies, and to genetic models for the deposits.

PREDICTION OF REE ABUNDANCES FROM OTHER DATA

The re-analysis program confirms earlier IOC analytical data, but also indicates some systematic differences. The best correlation between the datasets is for Y, but the recent analyses are on average 18% lower than the 1980s analyses. A similar discrepancy is noted for the Zr results, and the correlation of the two datasets for Zr is also significantly weaker. In the cases of Nb and Be, the 2010 results tend to be higher than the earlier analyses by about 20% and 13%, respectively. If the new analyses are indeed more accurate, these observations suggest that earlier resource estimates may have overestimated Zr and Y grades, but underestimated Nb and Be grades. It is much harder to assess the relationships between the 1980s analyses for REE (of which there are few) and the 2010 results, but there are indications that the 2010 analyses give higher values. From the perspective of predicting REE abundances, the good correlations between the two datasets for Y indicate that the 1980s data should provide a good starting point, even if they must first be corrected.

Investigation of the correlations between REE and Y suggest that the data may not have a simple linear relationship, notably at higher grades (>4000 ppm Y, or ~0.5% Y_2O_3). Although such high-grade material is volumetrically minor, it would have an important impact on overall resource estimates and therefore should be treated separately. Two methods for prediction of REE data were investigated; the first method uses direct regression of REE against Y, and the second method uses an indirect procedure in which

Table 4. Precision statistics for ca	Iculated R	EE abur	ndances t	or concer	itration 11	ntervals a	umongst r	e-analyz	ed core s	amples				
Element	La	Ce	Pr	Nd	Sm	Eu	Gd	τb	Dy	Ho	Er	Tm	Yb	Lu
Samples with < 1000 ppm Y (n= Mean - Direct Regression Median - Direct Regression	5) 19.7 18.2	17.2 12.4	15.6 8.3	16.6 10.0	16.3 11.7	17.6 11.3	16.0 13.9	16.1 15.8	17.3 18.5	18.9 20.7	20.0 14.4	21.8 24.7	15.7 10.5	16.8 13.8
Mean - Indirect Regression Median - Indirect Regression	23.8 18.3	21.8 18.8	23.3 20.3	26.1 24.6	16.3 11.7	14.6 6.2	17.4 16.2	17.0 17.4	17.3 18.5	15.8 15.3	13.3 8.6	13.8 9.2	15.6 16.3	18.4 18.6
Samples with 1000 - 2000 ppm Mean - Direct Regression Median - Direct Regression	¥ (n=57) 20.2 18.8	19.5 18.0	19.8 18.6	21.1 18.1	18.8 16.2	17.5 14.2	15.2 13.1	11.7 7.9	10.1 7.0	11.3 7.7	15.2 11.3	20.3 18.3	25.4 22.9	29.3 25.7
Mean - Indirect Regression Median - Indirect Regression	20.9 20.9	20.2 19.6	20.9 18.9	22.3 19.7	18.8 16.2	17.4 14.9	15.4 13.2	11.8 8.5	10.1 7.0	11.2 8.2	15.1 12.8	20.1 17.2	25.1 22.8	29.2 27.0
Samples with 2000 - 4000 ppm Mean - Direct Regression Median - Direct Regression	Y (n=17) 24.8 14.3	23.8 15.3	26.2 21.3	28.2 26.1	23.2 16.7	18.8 14.7	17.2 11.8	11.0 5.9	6.8 2.5	8.0 5.2	9.9 9.9	14.2 12.2	20.6 21.8	25.0 25.3
Mean - Indirect Regression Median - Indirect Regression	26.4 18.5	25.0 16.4	28.1 24.5	30.4 28.0	23.2 16.7	19.0 16.1	17.2 12.0	11.0 6.1	6.8 2.5	6.7 5.1	9.9 10.8	14.1 13.5	20.6 19.3	25.0 25.7
Samples with > 4000 ppm Y (n= Mean - Direct Regression Median - Direct Regression	4) 25.0 21.3	26.6 24.2	30.2 30.5	33.2 34.6	25.5 25.9	22.2 23.2	16.3 17.5	7.7 6.0	6.3 6.6	10.9 10.5	11.5 9.3	28.8 31.0	37.1 40.0	46.2 49.1
Mean - Indirect Regression Median - Indirect Regression	24.7 23.5	26.3 27.0	31.1 35.1	34.0 39.5	25.5 25.9	22.2 23.2	16.2 17.3	7.6 6.0	6.3 6.6	$11.1 \\ 10.7$	21.2 22.8	29.4 31.6	37.7 40.6	45.9 48.8
Complete Dataset Mean - Direct Regression Median - Direct Regression	21.3 18.4	20.6 17.5	21.3 18.7	22.9 18.7	19.8 16.3	18.0 14.7	15.8 13.3	11.7 8.0	9.7 6.8	11.1 7.9	14.2 11.3	19.5 18.5	24.3 22.0	28.3 25.3
Mean - Indirect Regression Median - Indirect Regression	22.5 20.1	21.6 19.2	23.1 20.6	24.9 24.6	19.8 16.3	17.8 15.1	16.0 13.7	11.8 8.4	9.7 6.8	10.5 7.9	14.2 12.6	18.9 16.8	24.1 22.6	28.3 25.7
Notes Precision calculated as the absolu For samples with > 4000 ppm Y, i	te differen the equation	ce betwe ons for h	een obser igher gra	ved and _f de materi	predicted al were 1	values, c tsed for p	livided by	y their m	ean value	e, express	ed as (+/·	(% -		

the 'anchor elements' Sm and Dy are estimated from Y data, and the remaining REE calculated using expressions that relate them to Sm and Dy. Preliminary testing suggests that the results of both are closely similar for the HREE, but diverge more for the LREE, for which the indirect method seems to provide a better fit to observed REE profiles. From the perspective of economic valuation, the accuracy of estimation of the less abundant but more valuable HREE is probably more important than the inaccuracy of estimation for the more abundant LREE, for which prices are generally lower. A comparison of the observed and predicted results for the database suggests that the precision of estimation is generally better than \pm 20%, and may be better than \pm 10% for some of the HREE. These constraints apply on a sample level but, given that there will be both overestimation and underestimation, some degree of self-neutralization is anticipated in treating larger amounts of data, and the overall estimates from such techniques should have better precision. In summary, the use of proxy methods to generate REE data for use in resource estimation seems valid, although any such procedure would require vetting through selective reanalysis. The next step in testing these methods, involving analysis of 50 more archived samples, will permit a more detailed assessment of precision, and possibly allow refinement of the regression equations. Such refinements could involve the exclusion of some outlying samples from calculations to obviate any undue influence from these anomalous results, or forcing regression lines to pass through zero. The influence of such refinements upon results will be more easily determined when the results of a second batch of analyses become available.

The assessment of relationships between multiple variables is in many cases attempted using so-called multivariate statistical methods, amongst which *Principal Component Analysis* and its derivative technique *Factor Analysis* are the best known. These techniques have not yet been applied to the Strange Lake data, but their evaluation is also a logical next step. The disadvantage of such methods lies in their complexity; unlike the methods discussed here, they require specialized statistical software rather than standard spreadsheet programs.

VARIATIONS IN RARE-EARTH ELEMENT (REE) PATTERNS

Chondrite-normalized REE patterns for the re-analyzed samples are remarkably similar, although their REE abundances vary. This attribute is very important from the perspective of data prediction, as discussed above. The greatest variation in REE profiles is seen in a small group of analyses representing high-grade pegmatite and aplite intervals, which are relatively depleted in the LREE and enriched in HREE compared to the more abundant subsolvus granite samples. Close similarities in REE patterns within a large group of samples are very typical of closely related igneous rocks that have common origins, and there is no sign of disturbance or scatter that would indicate mobilization of the REE by hydrothermal processes. If the REE were enriched by such processes, or were mobilized by such processes, they must have behaved as a coherent group. Although the REE are generally thought of as immobile elements, the LREE are generally considered to be more mobile than the HREE (e.g., Taylor and McLennan, 1985) Thus, the lower LREE abundances shown by pegmatites and aplites could possibly reflect loss of these elements to a hydrothermal fluid phase, but this is not the only possible explanation. If pegmatites and aplites formed from small-volume residual magma batches, their REE patterns would have been influenced by fractional crystallization of the precursor granites, which would likely involve some REE-enriched minerals. For example, crystallization of any accessory mineral enriched in LREE would deplete LREE in any residual magma that eventually formed the pegmatite or aplite. Further investigation of these alternatives requires geochemical data that are more closely linked to lithological and mineralogical information. This is in progress through a study in which archived drillcore has been systematically re-sampled for analysis.

Comparison of the REE profiles for the Main Zone deposit with data released from the B-Zone deposit suggests subtle differences in terms of REE proportions. Specifically, the mineralization in the B-Zone seems to be slightly richer in LREE, and correspondingly poorer in Y and HREE, compared to that of the Main Zone. The possible causes for such variation are a subject of interest for further research, especially as there is more field evidence for hydrothermal alteration in the B-Zone host rocks. Irrespective of these differences, Strange Lake shows strong relative enrichment of the HREE compared to most other deposits of its general type.

LINKS BETWEEN REE GEOCHEMISTRY AND MINERALOGY

Whole-rock geochemistry reflects the compositions and abundances of constituent minerals; in the case of the REE, minor (accessory) phases play an important role in controlling their behaviour. Although many different minerals have been identified at Strange Lake (Table 1), including some that are as yet found nowhere else on Earth, there is very little quantitative information concerning their abundances and minor element compositions. Metallurgical studies of the Zone 1 Lens in the 1980s identified the minerals gittinsite and pyrochlore (Table 1) as the principal sources of Zr and Nb, respectively (IOC, 1985). The poor correlations observed between the REE and Zr or Nb suggest that these neither of these minerals are important hosts for the REE. However, there is some correlation between Zr and the HREE, so it is possible that some of the latter are incorporated in alkali-zirconosilicates. Birkett *et al.* (1992) list microprobe analyses that suggest up to 1300 ppm La and 950 ppm Ce in gittinsite, but the HREE were not analyzed. There is also no indication that other alkali-zirconosilicates found in the subsolvus granites (*e.g.*, elpidite, armstrongite, vlasovite) contain signifcant amounts of the REE (Birkett *et al.*, 1992).

The only public-domain quantitative data on mineral abundances comes from the bulk sample collected from the Zone 1 Lens (IOC, 1985), but this may not be representative of the larger mineralized zone defined by IOC. Common silicates (quartz, albite, K-feldspar, Na-pyroxene and Naamphibole) accounted for almost 70% of the bulk sample. The remainder was dominated by 'clays' (unspecified, ~9%), fluorite (~5.5%), gittinsite (~5.5%), gerenite (~2.3%), zircon ($\sim 1.8\%$), titanite ($\sim 1.7\%$), pyrochlore ($\sim 1.5\%$) and gadolinite (~1.1%). Other minor minerals reported include kainosite, monazite, allanite, bastnaesite, hematite, thorite, galena and unspecified carbonates. Several of these minerals are potential hosts to the REE, but the IOC work suggested that gerenite, kainosite and gadolinite were the most important, and that gadolinite also contained most of the beryllium. Jambor et al. (1998) report that kainosite occurs as an alteration product of gerenite, and present electron microprobe data that confirm that gerenite, kainosite and gadolinite contain important quantities of Y and REE. The chondrite-normalized REE patterns for gerenite and kainosite are dominated by the HREE, whereas the gadolinite has a relatively flat REE profile (Jambor et al., 1998; Figure 12). Although not all of the LREE were analyzed in gerenite and kainosite, the low values reported for Sm and Nd suggest that none of these elements are abundant within these minerals. Gerenite is reported to contain 26.3% to 29.4% Y2O3 and 14.8% to 15.7% total REE oxides, indicating a TREO* of 42 to 44%, dominated almost entirely by HREE (Jambor et al., 1998). The TREO* reported for kainosite approaches 40%, and this is also dominated by HREE; its REE profile is broadly similar to that of gerenite. The gadolinite has more variable TREO* (~35% to 50%) but contains significant quantities of LREE, ranging from 3.6% to over 25%. The REE patterns for gadolinite are also more variable than for gerenite or kainosite. Assuming a mean value of about 40% TREO*, and assuming that all Y and REE are hosted by these 3 minerals, calculations from the mineral proportions reported for the bulk sample indicate approximately 1.2% TREO* in the bulk rock, which is lower than the observed value of 1.48% TREO* for material sampled from a storage drum at the site. The observed Y_2O_3 value for the 2010 sample (0.64%) can, however, be accounted for by the gerenite and kainosite alone, without any contribution from gadolinite.



Figure 12. Rare-earth element profiles for minerals discussed by Jambor et al. (1998) that are believed to host most of the REEs in the Zone 1 Lens at Strange Lake. (a) yttriumrich gerenite and kainosite. (b) yttriumrich gadolinite. Note that not all LREE were analyzed in gerenite and kainosite, but Ce, Nd and Eu returned low values (<0.4%) suggesting that they are not important constituents. Europium was not analyzed in gadolinite and a value of 500 ppm was arbitrarily assigned for graphing purposes.

Modelling the REE profiles using the compositional data from Jambor *et al.* (1998) is not easy, because the total LREE abundances and LREE profiles of the gadolinite are quite variable (Jambor *et al.*, 1998; Figure 12). It is also possible that these analyses, representing well-preserved mineral specimens, are not representative of all mineralization. Nevertheless, a series of hypothetical profiles representing various proportions of gerenite and gadolinite are readily constructed using the averages of the microprobe analyses as end-members (Figure 13). The results for such mixtures bear some similarity to the observed REE profiles of some pegmatite and aplite samples (Figure 9), but the model



Figure 13. Rare-earth element profiles representing various mixtures between the average compositions of gerenite and Y-rich gadolinite, based on the data presented by Jambor et al. (1998). The graph is scaled on the assumption that a hypothetical sample contains a combined total of 10 wt% gerenite and gadolinite, so as to facilitate comparisons with observed data in Figure 9.

LREE profiles are flat, whereas the natural data show fractionated patterns. Rare-earth element profiles that are LREE-enriched, such as those of the dominant mineralized granite samples (Figure 8), cannot be reproduced by any such mixing models, because both gerenite and gadolinite are enriched in HREE. As gadolinite reportedly contains most of the Be as a stochiometric component, it should be possible to constrain the proportion of this mineral using whole-rock Be data, although this has not yet been attempted.

The general conclusion from this exercise (assuming that the reported analyses of gerenite, kainosite and gadolinite are representative) is that some LREE must be contained in other minerals, especially in the lower grade samples. Possible candidates identified from the bulk sample are bastnaesite, monazite and allanite, all of which are typically LREE-enriched, and perhaps also fluorite; given the rich mineralogical inventory of the Strange Lake intrusion, there may be others yet to be identified. The present publicdomain information on mineralogy comes largely from the high-grade Zone 1 Lens, rather than from the surrounding granites. The distribution of the REE amongst different minerals in different settings is an important topic for future research aimed both at metallurgical assessment and genetic problems. In the 1980s, such work was inherently limited by available analytical technology, but there are now many sophisticated techniques, including the Mineral Liberation Analyzer (MLA) and laser-ablation ICP-MS methods. The application of some of these methods, in conjunction with the more petrologically oriented study using archived drillcore, will hopefully lead to a better understanding of this unique and fascinating mineral deposit.

ACKNOWLEDGMENTS

Discussions with Randy Miller, who completed much of the previous GSNL work in this area, helped to increase our understanding of the problems and the gaps in our knowledge. Similarly, this article benefited significantly from discussions with geologists representing Quest Rare Minerals, notably Pat Collins, who shared some more recent observations, and facilitated a visit by the senior author in the summer of 2011. The manuscript was improved and clarified following constructive reviews from James Conliffe and Steve Amor.

REFERENCES

Birkett, T.C. and Miller, R.R.

1991: Comment on "The role of hydrothermal processes in the granite-hosted Zr-Y-REE deposit at Strange Lake, Quebec-Labrador". Geochimica Cosmochimica Acta, Volume 55, pages 3443-3445.

Birkett, T.C., Miller, R.R. and Roberts, A.C.

1992: Zirconium-bearing minerals of the Strange Lake Intrusive Complex, Quebec-Labrador. Canadian Mineralogist, Volume 30, pages 191-205.

Boily, M. and Williams-Jones, A.E.

1994: The role of magmatic and hydrothermal processes in the chemical evolution of the Strange Lake plutonic complex, Quebec-Labrador. Contributions to Mineralogy and Petrology, Volume 118, pages 34-47.

Collins, P.

2011: Quest Rare Minerals' Strange Lake B-Zone deposit: An overview of mineralization and alteration. Paper presented at CIM Annual Meeting, Montreal, May 2011.

Iron Ore Company of Canada (IOC)

1985: Preliminary feasibility study and related documents, Strange Lake Project. Unpublished Report, Iron Ore Company of Canada, Geological Survey File 024A/08/0029.

Jambor, J.L., Roberts, A.C., Grice, J.D., Birkett, T.C., Groat, L.A. and Zajac, S.

1998: Gerenite-(Y), (Ca, Na)₂(Y, REE)₃Si₆O₁₈ - 2H₂O, A new mineral species, and an associated Y-bearing gadolinite-group mineral, from the Strange Lake peral-kaline complex, Québec-Labrador. Canadian Mineralogist, Volume 36, pages 793-800.

Kerr, A.

2011: Rare-earth element (REE) mineralization in Labrador: A review of known environments and the geological context of current exploration activity. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey Branch, Report 2011-1, pages 109-145.

Miller, R.R.

1984: A report on the geological, geophysical and geochemical assessment work, Exploration Permit 656, Strange Lake area, Quebec. Iron Ore Company of Canada, unpublished report. Québec Ministère des Ressources Naturelles et de la Faune, Rapport GM 41101.

1985: Geology of the Strange Lake Zr-Y-Be-Nb-REE deposit, Newfoundland - Quebec. Unpublished Report, Iron Ore Company of Canada, Geological Survey File 024A/08/0013.

1986: Geology of the Strange Lake alkalic complex and associated Zr-Y-Nb-Be-REE mineralization. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 11-19.

1988: Yttrium (Y) and other rare metals in Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 88-1, pages 229-247.

1990: The Strange Lake pegmatite-aplite hosted rare metal deposit, Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 171-182.

1996: Structural and textural evolution of the Strange Lake peralkaline rare-earth element (NYF) granitic pegmatite, Québec-Labrador. Canadian Mineralogist, Volume 34, pages 349-371.

Miller, R.R., Heaman, L.M. and Birkett, T.C. 1997: U-Pb zircon age of the Strange Lake peralkaline complex: implications for Mesoproterozoic peralkaline magmatism in north-central Labrador. Precambrian Research, Volume 81, pages 67-82.

Ramsay, D., McLaughlin, M., Zivkovic, A., Daigle, P., Broad, P. and Ni, W.

2010: Preliminary economic assessment on the Strange Lake B Zone, Quebec. Report commissioned by Quest Rare Minerals, available online at *www.questrarem-inerals.com*.

Salvi, S. and Williams-Jones, A.E.

1990: The role of hydrothermal processes in the granite-hosted Zr-Y-REE deposit at Strange Lake, Quebec-Labrador. Geochimica Cosmochimica Acta, Volume 54, pages 2403-2418.

1992: Reduced orthomagmatic C-O-H-N-NaCl fluids in the Strange Lake rare-metal granitic complex, Quebec-Labrador, Canada. European Journal of Mineralogy, Volume 4, pages 1155-1174.

2006: Alteration, HFSE mineralization and hydrocarbon formation in peralkaline igneous systems: Insights from the Strange Lake pluton. Lithos, Volume 91, pages 19-34.

Taylor, S.R. and McLennan, S.M.

1985: The continental crust its composition and evolution. Blackwell Scientific Press, Oxford, UK.