Geochemical and radiogenic isotope (Sr–Nd) characteristics of Paleoproterozoic anorthositic and granitoid rocks in the Umiakoviarusek Lake region, Labrador, Canada.

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Abstract: Recent work in the north-central Labrador has identified Paleoproterozoic anorthositic and granitoid rocks that are spatially associated with, yet temporally distinct from, younger Mesoproterozoic intrusions of the Nain Plutonic Suite. The Umiakoviarusek Lake (UL) region of Labrador contains several of these Paleoproterozoic intrusions and provides an opportunity to study their geochemical and radiogenic isotope (Sr–Nd) characteristics. Geochemically, the anorthositic and granitoid rocks have features consistent with contemporary anorthositic and granitoid rocks from other anorthosite–mangerite–charnockite–granite complexes. The anorthositic rocks contain elevated contents of Al₂O₃, CaO, Sr, and Eu with low Ba, Rb, K, Zr, total rare earth elements (REE), and light REE. The granitoid rocks, on the other hand, contain lower concentrations of these elements along with elevated SiO₂ and K₂O. Isotopic data at 2050 Ma for the anorthositic rocks (I⁰Sr = 0.7048–0.7082; εNd = −4.1 to −15.9) and granitoid rocks (I⁰Sr = 0.7036–0.7094, εNd = −5.1 to −9.7) are consistent with variable crustal and mantle contributions to their genesis. The relatively unradiogenic Sr and slightly evolved Nd isotopic data from the UL granitoid rocks is consistent with a significant juvenile mantle component, possibly derived from an underplating mantle plume; this component may also be present in the anorthositic rocks. The Nd and Sr isotopic data are also consistent with crustal contamination from Archean source materials; however, based on the existing isotopic database for the Nain Province gneisses, it is not possible to delineate a specific gneiss component. Furthermore, it is also quite possible that an Archean source, unlike any described at present, was a crustal source component in the UL intrusive rocks.

Résumé : Les études récentes de la région nord-centrale du Labrador ont révélé la présence de roches anorthositiques et granitoïdes datant du Paléoprotérozoïque, lesquelles sont associées spatialement aux intrusions plus jeunes, du Mésoprotérozoïque, de la suite plutonique de Nain, avec la réserve qu’elles sont considérées temporairement distinctes. La région du lac Umiakoviarusek du Labrador renferme plusieurs de ces intrusions paléoprotérozoïques propices à l’étude de leurs caractères géochimiques et de leurs isotopes radiogéniques (Sr–Nd). Géochimiquement, les roches anorthositiques et granitoïdes montrent des particularités compatibles avec les roches anorthositiques et granitoïdes de d’autres complexes d’anorthosite–mangerite–charnockite–granite datant de la même époque. Les roches anorthositiques contiennent des proportions élevées de Al₂O₃, CaO, Sr et Eu et de faibles teneurs de Ba, Rb, K, Zr, terres rares totales et terres rares légères. D’autre part, les roches granitoïdes affichent des concentrations plus faibles de ces éléments et de fortes proportions de SiO₂ et K₂O. Les données isotopiques à 2050 Ma des roches anorthositiques (I⁰Sr = 0.7048–0.7082; εNd = −4.1 à −15.9) et des roches granitoïdes (I⁰Sr = 0.7036–0.7094, εNd = −5.1 à −9.7) sont en accord avec l’hypothèse évoquant que leur formation implique des contributions variables de la croûte et du manteau. Les données isotopiques du Sr relativement nonradiogénique et du Nd peu évolué des granitoïdes de type lac Umiakoviarusek cadrent bien avec la présence d’un composant mantellique significativement juvénile, dérivé probablement d’un panache mantellique sous-plaque; ce composant est probablement présent aussi dans les roches anorthositiques. Les données isotopiques du Nd et Sr sont en accord également avec une contamination crustale par des matériaux d’origine archéenne, cependant l’examen de la base de données des isotopes dans les gneiss de la Province de Nain ne peut conforter l’identification d’un tel composant gneissique spécifique. De plus, il est aussi fort probable que la source archéenne, contrairement à toutes celles décrites jusqu’à présent, correspondait à un composant de source crustale dans les intrusions de type lac Umiakoviarusek.

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Introduction

Recent research, including field mapping (e.g., Ryan et al. 1997, 1998; Piercey 1998) and geochronological studies (Emslie and Loveridge 1992; Ryan and Connelly 1996), in north-central Labrador have shown that anorthositic and granitoid rocks previously assigned to the Mesoproterozoic Nain Plutonic Suite (NPS; Ryan 1990) are, in fact, not members of this suite, as they have Paleoproterozoic emplacement ages (2137–2032 Ma; Hamilton et al. 1988). This suite of intrusions is proximal to the younger NPS (e.g., Ryan et al. 1998), but display postemplacement metamorphic and structural overprinting due to the 1.86–1.74 Ga. Tornagat Orogeny (e.g., Bertrand et al. 1993; Van Kranendonk and Wardle 1997; Van Kranendonk 1996); such features are not observed in the NPS (e.g., Emslie et al. 1994; Ryan et al. 1997, 1998).

Anorthositic and granitoid rocks in the Umiakoviarusek Lake (UL) region of Labrador have field and geochronological features similar to those of Paleoproterozoic intrusions elsewhere in the Okak Bay region (e.g., Ryan et al. 1997, 1998; Hamilton et al. 1998; Piercey 1998) and lie on the northern extremity of the 15 × 30 km belt of Paleoproterozoic intrusions that have thus far been identified and subdivided from the Mesoproterozoic massifs by Ryan et al. (1998) (Fig. 1). This region is particularly interesting because it hosts three granitoid and two anorthositic (sensu lato) intrusions, presumably belonging to this older suite (e.g., Ryan et al. 1998; Piercey 1998). In this paper, we provide geochemical and isotopic data from these Paleoproterozoic anorthositic and granitoid rocks to document their geochemical and isotopic characteristics and to provide an understanding of the petrogenetic controls and the role of basement in the genesis of this older suite. Whether these intrusions have similar geochemical and isotopic characteristics, basement contamination influences, and petrogenesis as compared to the Mesoproterozoic suite is at present unknown. Thus the aim of this new dataset is to provide insight into the nature of the Paleoproterozoic anorthositic–granitoid magmatism and the Paleoproterozoic crustal evolution of this part of North America.

Regional setting

The geology of the UL area consists of an eastern and northern portion, underlain by quartzofeldspathic and mafic granulite–amphibolitic basement gneiss of the Archean Nain Province, and a western portion, underlain by a group of Mesoproterozoic (1350–1290 Ma; Ryan et al. 1991; Ryan and Emslie 1994; Emslie et al. 1994), bulbous-shaped anorthositic and granitoid intrusive rocks forming the northernmost component of the Nain Plutonic Suite (Ryan 1990; Fig. 1). The NPS is a typical multiphase anorthosite–mangerite–charnockite–granite (AMCG) intrusive complex that intruded episodically from ca. 1350 to 1290 Ma (Ryan and Emslie 1994). The igneous phases within the NPS generally lack any structural fabric.

In contrast to the NPS intrusive rocks is a northwest-striking linear swath of variably foliated, Paleoproterozoic, metamorphosed and deformed anorthositic, granitoid and basic dyke intrusive rocks (Fig. 1; Emslie and Loveridge 1992; Emslie et al. 1997; Ryan and Connelly 1996; Ryan et al. 1997, 1998; Hamilton et al. 1998). The granitoid magmatism is bracketed between ca. 2137 and 2032 Ma (Wheeler Mountain, Sheet Hill, Loon Island, Halbach, Illulik, Alligator Lake plutons; Emslie and Loveridge 1992; Ryan and Connelly 1996; Hamilton et al. 1998; Fig. 1), and anorthositic and basic dyke magmatism is between 2121 and 2045 Ma (Aupalukitak Mountain intrusive and two metamorphosed basic dykes; Hamilton et al. 1998; Fig. 1). Although, of all the intrusive rocks in the UL area, only the Illulik granite at 2124 Ma (Hamilton et al. 1998) has actually been dated, the proximity to dated Paleoproterozoic intrusions and common field characteristics (Piercey 1998; Ryan et al. 1998) make them likely members of this older suite.

Geology and petrography of anorthositic and granitoid rocks in the Umiakoviarusek Lake region

The geology of the UL region has been the focus of regional work by Ryan et al. (1998) and a detailed scale study by Piercey (1998). The geology of the area consists of at least three granitoid plutons and two anorthositic plutons (sensu stricto), with lesser felsic and mafic dykes (Fig. 2); as mapped to date, none of these plutons contains supracrustal enclaves. The oldest granitoid rocks comprise foliated fayalite–orthopyroxene granitoid rocks that are the northerly extension of the Paleoproterozoic Illulik pluton (Fig. 2). These eastern granitoid rocks have a wide range in composition from quartz monzonite to granite and K-feldspar granite with variable amounts of mafic minerals. Clinopyroxene and orthopyroxene dominate the mafic mineral mode, with lesser biotite, hornblende, and fayalite. Typically, green–brown hornblende, and lesser red biotite, form coronas which partially, and in some cases fully, replace the pyroxenes; in other cases, actinolite is present on the fringes of the pyroxene grains. Accessory zircon, apatite, and titanite are common inclusions within the hornblende and biotite, whereas myrmekitic plagioclase and perthitic and microclinic K-feldspar often contain sericite and epidote dustings. The foliated (defined by K-feldspar and hornblende clots) granitoid intrusive lies in sinistral strike-slip fault contact with the Archean Nain Province amphibolites, mafic granulites, and quartzofeldspathic gneisses, and exhibits the same structural grain as the gneisses (Fig. 2).

The Illulik granitoid rocks were intruded by lesser foliated to unfoliated, buff-weathering leucocratic to gabbronitocrime of the Pripet Marshes pluton (Fig. 2; Ryan et al. 1998). Within the study area, the Pripet Marshes pluton consists predominantly of an oxide-rich leucosome. It differs from the anorthositic rocks of the Goudie Lake pluton to the west with its buff colouration, greater modal orthopyroxene oxide minerals, and lesser developed greenish facies mineral assemblages. This being said, the euhedral to subhedral plagioclase in the leucosomes have sericite and epidote dustings and variable replacement of the mafic minerals by actinolite–chlorite assemblages.

The Goudie Lake pluton (Ryan et al. 1998) in the western portion of the study area is dominated by anorthosite (sensu stricto) and leucosome (Fig. 2). North of UL, the Goudie Lake pluton consists predominantly of dark black to grey anorthosite (sensu stricto; e.g., P96-3A, P96-19, P96-33),
which appears to grade into leuconorite south of UL. The anorthositic rocks are variably metamorphosed with partial to complete replacement of orthopyroxene and plagioclase by actinolite–chlorite and epidote–sericite assemblages, respectively. Some samples contain crosscutting polymineralic veinlets (ca. 1–2 mm) of calcite, dolomite, sericite, or chlorite. Local pockets of unmetamorphosed leuconorite exist south of UL, which are characterized by pristine cumulus plagioclase with unaltered intercumulus orthopyroxene containing rod-like exsolution lamellae of rutile.

North of UL, the anorthositic rocks of the Goudie Lake pluton are intruded by mafic dykes and granular, aplitic to granitic dykes (P96-3B, P96-28B). The granitic dykes are dominated by recrystallized quartz, sericite, carbonate, and lesser epidote. Both the Goudie Lake pluton and the felsic dykes have been deformed by ca. 2–5 m wide zones of south-southwesterly directed ductile (mylonitic) shearing, and the dykes themselves exhibit south-southwesterly vergent folding.

Mafic dykes also intrude the Goudie Lake pluton south of UL. These dykes exhibit variable strikes (e.g., northwest, east-northeast, north) and range from diabase to lesser gabbro. Shearing along dyke margins was not observed in the dykes documented in this study, but is typical of other dykes.
Fig. 2. Geology of the Umiakoviarusek Lake area and related intrusions. Mapping inside study area from Piercey (1998), outside study area is modified from Ryan et al. (1998). GLP, Goudie Lake pluton; PMP, Priptet Marshes pluton; ORVP, Owl River Valley pluton; QMG, quartz monzonite group.
in the region (e.g., Ryan et al. 1997, 1998). Widespread retrogression of mafic minerals to greenschist facies assemblages of chlorite–actinolite–tremolite–sericite–epidote is common in all Paleoproterozoic dykes (Ryan et al. 1998) including the UL ones. Anorthositic rocks in contact with the dykes have a distinctive bright white bleaching with bright green patches of altered mafic minerals.

Leuconoritic rocks of the Goudie Lake pluton south of UL were intruded by the Owl River Valley pluton (Ryan et al. 1998; Piercey 1998; Fig. 2), a variably foliated, brown to rusty coloured, hornblende–biotite–clinopyroxene–fayalite-bearing intrusive of monzonite to syenite. Higher temperature mafic minerals (fayalite, clinopyroxene) exhibit significant hydration as coronitic overgrowths of hornblende ± biotite, which lend a speckled appearance to the granitoid rocks. Complete replacement of fayalite and clinopyroxene by hornblende is common, and in other cases hornblende and biotite occur as small patches along the crystallographic axes of these primary minerals. Accessory titanite, zircon, and particularly apatite are common within the hornblende and biotite grains. Of particular note is that quartz is absent in the Owl River Valley pluton (cf. Ryan et al. 1998), while plagioclase and perthitic K-feldspar are present in roughly subequal proportions. Foliations in the Owl River Valley pluton granitoid rocks, defined by felspars and hornblende, are strongest near their contact with the Goudie Lake anorthositic rocks, have variable orientation and dip, and appear to be present not only along their margins, but also sporadically within the intrusion (Fig. 2).

In the western edge of the study area, the Owl River Valley pluton is intruded by a regional unit of ovoidal-feldspar quartz–monzonite (Ryan et al. 1998; QMG, quartz monzonite group). These granitoid rocks are volumetrically minor inside the study area and are texturally variable; some intrusive rocks are granular with abundant quartz and recrystallized plagioclase and K-feldspar. The granular intrusive rocks contain lesser mafic minerals, which are restricted to hornblende and biotite that exhibit a distinctive metamorphic parallelism on the hand-specimen scale. In contrast, a coarse variant observed in one locality contained coarse-grained plagioclase and hornblende, and biotite, along with ovoidal feldspars and recrystallized feldspars and quartz.

**Geochemistry**

**Sampling and analytical protocol**

A total of 22 samples were collected from the different plutons and petrographic groups in the Umiakoviarusek region. Anorthositic rocks (n = 11) include (1) three anorthosites (sensu stricto) and five leuconorites from the Goudie Lake pluton, and (2) two leuconorites from the Priest Marshes pluton. Granitoid rocks (n = 12) include (1) two felsic (quartz monzonite) dykes that intrude anorthosite north of Umiakoviarusek Lake; (2) four fayalite–hornblende (± biotite) monzonites and one syenite from the Owl River Valley pluton; (3) monzonite, quartz syenite, and quartz monzonite (n = 3) from the QMG; and (4) one monzonite and K-feldspar granite from the foliated granitoid rocks in the eastern sector of the property. Trace elements (Ba, Rb, Sr, Zr, Y, Nb, K, Ti) and rare earth elements (REE) + Th geochemistry were determined by pressed-powder-pellet X-ray fluorescence (XRF) and Na₂O₂ sinter inductively coupled plasma mass spectrometry (ICP–MS) techniques following the methods, respectively, of Longerich (1995) and Longerich et al. (1990), and Jenner et al. (1990). Major element determinations were also undertaken on the pellets by XRF; the light element (SiO₂, MgO, Al₂O₃, Na₂O) determinations are semiquantitative (Longerich 1995); however, given the monomineralic character of the rocks, these results are sufficient for the purposes of this study. Precision in the trace element analyses by XRF and ICP–MS, measured as percent relative standard deviation (%RSD), is 0–3% for all elements (Longerich 1995; Longerich et al. 1990; Jenner et al. 1990).

All anorthositic and granitoid rocks, with the exception of the foliated granitoid rocks, were analysed for Rb–Sr and Sm–Nd isotopic composition by thermal ionization mass spectrometry (TI–MS) using the isotope-dilution preparation technique outlined by MacLachlan and Dunning (1998) and Horan (1998).

The sample powder was weighed to the fifth decimal and attacked with 8N nitric and 2× hydrofluoric acids, with two to seven days refluxing. Following redissolution, the sample was split into isotopic concentration (IC) and isotopic dilution (ID) fractions. The ID fraction was spiked with ORNL 150Nd–147Sm mixed spike based on Nd concentration. Initial Rb and Sr separation was completed with EICHROM TRU-Spec ion exchange resin; the Rb and Sr were collected using 2B 3N nitric acid, evaporated to dryness, and loaded onto EICHROM SR–Spec ion exchange resin, from which Rb (2B 3N nitric acid) and Sr (2B water) were collected. For the Nd and Sm separation, the fraction was loaded into Teflon columns with 2× 0.15N HCl; the Nd fraction was collected with 2× 0.17N HCl, and the Sm IC by 2× 0.50N HCl. Two drops of 1N phosphoric acid were added to all three fractions prior to evaporation.

Analyses were completed using a Finnigan MAT 262V TI–MS on outgassed Re double filaments. The Rb fraction was analysed via single-peak jumping routine on either Daly or Faraday collectors. The Sr IC fraction was analysed using a simultaneous Faraday multicollector routine. The Sr ID fraction was analysed using a simultaneous Faraday multicollector routine for ⁸⁴Sr/⁸⁶Sr and ⁸⁸Sr/⁸⁶Sr ratios. Each routine analysed five data blocks of 20 scans for a total of 100 scans. ⁸⁷Rb/⁸⁶Sr ratios were calculated via a LOTUS 123 97 spreadsheet, based on measured ⁸⁷Rb/⁸⁶Rb and ⁴⁴Sr/⁸⁶Sr spiked ratios (⁶⁸Rb/⁸⁶Rb errors are absolute at 95% confidence levels (2σ), quadratically added using 2σ errors for ⁸⁷Rb/⁸⁶Rb and ⁸⁴Sr/⁸⁶Sr measured ratios (⁸⁷Sr/⁸⁶Sr errors are reported at 2σ and are based solely on spectrometry measurements).

Nd and Sm IC and ID fractions were analysed using static Faraday multicollector routines consisting of five blocks of 20 scans for a total of 100 scans with online drift and mass fractionation correction and statistical analysis. The ⁱ⁴⁳Sm/¹⁴⁴Nd ratios were calculated via a LOTUS 123 97 spreadsheet, based on measured ⁴³Sm/⁴⁰Sm and ¹⁵⁰Nd/¹⁴⁴Nd spiked ratios (⁴³Sm/¹⁴⁴Nd errors are absolute ±2σ quadratically added using 2σ errors for ⁴³Sm/⁴⁰Sm) and ¹⁵⁰Nd/¹⁴⁴Nd measured ratios (¹⁴³Nd/¹⁴⁴Nd errors are reported 2σ levels and are based solely on spectrometry measurements). Values of eNd are calculated using ¹⁴³Nd/¹⁴⁴Nd (CHUR) of 0.512638 and ¹⁴⁷Sm/¹⁴⁴Nd (CHUR) of 0.19659.
The average of 51 analyses of NBS 987 standard was 0.710251 (errors as two sigma $2\sigma = 12$); accepted is 0.710250 ($2\sigma = 15$). Average of three analyses of NBS 984 Rb standard was 2.59265 ($2\sigma = 400$); accepted is 2.59265 ($500$). Average of 37 analyses of La Jolla standard was 0.511855 ($2\sigma = 12$); accepted is 0.511850 ($15$). Average of 23 analyses of AMES Sm standard was 1.084951 ($2\sigma = 89$); accepted is 1.084955 ($150$).

Initial $\Delta^t$Nd and $f^{\delta{\text{Sm/Nd}}}$ were calculated using the present day chondrite uniform reservoir values of $^{147}\text{Sm}/^{144}\text{Nd} = 0.1966$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$; while depleted mantle model ages ($T_{\text{DM}}$) were calculated using depleted mantle values of $^{147}\text{Sm}/^{144}\text{Nd} = 0.21144$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.513113$, and a decay constant of $\lambda = 6.54 \times 10^{-12}$ a$^{-1}$ (Faure 1986). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were fractionation corrected by normalization to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$.
Initial $^{143}$Nd/$^{144}$Nd, $^{87}$Sr/$^{86}$Sr ($I_{Sr}$), and εNd values were calculated at 2050 Ma, the published lower limit of Paleoproterozoic magmatism in this region (ca. 2045 Ma; Hamilton et al. 1998). To account for potential age variations, the εNd and $I_{Sr}$ values were calculated at 100 Ma year intervals of 2050 Ma (within the known range of Paleoproterozoic magmatism; cf. Hamilton et al. 1998) and yielded variations of 0.75–1.73 and 0.88–1.27 εNd units, with averages of 1.17 and 1.06 for the anorthositic and granitoid rocks, respectively. Variations in $^{87}$Sr/$^{86}$Sr ratios range from 0.00001 to 0.00009 and 0.00071 to 0.00305 for the anorthositic and granitoid rocks, respectively.

**Results**

**Geochemistry**

Geochemical data are presented in Table 1 and Figs. 3 and 4. Given the cumulate nature of the anorthositic rocks from...
the UL region, it is not surprising that the major element and, to a lesser extent, the trace element geochemical signatures of these rocks strongly reflect their cumulate mineralogy. In particular, all of the anorthositic rocks have elevated Al₂O₃, CaO, Sr, and to a lesser extent Ba (Table 1). Other notable features of the anorthositic rocks can be observed in the form of chondrite-normalized REE and primitive mantle-normalized trace element plots in Figs. 3 and 4. Notably, all the anorthositic rocks are characterized by downward-sloping profiles from light REE (LREE) to heavy REE (HREE) and variable fractionation ((La/Yb)ₙ = 5.7–149), with variably developed positive Eu anomalies (Eu/Eu* = 0.61–2.6), with increasing pyroxene content in the anorthositic rocks (Table 1; Figs. 3a–3c). The REE profiles for the anorthositic rocks are broadly similar, with slightly fractionated REE patterns ((La/Yb)ₙ = 4.3–16) and generally flat to weakly positive anomalies (Eu/Eu* = 1.6–12) (Figs. 3a–3c; Table 1). Within the anorthositic rocks, there are subtle differences in REE chemistry that appear to be related to their mineralogy. For instance, the anorthosites (sensu stricto) from the Goudie Lake pluton have the steepest REE patterns and largest Eu anomalies (Fig. 3a; Table 1), whereas the leucoritites (15–25% orthopyroxene) from the same pluton have a less steep pattern with a smaller Eu anomaly (Fig. 3b), and the leucoritites from the Pripet Marshes pluton (25% orthopyroxene) exhibit the flattest pattern and smallest Eu anomaly (Fig. 3c). A similar relationship is observed for Sr in the primitive mantle normalized plots (Figs. 3a–3c; Table 1). The mafic intrusive rocks are also characterized by relatively high Rb and Ba relative to Th and U (Figs. 4a–4c; Table 1). Similarly, the Nb contents are variable, but generally show negative anomalies (Figs. 4a–4c) and exhibit a rough positive correlation with Th contents (Table 1). The other high field strength elements (HFSE) have variable concentrations with broad increases, for the most part, in Hf, Zr, Y, TiO₂, and P₂O₅, with increasing pyroxene content in the anorthositic rocks (Table 1; Figs. 4a–4c).

The granitoid rocks from the UL region, for the most part, are characterized by elevated K₂O, SiO₂, and Fe₂O₃T contents, and have variable trace element signatures (Table 1; Figs. 3e–3h, 4d–4g). The REE profiles for the granitoid rocks are broadly similar, with slightly fractionated REE patterns ((La/Yb)ₙ = 4.3–16) and generally flat to weakly positive or negative Eu anomalies (Eu/Eu* = 0.61–2.6), with the exception of the felsic dykes (Eu/Eu* = 2.68, 3.05; Figs. 3e–3h). Similar to the anorthositic rocks, the primitive mantle normalized patterns of the granitoid rocks exhibit low Th and U relative to Ba and Rb, but variable Nb contents ranging from flat to negative, to slightly positive anomalies (Figs. 4d–4g). All the granitoid rocks are characterized by elevated Zr and depletion in Sr and Ti relative to the primitive mantle (Figs. 4d–4g; Table 1).

Neodymium and Strontium isotope geochemistry

Neodymium and strontium isotopic data are presented in Table 1 and Fig. 5. Anorthositic and granitoid rocks from the UL region display distinctive vertical and horizontal trends, respectively, in εNd–Ig space (Fig. 5), typical of AMCG complexes (e.g., Geist et al. 1989, 1990; Emslie et al. 1994). Anorthositic rocks from the UL region have very restricted εNd (at 2050 Ma) values, ranging from 0.7048 to 0.7082, with most between 0.7048 and 0.7060 (Fig. 5; Table 2). The Nd isotopic data are more variable with εNd (at 2050 Ma) ranging from −4.11 to −15.88, fSmNd from −0.30 to −0.68, and TDM from 2.54 to 3.80 Ga (Fig. 5; Table 1).

The TDM ages for the granitoid rocks from the UL region are broadly similar (2.82–3.26 Ga). Even though the TDM extends to lower values in the granitoid rocks relative to the anorthosites, both groups have average values within 0.13 Ga of each other (3.03 Ga for granitoid rocks, 3.16 Ga for anorthositic rocks). The εNd (at 2050 Ma) values for the granitoid rocks range from −5.14 to −9.70, whereas fSmNd values are from −0.34 to −0.50 (Fig. 5; Table 2). Initial strontium ratios for the granitoid rocks range from 0.7091 to 0.7094, however, the lower values (<0.70) may have been reset by the Torngat Orogen-related metamorphism (as evidenced by sericitic alteration of feldspars and hornblende replacement of pyroxene), and if removed from the dataset, the values range from 0.7036 to 0.7095 (Fig. 5; Table 2).

Discussion

Traditionally, AMCG complexes in north-central Labrador have been considered to be Mesoproterozoic (e.g., Emslie 1978, 1980, 1985; Ryan 1990; Emslie et al. 1994). Recent work, however, has also identified a Paleoproterozoic AMCG magmatic event (Emslie and Loveridge 1992; Ryan and Connelly 1996; Hamilton et al. 1998; Ryan et al. 1997, 1998). Geological features of the anorthositic and granitoid rocks described in this paper and their proximity to dated Paleoproterozoic intrusions (e.g., Hamilton et al. 1998) indicate that the UL intrusive rocks are part of this Paleoproterozoic suite, and Ryan et al. (1998) have explicitly mapped the UL intrusive rocks as Paleoproterozoic. Some of the diagnostic physical features used by Ryan et al. (1998) to define the intrusive rocks as Paleoproterozoic include greenschist facies assemblages, faulting, and localized shearing and folding. Hence, the geochemical and isotopic characteristics as defined above for the UL intrusive rocks provide new information on the origin of the whole Paleoproterozoic AMCG suite.

Geochemical attributes

The high SiO₂, K₂O, Rb, Zr, and LREE, coupled with low Al₂O₃, CaO, TiO₂, and Sr contents (e.g., Figs. 4d–4g; Table 1) of the Paleoproterozoic granitoid rocks are typical of AMCG-related granitoid rocks (e.g., Emslie 1991; Emslie and Stirling 1993; Emslie et al. 1994, 1997). Similarly, the anorthosite geochemical character, with elevated Al₂O₃, CaO, TiO₂, Sr, Eu, and Ba, and depletion in K₂O, Rb, and Zr contents (e.g., Figs. 4a–4c; Table 1), is also typical of AMCG-related anorthositic and basic rocks (e.g., Xue and Morse 1993; Emslie et al. 1994, 1997). Various interpretations have been proposed to explain the geochemical variations between the granitoid and anorthositic suites, and most recent models for the NPS advocate a petrogenetic link between the two. For instance, Emslie and Stirling (1993); Emslie and Hegner (1993), and Emslie et al. (1994) proposed that basaltic underplating of the lower continental crust by a mantle plume could induce crustal melting and generation of granitoid magmas. Such a melting episode would result in a hot, pyroxene–plagioclase residue enriched in Al, Ca, Ti, Sr, and Eu that, when assimilated by the basaltic plume, would place plagioclase on the liquidus for extended periods of time, forming anorthositic magmas and ultimately giving rise to the anorthositic rocks of AMCG.
Fig. 3. Chondrite-normalized REE plots for the intrusive bodies from the Umiakoviarusek Lake region, including (a) Goudie Lake pluton anorthosites, (b) Goudie Lake pluton leuconorites, (c) Pripet Marshes pluton leuconorites, (d) all Paleoproterozoic intrusives in UL area, (e) Owl River Valley pluton granitoid rocks, (f) quartz monzonite group granitoid rocks, (g) Illulik foliated granitoid rocks, and (h) felsic dykes. Chondrite values from Taylor and McLennan (1985).
Fig. 4. Primitive mantle normalized multielement plots for the intrusive bodies from the Umiakoviarusek Lake region, including (a) Goudie Lake pluton anorthosites, (b) Goudie Lake pluton leuconorites, (c) Pripet Marshes pluton leuconorites, (d) Owl River Valley pluton granitoid rocks, (e) QMG granitoid rocks, (f) Illulik foliated granitoid rocks, and (g) felsic dykes. Primitive mantle values from Hoffman (1988).
suites (Emslie and Stirling 1993; Emslie and Hegner 1993; Emslie et al. 1994; Xue and Morse 1993).

Alternatively, the granitic (or jotunite–charnockite) phases of AMCGs have been modelled as fractionates from a more primitive jotunite suite (e.g., Auwera et al. 1998). Duchesne and Wilmart (1997) indicated that mixing of a fractionating olivine-bearing residual magma with replenishing magmas, coupled with extensive crustal contamination of jotunite–charnockite phases, was involved in the generation of AMCG granitoid rocks.

To summarize the geochemical features, the data provided for the Paleoproterozoic UL anorthositic and granitoid rocks are consistent with current models for AMCG genesis. Our isotopic data were generated with a view to determining if contamination of the magmatic suite was also important in the generation of AMCG granitoid rocks.

The distribution of isotopic data for the UL intrusive rocks is very similar to that in younger Mesoproterozoic AMCG suites (e.g., NPS, Emslie et al. 1994; Laramie, Geist et al. 1989, 1990; Scoates and Frost 1996), with horizontal and vertical trends in eNd–I$_{Sr}$ space for the granitoid rocks and anorthositic rocks, respectively (Fig. 5). The data for most of the granitoid rocks of the UL region (Fig. 5) have low I$_{Sr}$ values when compared to signatures in the younger NPS granitoid rocks at their time of formation. For instance, with the exception of the QMG, all of the granitoid rocks have less radiogenic I$_{Sr}$ values than the NPS granitoid rocks (Fig. 5). In contrast, the QMG granitoid rocks have more evolved signatures, but still have a strong juvenile component when compared to the range of possible crustal contaminants (e.g., Fig. 6a). The Nd isotopic data mimic the Sr isotopic data and are consistent with an Archean crustal component (e.g., T$_{DM}$ ages, low eNd), but a less radiogenic component must also be present given the higher eNd values (Fig. 5; Table 1).

Based on Nd isotopic data, Emslie et al. (1994) showed that even with up to 90% crustal influence, granitoid rocks from the NPS needed a juvenile mantle component to explain their observed Nd isotopic signatures. The Paleoproterozoic Wheeler Mountain granites, which are probably correlative to the UL intrusive rocks, also have a significant documented juvenile component, and akin to the NPS, the component was likely derived from a basaltic underplate (plume) that drove crustal anatexis and granitoid genesis (Emslie and Loveridge 1992). We hypothesize that the juvenile component could have been sourced from a basaltic underplate related to plume activity. The isotopic data for the UL granitoid rocks are also consistent with this interpretation.

Fig. 5. Epsilon Nd vs. I$_{Sr}$ (at t = 2050 Ma) for the Umiakoviarusek Lake granitoid rocks and anorthositic rocks in comparison to other anorthositic and granitoid rocks from north-central Labrador. KI, Kiglapait intrusion (DePaolo 1985); AW, NPS anorthositic rocks west of Nain–Churchill Province suture; GW, NPS granitoid rocks west of Nain–Churchill Province suture; AE, NPS anorthositic rocks east of Nain–Churchill Province suture; GE, NPS granitoid rocks east of Nain–Churchill Province suture (Emslie et al. 1994); WM, Paleoproterozoic Wheeler Mountain granite (Emslie and Loveridge 1992). All of the Mesoproterozoic units (KI, AE, AW, GE, GW) are calculated at 1300 Ma, all Paleoproterozoic units (this study, WM) are calculated at 2050 Ma. The granitoid and anorthositic rocks from the UL intrusions have distinctive horizontal and vertical trends similar to rocks from other anorthositic–granitoid complexes (e.g., Geist et al. 1990; Emslie et al. 1994). Granitoid rocks from the UL region have very radiogenic signatures, akin to the temporally equivalent (?) Wheeler Mountain granites, suggesting a possible mantle component in their genesis. Other details are discussed in the text.

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Table 2. Neodymium and Strontium isotope data for the Umiakoviarusek Lake intrusions.

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Notes: ND, not determined; NA, not applicable.

*Calculated at 2050 Ma.

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Fig. 6. (a) εNd–I_{Sr} data for the Umiakoviarusek Lake intrusive rocks and potential basement contributors. Fields for the middle Archean and early Archean Nain Province gneisses are from Schiøtte et al. (1993) and Collerson et al. (1989), respectively. Mixing lines were calculated using the equations of Langmuir et al. (1989). Subdivisions on each curve represent 10% mixing of the components. HALG, isotopic composition of high-alumina gabbro from the Laramie Complex, Wyoming (Mitchell et al. 1995). (b) εNd–f_{SmNd} for the UL relative to possible middle (Schiøtte et al. 1993) and early Archean (Collerson et al. 1989) Nain Province gneisses. CHUR, chondrite uniform reservoir. Details are provided in the text.
Table 3. Neodymium crustal index calculations for the Umiakoviarusek Lake intrusions using different mantle end-members and various middle Archean (Schiøtte et al. 1993) and early Archean (Collerson et al. 1989) Nain Province gneisses.

<table>
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Notes: CHUR, chondrite uniform reservoir (eNd = 0); DM, depleted mantle (eNd = 5.38); HALG, high-alumina gabbro (eNd = 0.7); KIG, Kiglapait intrusion (eNd = –3.0). An, Anorthosite; Ln, Leuconorite. Dyke, felsic dykes; ORVP, Owl River Valley pluton; QMG, Quartz monzonite group; GLP, Goude Lake pluton; PMP, Pripet Marshes pluton.

<sup>a</sup>Middle Archean Nain Province gneisses (eNd = –14.55); early Archean Nain Province gneisses (eNd = –17.8).

Conclusions

(1) Anorthositic rocks from the Umiakoviarusek Lake region have lower Ba, Rb, K, K/Ti, Zr, REE, and LREE contents, but higher Sr and Eu relative to the granitoid rocks in this region. Both groups contain low Nb and Th contents, and somewhat similar Ti contents. The REE contents of the anorthositic rocks appear to be controlled by plagioclase: orthopyroxene ratios, with decreases in both the total REE and the size of the Eu anomaly with increasing orthopyroxene relative to plagioclase from the Goude Lake pluton anorthosites and leuconorites (with 15–25% orthopyroxene) through Pripet Marshes pluton leuconorites (with 25–35% orthopyroxene).

(2) Strontium and Nd isotopic data for anorthositic and granitoid rocks of the Umiakoviarusek Lake region are consistent with crustal contamination. Initial Sr ratios at 2050 Ma for the granitoid rocks (0.6901–0.7094, average = 0.7032) are consistent with crustal influence, but the lower...
values may be the result of isotopic resetting associated with Torngat Orogen-related greenschist facies metamorphism. In contrast, the anorthositic rocks retained crustally influenced high initial Sr ratios at 2050 Ma (0.7048–0.7082, average = 0.7058). The high $f_{\text{Sr}}$ values imply a source with significant crustal residence time.

(3) Epsilon Nd values ($\epsilon$Nd at 2050 Ma) in the anorthosites (~4.11 to ~15.88) and granitoids (~5.14 to ~9.70); fractionation factors ($f_{\text{Sm/Nd}}$, anorthosite = ~0.30 to ~0.68, granitoid = ~0.34 to ~0.50); and depleted mantle model ages ($T_{\text{DM}}$, anorthosite = 2.54–3.80 Ga, granitoid 2.82–3.26 Ga) are all consistent with the Sr isotope data and require a LREE-enriched source with significant crustal residence time.

(4) The similarities in radiogenic isotope systematics with the younger Nain Plutonic Suite and other AMCG complexes, suggest that the Paleoproterozoic UL intrusive rocks likely formed in a similar manner to other Mesoproterozoic AMCG complexes.

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