Sm–Nd ISOTOPIC GEOCHEMISTRY OF RARE-EARTH-ELEMENT (REE) MINERALIZATION AND ASSOCIATED PERALKALINE GRANITES OF THE STRANGE LAKE INTRUSION, LABRADOR

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ABSTRACT

Perakaline granites of the ca. *1240 Ma Strange Lake intrusion host two large Y–Nb–REE deposits, both noted for high relative contents of the more valuable heavy REE (Gd, Tb, Dy, Ho, Er). Previous studies have proposed divergent models that emphasize magmatic and hydrothermal processes, respectively. This article presents REE analyses and Sm–Nd isotopic data that provide valuable new constraints for this debate.*

Granites from the Strange Lake intrusion have steep (fractionated) light REE profiles, but their heavy REE profiles are generally flat, indicating relative heavy REE enrichment. In contrast, the REE profiles of older metamorphic and igneous country rocks are steep and fractionated throughout (light REE-enriched). The REE patterns of the Strange Lake intrusion (SLI) change progressively as the total REE content of the rocks increases. The most REE-enriched granites and the highest grade pegmatites and aplites become depleted in La, Ce, Pr and Nd, and develop a positive Sm anomaly; at highest grades, their heavy REE profiles become upwardly convex. These patterns are consistent with crystallization and removal of a light REE-enriched mineral from the magmas and/or transfer of some lighter REE into an exsolved fluid phase. The wide variations in Sm/Nd ratios in the SLI are unusual, and result from these processes.

The Nd isotopic compositions in the SLI are very consistent, with average $\varepsilon_{Nd}t$ values of about -2 ± 1 for most samples; the data define an imprecise age of 1248 ± 58 Ma, in general agreement with U–Pb zircon data. The $\varepsilon_{Nd}t$ values are much lower than the predicted value for the depleted mantle at 1240 Ma (>+5) but also much higher than the $\varepsilon_{Nd}t$ of surrounding granitoid gneisses (about -12) and quartz monzonite (about -9) at 1240 Ma. In conjunction with the contrasts between the REE profiles of the SLI and its country rocks, these results preclude formation of parental magmas entirely by partial melting of crustal sources. It is more likely that the parental magmas formed by interaction and mixing between mantle-derived mafic magmas and older crustal rocks, followed by protracted fractional crystallization. The exsolution of hydrothermal fluids may have depleted La, Ce, Pr and Nd in late aplite and pegmatite units that have very strong REE enrichment, but there is no evidence that such processes played a major role in concentrating REE to form economic deposits. More work is required to constrain the proportions of juvenile and crustal source components, and to develop quantitative models for the subsequent fractionation processes.

INTRODUCTION

The Strange Lake deposit was discovered in the late 1970s in a remote area along the Québec–Labrador border (Figure 1), about 120 km west of Nain, and 250 km northeast of Schefferville. It was initially evaluated for yttrium (Y) and zirconium (Zr), but is currently of most interest for its rare-earth-element (REE) mineralization. A generalized resource of some 57 million tonnes at about 0.9% total REE oxides was defined by exploration to the mid-1980s, but a development plan for a smaller high-grade zone within this was abandoned. Since about 2008, exploration in adjacent Québec has now defined a similar but physically discrete

REE deposit (known as the 'B-Zone') for which larger scale development plans are now under consideration. The original discovery in Labrador (known imaginatively as the 'Main Zone') is currently closed to exploration as an exempt mineral land (EML). These two deposits are highly unusual, and collectively represent important potential sources of the REE.

Papers published in the 1980s and 1990s discuss the geology, mineralogy and geochemistry of the Strange Lake Intrusion (SLI) and its REE–Zr–Nb deposits. These focused largely on mineralogy and geochemistry, and did not include any systematic isotopic studies. This report presents Sm–Nd
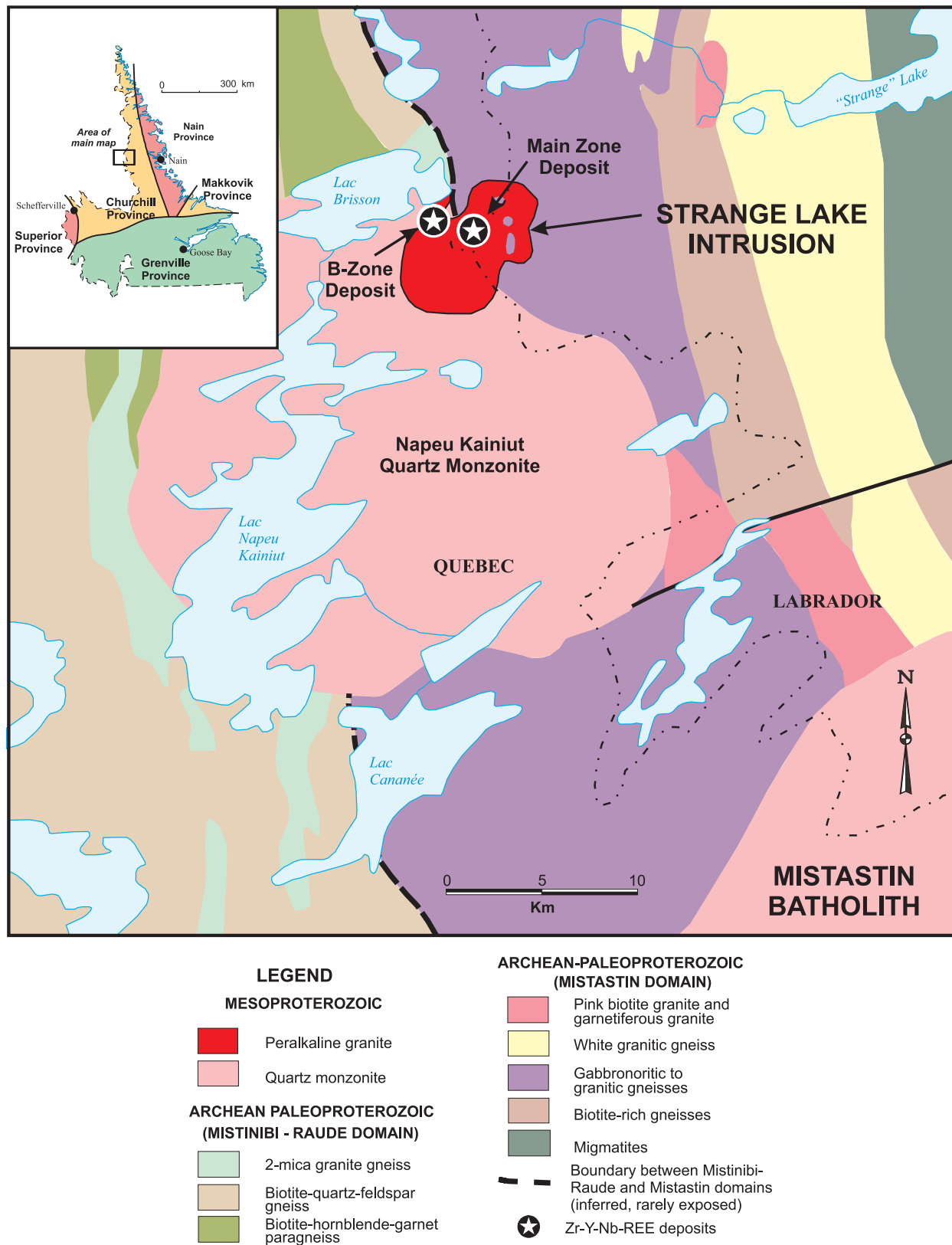
Figure 1. *Regional tectonic map of Labrador, showing the location of the Strange Lake intrusion, and the regional geology of the area surrounding it on both sides of the Québec–Labrador border. Geological map is after Miller* et al. *(1997), and based, in part, on Bélanger (1984) and Ryan (2003).*
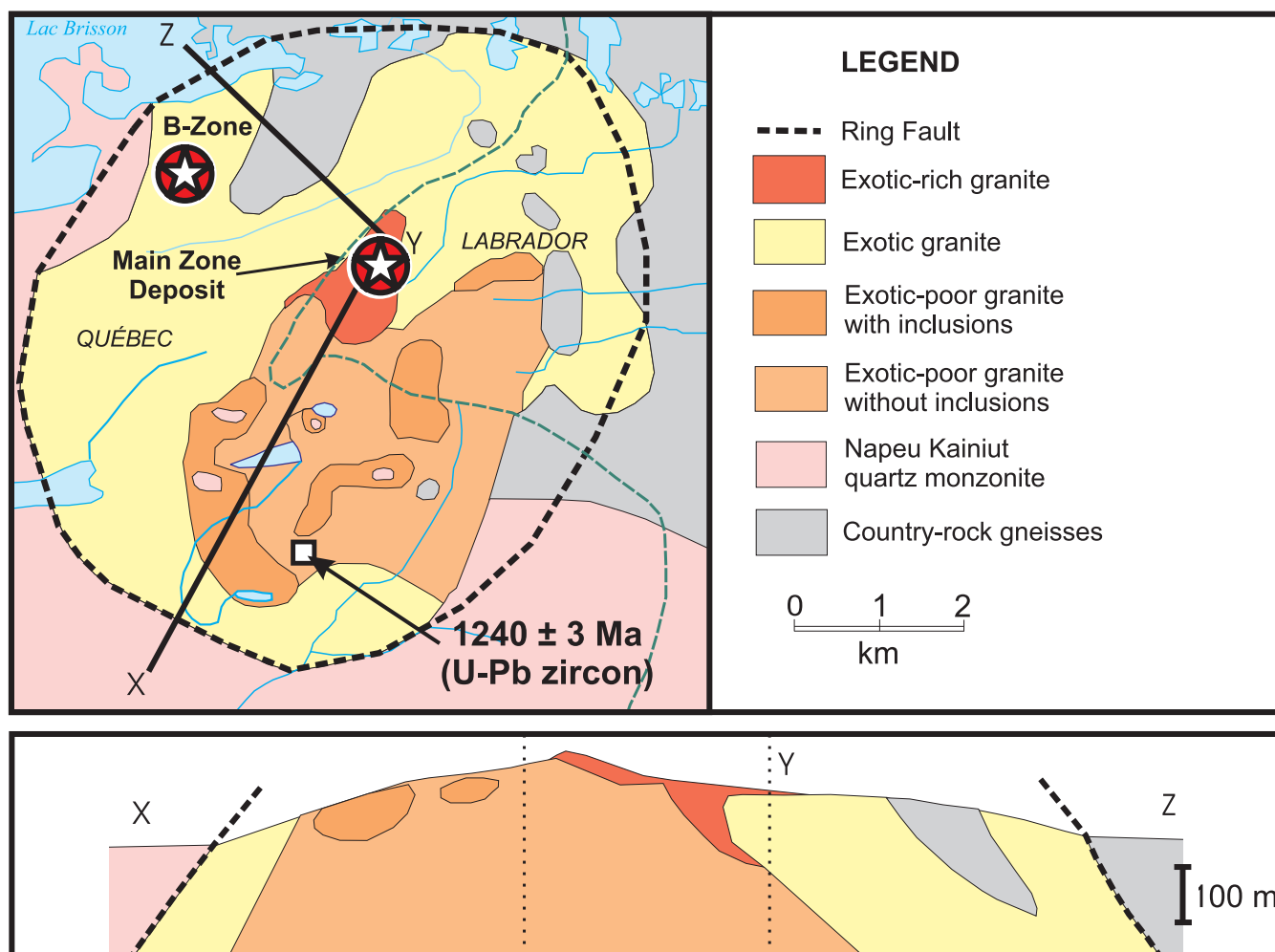
Figure 2. *Simplified geological map of the Strange Lake intrusion showing the locations of the Main Zone and B-Zone deposits, and the location of U–Pb geochronology sampling. Geology is after Miller (1986) and Miller* et al. *(1997). See Figure 3 for locations of samples within the Main Zone deposit area. The lower part of the diagram is a schematic cross-section along the line X-Y-Z.*

isotopic data acquired since 2011, and discusses their implications for the origins of the mineralization and the host peralkaline granites. Previous reports (Kerr, 2011, 2013; Kerr and Rafuse, 2012) provide regional background on REE mineralization in Labrador, and evaluate the overall resource at Strange Lake.

GEOLOGICAL FRAMEWORK

Mesoproterozoic 'anorogenic' magmatism is widespread in Labrador. In the Nain and Churchill provinces, major plutonic suites including anorthosites, intermediate rocks and potassic granites range in age from *ca.* 1470 Ma to *ca.* 1290 Ma and are essentially undeformed (Emslie *et al.*, 1994; Ryan, 1998). Peralkaline plutonic and volcanic rocks occur in several areas, and the best-known examples (Figure 1) are the *ca.* 1290 Ma Flowers River intrusion (Hill, 1991) and the *ca.* 1240 SLI (Miller *et al.*, 1997). These

suites are dominated by quartz-rich (silica-saturated) granites. Peralkaline rocks at the northern fringe of the Grenville Province, in the Letitia Lake–Red Wine Mountains area, are dated *ca.* 1330 Ma (Gandhi *et al.*, 1988), and also include silica-undersaturated (nepheline-rich) syenites. All these peralkaline suites contain REE and/or rare-metal mineralization, but the styles of mineralization and mineral assemblages vary widely (Kerr, 2011). REE mineralization is also locally associated with *ca.* 1439–1423 Ma granite and syenite of the Mistastin batholith (Figure 1; Kerr and Hamilton, 2014).

The SLI forms a circular body about 10 km in diameter, surrounded by a prominent ring-fault associated with fluorite mineralization (Figure 2), but the rocks are exposed only on a few scattered hilltops. The geology is largely deduced from drillcores, and summarized in several reports and papers (Miller, 1986, 1990; Salvi and Williams-Jones, 1991;

Miller *et al.*, 1997). The country rocks to the SLI include granitic to intermediate gneisses in the east, and a quartz-monzonite to monzogranite body in the west, termed the Napeu Kainiut Intrusion by Bélanger (1984). These country-rock units also occur as screens (or roof pendants) within the SLI. There are three granitic units in the SLI, which are termed the exotic-poor, exotic and exotic-rich granite, and defined in part by progressive enrichment in Zr, Y, Nb, Th and REE (Miller, 1986, 1990). This classification was developed as an exploration tool, and these three units can generally be recognized visually and through scintillometer measurements. However, there is some compositional overlap between them. Salvi and Williams-Jones (1991) suggested that the exotic- and exotic-rich granites represent less- and more-altered variants of the same subsolvus granite, and this classification was applied in recent exploration in Québec (Collins and Cashin, 2011). However, the most evolved (exotic-rich) granite is clearly spatially associated with pegmatitic and aplitic segregations that constitute much of the highest grade mineralization in Labrador, and it is distinguished from the other granite units by its lack of dark cognate inclusions. These features suggest that it is a discrete unit, rather than a strongly altered facies.

The SLI contains REE–Zr–Nb mineralization in two main areas (Figure 2), but all of its rock types are strongly enriched in these elements. The Main Zone deposit, located in Labrador (Figure 2), was estimated to contain some 57 Mt at 3% ZrO_2, 0.38% Y_2O_3, 0.31% Nb_2O_5 and 0.54% REE (lanthanide) oxides (Iron Ore Company of Canada, 1985). The REE data from 1980s exploration are not comprehensive, but the overall REE oxide grade of this resource (including the yttrium with the lanthanide elements) would be around 0.9%. Re-analysis of archived sample material for REEs (Kerr and Rafuse, 2012; Kerr, 2013) generally verifies this grade estimate, and also broadly reproduces tonnage calculations. The resource defined at the Main Zone is mostly near-surface, and the average depth of exploration drilling is only about 45 m. The B-Zone deposit in Québec has been explored to greater depths, and the current resource estimates are in excess of 278 million tonnes at similar grades; a high-grade zone containing about 20 million tonnes at 1.44% total REE oxides is targeted for eventual development. The highest grade mineralization in both the Main Zone and B-Zone is associated with pegmatite (± aplite) zones, but large resources of lower grade disseminated mineralization exist in the form of the exotic-rich host granite unit in Labrador (Figures 2 and 3). The high-grade zone in Labrador is called the Zone 1 Lens.

Mineralization at Strange Lake was described by Miller (1986, 1990, 1992) and by Salvi and Williams-Jones (1990) and is not discussed in detail here. The metals of interest occur in unusual minerals that form clots and masses in peg-matite and aplite zones, and fine disseminations in the exotic-rich granite. These minerals include the zirconosilicates gittinsite (Ca-rich) and elpidite (Na-rich), and the REE-enriched Ca–Y-silicates kainosite, gadolinite and gerenite. Many other unusual minerals are reported from these deposits. Gerenite (Jambor *et al.*, 1998) is unique to Strange Lake, and is named for the late Richard Geren, former president of the Iron Ore Company of Canada. It is thought to be the principal host mineral for the REE in the deposit, along with a Y-rich variant of gadolinite, which is rare, but not as rare as gerenite. Zirconium is largely hosted in the rare mineral gittinsite (named for John Gittins, a well-known Canadian specialist on alkaline igneous rocks), but 'hydrous' zircon is also present (Zajac, *in press*). Niobium is largely hosted in pyrochlore [$(Na,Ca)_2Nb_2O_5$].

The variably mineralized host rocks of the SLI are hypersolvus and subsolvus peralkaline granites, and contain sodic amphibole (riebeckite–arfvedsonite) and pyroxene (aegirine) as ferromagnesian minerals. Only the oldest (exotic-poor) unit is hypersolvus (*i.e.*, it contains only a single primary K-feldspar with exsolution of albite), whereas the other units contain discrete primary albite in addition to K-feldspar. The granites locally contain mafic phenocrysts, and some contain diffuse pseudomorphs that were probably originally alkali-zirconosilicate phenocrysts rather than feldspars. Rounded melanocratic inclusions contain better preserved examples of these primary phenocrysts, especially in some subsolvus granites (notably the 'exotic' granite of Miller, 1986); these resemble 'cognate' inclusions described from many granites and interpreted as evidence of coeval mafic to intermediate magmas (*e.g.*, Wiebe *et al.*, 1997). Miarolitic textures are locally present, notably in pegmatites, suggesting a relatively high level of emplacement. Geochronological studies of the SLI include K–Ar determinations of 1271 ± 31 Ma (Currie, 1985) and 1163 ± 21 Ma (Pillet *et al.*, 1989), and a Rb–Sr isochron age of 1189 ± 32 Ma (Pillet *et al.*, 1989). A precise U–Pb zircon age of 1240 ± 2 Ma for the hypersolvus (exotic-poor) granite (Miller *et al.*, 1997), suggests that the K–Ar and Rb–Sr ages are variably disturbed. The younger subsolvus units (exotic and exotic-rich granites of Miller, 1986) contain little zircon, but rather contain unusual alkali-zirconosilicates, notably elpidite ($Na_2ZrSi_6O_{15}$; $3H_2O$). The 1240 Ma age of Miller *et al.* (1997) is used here as a basis for all interpretation of isotopic data.

GEOCHEMISTRY

SAMPLE SELECTION, PREPARATION AND ANALYSIS

The samples analyzed for this study were collected in 2010 and 2011, or were drawn from archived material of
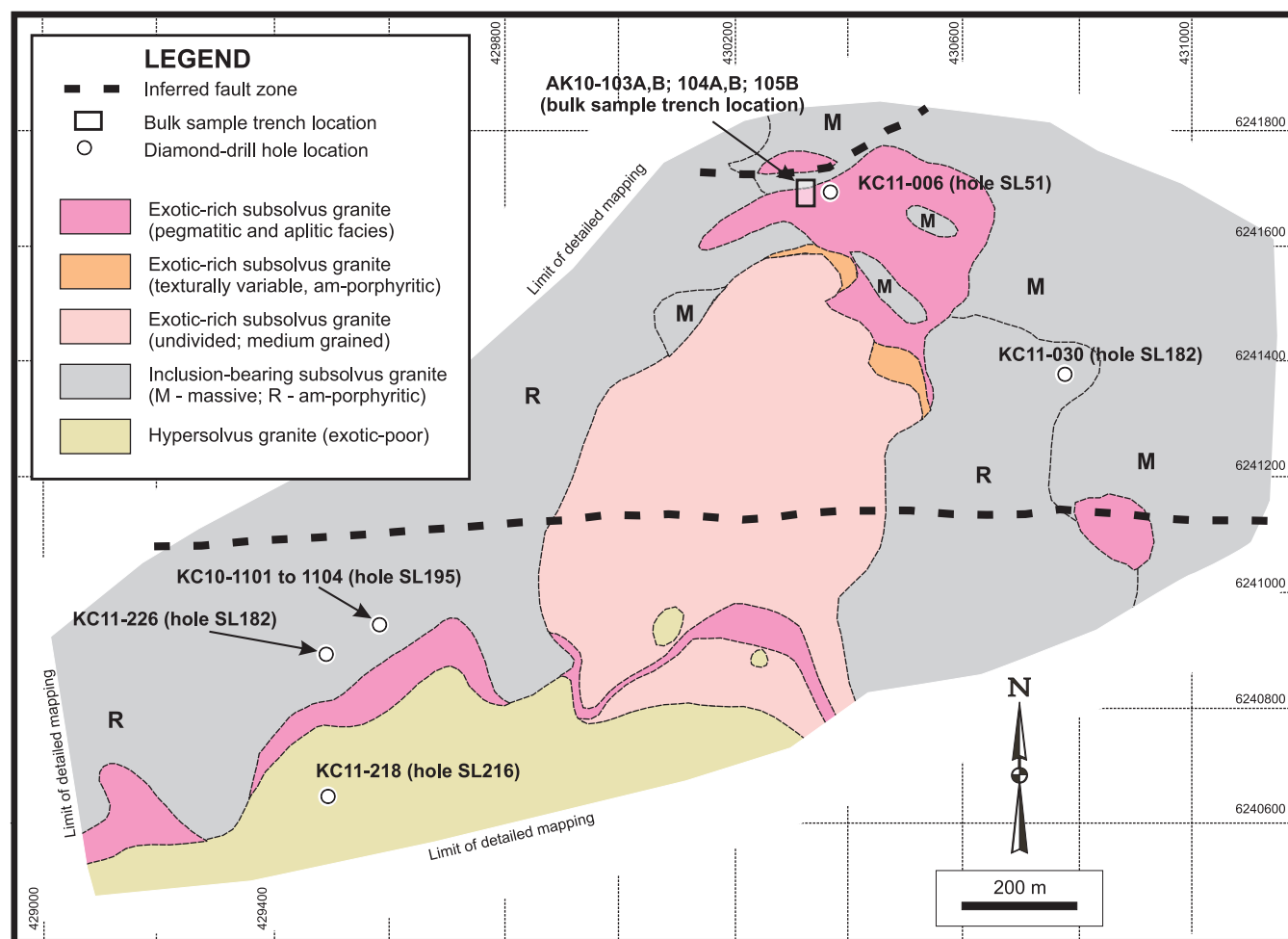
Figure 3. *Geology of the Main Zone deposit area showing the location of the bulk sample trench, and diamond-drill holes from which archived drillcores were collected. For locations of other samples, see Table 1.*

several types. Natural outcrop in the area is very limited, and several samples were collected from archived drillcore now stored in the Department of Natural Resources core library in Goose Bay, Labrador. The locations of most samples are indicated in Figures 2 and 3, and relevant details are provided in Table 1. Collectively, the analyzed samples fall into three groups: older country rocks (granitoid gneisses and Napeu Kainiut quartz monzonite), the host granitic rocks of the SLI, and high-grade mineralized pegmatite and aplite. The data discussed here form a subset of a much larger geochemical database that has not yet been fully evaluated, but will form the basis for future publications.

A single outcrop sample of the exotic-poor (hypersolvus) granite was collected from a ridge along the Québec–Labrador border, southwest of the deposit (AK10-090). Three archived outcrop samples (BR-87-556, 563 and 565) representing the Napeu Kainiut quartz monzonite were provided from archived material by B. Ryan (GSNL), who mapped in this area. These are located several kilometres

south of the deposits, outside the area in Figure 2. Five samples were collected from the bulk sampling trench located on part of the high-grade Zone 1 Lens representing aplite, pegmatite and granite (Figure 3; AK10-103A, B; 104 A, B; 105B). The remaining samples were collected from archived drillcore material, as shown on Figures 2 and 3, and listed in Table 1. Two samples represent country-rock gneisses intersected in holes drilled outside the mineralized zones (KC-11-233, 238); note that the latter sample is from a drillhole located in Québec from which core is now archived in Goose Bay. The remaining samples are typical examples of the host peralkaline granites, including three samples that represent the characteristic melanocratic inclusions noted in some subsolvus granites (KC10-1103; KC11-006, 226).

Aside from sample AK10-090, prepared at the Department of Natural Resources Laboratory, all samples were prepared for analysis at the Department of Earth Sciences, Memorial University, using sodium peroxide (Na_2O_2) fusion techniques to ensure dissolution of all refractory phases.

Table 1. Locational and descriptive information for samples analyzed in this study

Sample Number	UTM (easting)	UTM (northing)	Drillhole and Depth	Comments
Napeu Kainiut Intrusion				
BR-87-556	432400	6235750	N/A	Archived sample from B. Ryan
BR-87-563	436900	6224350	N/A	Archived sample from B. Ryan
BR-87-565	437675	6221300	N/A	Archived sample from B. Ryan
Granitoid gneisses				
KC11-233	438270	6242100	SL-11; 14 m	Medium-grained, lineated orthogneiss
KC11-238	431000	6244250	LB-17; 18.3 m	Coarse-grained, foliated orthogneiss
Inclusions in Granites of the Strange Lake Intrusion				
KC11-006	430396	6241711	SL-51; 21.6 m	
KC11-226	429493	6240884	SL-98; 41.8 m	
KC10-1103	429589	6240922	SL-195; 49.5 m	
Homogeneous Granites of the Strange Lake Intrusion				
AK10-090	428950	5240177	N/A	Exotic-poor granite, natural outcrop
KC10-1104	429589	6240922	SL-195; 70.3 m	Exotic-poor granite
KC11-218	430218	6241626	SL-216; 2.7 m	Exotic-poor granite
KC10-1102	429589	6240922	SL-195; 44.9 m	Exotic granite
KC10-1101	429589	6240922	SL-195; 24.1 m	Exotic-rich granite
KC11-030	430788	6241354	SL-182; 59 m	Exotic-rich granite
High-grade Mineralization from the Zone 1 Lens				
AK10-103A	430306	6241680	N/A	Aplite with poikilitic gittinsite
AK10-103B	430306	6241680	N/A	Pegmatite
AK10-104A	430306	6241680	N/A	Aplite with poikilitic gittinsite
AK10-104B	430306	6241680	N/A	Pegmatite
AK10-105B	430306	6241680	N/A	Fine-grained granite

Notes: The depth indicated in drillholes is the midpoint of sample interval; samples were generally <20 cm of AQ size drill-core. Coordinates indicated for samples in the Zone 1 lens do not indicate that all samples come from exactly the same location, but rather that GPS coordinates cannot resolve the actual locations within error, or account for movement of material during excavation. All drillcore samples are from vertical drillholes archived by the Department of Natural Resources in Goose Bay, Labrador. All coordinates are Zone 21 (NAD1927 Datum) and located on NTS map sheet 24A/08.

Trace-element and REE analyses were completed by ICP-MS techniques. For Sm–Nd isotopic analyses, approximately 0.05 to 0.2 g of rock powder was dissolved in Savilex© Teflon beakers using a mixture of concentrated HF–HNO$_3$ acids. A mixed ^{150}Nd/^{149}Sm spike was added to each sample prior to acid digestion. Both sample and spike were weighed on a high-precision balance. After five days of digestion, the solution was evaporated to dryness and then dissolved in 6 N HCl acid for two days. The solution was then dried and taken up in 2.5 N HCl and loaded for cationic exchange chromatography using AG50W–X8 resin to collect the REE fractions. The REE fractions were then purified and Sm and Nd were isolated using a secondary column loaded with Eichrom© Ln resin. All reagents were previously purified to ensure a low contamination level. The average total chemi-cal blank measured at the TIMS laboratory is 100 pg for Nd and is considered negligible. The Sm and Nd concentrations and Nd isotopic compositions were analyzed using a multi-collector Finnigan Mat 262 mass spectrometer in static mode. The Nd isotopic ratios are normalized to ^{146}Nd/^{144}Nd = 0.7219. The reported values are adjusted to the JNdi-1 standard (^{143}Nd/^{144}Nd = 0.512115, Tanaka *et al.*, 2000). During the course of data acquisition replicates of the standard yielded a mean value of ^{143}Nd/^{144}Nd = 0.512101 ± 8. The in-run precision on Nd isotopic ratio is given at the 95% confidence level. Errors on Nd isotopic compositions are <0.002% and errors on the ^{147}Sm/^{144}Nd ratio are estimated to be lower than 0.1%. The results are listed in Table 2 (REE data and some other relevant trace elements) and Table 3 (Sm–Nd isotopic data).

Table 2. Rare-earth-element (REE) analyses from the Strange Lake intrusion and nearby rocks

Sample [ppm]	Napeu Kainiut Intrusion			Granitoid gneiss		Inclusions in granites		
	BR87-556	BR87-563	BR87-565	KC11-233	KC11-238	KC11-006	KC11-226	KC10-1103
Y	66.67	52.02	59.573	9.52	5.83	354.53	562.79	566.19
La	143.47	117.2	84.1	25.75	18.26	408.02	321.79	163.27
Ce	273.76	227.8	174.6	48.86	31.45	738.75	667.28	395.14
Pr	31.26	27.1	22.1	5.70	3.28	80.28	83.02	54.31
Nd	114.93	100.4	88.6	21.11	11.50	258.03	309.85	210.58
Sm	18.88	15.8	16.5	3.38	1.87	47.73	68.51	56.25
Eu	2.21	2.1	2.0	1.39	0.95	2.91	4.12	2.31
Gd	16.25	12.7	14.0	2.67	1.50	43.40	72.14	64.45
Tb	2.25	1.7	2.0	0.33	0.19	7.87	13.08	12.73
Dy	13.22	9.8	11.7	2.03	1.14	58.64	88.26	84.73
Ho	2.76	2.1	2.4	0.36	0.22	14.31	19.16	17.03
Er	7.61	5.9	6.9	1.10	0.71	50.31	55.26	48.14
Tm	1.13	0.9	1.0	0.16	0.10	9.17	7.83	6.74
Yb	7.19	5.7	6.4	1.01	0.64	67.37	49.64	47.24
Lu	1.04	0.8	0.9	0.14	0.12	10.19	6.85	7.67
Total REE (excl. Y)	635.97	529.89	433.21	113.98	71.93	1796.97	1766.77	1170.60
Total LREE (La to Sm)	582.30	488.20	385.90	104.79	66.36	1532.81	1450.45	879.55
Total HREE (Gd to Lu)	51.46	39.64	45.29	7.80	4.62	261.25	312.21	288.74
Total REE + Y	702.63	581.91	492.78	123.50	77.76	2151.50	2329.56	1736.78

Note: The normalizing values are taken from Taylor and MacLennan (1985). All analyses by ICP-MS methods at Memorial University.

Table 2. Continued

Sample [ppm]	Homogeneous granites				Homogeneous granites		
	AK10-090 [Ex-poor]	KC10-1104 [Ex-poor]	KC11-218 [Ex-poor]		KC10-1102 [Exotic]	KC10-1101 [Ex-rich]	KC11-030 [Ex-rich]
Y	359.04	530.79	618.60		386.70	733.74	655.90
La	307.81	692.49	389.15		552.34	336.80	355.35
Ce	665.70	1454.50	884.31		1104.53	852.60	943.59
Pr	79.79	175.88	101.72		128.99	90.82	105.51
Nd	308.62	696.54	341.31		477.37	282.30	321.08
Sm	65.67	142.73	82.77		103.39	62.41	66.41
Eu	4.57	8.43	4.20		5.75	4.61	3.31
Gd	62.46	136.30	80.33		95.09	63.68	53.91
Tb	12.65	21.37	18.03		19.74	18.93	11.12
Dy	94.33	140.86	131.45		154.39	185.52	94.27
Ho	23.54	32.69	27.98		41.52	61.74	26.75
Er	75.87	97.06	91.51		151.52	263.28	116.61
Tm	11.79	14.12	14.67		27.48	53.10	23.64
Yb	71.14	83.66	98.20		190.59	386.56	193.69
Lu	9.13	11.02	13.46		27.75	58.68	29.83
Total REE (excl. Y)	1793.07	3707.64	2279.09		3080.45	2721.02	2345.06
Total LREE (La to Sm)	1427.60	3162.14	1799.26		2366.62	1624.93	1791.93
Total HREE (Gd to Lu)	360.90	537.07	475.63		708.08	1091.48	549.82
Total REE + Y	2152.11	4238.43	2897.69		3467.15	3454.75	3000.96

Note: The normalizing values are taken from Taylor and MacLennan (1985). All analyses by ICP-MS methods at Memorial University.

Table 2. Continued

Sample [ppm]	High-grade mineralization				
	AK10-103A [aplite]	AK-10-103B [pgmt]	AK10-104A [aplite]	AK10-104B [pgmt]	AK10-105B [Ex-rich]
Y	25882.16	17324.74	3678.87	15238.45	2579.50
La	1427.45	921.52	454.32	1621.77	983.75
Ce	3324.24	2028.95	1190.35	3890.39	1935.49
Pr	397.59	262.95	132.32	421.93	215.61
Nd	1513.20	1069.05	452.71	1382.01	714.96
Sm	766.17	659.93	208.85	567.41	186.03
Eu	72.21	58.25	17.46	50.72	11.86
Gd	1567.00	1339.06	357.01	1122.96	251.10
Tb	499.55	371.68	148.23	330.51	75.17
Dy	4253.73	2882.99	1344.43	2720.52	644.86
Ho	1005.29	643.37	252.93	627.16	128.13
Er	2971.41	1869.73	883.61	1899.36	467.81
Tm	394.14	248.25	146.22	259.28	78.99
Yb	1996.88	1303.20	967.26	1400.89	508.74
Lu	199.24	135.63	126.21	146.11	65.17
Total REE (excl. Y)	20388.11	13794.57	6681.90	16441.00	6267.69
Total LREE (La to Sm)	7428.65	4942.40	2438.55	7883.50	4035.85
Total HREE (Gd to Lu)	12887.25	8793.92	4225.89	8506.78	2219.98
Total REE + Y	46270.27	31119.31	10360.77	31679.45	8847.19

Note: The normalizing values are taken from Taylor and MacLennan (1985). All analyses by ICP-MS methods at Memorial University.

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Table 2 lists the Y and REE concentrations for the samples. Figure 4 shows chondrite-normalized REE profiles, using the reference data of Taylor and MacLennan (1985). All of the analyzed samples have elevated REE concentrations and high Y concentrations. The samples fall into four broad groups. Samples of the country-rock units have the lowest overall Y and REE concentrations, whereas those from high-grade mineralization contain percent-level concentrations of Y and REE. The granitic rocks of the SLI fall between these two extremes, and can be divided into subgroups on the basis of their REE concentrations and profiles.

The two samples of granitoid gneiss have the lowest overall REE and Y contents (72 and 114 ppm total REE + Y, respectively), and are strongly depleted in the heavy REE. The REE profiles of these samples are steep, with small positive Eu anomalies, and abundances are from <10 to around 100 * chondritic values (Figure 4A). The three samples from the Napeu Kainiut quartz monzonite have substantially higher overall REE and Y contents (493 to 703 ppm total REE + Y; 50 to 600 * chondrite). The REE profiles of these samples are closely similar, and steep, indicating enrichment in light REE. In contrast to the gneisses, these profiles have modest negative Eu anomalies (Figure 4B).

The nine samples representing various granitic units in the SLI fall into three subgroups. Three samples representing melanocratic inclusions are enriched in Y and REE (1737 to 2330 ppm Y + REE; 300 to 2000 * chondrite), but generally have lower REE contents than their host granitic rocks (*see* below). The inclusions have steep light REE profiles but relatively flat heavy REE profiles, and have deep negative Eu anomalies (Figure 4D). Three samples from the 'exotic-poor' granite unit have Y and REE concentrations that are slightly higher than the inclusions (2152 to 4300 ppm Y + REE). Their REE profiles resemble those of the inclusions, notably in having a similar flat heavy REE profile (Figure 4C). Samples that represent the 'exotic' and 'exotic-rich' granite units have stronger Y and REE enrichment (3001 to 3500 ppm Y + REE; 1000 to 3000 * chondrite), but overlap with the exotic-poor unit (Figure 4E). The exotic and exotic-rich granite units have distinct heavy REE profiles in which normalized values increase progressively from Gd to Lu, rather than remaining flat; these two granite units are enriched in heavy REE compared to the exotic-poor unit.

Granitic, aplitic and pegmatitic rocks that form high-grade mineralization in the Zone 1 Lens have extreme enrichment in Y and REE, ranging from 8847 ppm (0.88%) to 46 270 ppm (4.62%) Y + REE. These values range up to 20 000 * chondrite for some of the heavy REE. The REE

Table 3. Sm–Nd isotopic data from the Strange Lake Intrusion and nearby rocks

Sample	Description	Age (Ma)	Nd(ppm)	Sm(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(t)$	$^{143}Nd/^{144}Nd$ (t)	Age (Ma)	T(dm) (Ma)
Napeu Kainiut Intrusion										
BR-87-556	qz monzonite	1240	115.33	19.94	0.1045	0.511425	-9.05	0.5105741	1240	2250
BR-87-563	qz monzonite	1240	102.59	17.47	0.1029	0.511420	-8.89	0.5105821	1240	2220
BR-87-565	qz monzonite	1240	83.12	16.38	0.1191	0.511540	-9.12	0.5105702	1240	2420
Granitoid gneisses										
KC-11-233	granitoid gneiss	1240	25.96	3.86	0.0898	0.511132	-12.44	0.5104008	1240	2340
KC-11-238	granitoid gneiss	1240	12.81	1.96	0.0922	0.511123	-13.00	0.5103723	1240	2400
Inclusions in Granites of the Strange Lake Intrusion										
KC-11-006	dark inclusion	1240	251.65	51.63	0.1240	0.511895	-2.96	0.5108853	1240	1940
KC-11-226	dark inclusion	1240	307.86	72.07	0.1415	0.512050	-2.71	0.5108978	1240	2080
KC-10-1103	dark inclusion	1240	233.00	64.19	0.1666	0.512260	-2.60	0.5109034	1240	2550
Homogeneous Granites of the Strange Lake Intrusion										
AK-10-090	Ex-poor	1240	254.10	54.41	0.1294	0.511932	-3.09	0.5108784	1240	2000
KC-10-1104	Ex-poor	1240	588.00	122.70	0.1261	0.511942	-2.37	0.5109152	1240	1905
KC-11-218	Ex-poor	1240	411.20	100.60	0.1479	0.512044	-3.85	0.5108397	1240	2305
KC-10-1102	Exotic	1240	385.70	86.08	0.1349	0.512037	-1.91	0.5109386	1240	1935
KC-10-1101	Ex-rich	1240	234.90	52.82	0.1359	0.512029	-2.23	0.5109224	1240	1975
KC-11-030	Ex-rich	1240	387.20	80.62	0.1259	0.511941	-2.36	0.5109159	1240	1900
High-grade Mineralization from the Zone 1 Lens										
AK-10-103A	high-grade aplite	1240	1556.80	825.40	0.3206	0.513570	-1.50	0.5109595	1240	750
AK-10-103B	high-grade pegmatite	1240	994.00	641.50	0.3903	0.514144	-1.38	0.5109660	1240	950
AK-10-104A	high-grade aplite	1240	482.50	225.50	0.2827	0.513059	-5.46	0.5107571	1240	NA
AK-10-104B	high-grade pegmatite	1240	1469.40	657.80	0.2707	0.513089	-2.97	0.5108848	1240	50
AK-10-105B	medium-grained granite	1240	760.50	211.70	0.1683	0.512309	-1.91	0.5109386	1240	2470

Notes: For discussion of methods and calculation, *see* text. The chondritic uniform reservoir (CHUR) used in calculation is assumed to have $^{147}Sm/^{144}Nd$ of 0.1966 and present-day $^{143}Nd/^{144}Nd$ of 0.512638. Analytical errors for $^{147}Sm/^{144}Nd$ are estimated to be less than 0.1% (~ 0.0001 to 0.0004), and errors for $^{143}Nd/^{144}Nd$ are estimated to be less than 0.002% (~0.00001) at 2 sigma. Calculation of depleted mantle model ages (where possible) follows the model of De Paolo (1988). The 'Age' column refers to the value used in calculation of initial isotopic compositions; for the country rock samples, this value does not correspond to the formation age. The 1240 Ma age for the Strange Lake Intrusion is based upon the U–Pb results of Miller *et al.* (1997).
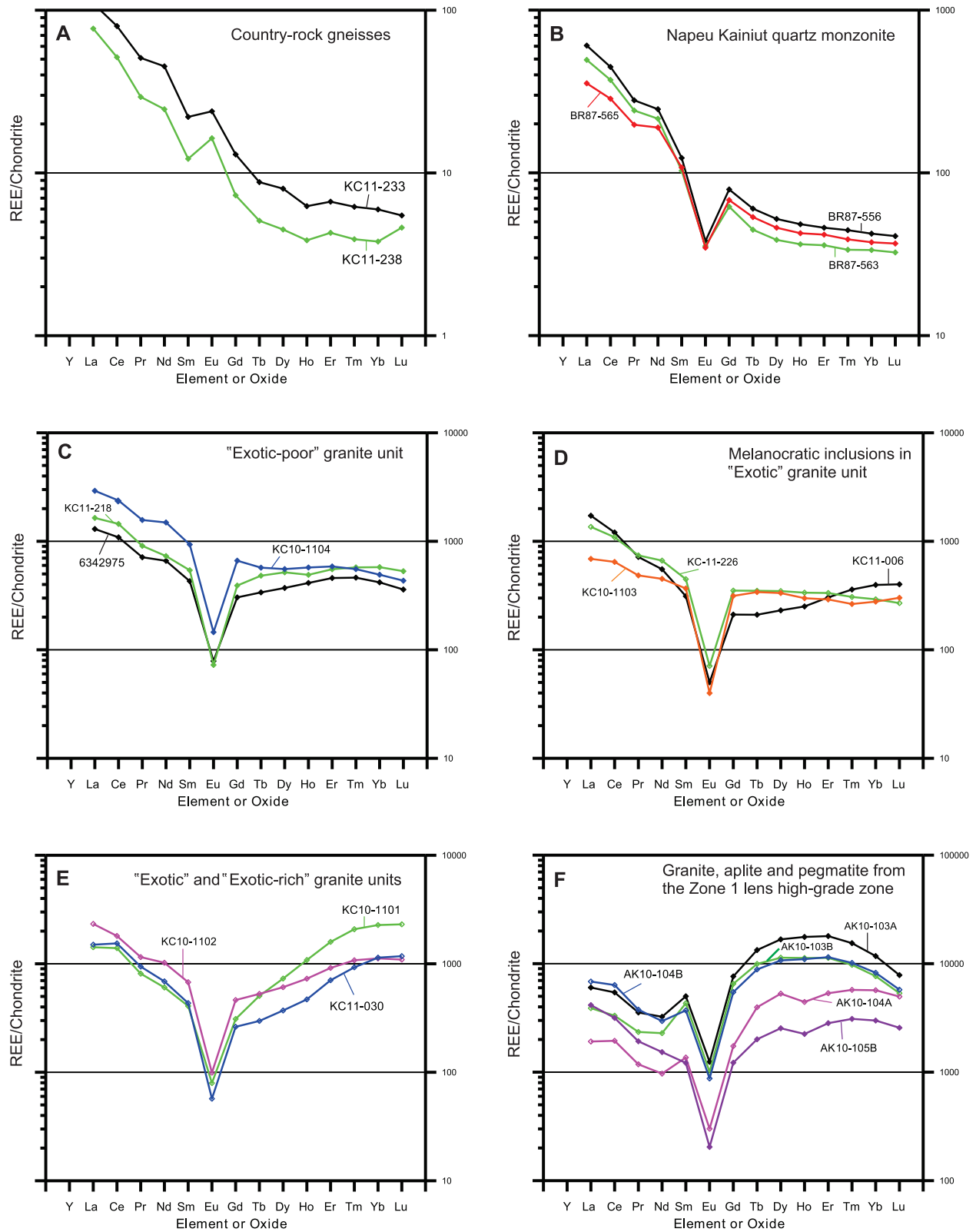
Figure 4. *Rare-earth-element (REE) profiles for samples discussed in this study, all normalized to chondritic values from Taylor and MacLennan (1985).* A) *Granitoid gneiss samples;* B) *Samples from the Napeu Kainiut quartz monzonite unit;* C) *Melanocratic inclusions in exotic-poor and exotic granites from the Strange Lake intrusion;* D) *Exotic-poor granites;* E) *Exotic and exotic-rich granites; and* F) *Granite, aplites and pegmatites from the high-grade Zone 1 Lens.*

profiles for these samples are very distinctive, in that their chondrite-normalized heavy REE abundances equal or exceed values for the light REE. The profiles for the light REE are similar to those of the less-enriched granites and the melanocratic inclusions, aside from a weak positive Sm anomaly noted in four of the five samples. Their heavy REE profiles range from positively sloped to variably convex, with highest normalized abundances typically from Tb to Tm (Figure 4F). Of these samples, only AK10-105B (which has the lowest REE content) has similar normalized-light REE and heavy REE abundances. The remaining samples show three to fourfold relative enrichment in heavy REE (normalized). Such patterns are very unusual.

Due to the wide range of total REE contents, it is difficult to represent all results at the same scale, but this is attempted in Figure 5. This differences in overall REE profile between the country-rock units (granitoid gneisses and Napeu Kainiut quartz monzonite) and the samples from the SLI are clear. The country-rock units have steeper REE patterns compared to all samples from the SLI. Amongst the latter, REE profiles progressively change as the total REE content increases (*i.e.*, from melanocratic inclusions and exotic-poor granites to the exotic and exotic-rich units, and then to high-grade mineralization). There is a shift from relatively flat heavy REE profiles to positively sloped or convex heavy REE profiles, and to progressively greater relative heavy REE enrichment. The high-grade samples develop the unusual positive Sm anomaly. The latter feature is important as ^{147}Sm is the parent isotope in the Sm–Nd system, and these samples thus also contain larger amounts of radiogenic ^{143}Nd than typical crustal rocks.

NEODYMIUM ISOTOPE GEOCHEMISTRY

Calculation of Parameters

The Sm–Nd isotopic data acquired from this study are listed in Table 3. Calculations of $\varepsilon_{Nd}t$ are conducted on the basis of a chondritic uniform reservoir (CHUR) as outlined above; the initial ^{143}Nd/^{144}Nd values calculated for each sample are also listed. The model ages listed in the table are all calculated with respect to depleted-mantle evolution, using the assumptions of De Paolo (1988); for reference, the calculated $\varepsilon_{Nd}t$ value of the depleted mantle at 1240 Ma (age of the SLI from Miller *et al.*, 1997) would be +5.2. Note that these depleted-mantle model ages do not necessarily have geochronological significance, despite being expressed in Ma (*see* later discussion). The formation ages of the Napeu Kainiut quartz monzonite and the granitoid gneisses are unknown, and their $\varepsilon_{Nd}t$ values are also calculated for the time of formation of the SLI, *i.e.*, 1240 Ma. Given its proximity and similarity to granitoid rocks within the adjacent Mistastin batholith, an age of *ca.* 1420 Ma seems reasonable
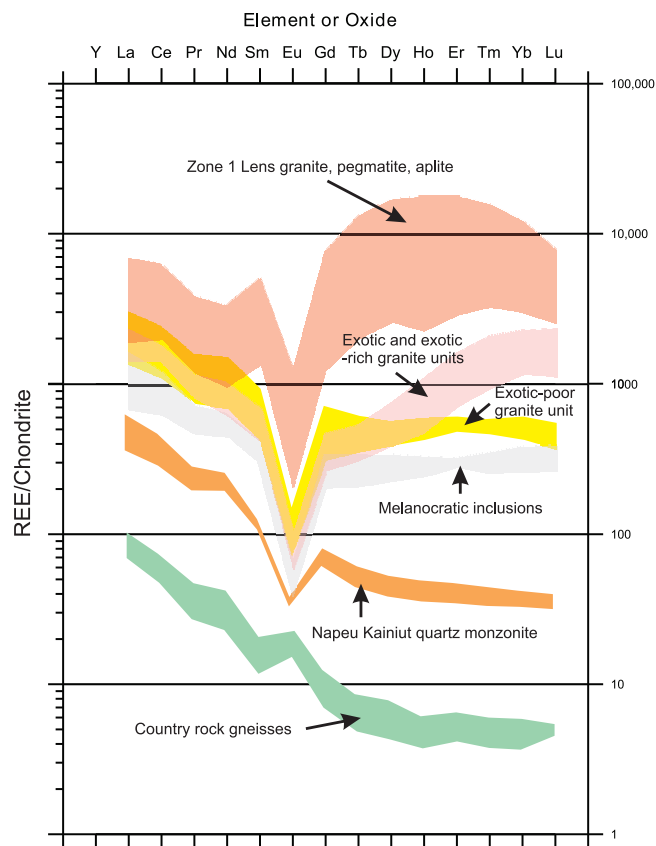

Figure 5. *A comparison between rare-earth-element (REE) profiles for all groups of samples, redrawn to use a common vertical scale, and to better reveal the progressive changes in the REE profiles as the total REE content increases.*

for the Napeu Kainiut quartz monzonite, and this would increase its calculated $\varepsilon_{Nd}t$ values by less than 2 ε units. A decay constant for ^{147}Sm of 6.54* 10^{-12} y^{-1} was employed for all isochron age calculations discussed below, and in calculation of $\varepsilon_{Nd}t$ and ^{143}Nd/^{144}Nd (initial) values. Isochron calculations were accomplished with the Isoplot/EX program (Ludwig, 2003).

Sm–Nd Geochronology

Geochronology was not a prime objective of this study, but the results listed in Table 3 do provide broad geochronological constraints, and can be used to calculate approximate isochron ages. A simple plot of ^{143}Nd/^{144}Nd *vs* ^{147}Sm/^{144}Nd (Figure 6A) shows that the samples fall into three discrete groups, which correspond to the general age ranges inferred for each.

The samples from the granitoid gneisses and the Napeu Kainiut quartz monzonite have low ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd compared to all others, and plot below the broadly linear array that is defined by the data from the SLI,
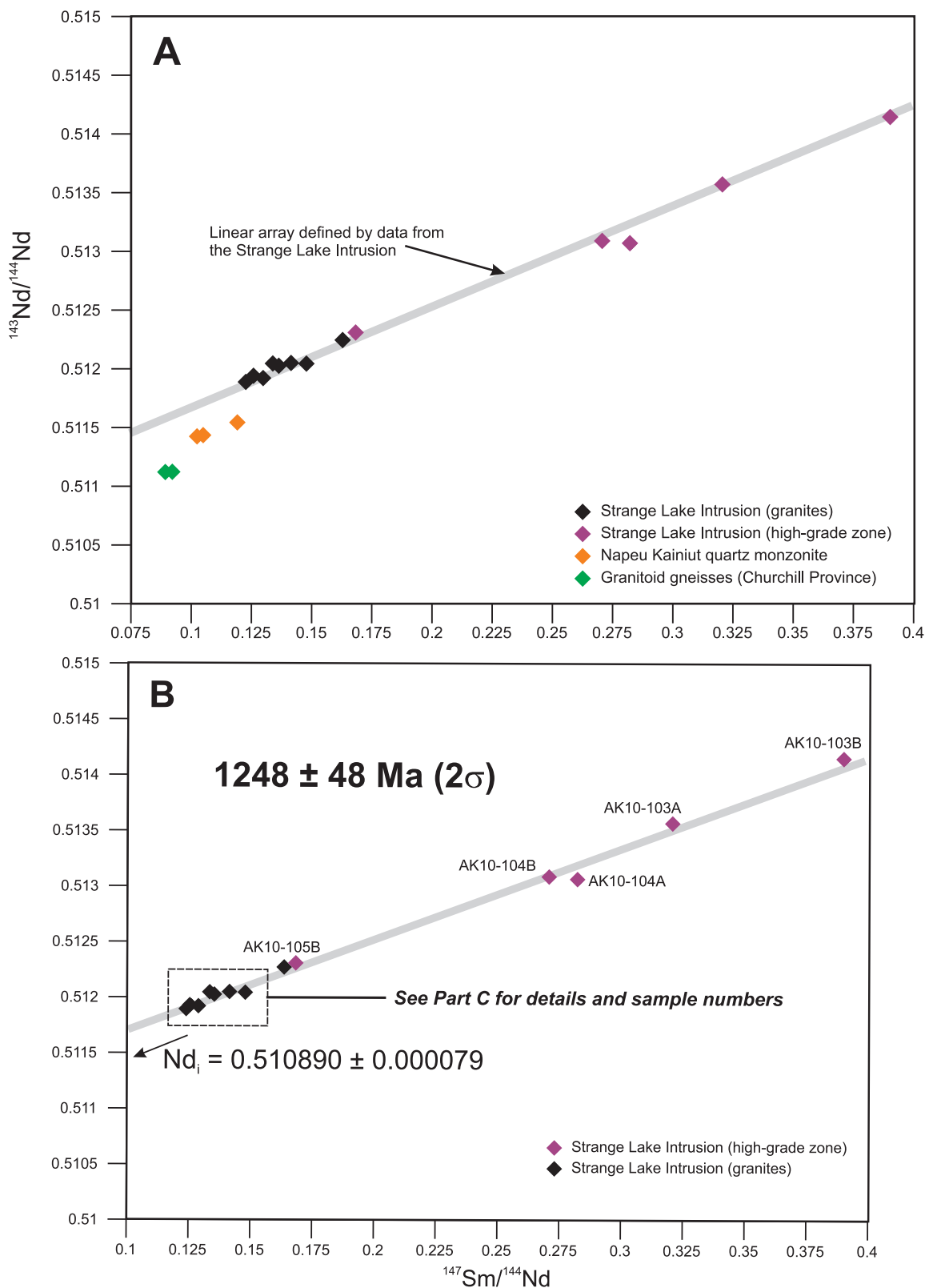
Figure 6. *Plots of $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$.* A) *All data, showing contrast between country rock samples and those of the Strange Lake intrusion;* B) *Expanded view of data from the Strange Lake intrusion, showing the 'errorchrons' defined by these data;* C) *Expanded view of samples that have $^{147}Sm/^{144}Nd$ values below 0.175; and* D) *Plot of initial Nd isotopic ratios calculated for 1240 Ma, showing the generally flat data array for the Strange Lake intrusion.*
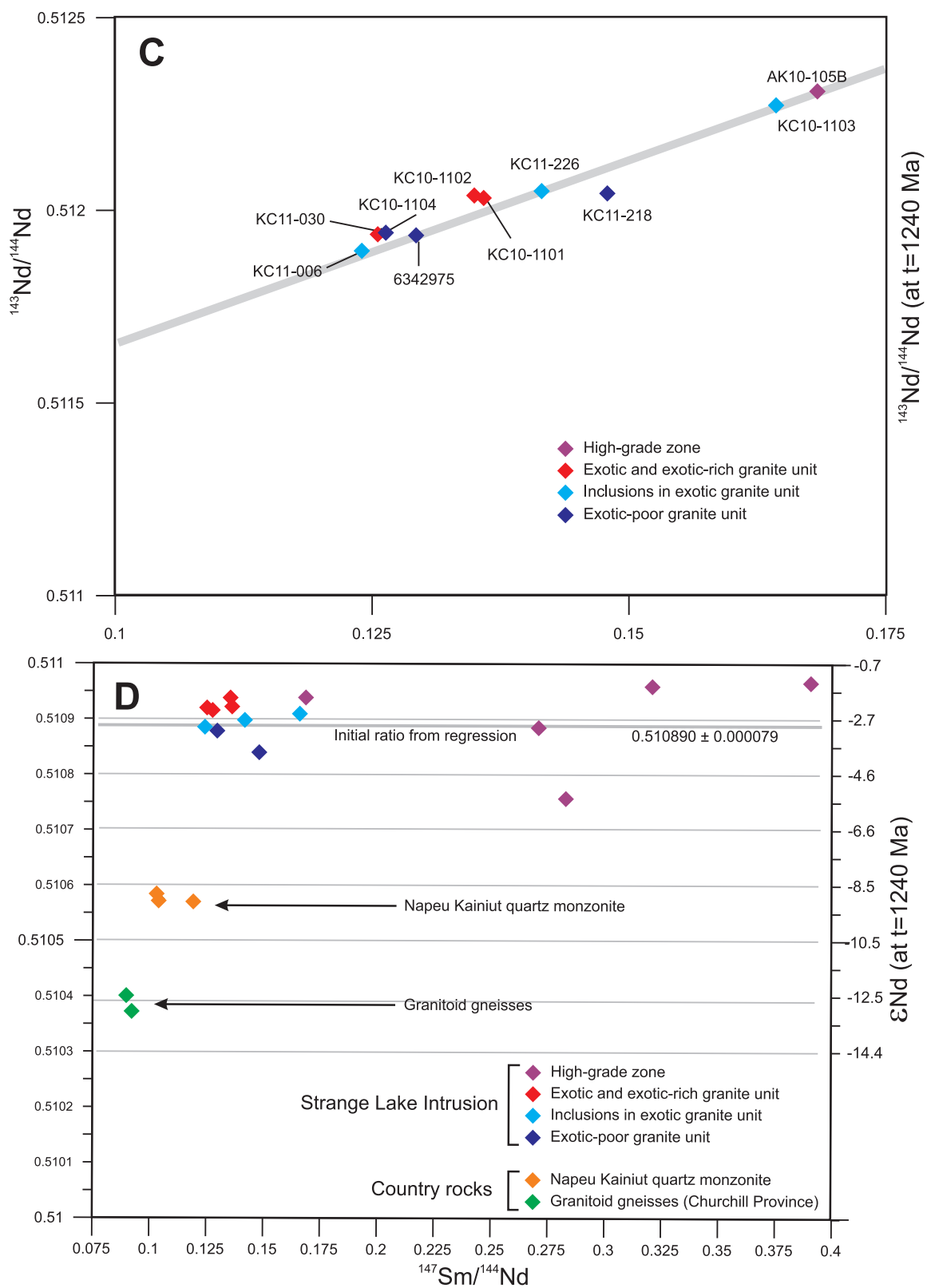
Figure 6. *Continued*

which have a much wider range of $^{147}Sm/^{144}Nd$ values (Figure 6A). No age calculation can be completed for the granitoid gneisses, as there are only two analyses, and these plot almost in the same location. The three samples from the Napeu Kainiut quartz monzonite also approximate to a two-point isochron with little contrast in $^{147}Sm/^{144}Nd$, and this defines an age of approximately 1160 Ma. This is not considered geologically meaningful, as it is younger than the age of the SLI (~1240 Ma), which intrudes the quartz monzonite.

The data from the SLI form a well-defined linear array, which has a wide range in $^{147}Sm/^{144}Nd$, from around 0.1 to 0.4, and whose slope is largely controlled by the samples from high-grade mineralization (Figure 6B). The latter samples have high $^{147}Sm/^{144}Nd$ ratios (>0.2) compared to less-enriched granitic rocks (<0.2); the latter form a much tighter data cluster, for which individual samples are identified in an enlarged plot (Figure 6C). This array is not a true isochron, as some samples lie off the regression line and the probability of fit is 0, but it yields a Model 3 (errorchron) age of 1248 ± 58 Ma, with an initial $^{143}Nd/^{144}Nd$ ratio of 0.510890 ± 0.000079 (MSWD = 111). This result is within error of the 1240 ± 3 Ma U–Pb zircon age obtained from the exotic-poor granite unit by Miller *et al.* (1997). A similar age calculation from the high-grade samples alone gives a result of 1270 ± 290 Ma (MSWD = 349), which improves to 1266 ± 160 Ma (MSWD = 60) if sample AK10-104A (which plots below the regression line) is excluded. Although not accurate in any strict sense, the results confirm that all these samples likely have a common age of formation, as represented by the 1240 Ma U–Pb zircon data of Miller *et al.* (1997). A plot of $^{143}Nd/^{144}Nd$ (initial value, calculated at 1240 Ma) *vs* $^{147}Sm/^{144}Nd$ (Figure 6D) shows that the Strange Lake data form a flat array around a line represented by the initial $^{143}Nd/^{144}Nd$ ratio of 0.510890 ($\varepsilon_{Nd}t$ of about -2.7), providing further evidence of their common isotopic heritage.

### Neodymium Isotopic Compostion Variations

Some indication of variations in Nd isotopic composition amongst samples is provided by Figure 6. The fact that most samples from the SLI form a linear array that corresponds broadly with the *ca.* 1240 Ma age reported by Miller *et al.* (1997) indicates that these rocks are isotopically homogeneous. Samples from the granitoid gneisses and the Napeu Kainiut quartz monzonite plot below this line, and have distinctly different isotopic compositions (Figure 6A, D).

Variations in Nd isotopic compositions are commonly assessed through the calculation of $\varepsilon_{Nd}t$ values, which compare the small variations of $^{143}Nd/^{144}Nd$ to the predicted evolution of a chondritic undepleted reservoir (CHUR) representative of the bulk Earth. Postive values of $\varepsilon_{Nd}t$ indicate a more evolved isotopic composition than predicted for CHUR (*i.e.*, higher values of $^{143}Nd/^{144}Nd$) whereas negative values of $\varepsilon_{Nd}t$ indicate less-evolved isotopic compositions (*i.e.*, lower values of $^{143}Nd/^{144}Nd$). Because the Earth's mantle has become relatively depleted in Nd compared to Sm as a result of magma extraction over time, it evolves to progressively higher $\varepsilon_{Nd}t$ values compared to CHUR (Figure 7). Conversely, crustal rocks formed from the mantle at various times are depleted in Sm compared to Nd, so they evolve to lower $\varepsilon_{Nd}t$ values over time (Figure 7). In general, old crustal rocks, or those that incorporate old crustal components, will evolve to strongly negative $\varepsilon_{Nd}t$ values, as shown by the granitoid gneisses and Napeu Kainiut quartz monzonite. The term 'model age' represents the time when the evolution of a sample and a given reservoir had identical Nd isotopic compositions. Here, model ages are calculated with respect to depleted mantle evolution, after De Paolo (1988). If a rock was derived by melting of an existing crustal source rock, and that melting process did not affect the Sm/Nd ratio, the model age would indicate the approximate time that the source rock was itself derived from the depleted mantle. Although model ages may be useful parameters, they need not have real geochronological significance. In the case of the SLI, there is a wide range of $^{147}Sm/^{144}Nd$ values, indicating fractionation of Sm from Nd; conventionally, model ages calculated from samples that have $^{147}Sm/^{144}Nd$ > about 0.15 are considered unreliable (De Paolo, 1988). A second complication is that many igneous rocks likely involve contributions from mantle-derived magmas and pre-existing crustal rocks, so their $\varepsilon_{Nd}t$ values and $^{147}Sm/^{144}Nd$ ratios are merely artifacts of the mixing process(es). For an illustration of the principles of Nd isotope geochemistry as applied to this case, *see* Figure 7 and its caption. The Sm–Nd isotopic data from this study are also represented graphically in Figure 7. Table 3 and Figure 7 make reference to model ages, but this should not be taken as an indication of geological significance; individual cases are discussed below.

The two samples of granitoid gneisses (KC11-233, 238) have strongly negative $\varepsilon_{Nd}t$ of -12.4 and -13.0 at 1240 Ma (Table 3) but this does not represent their signature at the time of their formation, which is unknown. Both have closely similar depleted-mantle model ages in the Archean (~2700 Ma), which provides an older limit. These samples evolve toward lower ε_{Nd} with time, as their $^{147}Sm/^{144}Nd$ ratios are less than those of the bulk Earth (CHUR). This is a normal pattern for rocks of this general composition.

Three samples from the Napeu Kainiut quartz monzonite (BR87-556, 563, 565) also have negative $\varepsilon_{Nd}t$ values at 1240 Ma, but these are higher than those of the granitoid gneisses, at about -9 (Table 3). These rocks crystallized prior
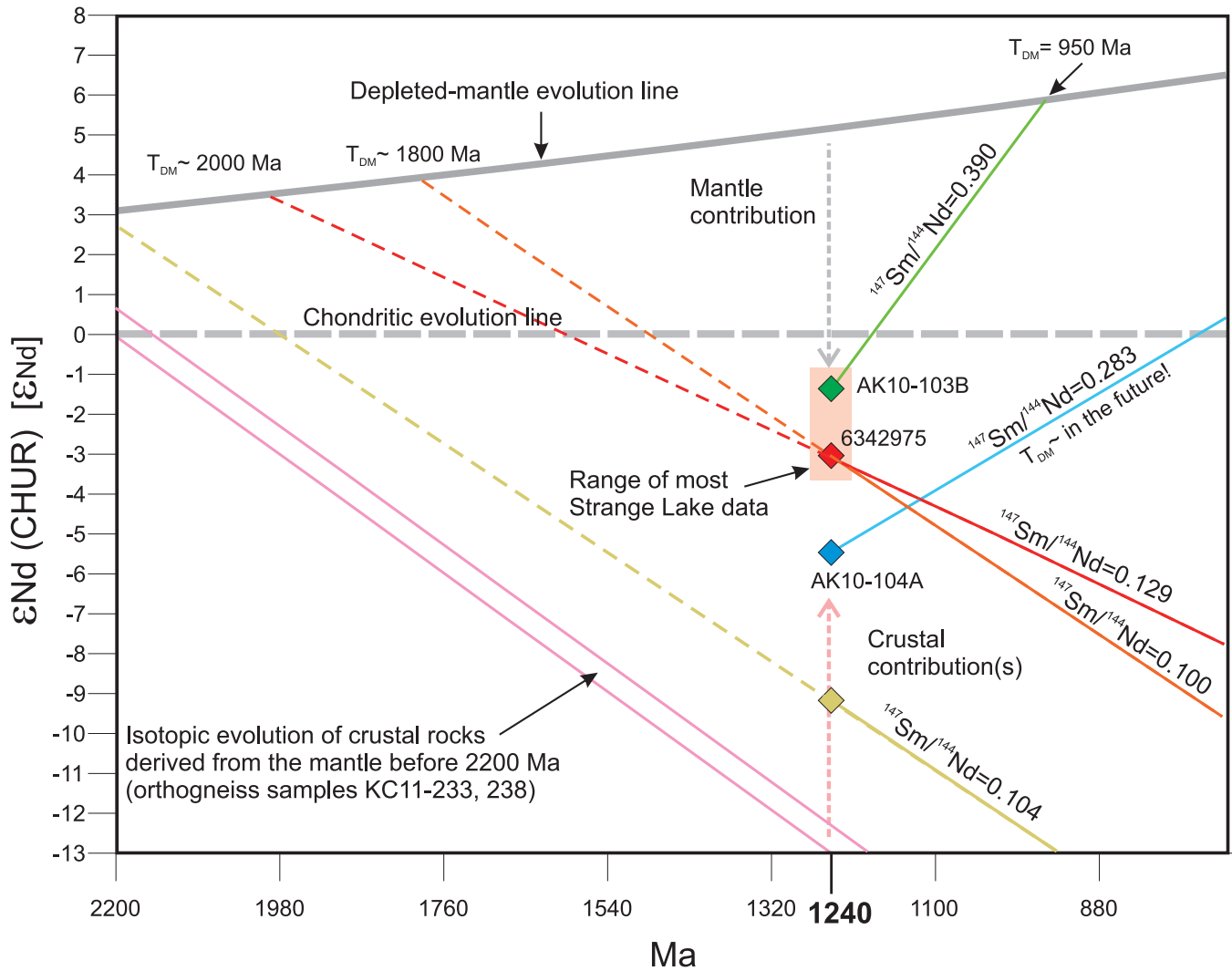
Figure 7. *Summary diagram showing the Sm–Nd isotopic compositions of samples analyzed in this study, and the principles of Nd isotope geochemistry as applied to petrogenetic problems. Samples that have $^{147}Sm/^{144}Nd$ values below that of a chondritic reservoir will evolve to lower $\varepsilon_{Nd}t$ values with time. This applies to the country-rock units, and most of the data from the Strange Lake Intrusion, other than samples from the high-grade zone. If an isotopic growth line is back-calculated, it will eventually intersect the depleted-mantle evolution curve at some earlier time, and this provides the depleted-mantle model age (T_{DM}). In some cases, such ages are interpreted as the formation ages of crustal sources that were later remelted to produce granitic magmas. However, this is only a hypothesis, and even if it is true, a slight change in Sm/Nd during remelting will cause significant changes in the calculated T_{DM} value. A more likely explanation preferred here is that the parental magmas for the Strange Lake intrusion were derived from mixed mantle and crustal sources and that their T_{DM} values have no geochronological significance. Note also that the slope of the isotopic evolution line depends on the $^{147}Sm/^{144}Nd$ of the sample; if this is higher than chondritic, the isotopic composition becomes more radiogenic with time. This situation applies to four of the five samples from the high-grade zone, of which two are illustrated. In these cases, the calculated T_{DM} age is younger than the time of formation; in the case of one sample (AK10-104A), it would actually lie in the future because the isotopic evolution path is almost parallel with that of the depleted mantle reservoir.*

to 1240 Ma, and based on the data from Kerr and Hamilton (2014), are likely not older than *ca.* 1400 Ma. At this time, their $\varepsilon_{Nd}t$ values would have been from -7.0 to -7.5, and the granitoid gneisses discussed above would have had $\varepsilon_{Nd}t$ values around -10.5. These samples also evolve toward lower $\varepsilon_{Nd}t$ with time, as a consequence of their low $^{147}Sm/^{144}Nd$

ratios. Depleted-mantle model ages for these samples range from 2220 Ma to 2420 Ma. The results from these rocks are broadly similar to those presented by Kerr and Hamilton (2014) for mineralized granites within the nearby Mistastin batholith.

The samples from the SLI have $\varepsilon_{Nd}t$ values that range from -1.5 to -5.5, but most samples fall within a narrow range between -2.0 and -3.0. The mean value of all the data is -2.7, but this is influenced by the two samples that have $\varepsilon_{Nd}t$ of -3.8 and -5.5. If the latter are excluded, the mean $\varepsilon_{Nd}t$ value for all data is -2.3. The greatest variation in $\varepsilon_{Nd}t$ is shown by the samples from high-grade mineralization ($\varepsilon_{Nd}t$ from -1.5 to -5.5), which also have the highest $^{147}Sm/^{144}Nd$ values (Table 3; Figure 6). Depleted-mantle model ages for these samples vary widely, from essentially zero (50 Ma) to 2470 Ma, but this variation largely reflects the wider range of Sm/Nd ratios. Samples that have model ages that are younger than 1240 Ma have $^{147}Sm/^{144}Nd$ ratios greater than those assumed for the depleted mantle or the bulk Earth. Consequently, they evolve to more radiogenic Nd isotopic compositions over time, which is the opposite to the normal pattern for crustal rocks. One sample from the high-grade zone (AK10-104A) yields no valid model age, because its $^{147}Sm/^{144}Nd$ ratio is only slightly higher than that assumed for the depleted mantle, and the isotopic evolution lines intersect hundreds of millions of years in the future (Figure 7). None of these model ages are ascribed any geological significance. Granite samples that have more typical $^{147}Sm/^{144}Nd$ ratios (< 0.13) typically have depleted-mantle model ages around 2000 Ma, significantly younger than those given by the granitoid gneisses or the Napeu Kainiut quartz monzonite. The wide range of $^{147}Sm/^{144}Nd$ ratios amongst samples from the SLI is very unusual amongst granitic rocks.

DISCUSSION

The REE patterns (Figures 4 and 5), and the Sm–Nd isotopic results (Figures 6 and 7) allow inferences about the nature of mineralization at Strange Lake, the sources of the REE and other metals, and the processes involved in formation of the deposits and their host rocks. Previous discussions of these topics generated two divergent models that emphasize magmatic or hydrothermal processes, respectively. Miller (1986, 1990, 1992) considered enrichment of the REE and other metals to be caused by magmatic fractionation processes, followed by minor late alteration linked to residual magmatic fluids, which had accumulated in the pegmatite and aplite units. Salvi and Williams-Jones (1990, 1995, 1996) attributed some concentration of the REE to magmatic fractionation processes, but proposed that hydrothermal transport was critical in enrichment and ore formation, and that development of the deposits was prompted by interaction between magmatic fluids and meteoric fluids from the country rocks. This debate was also explored by Zajac *et al.* (1984), Birkett and Miller (1991), Birkett *et al.* (1992), Williams-Jones (2010), Kerr and Rafuse (2012) and Zajac (*in press*), and it continues today. The data presented here do not provide complete and final resolution, but they are important in constraining models.

SOURCE(S) OF PARENTAL MAGMAS

The results from the granitoid gneisses indicate that they represent ancient crustal material, which is consistent with general geological constraints that suggest reworked Archean crust to be important across this part of the Churchill Province (*e.g.*, Bélanger, 1984; Wardle *et al.*, 1990). The results from the Napeu Kainiut quartz monzonite are similar to those obtained from granites in the Mistastin batholith (Kerr and Hamilton, 2014), but the mismatch of ε_{Nd} values in these rocks and the granitoid gneisses at any chosen time (Figure 7) indicates that the quartz monzonites cannot be derived by anatexis of the granitoid gneisses, and likely also include at least some mantle-derived material. Collectively, the gneisses and the Napeu Kainuit quartz monzonite are candidates for crustal contributions to the magmas that formed the SLI, although other materials not presently exposed at surface could be involved.

The formation of magmas is ultimately a consequence of the partial melting of pre-existing source materials. Because the typical mineral assemblage of granites (quartz and two feldspars in roughly equivalent amounts) corresponds to the minimum melting composition in the quartz–albite–orthoclase–anorthite quaternary system (Tuttle and Bowen, 1958), it has long been suggested that granitoid magmas form by partial melting (anatexis) of crustal rocks of broadly intermediate to felsic compositions. However, the extended fractional crystallization of mafic magmas, themselves formed through partial melting of the mantle, can also generate residual liquids of granitic composition. Thus, there is more than one way to make a granitic magma, and if both processes are involved, more than one source might contribute. The Sm–Nd isotopic system is a powerful tracer of such sources, because crustal rocks *generally* have lower Sm/Nd than the residual mantle, but processes within the crust or within the mantle *generally* do not fractionate Sm from Nd (Figure 7). Thus, magmas that have sources dominated by ancient crust will have strongly negative $\varepsilon_{Nd}t$ compared to those that have mantle sources, which will have variably positive $\varepsilon_{Nd}t$ (Figure 7). In the case of so-called 'A-type' granites, which would include REE-bearing peralkaline suites, Kerr and Fryer (1993) suggested mixed crust and mantle sources. In other words, parental magmas were generated by the interaction of mantle-derived mafic magmas and lower crustal rocks, during which elemental and isotopic compositions were homogenized.

The Sm–Nd isotopic data from the SLI are very consistent, defining $\varepsilon_{Nd}t$ values averaging just less than -2 (Table 3; Figures 6 and 7). Only two samples depart from this pattern, and these are discussed separately below. These $\varepsilon_{Nd}t$ values between -1 and -3 are well below those expected for the depleted-mantle reservoir at *ca.* 1240 Ma (+5.2) but are

also significantly higher than those of the older country rocks, which have $\varepsilon_{Nd}t$ of -9 to -13 (Figure 7). These results preclude derivation of the parental magmas to the SLI *entirely* from these older crustal rocks, assuming that surface country rocks are representative of its deeper regions. The REE profiles (Figure 5) provide an independent argument against these country rocks as sources, because they have steep REE patterns (enriched in the light REE) that are totally unlike those of the Strange Lake intrusion, which are enriched in the heavy REE. Partial melting processes cannot produce a magma that has a less fractionated REE pattern than its source, unless the residual mineralogy of the source material is very unusual. Thus, the granitoid gneisses and/or the Napeu Kainiut quartz monzonite do not (alone) represent viable sources for magmas of the SLI.

If the parental magmas were derived by partial melting of some *other* older crustal source, now unrepresented at surface, and if their generation did not involve any significant fractionation of Sm from Nd, the depleted-mantle age (T_{DM}) provides a general estimate of the age of that crustal source, if it were itself derived from the mantle. However, as discussed previously, there are complications in interpreting T_{DM} ages in such a simplistic way. The T_{DM} values for the SLI vary widely (*see* later discussion) but most samples that have low $^{147}Sm/^{144}Nd$ (<0.15) have T_{DM} ages between 1900 and 2100 Ma (Table 3). There are very few magmatic rocks in the Churchill Province that have crystallization ages in this time interval – or in the Canadian Shield generally – so this option seems unlikely. Derivation entirely from an older unrepresented crustal source akin to the granitoid gneisses would require that source to have a higher $^{147}Sm/^{144}Nd$ ratio than expected for most crustal rocks, and this is also considered unlikely, although it cannot be ruled out.

The negative $\varepsilon_{Nd}t$ values from the SLI similarly preclude the direct derivation of parental magmas from the depleted mantle, which would have evolved to $\varepsilon_{Nd}t$ of +5.2 at 1240 Ma. It remains possible that parental magmas were derived from a mantle region that had Sm/Nd ratios closer to chondritic values (*i.e.*, material not depleted in Nd by previous melt extraction) but such a premise contradicts current thought about the Earth's mantle, and the partial melting of such a source would inevitably generate magmas that had steep, fractionated REE patterns unlike those of the SLI.

The Sm–Nd isotopic studies rarely give rise to unique solutions, and this case is no exception; some preferences have to be expressed. My preference is that the parental magmas to the SLI were generated by mixing of mantle-derived magmas and crustal rocks (*cf.*, Kerr and Fryer, 1993). This qualitative model is evaluated below, but its discussion first requires a consideration of the variations in REE patterns and Sm/Nd ratios revealed by the data from the Strange Lake intrusion.

GEOCHEMICAL EVOLUTION OF PARENTAL MAGMAS AND ORE DEPOSITS

The Sm–Nd isotopic data from the SLI show wide and systematic variation in $^{147}Sm/^{144}Nd$, manifested by the linear data array (Figure 6), which provides a generalized isochron that is broadly consistent with the U–Pb zircon age for the intrusion. However, two samples lie below this isochron (Figure 6) and have $\varepsilon_{Nd}t$ values below the range defined by most of the data (Figures 6 and 7). These two samples are a high-grade aplite (AK10-104A; $\varepsilon_{Nd}t$ of -5.5) and an exotic-poor granite (KC11-218; $\varepsilon_{Nd}t$ of -3.9). At face value, these deviations could be interpreted to indicate a higher proportion of contained crustal material compared to the other samples. In the case of KC11-218, which has a relatively low total REE content, the discrepancy is slight and might be due to undetected inclusions of older material, but this explanation is not viable for the REE-enriched aplite. An alternative explanation is that mild post-crystallization disturbance of Sm/Nd ratios might have occurred; a small increase in Sm/Nd at some later time would shift the the calculated value of $e_{Nd}t$ (1240 Ma) to a lower value. Sample AK10-104A does have an anomalously high $^{147}Sm/^{144}Nd$ ratio compared to the less-mineralized granites, but all samples from the high-grade zone have similar or higher values (0.17 to 0.39) compared to typical values of 0.15 or less in the granites. The high Sm/Nd ratios are a general characteristic of high-grade samples, and there is no indication of any relationship between variation in $^{147}Sm/^{144}Nd$ and $\varepsilon_{Nd}t$ (Table 3; Figure 6D). These contrasts between host granites and high-grade mineralization merit further discussion.

The very high $^{147}Sm/^{144}Nd$ values for four of these samples (aplite and pegmatite) mean that they evolve toward more radiogenic Nd isotopic compositions (*i.e.*, higher $\varepsilon_{Nd}t$) with time, which is the opposite of the normal behaviour for crustal rocks (Figure 7). As a result, the depleted-mantle model ages (T_{DM}) for three of the four are younger than their crystallization ages (Figure 7). The Nd isotopic evolution of sample AK10-104A is closely similar to that of the depleted mantle, and the two paths have yet to intersect (Figure 7). The calculated $\varepsilon_{Nd}t$ values for the remaining high-grade samples are consistent with the the data from less-mineralized granites, which argues against widespread post-crystallization disturbance of Sm/Nd. The high Sm/Nd ratios are also clearly visible in the REE profiles for the high-grade samples, which all have a small positive Sm anomaly (Figures 4 and 5). The same feature is present in the REE profiles for the Y-rich gadolinite that likely contains much of the light REE at Strange Lake (Jambor *et al.*, 1998). Kerr and Rafuse (2012) showed that REE patterns that closely resemble those of the high-grade rocks, including their positive Sm anomalies, could be reproduced by two-component mixing of the gerenite and gadolinite REE compositions

reported by Jambor *et al.* (1998). Similar positive Sm anomalies are also evident in the REE patterns of drillcore intervals reported to consist of mixtures of aplite and/or pegmatite (Kerr and Rafuse, 2012). This pattern is clearly a general feature of strongly mineralized rocks at Strange Lake.

The distinct REE geochemistry of the high-grade samples could be interpreted to represent selective enrichment in Sm, or selective depletion of the REE that have lower atomic numbers than Sm (*i.e.*, La, Ce, Pr and Nd), such that Sm appears to be enriched. The relative normalized abundance of Sm compared to the heavy REE in these rocks is about the same as in less-mineralized samples, and the second explanation is preferred. Such depletion of La, Ce, Pr and Nd could have occurred prior to crystallization of the magmas, during their crystallization, or during post-crystallization alteration. The processes involved could be magmatic or hydrothermal, or a combination of both. Light REE depletion prior to crystallization could be caused by the crystallization of a light-REE-enriched mineral or by the transfer of these more mobile light REE into a fluid phase that separated from the late-stage magmas prior to or during their solidification. Post-solidification extraction and removal of these light REE through hydrothermal alteration cannot be ruled out, but it seems unlikely that this process could generate such consistent REE patterns. Kerr and Rafuse (2012) showed that the REE patterns of high-grade intervals in archived drillcores consistently show light REE depletion, and that the size of the positive Sm anomaly increases with total REE contents. This trend is more suggestive of fractional crystallization or an early stage fluid-phase separation. The progressive change in the REE patterns as total REE content increases (Figure 5) is most consistent with a magmatic crystallization process as the fundamental control of geochemical evolution. A fluid phase may indeed have exsolved and removed some of the more mobile light REE, but if this is so, there is no indication that these elements have been enriched elsewhere in the area, unless they reside within the fluorite-rich breccia zone around the complex, or in zones that have since been removed by erosion.

ECONOMIC IMPLICATIONS

The results of this investigation confirm the previous observations of Kerr and Rafuse (2012) and Kerr (2013) that the REE profiles and light REE to heavy REE ratios are subtly different amongst various rock types of the SLI. Specifically, the pegmatite and aplite units that constitute the highest grades of mineralization also show the highest proportions of the heavy REE, notably those elements in the middle of the heavy REE sequence (*e.g.*, Tb, Dy, Ho, Er), and also yttrium. The lower grade mineralized granites that constitute the largest fraction of the overall resource at Strange

Lake have a higher relative proportion of the more abundant light REE elements (La, Ce, Pr and Nd). In evaluating resources at Strange Lake and other similar deposits, it is obviously important that the individual REE be both analyzed and reported, in addition to summary variables such as total REE oxides. Given the higher demand for and higher prices applicable to the heavy REE, the overall value of the pegmatite and aplite-rich material is greater than it would appear from its total REE content, and mining such material would produce lesser amounts of light REE that are predicted to be oversupplied, and therefore of lower value.

The pegmatite and aplite zones in the mineralized section of the SLI are typically thin, discontinuous and sporadic in occurrence, and would be difficult to extract on a selective basis. The Zone 1 Lens represents one of the few places in the area where such material is extensive, and it thus represents a small but very important resource. Furthermore, if such material could be defined as more continuous units at depth, it might hold tonnages and grades amenable to selective underground mining. In this context, the deepest holes completed in the 1980s (SL-178 and SL-147) both intersected a thick (>10 m) band of such material at depths below 100 m, which has yet to be traced laterally (Miller, 1985; Kerr, 2013). Newly acquired REE data from resampling of archived drillcores should in time provide a more comprehensive picture of the variation in REE profiles amongst different rock types and mineralization styles.

A QUALITATIVE MODEL FOR PETROGENESIS AND EVOLUTION

Any petrogenetic model for the SLI must explain three key features. First, it must explain how the parent magmas evolved such extraordinarily high REE contents, and also such strong enrichment in other incompatible elements. Second, it must explain the strong relative enrichment in the heavy REE (Gd to Lu), compared to more typical granites and the country rocks around the intrusion, and the progressive changes in REE patterns from less-evolved granites to high-grade pegmatite and aplite. Third, it must explain the consistent Nd isotopic signatures of almost all the samples, which preclude any simple model that involves the remelting of older crust similar to the country rocks, or derivation of parental magmas entirely from the depleted mantle.

Strong enrichment in incompatible trace elements and REE is most easily explained by protracted fractional crystallization. The Nd isotopic signatures imply that parental magmas had both mantle-derived and crustal-derived components, and are mixtures of these two sources, but the proportions of each are hard to constrain. In any two-component isotopic mixing, the composition of the final mixture is strongly dependent on the concentration contrasts for Nd (and, by inference, other REE) between the end-member

components. If the mantle-derived magma had undergone significant fractionation to generate a high overall REE content *prior* to mixing with a crustal component, very large contributions of the latter would be required to produce the observed Nd isotopic signatures. The recognition of a crustal Nd isotope contribution implies that the concentration of REE by extended fractionation *postdated* the interaction and mixing of mantle-derived magmas and older crust. The most likely candidates for a crustal REE source component would be older Mesoproterozoic rocks that resemble the Napeu Kainiut quartz monzonite, which has elevated REE contents. It is suggested that the hybrid magma formed by interaction of mantle-derived mafic magmas and older crust underwent extensive fractional crystallization, to eventually form the highly enriched residual magmas that crystallized to form the SLI. The melanocratic inclusions that are common in the exotic-poor and exotic granite units resemble those that are commonly interpreted to record mingling between coexisting mafic-intermediate and felsic magmas (*e.g.*, Vernon, 1984; Wiebe *et al.*, 1997). However, the isotopic data indicate homogenization of Nd isotopic signatures within this composite magma chamber. At later stages in evolution, the crystallization of REE-bearing minerals progressively modified the REE profiles of magmas, and fractionated Nd from Sm, leading to the highly unusual compositions of the late-stage pegmatites and aplites, which have high REE contents and relative light REE depletion. It is also possible that the exsolution of a fluid phase during this late-stage crystallization selectively removed some light REE. The extreme relative heavy REE-enrichment in the Strange Lake deposits is in part a function of these processes, but the more general enrichment seen in the granites is likely a feature inherited from the original parental magmas. Mantle-derived magmas formed by high degrees of partial melting might not have high REE contents, but they would have relatively flat (unfractionated) REE patterns. The high liquidus temperatures and thermal capacity of such magmas enables digestion of lower crustal rocks that were relatively light REE-enriched, like those of the Napeu Kainiut quartz monzonite. The assimilation of such rocks would have greater impact on the light REE contents of mixtures but lesser effects on the heavy REE.

The model outlined above seems to be the most viable mechanism by which to produce the distinctive REE geochemistry of the SLI and its associated deposits, based on present data. The reasoning is at this point qualitative, but it can eventually be constrained by numerical calculations using the data in this report and other information from work in Labrador and elsewhere. The results of more detailed petrogenetic modelling for the Strange Lake intrusion will be presented elsewhere.

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