Country-rock contamination of marginal mafic granulites bordering the Nain Plutonic Suite: implications for mobilization of Sr during high-grade contact metamorphism

K.R. Royse, S.R. Noble, J. Tarney, and A.C. Cadman

Abstract: The marginal mafic granulites that locally border the Nain Plutonic Suite (NPS) have a range of initial Nd-isotope ratios that overlap with that of the NPS anorthosites and associated Nain dykes. The similarity in Nd-isotope data suggests that gneissic Archaean country rocks have contaminated all the anorthosites, marginal mafic granulites, and dykes. Sr-isotope data for the mafic granulites and dykes support a country rock contamination scenario but preclude wholesale assimilation of rocks such as the host Archaean tonalite gneisses as the sole contaminant. Initial ε_{Sr} values of +10 to +403 and +0.9 to +242 for the mafic granulites and dykes, respectively, are significantly higher than values for NPS country rocks examined thus far. The elevated initial ε_{Sr} values are therefore interpreted to result from the introduction of radiogenic Sr into the granulites and dykes via Sr-rich fluids, generated by the breakdown of Rb-rich mineral phases such as biotite in the country rocks during NPS.

Résumé : Les granulites mafiques marginales, qui bordent localement la Suite plutonique de Nain, fournissent des variations de rapports isotopiques initiaux de Nd qui chevauchent les valeurs des anorthosites de la Suite plutonique de Nain, et des dykes associés dans la Province de Nain. Cette similitude des données isotopiques de Nd suggère que des roches gneissiques encaissantes archéennes ont contaminé toutes les anorthosites et les granulites mafiques marginales, et les dykes également. Les données isotopiques de Sr obtenues pour les granulites mafiques et les dykes plaident en faveur d'un scénario de contamination des roches encaissantes, mais elles excluent que l'unique mécanisme de contamination serait l'assimilation en gros des roches hôtes, par exemple les gneiss tonalitiques d'âge archéen. Les valeurs ε_{Sr} de +10 à +403 et de +0,9 à +242 que procurent les granulites mafiques et les dykes, respectivement, sont significativement plus élevées que les valeurs obtenues pour les roches encaissantes de la Suite plutonique de Nain qui ont été examinées jusqu'à présent. Les fortes valeurs des ε_{Sr} initiaux sont donc interprétées comme le résultat de l'ajout de Sr radiogénique dans les granulites et les dykes par les venues de fluides riches en Sr, suite à la destruction des minéraux riches en Rb, comme la biotite des roches encaissantes, durant la mise en place de la Suite plutonique de Nain.

[Traduit par la Rédaction]

Introduction

The petrogenesis of the anorthosite-dominated Nain Plutonic Suite (NPS) has been discussed by several workers but remains controversial (Morse 1982; Wiebe 1992; Emslie et al. 1994). Granulite-facies mafic rocks occur along the margin of the NPS and have been considered part of the host Archaean rocks and the NPS. Rocks similar to these have been credited with having played an important role in the petrogenesis of the anorthositic rocks (Emslie 1978*a*, 1978*b*, 1980; Morse 1982; Olson and Morse 1990). This study examines their field, geochemical, and Sr- and Nd-isotope characteristics to better understand their relationship with the NPS. New Nd- and Sr-isotope data and geochemical data are presented for the marginal mafic granulites from the Jonathon and Nukasusutok island intrusions and compared with existing data from the NPS anorthosites (Hamilton 1993; Emslie et al. 1994) and associated Nain dykes (A.C. Cadman, unpublished data). On the basis of this new data, we propose that the mafic granulites are related to the NPS. Furthermore, Sr-isotope data indicate that the marginal granulites were also affected by significant contamination by a source of radiogenic Sr, similar to some NPS anorthosites.

Regional geology

The geology of northern and central Labrador comprises two major lithotectonic subdivisions: the Archaean Nain Province and the Proterozoic Churchill Province (Fig. 1) (Ermanovics et al. 1989; Wardle et al. 1990). The north–

Received May 20, 1998. Accepted February 8, 1999.

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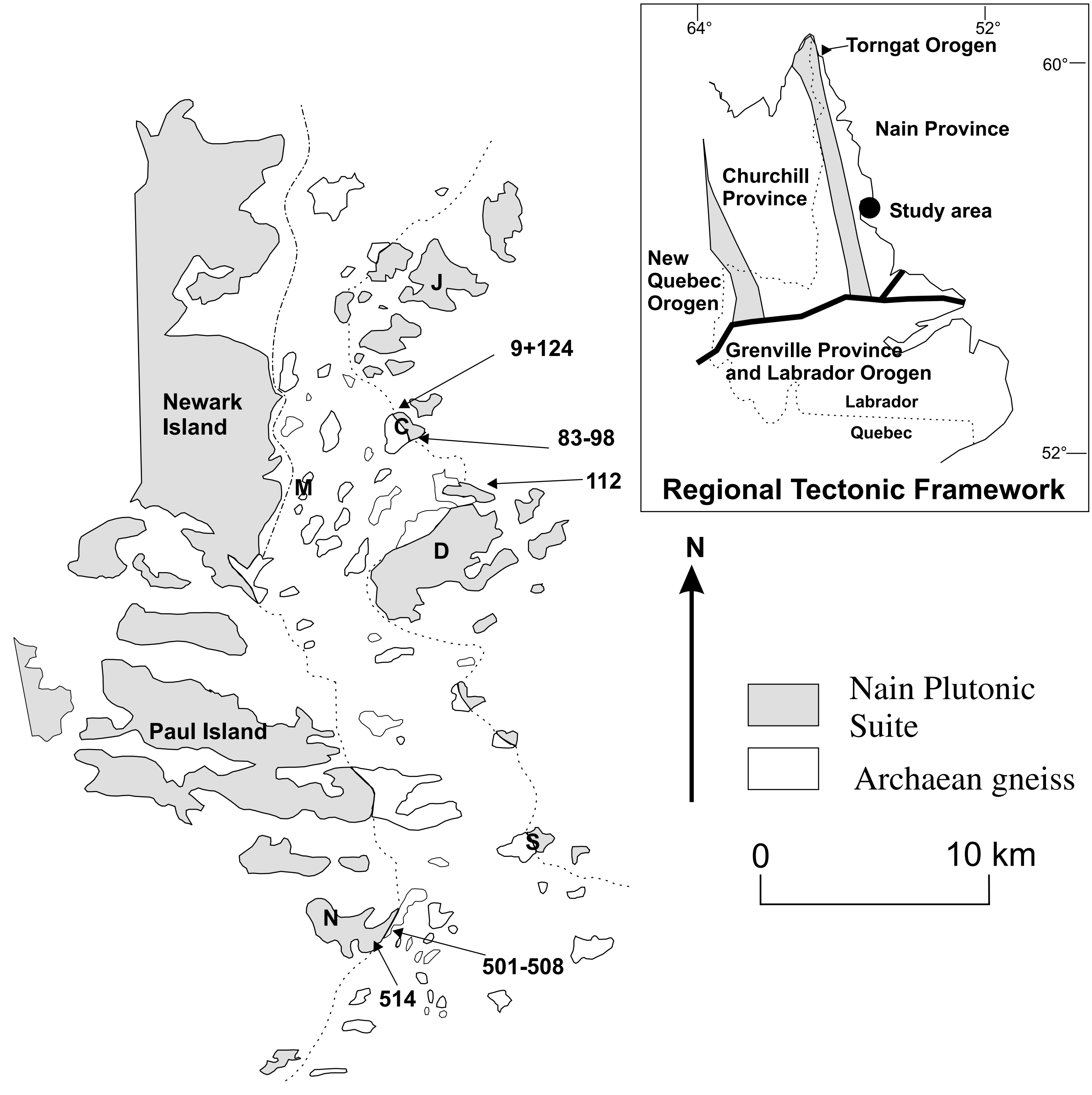
Fig. 1. Geological map of the Nain area, northeastern Labrador. C, Carey Island; D, Dog Island; J, Jonathon Island; M, Mary Island; N, Nukasusutok Island; S, Sandy Island. The inset map shows the regional tectonic framework of Labrador, displaying the main geological provinces (from Wardle et al. 1990). Numbers indicate sample locations for the marginal mafic granulites.



south boundary between the two provinces is marked by the ca. 1.8 Ga (Wardle et al. 1990) collisional Torngat Orogen. This collisional suture was intruded by a diverse array of plutonic rocks of anorthosite, troctolite, diorite, and granitic rocks (between 1.35 and 1.29 Ga) that make up the NPS (Morse 1971–1983; Ryan 1990; Ryan and Emslie 1994).

The Churchill Province boundary with the Nain Province consists of a band of garnetiferous gneisses known as the Tasiuyak gneisses (Wardle et al. 1990), spatially coincident with the collisional Torngat Orogen. Much of the Churchill Province consists of reworked Archaean basement. East of the Churchill Province lies the Archaean Nain Province (3.8–2.7 Ga) consisting largely of high-grade gneisses, representing the Labrador segment of the North Atlantic Craton. These gneisses can be split into two blocks according to their structural and lithological affinities and geochronology: the Saglek Block in the north and the Hopedale Block in the south (Fig. 1). The blocks have distinct lithological and tectonic histories (Bridgwater and Schiøtte 1991) until the late Archaean (ca. 2.57 Ga), suggesting that they were separate terranes until this time (Connelly and Ryan 1996).

Pioneering work by Wheeler (1942, 1960) showed that the NPS was a polyphase batholithic igneous terrane. Later detailed studies of the Nain Anorthosite Project (Morse 1971–1983; Emslie et al. 1972; Taylor 1979; Emslie 1980; Morse 1982) revealed a diversity of compositions and intrusive forms (e.g., bulbous, saucer-shaped layered intrusions and large dykes) and identified multiple intrusive events within superficially simple plutonic units, the accepted nomenclature of which is summarized by Ryan (1990). A contact-metamorphic aureole adjacent to the NPS (Berg 1977) is locally developed within the country-rock gneisses and mafic enclaves. Paragneisses in the contact aureole contain cordierite and spinel pseudomorphs after sillimanite, indicative of pyroxene-hornfels facies metamorphism.

The anorthosites within the Grenville and northern Labrador are characterized by light rare earth elements (REE) enrichment, positive Eu anomalies (Ashwal and Seifert 1980), and a consistent slope to the heavy REE. In contrast, some leucogabbros have high total REE abundances and no Eu anomaly (Watson 1979). The margins of many of the anorthosite intrusions show enrichment in large ion lithophile elements (LILE), consistent with crustal contamination (Emslie et al. 1994). Noritic (orthopyroxene-bearing) plutons isotope signature reflects a greater crustal component than the more olivine-rich varieties (Emslie et al. 1994; Ashwal and Wooden 1983).

Mafic granulites

Granulite-facies mafic rocks occur as enclaves in the gneisses that host the NPS and as larger bodies that locally border the NPS anorthosites (Wheeler 1942; Ryan 1991, 1993; Berg et al. 1994; Royse and Ryan 1995). The origin of these mafic granulites has been the subject of considerable debate, and in particular whether they are a component of the country rocks or the NPS (Isachsen 1968; Nolan and Morse 1986; Olson and Morse 1990). During the course of this study, the mafic granulites immediately bordering the NPS, herein referred to as the marginal mafic granulites, were found to differ from mafic granulite enclaves occurring more distal to the NPS in the host rock gneisses in that the former retain their primary textures, such as well-developed igneous layering. In addition, the marginal mafic granulites are unmetamorphosed and do not contain podiformed hornblende.

Two marginal mafic granulite suites are examined here: the southwestern margin of the Jonathon Island intrusion, and the eastern margin of the Nukasusutok Island intrusion (Fig. 1). Other similar marginal granulites occur at Moskie Island, Myrtle Island, Mary Island (which also form the outer marginal zone of the Newark Island intrusion, Fig. 1), and the eastern side of the Paul Island intrusion.

The southwestern margin of the Jonathon Island intrusion is best exposed on Carey Island (Royse and Ryan 1995). The contact between the marginal mafic granulites and the anorthosites is diffuse, suggesting that the marginal mafic granulites and anorthosites are components of the same intrusive body. The composition of the marginal mafic granulites ranges from olivine gabbro–norite to olivine norite. Within the unit there are inclusions and rafts of paragneisses, quartzo-feldspathic rocks, and older hornblende-rich mafic granulite, as well as brecciated fragments of leuconorite. The marginal mafic granulites show well-developed igneous layering that is locally chaotic and display slump folding. Large orthopyroxene pods and pegmatitic xenoliths of leuconorite disrupt the layering within the marginal series. The unit and the outer border zone of the Kiglapait intrusion (Nolan and Morse 1986) share a number of similar characteristics (i.e., both are granulitic olivine gabbro–norites with locally chaotic layering).

The marginal mafic granulites occurring along the western margin of the Nukasusutok Island intrusion make up a layered unit of olivine norite. The layering in this unit is not as chaotic as that observed in the Jonathon Island marginal mafic granulites. Recrystallized mafic dykes that are discordant to the primary igneous layering have a strong foliation parallel to the pervasive foliation in the layered olivine norite, indicating predeformation emplacement of the layered olivine norite and the dykes. The marginal mafic granulites are clearly earlier than the Nukasusutok Island anorthosite intrusion to the west, which is not crosscut by mafic dykes. The original igneous textures in the marginal mafic granulites, however, serve to distinguish the unit from older granulite mafic bodies occurring in the Archaean country rocks.

Nain dykes

Archaean gneisses that form the country rocks to the NPS are intruded by a variety of metamorphosed mafic dykes (Ryan 1995; Cadman and Ryan 1994). Dyke emplacement probably took place during three episodes at ca. 2560 Ma (cf. Connelly and Ryan 1994), ca. 2.05 Ga (Connelly and Ryan 1993), and between 1328 and 1316.5 Ma, the time when the latest and predominant group intruded (Cadman et al. 1999). The last group of metamorphosed dykes is probably directly associated with NPS emplacement and possibly represents leaks from NPS feeder chambers (Cadman et al. 1999).

The textures of the main 1328–1316.5 Ma group of dykes (referred to as Nain dykes) vary from diabasic to granular to strongly foliated, although massive to porphyritic types are also present. Cadman et al. (1999) described three principal varieties of Nain dykes: black two-pyroxene–hornblende dykes, grey two-pyroxene dykes, and black amphibolite dykes. Crosscutting relationships indicate that the dykes were intruded over the same time period.

Marginal mafic granulite geochemistry

Major and trace element data, in addition to Sr- and Nd-isotope data, were obtained on the marginal mafic granulites to characterize their composition and permit comparison with the adjacent confirmed NPS and country-rock gneisses.

Analytical methods

Fresh representative whole rock samples were trimmed, jaw crushed, and ground to a fine flour in an agate mill. Major element compositions were determined on fused discs using Rh anode excitation, and the trace elements Sc, V, Cr, Ni, Zn, Ga, Rb, Sr, Y, Zr, Nb, La, Ce, Nd, and Ba were measured on pressed powder briquettes using either Rh or W excitation on a Phillips PW1600 X-ray fluorescence spectrometer (for techniques see Marsh et al. 1983).

Samples analyzed for their isotope compositions were digested in PFA Teflon vessels using HF–HNO_3. Rb, Sr, Sm, and Nd concentrations were determined by isotope dilution using enriched ^{85}Rb, ^{84}Sr, and mixed ^{149}Sm/^{150}Nd isotope tracer solutions. Rb, Sr, and the REE were separated by eluting distilled 2.5 M and 6.2 M HCl through AG50-X8 cation exchange resin in quartz columns. Sm and Nd were purified by reverse-phase chromatography in quartz columns, using a 0.2 M and 0.6 M HCl elution. All Sr-isotope results were obtained on a MAT262 mass spectrometer via static multicollection in two different periods, during which analyses of NBS987 yielded ^{87}Sr/^{86}Sr = 0.710202 ± 22 (1σ, n = 29) and 0.710211 ± 20 (1σ, n = 21), respectively. Sm- and Nd-isotope data were obtained on the Nerc Isotope Geoscience Laboratories (NIGL) VG354 and MAT262 mass spectrometers via static multicollection. During the course of analysis on the VG354 the La Jolla international standard yielded ^{143}Nd/^{144}Nd = 0.511853 ± 9 (1σ, n = 48). Repeated analyses of an NIGL internal standard prepared from Johnson and Matthey Nd_2O_3 gave ^{143}Nd/^{144}Nd = 0.511125 ± 7 (1σ, n = 82) on the VG354, and ^{143}Nd/^{144}Nd = 0.511134 ± 18 (1σ, n = 52) on the MAT262. The standard data indicate that there is no significant systematic bias for data obtained on the two mass spectrometers. Total analytical blanks were <<200 pg and <<500 pg for Nd and Sr, respectively. Mass fractionation corrections were made relative to ^{86}Sr/^{88}Sr = 0.1194 and ^{146}Nd/^{144}Nd = 0.7219. The ^{87}Rb and ^{147}Sm decay constants used here are 1.42×10^{-12} a^{-1} and 6.54×10^{-12} a^{-1} (Stager and Jäger 1977; Langmuir et al. 1978). Calculations of $\varepsilon_{Nd}(t)$, T_{CHUR}, and T_{DM}; $(^{143}Nd/^{144}Nd)_{CHUR}$ = 0.512638, $(^{143}Nd/^{144}Nd)_{DM}$ = 0.5131, $(^{147}Sm/^{144}Nd)_{CHUR}$ = 0.1967, and $(^{147}Sm/^{144}Nd)_{DM}$ = 0.225 (McCulloch et al. 1985), were calculated following DePaolo (1981).

Results

Major element geochemistry

SiO_2 contents of the marginal mafic granulites vary from 42 to 61 weight percent (wt.%) and magnesium numbers (Mg#) range from 20 to 75 (Table 1). For comparison, the 1316.5–1328 Ma Nain dykes have SiO_2 values from 42 to 58 wt.% with Mg# from 31 to 85 (Table 1). The marginal mafic granulites and the dykes within the area have relatively high Al_2O_3 and Fe_2O_3 values, the majority of which lie in the range 5–15 and 11–18 wt.%, respectively. Most of the marginal mafic granulites and the dykes are Fe basalts, as defined by Shirey and Hanson (1986), but they have notably higher Al contents than typical Fe–Ti basalts. Similar Al–Fe-rich mafic rocks have been noted in other anorthosite-bearing terranes by Olson and Morse (1990).

In comparison to the marginal mafic granulites, the anorthosite silica values (Hamilton 1993; Emslie et al. 1994) typically range from 42.3 to 69.9 wt.%, Al_2O_3 values range between 29.8 and 10.5 wt.%, and Mg# between 13 and 70. Rb/Sr ratios are low, ranging from 1.000 to 0.003, and suggest that the plutons in the NPS have undergone large-scale differentiation since separation from the parental magma.

Trace element geochemistry

Trace element concentrations for the marginal mafic granulites, anorthosites, and the Nain dykes are listed in Table 1 and plotted on trace element distribution plots in Figs. 2*a*–2*e*. The marginal mafic granulites from the Jonathon Island intrusion have negative Nb anomalies, with a positive anomaly in Sr (Fig. 2*a*), whereas the layered olivine norite from Nukasusutok Island (Fig. 2*b*) has positive Ba, Nb, and Sr anomalies.

The anorthosites have trace element distribution patterns (Fig. 2*c*) that reflect the plagioclase-rich nature of these rocks (Duchesne 1978; Xue and Morse 1993; Emslie et al. 1994). They are all enriched in Ba, K, La, Ce, Sr, and Nd compared to primitive mantle. The low overall abundance of REE and a positive Eu anomaly for the anorthosites are consistent with the accumulation of plagioclase (Emslie et al. 1994).

Not all trace element characteristics in the anorthosites can be attributed to differences in cumulus mineralogy. For example, decreases in Y associated with decreasing magnitude of Eu anomalies cannot be accounted for by the accumulation of olivine and pyroxene and therefore must reflect the parental magma or source from which the anorthosites were derived. In addition, the observed Rb, Ba, and Sr contents cannot be accounted for in light of the distribution coefficients for plagioclase and, therefore, must be a characteristic of the magma source (Xue and Morse 1993).

Cadman et al. (1993, 1995) and Cadman and Ryan (1994) have described the geochemistry of the Nain dykes in detail. The dykes can be divided into two chemical groups on the basis of their high field strength elements (types A and B). These two chemically distinct groups are not distinguishable on the basis of their field characteristics, particularly with respect to inconsistent relative ages as determined by cross-cutting relationships of the dykes within the study area. Multielement plots of group A dykes indicate enrichment in elements from Nb to Nd and depletion in Y (Fig. 2*d*) compared with group B dykes (Fig. 2*e*). Group B dykes (Fig. 2*e*) have relatively flat multielement profiles with slightly negative Nb anomalies, and fractionation of La and Ce, due to the accumulation of mafic minerals such as olivine and pyroxene. A positive Rb anomaly, as measured against Ba abundance, is found for some dykes in group B and is probably a metamorphic effect (Pearce 1983).

Isotope geochemistry

The marginal mafic granulites of the Jonathon Island intrusion have initial $\varepsilon_{Sr(1317\ Ma)}$ ranging from +54 to +403 (Table 2), and layered olivine norites from Nukasusutok Island have initial ε_{Sr} ranging from +10 to +384. These values are considerably more radiogenic than bulk Earth at 1317 Ma ($^{87}Sr/^{86}Sr_i$ = 0.7029; Taylor and McLennan, 1981). In contrast to the Sr-isotope data, the Nd-isotope data show a significantly more limited range of ε_{Nd} values. The marginal mafic rocks of the Jonathon Island intrusion have $\varepsilon_{Nd(1317\ Ma)}$ values from +0.3 to –17.0, whereas the layered olivine norite from Nukasusutok Island has values from –4 to –11 (Table 2).

Discussion

Isotope geochemistry

Regional Sr- and Nd-isotope studies on the anorthosites of the eastern Canadian Shield reveal a good correlation be-

Table 1. Marginal mafic granulites: Sm/Nd and Rb/Sr isotope data.

Sample No.	Sm (ppm)[a]	Nd (ppm)[a]	$\frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}}$	$\frac{^{147}\mathrm{Nd}}{^{144}\mathrm{Nd}}$[b]	$\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}$	$\varepsilon_{\mathrm{Nd}}$ (0)	$\varepsilon_{\mathrm{Nd}}$ (1317 Ma)	T_{CHUR}	T_{DM}	Sr[a] (ppm)	Rb[a] (ppm)	$\frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}$	$\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}$	$\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}_{\mathrm{i}}$	$\varepsilon_{\mathrm{Sr}}$ (1317 Ma)
D9	3.42	14.25	0.1451	0.145058	0.511317±7	–25.77	–17.08	3856	3939	239.60	6.35	0.076792	0.722884	0.721434	263.45
D9[c]	4.45	18.29	0.1471	0.147054	0.511326±6	–25.59	–17.24	3982	4051						
D83										564.18	4.09	0.020988	0.708479	0.708083	73.50
D84	1.64	5.12	0.1935	0.193507	0.512648±15	0.20	0.73	—[d]	—[d]	79.94	2.74	0.099234	0.710780	0.708907	85.22
D88	2.54	5.79	0.2655	0.265544	0.513249±16	11.92	0.34	1355	583	99.97	0.61	0.017812	0.731621	0.731285	403.58
D98	2.81	8.48	0.2001	0.200143	0.512478±7	–3.12	–3.70	—[d]	—[d]	269.60	0.19	0.002027	0.706758	0.706720	54.11
N501	1.71	6.44	0.1607	0.160647	0.512119±19	–10.12	–4.06	2177	2663	291.61	0.42	0.004215	0.703727	0.703647	10.40
N503	1.93	7.98	0.1465	0.146493	0.511833±4	–15.70	–7.26	2426	2752	322.86	0.23	0.002057	0.706256	0.706217	46.96
N505[c]	2.85	11.63	0.1483	0.148290	0.511856±6	–15.25	–7.11	2444	2776	299.32	0.45	0.004383	0.706069	0.705986	43.68
N506	1.82	7.44	0.1481	0.148132	0.511726±7	–17.79	–9.62	2837	3090	303.62	3.24	0.030890	0.709766	0.709183	89.15
N507	6.65	28.61	0.1405	0.140523	0.511566±8	–20.91	–11.46	2885	3102	243.93	1.24	0.014752	0.730243	0.729965	384.80
N508	3.65	13.93	0.1582	0.158198	0.511932±3	–13.77	–7.29	2771	3091	247.34	0.15	0.001712	0.711317	0.711285	119.05
N532	3.76	11.79	0.1930	0.192983	0.512591±8	–0.92	–0.29	1839	—[d]	198.53	2.57	0.037378	0.705645	0.704939	28.78
N532[c]	3.68	11.46	0.1941	0.194105	0.512595±8	–0.84	–0.40	2397	—[d]						
N536[c]	0.89	3.73	0.1451	0.145096	0.511862±8	–15.14	–6.45	2276	2625	440.84	0.71	0.004646	0.703401	0.703313	5.65

Notes: All Rb/Sr data were obtained on a MAT262 mass spectrometer in two different periods, during which analyses of NBS987 yielded 0.710202 ± 22 ($^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$, 1σ, $n = 29$) and 0.710211 ± 20 (1σ, $n = 21$). Nd data were obtained on both a MAT262 and a VG354 mass spectrometer. During the course of analysis on the VG354 the LaJolla standard yielded $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.511853 \pm 9$ (1σ, $n = 48$). An NIGL internal standard gave $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.511125 \pm 7$ (1σ, $n = 82$) on the VG354, and during the same period data from the MAT262, gave $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.511134 \pm 18$ (1σ, $n = 52$). Duplicates listed above were measured for separate dissolutions and show that no bias was detectable for data obtained on the two mass spectrometers. Blanks during the course of analyses were <200 pg Nd and <500 pg Sr.

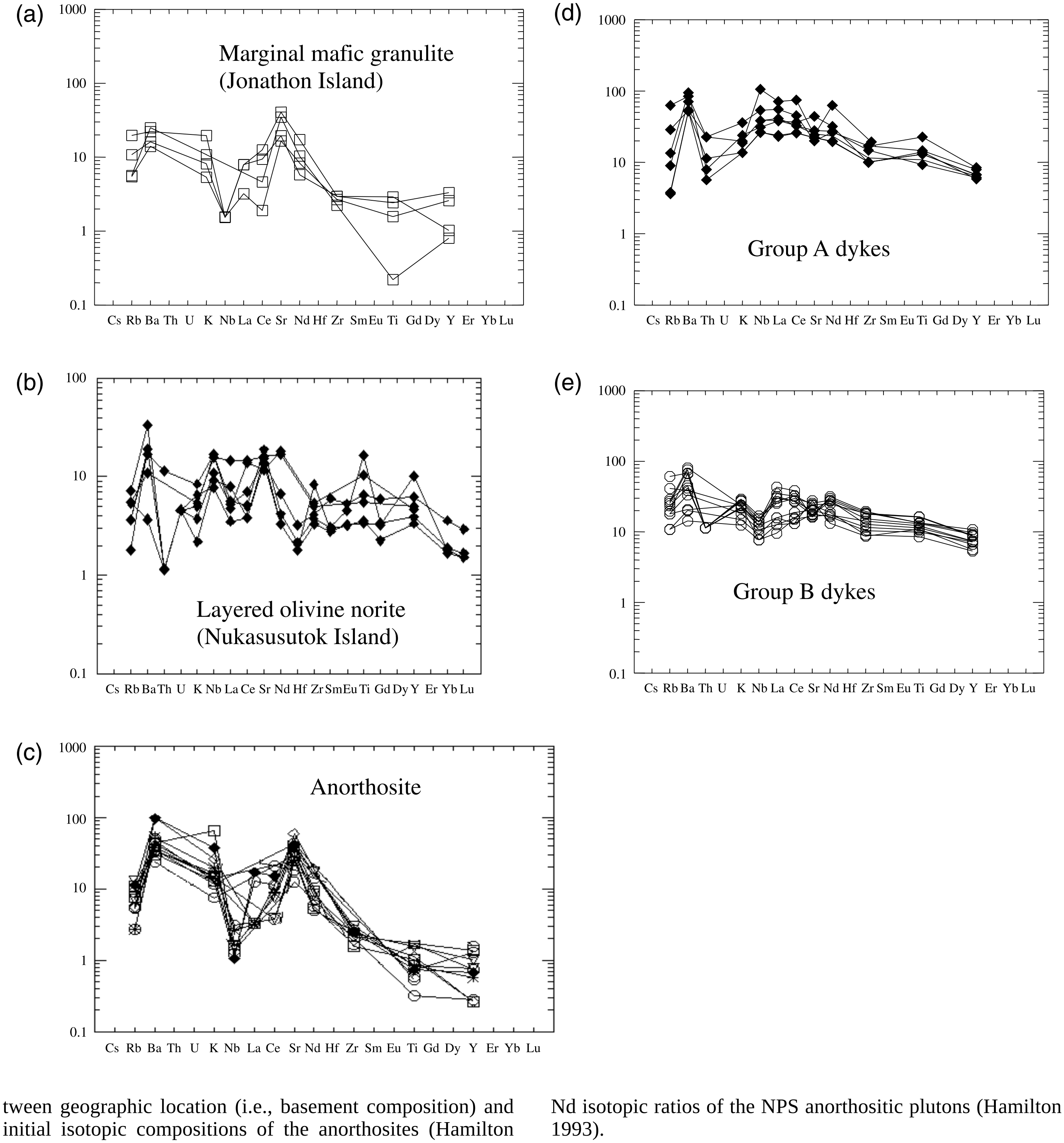
[a] Sm and Nd concentration data were obtained by isotope dilution and measured to a precision of ±0.1% (2σ), and Rb and Sr concentrations were measured by X-ray fluorescence to a precision of ±0.5%.

[b] Present-day $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ ratios; errors are ±2 standard errors of the mean.

[c] Sample run on the MAT262 mass spectrometer. Other samples were run on the VG354 mass spectrometer.

[d] Model ages greater than 4.5 Ga or less than 0 Ga obtained when $\varepsilon_{\mathrm{Nd\ (0\ Ma)}}$ is greater that 0 and $^{147}\mathrm{Sm}/^{144}\mathrm{Nd}$ is significantly greater than approx. 0.1000.

Fig. 2. Multielement diagrams for the mafic rocks bordering the Jonathon Island intrusion (*a*), the layered olivine norite from Nukasusutok Island (*b*), the anorthosites of the NPS (*c*), and group A (*d*) and group B (*e*) mafic dykes associated with the Nain Plutonic Suite (Cadman et al. 1999). Mantle-normalized values after Taylor and McLennan (1981).



tween geographic location (i.e., basement composition) and initial isotopic compositions of the anorthosites (Hamilton 1993). Proterozoic anorthosites northwest of the Grenville front have significantly different isotopic signatures than those within the Grenville Province (Emslie et al. 1994). The isotopic signature of the NPS exhibits the same correlation and is profoundly influenced by the crustal signatures of the host province to the extent that the location of the Nain–Churchill boundary can be inferred from differences in the Nd isotopic ratios of the NPS anorthositic plutons (Hamilton 1993).

In general, the range of initial ε_{Sr} and ε_{Nd} values obtained for the marginal mafic granulites significantly overlaps with data obtained elsewhere in the NPS and the host gneisses (Table 3; Fig. 4), although in detail there are some important differences. ε_{Sr} values for the NPS anorthosite range between +9 and +45 at 1317 Ma (Hamilton and Shirey 1992; Hamilton 1993) and show that the majority of NPS rocks (i.e.,

Table 2. Isotope data for the Mesoproterozoic Nain dykes.

Sample No.	Sm (ppm)[a]	Nd (ppm)[a]	$\frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}}$[b]	$\frac{^{147}\mathrm{Nd}}{^{144}\mathrm{Nd}}$[b]	$\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}$	$\varepsilon_{\mathrm{Nd}}$ (0)	$\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}_i$	$\varepsilon_{\mathrm{Nd}}$ (1317 Ma)	T_{CHUR}	T_{DM}	Sr[a] (ppm)	Rb[a] (ppm)	$\frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}$	$\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}$	$\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}_i$	$\varepsilon_{\mathrm{Sr}}$ (1317 Ma)
N26-92	7.925	40.470	0.1184	0.118346	0.511426	–23.64	0.510402	–10.46	2347.07	2 469.99	238.9	66.83	0.811542	0.735252	0.719932	242.08
N39-92	4.561	19.172	0.1438	0.143803	0.511894	–14.51	0.510650	–5.61	2135.66	2 367.17	252.4	4.82	0.055235	0.704565	0.703522	8.62
N37-92	4.311	15.778	0.1652	0.165157	0.512482	–3.04	0.511053	2.26	754.355	1 690.68	273.5	8.86	0.093703	0.704049	0.702280	–9.05
N66-92	3.460	13.162	0.1589	0.158905	0.512254	–7.49	0.510879	–1.13	1545.7	2 070.06	249.7	35.49	0.411514	0.713776	0.706008	43.98
N80-92	11.067	63.174	0.1059	0.105869	0.511012	–31.72	0.510096	–16.44	2713.01	2 742.88	644.1	12.1	0.054347	0.706645	0.705619	38.45
N274-93	2.097	5.701	0.2224	0.222412	0.513165	10.28	0.511241	5.95	3102.35	1 786.4	112	0.86	0.022215	0.705485	0.705066	30.58
N224-93	3.588	13.891	0.1561	0.156114	0.512085	–10.79	0.510735	–3.96	2069.33	2 369.6	189	2.94	0.045000	0.706219	0.705370	34.90
N210-93	1.672	10.518	0.0961	0.096084	0.511075	–30.49	0.510244	–13.56	2357.02	2 456.21	127	59.54	1.360291	0.740156	0.714477	164.47
N324-93	6.747	28.115	0.1451	0.145065	0.511968	–13.07	0.510713	–4.38	1971.29	2 260.83	181.5	11.46	0.182653	0.706681	0.703233	4.51
N277-93	8.617	47.091	0.0986	0.110598	0.511491	–22.37	0.510534	–7.89	2023.47	2 211.59	560.4	33.69	0.174006	0.711460	0.708175	74.82
N266-92	5.541	27.084	0.1237	0.123651	0.51165	–19.27	0.510580	–6.98	2054.22	2 259.34	499.7	18.29	0.105882	0.705689	0.703690	11.01
N220-92	2.615	8.544	0.1851	0.185059	0.512546	–1.79	0.510945	0.16	1203.71	2 333.18	147.4	4.47	0.087752	0.706383	0.704726	25.75
N115-92	6.866	30.137	0.1377	0.137707	0.511865	–15.08	0.510674	–5.15	1990.55	2 249.03	394.6	1.31	0.009602	0.704790	0.704609	24.08
N262	13.995	73.414	0.1152	0.115211	0.511323	–25.65	0.510326	–11.94	2447.75	2 543.16	899.6	3.16	0.010159	0.703169	0.702977	0.87
N260 (gneiss)	2.256	17.322	0.0787	0.078701	0.510466	–42.37	0.509137	–22.51	2788.93	2 799.73	575.9	55.1	0.277104	0.718339	0.708080	95.33
N264 (gneiss)	0.492	4.538	0.0655	0.065492	0.510284	–45.92	0.509178	–23.84	2718.95	2 740.16	378	20.4	0.156220	0.712693	0.706910	78.64

Notes: All Rb/Sr data were obtained on a MAT262 mass spectrometer. Analyses of NBS987 yielded 0.710202 ± 22 (^{87}Sr/^{86}Sr, 1σ, *n* = 29). Nd data were obtained on a VG354 mass spectrometer. During the course of analysis on the VG354 the LaJolla standard yielded ^{143}Nd/^{144}Nd = 0.511853 ± 9 (1σ, *n* = 48), and an NIGL internal standard gave ^{143}Nd/^{144}Nd = 0.511125 ± 7 (1σ, *n* = 82). Blanks during the course of analyses were <200 pg Nd and <500 pg Sr.

[a] Sm and Nd concentration data were obtained by isotope dilution and measured to a precision of ±0.1% (2σ), and Rb and Sr concentrations were measured by X-ray fluorescence to a precision of ±0.5%.

[b] Present-day ^{143}Nd/^{144}Nd ratios; errors are ±2 standard errors of the mean.

Table 3. Comparison of Sr- and Nd-isotope data for NPS intrusions, Nain dykes, and mafic granulites.

	ε_{Sr}	ε_{Nd}
Marginal mafic granulites	+10 to +403	+0.74 to –11.4 (with one at –17.1)
Nain dykes	+0.87 to +242	+5.9 to –11.9
NPS anorthosites (east)	+13 to +175.4	–9.8 to –14.8[a]
NPS anorthosites (west)	+9.3 to +36.5	–3.6 to –8.7[a]

[a](data from Emslie et al. 1994 and Hamilton 1993)

samples taken from within major plutons) have a more limited range of ε_{Sr} than the marginal mafic granulites. Nevertheless, the marginal mafic granulite data are not anomalous in the light of data obtained for rocks from anorthosite pluton margins, for example at Higher Bight (ε_{Sr} = +64 to +123), and an anorthositic dyke (ε_{Sr} = +463; Hamilton 1993). The Nain dykes (Cadman et al. 1998) also have a large range in initial ε_{Sr} values from –9 to +242. The ε_{Sr} values of some dykes and marginal facies rocks are sufficiently high to suggest they are not primary, as has been concluded for some components of the NPS (Hamilton and Morse 1988; Hamilton 1993).

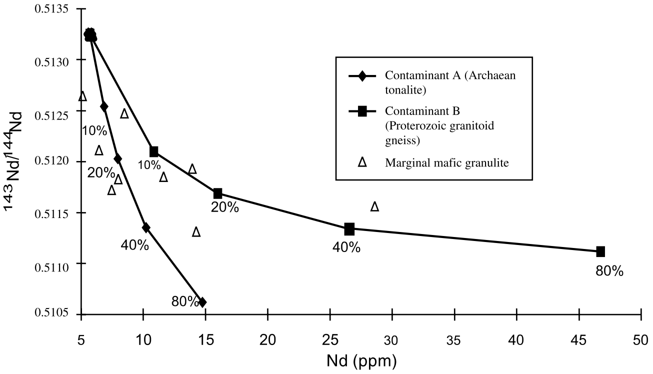
The Nd-isotope signatures of the marginal mafic granulites essentially fall within the range exhibited by the components of the NPS located in the Nain Province. The marginal mafic granulites from the southwestern margin of the Jonathon Island intrusion are the most varied, having ε_{Nd} values from +0.3 to –17.0. The marginal mafic granulites from Nukasusutok Island have values from –4.0 to –11.0 (Tables 2, 3), akin to the observed range of the NPS anorthosites and associated rocks (Higher Bight and anorthositic dykes) of –3.7 to –14 (Ashwal et al. 1992; Hamilton 1993; Emslie et al. 1994). The Nain dykes have ε_{Nd} values in the range +5.9 to –3.8, distinct from most NPS rocks, although the ε_{Nd} value of 5.9 for this unit is the only value above depleted mantle.

Crustal contamination of marginal mafic granulites and Nain dykes

The ε_{Nd} values for the Nain dykes and marginal mafic granulites are significantly lower than depleted mantle and are clearly not solely derived from a simple mantle reservoir. A satisfactory interpretation of the data for the marginal mafic granulites and Nain dykes therefore requires an assessment of the role of crustal contamination to investigate the mechanisms responsible for the production of negative ε_{Nd} and extremely positive ε_{Sr} values. A similar interpretation was reached for the NPS anorthosites (Hamilton 1993, 1987).

The predominantly granitic Archaean and Proterozoic NPS country rocks had much higher REE contents and more negative ε_{Nd} values than the NPS (Hamilton 1993), Nain dykes, or marginal mafic granulites, indicating that only a small amount of assimilation would significantly modify the ε_{Nd} signature of these rocks. Figure 3 presents mixing relations of a hypothetical mafic melt derived from depleted mantle with Nain Province Archaean and Proterozoic rocks.

Fig. 3. $^{143}Nd/^{144}Nd$ vs. Nd illustrating calculated mixing hyperbole for contaminants A (Archaean tonalite) and B (Proterozoic granitoid gneiss), with a primary asthenospheric magma (see Hamilton 1993).



The $^{143}Nd/^{144}Nd$ ratio and Nd concentration of mixtures can be calculated using

$$[1] \quad (^{143}Nd/^{144}Nd)_m = (^{143}Nd/^{144}Nd)_a\ (Nd_a f/Nd_m) + (^{143}Nd/^{144}Nd)_b\ [Nd_b(1 - f)/Nd_m]$$

$$[2] \quad Nd_m = Nd_a f + Nd_b(1 - f)$$

where a and b are the components being mixed together, e.g., NPS anorthosite and country-rock gneisses; *m* is the resultant mixture; and *f* is the proportion of a in the mixture (DePaolo 1981). Country-rock compositions used here are Archaean tonalitic migmatized gneiss (contaminant A) and Proterozoic granitoid gneiss (contaminant B) taken from Hamilton (1993). Figure 3 shows that even small amounts (approx. 10%) of gneiss shift the Nd-isotope ratios of an asthenospheric melt a considerable degree away from depleted mantle.

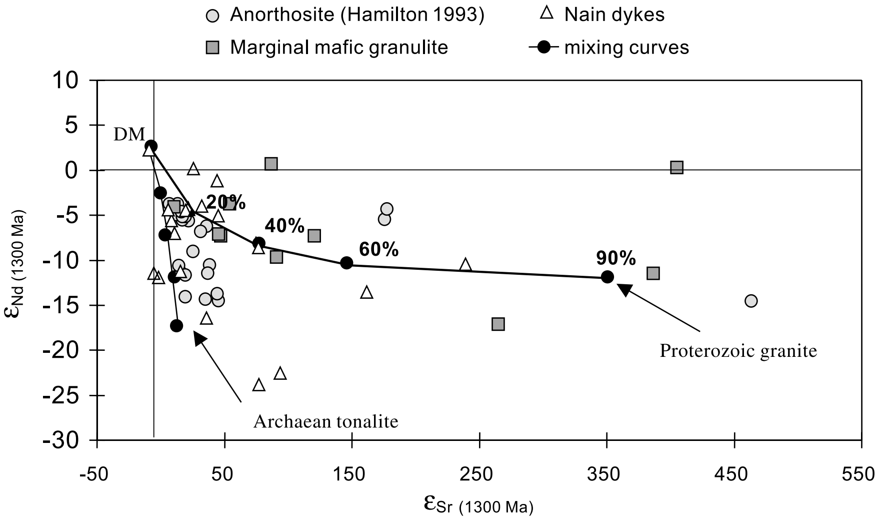
Simple binary mixing equations (Langmuir et al. 1978) were used to calculate the relative proportions of crustal and mantle components to further examine the effects of contamination, particularly as it effects Sr isotopes. Binary mixing can be described by the equation

$$[3] \quad R^x_m = R^x_a X_a f + R^x_b X_b(1{-}f)/X_a f + X_b(1{-}f)$$

where R^x_m is an isotope ratio of X in a mixture of components a and b; X_b and X_a are the concentrations of X in a and b, respectively; and *f* is the weight fraction of a. In this case Nd- and Sr-isotope ratios for the marginal mafic granulites and the country-rock gneisses are compared. A depleted mantle isotopic composition of ε_{Nd} = +2, $^{87}Sr/^{86}Sr_i$ = 0.7026 at 1.3 Ga (Taylor and McLennan 1981; Albarède and Brouxel 1987) is used to represent hypothetical initial conditions of a NPS asthenospheric melt prior to interaction with the crust. A depleted mantle composition is a reasonable starting condition given that it is approximately equivalent to the potentially least modified signature observed for the Nain dykes (ε_{Nd} = +2.26, $^{87}Sr/^{86}Sr_i$ = 0.702; Cadman et al. 1999). The end-member Sr- and Nd-isotope compositions for the country-rock gneisses of the Nain Province are those of Hamilton (1993).

Figure 4 illustrates isotope mixing lines on an ε_{Sr} versus ε_{Nd} diagram for Archaean and Proterozoic country-rock con-

Fig. 4. ε_{Nd} vs. ε_{Sr} diagram displaying mixing hyperbolas for the mafic granulites. Trajectories shown are for contaminants A (Archaean tonalite) and B (Proterozoic granitoid gneiss) mixing with a primary asthenospheric magma. DM, depleted mantle quadrant.



taminants and depleted mantle. Contaminants A and B are the same as in Fig. 3. Most of the available data for NPS anorthosites, and some of the marginal mafic granulites and the Nain dykes, have ε_{Sr} versus ε_{Nd} values that plot between the mixing curves for depleted mantle, Archaean and Proterozoic gneisses and thus could be explained in terms of local country rock contamination. The most primitive members of the array can be accounted for by as little as 10% bulk assimilation of crustal material. The more extreme apparent contamination levels involving Proterozoic crust, however, require at least 40% crustal assimilation. Such levels of assimilation are completely unrealistic, as the bulk composition of the rocks would be modified to excessively felsic compositions. Furthermore, several marginal mafic granulites samples have ε_{Sr} values higher than that of any Proterozoic and Archaean gneisses proximal to the NPS but do not have correspondingly negative ε_{Nd} ratios. The high ε_{Sr} values and apparent decoupling of Sr and Nd isotopes indicates that bulk contamination of a depleted mantle source with gneisses presently exposed in the Nain Province is not adequate in explaining the isotope characteristics of the Nain dykes and marginal mafic granulites.

A number of mechanisms could account for the fact that marginal mafic granulites, Nain dykes, and the NPS anorthosites do not follow a single mixing path. Assimilation of a wide range of rock types with varied composition or concurrent assimilation and fractional crystallization (AFC; DePaolo 1981) could have occurred, but both are unlikely. First, assimilation would require availability of high-ε_{Sr}, low-ε_{Nd} material, probably with relatively mafic major element chemistry so that the final bulk geochemical composition is not shifted to an intermediate to felsic composition. Rocks within the Nain Province with ε_{Sr} in excess of +500 have not been reported, but would be necessary to produce the high ε_{Sr} values observed in some of the mafic granulites. Second, low temperatures (200–300°C, 6–14 km; Berg 1977) of the crust, far below that of mantle melts, would result in rapid heat loss and crystallization of the assimilating magma. AFC does not appear to be a viable mechanism, therefore, because wholesale assimilation of cold crust would result in rapid freezing, precluding continuation of fractionation. The Nd signatures of anorthosites and marginal mafic granulites are consistent with derivation by partial melting of an asthenospheric mantle source (DePaolo 1981; Hamilton 1993). If the marginal mafic granulites are indeed related to the NPS, then they have the most primitive Nd signatures so far recorded in the NPS (ε_{Nd} = 0.74 for the marginal mafic rocks). To summarize, the ε_{Nd} values of the marginal mafic granulite and the Nain dykes can be adequately accounted for by contamination with gneisses of the Nain Province. This is similar to the scenario proposed for NPS anorthosites by Hamilton (1993). Those samples which possess very high ε_{Sr} values but do not have correspondingly negative ε_{Nd} ratios cannot be accounted for in this model.

Origin of high ε_{Sr} values in mafic granulites

Contamination of the marginal mafic granulites by a high-ε_{Sr} source, without imposing significant changes to the major element content of the granulites, requires a selective contribution of Sr from a high-ε_{Sr}, Sr-rich reservoir. The production of magmas with high ε_{Sr} values by contamination with a Sr-rich source has been documented in subduction-related systems, where fluids have introduced Sr ultimately derived from seawater (O'Nions et al. 1978). A similar process is unlikely in the case of the marginal mafic granulites because the rocks of the Nain area are anhydrous and not subduction related (Berg 1976, 1977; Morse 1982). Nevertheless, local sources of appropriate Sr are available to the marginal mafic granulites. Krogh and Davis (1973) and Collerson (1982) noted that Sr migrated over relatively short distances during amphibolite-facies metamorphism, driven by chemical gradients existing between rock layers with strongly contrasting chemical composition. It is possible that a similar process could have introduced Sr with a high ε_{Sr} signature from the host gneisses into the marginal mafic granulites.

Patchett (1980) suggested that one of the most effective methods of contamination in basaltic sheets is the breakdown of hydrous minerals (particularly significantly older sheet silicates) in the surrounding country rock. In the case of the marginal mafic granulites, the most plausible source

Fig. 5. All analyzed samples from the NPS plotted on an $^{87}Sr/^{86}Sr$ vs. Sr diagram. Data points for the anorthosites are from Hamilton (1993) and for the Nain dykes from Cadman et al. (1999). The data suggest that not only the marginal granulites, but also the margins of the anorthosites and the dykes have been affected by thermal breakdown of biotite in the host rocks and transport of accumulated radiogenic Sr by metasomatic fluids.

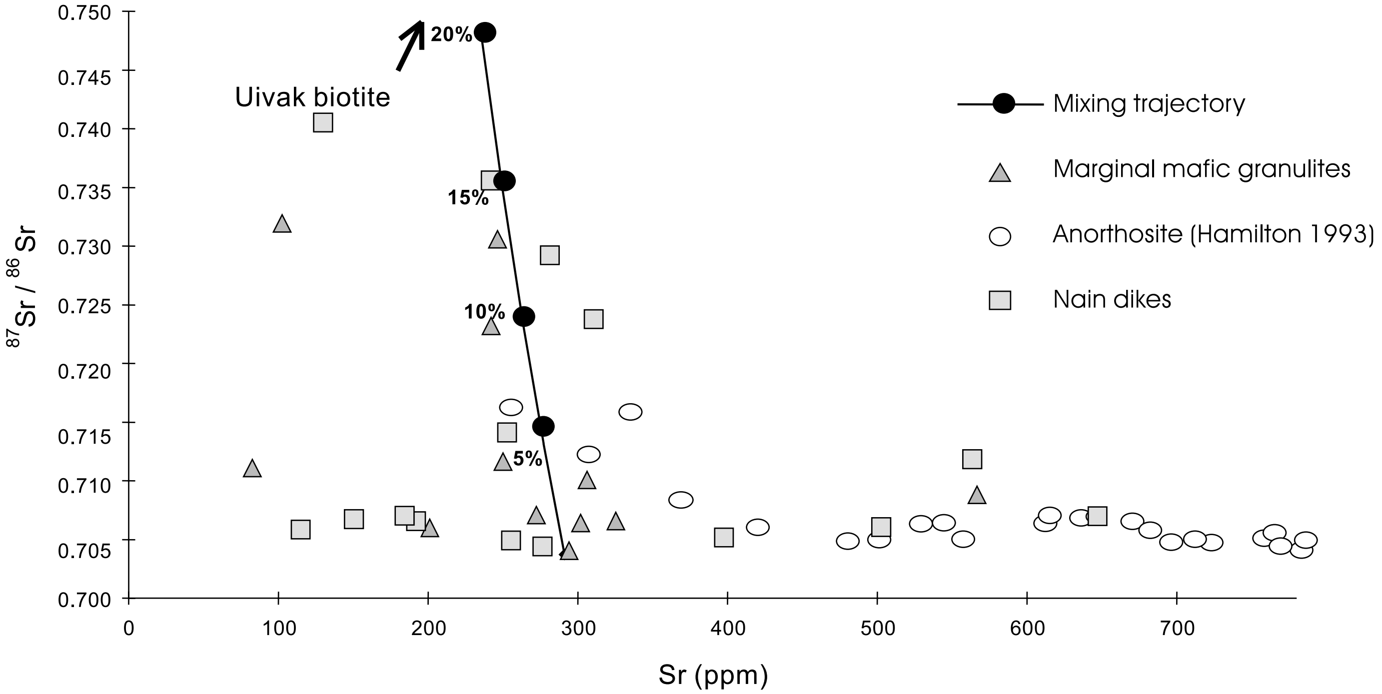
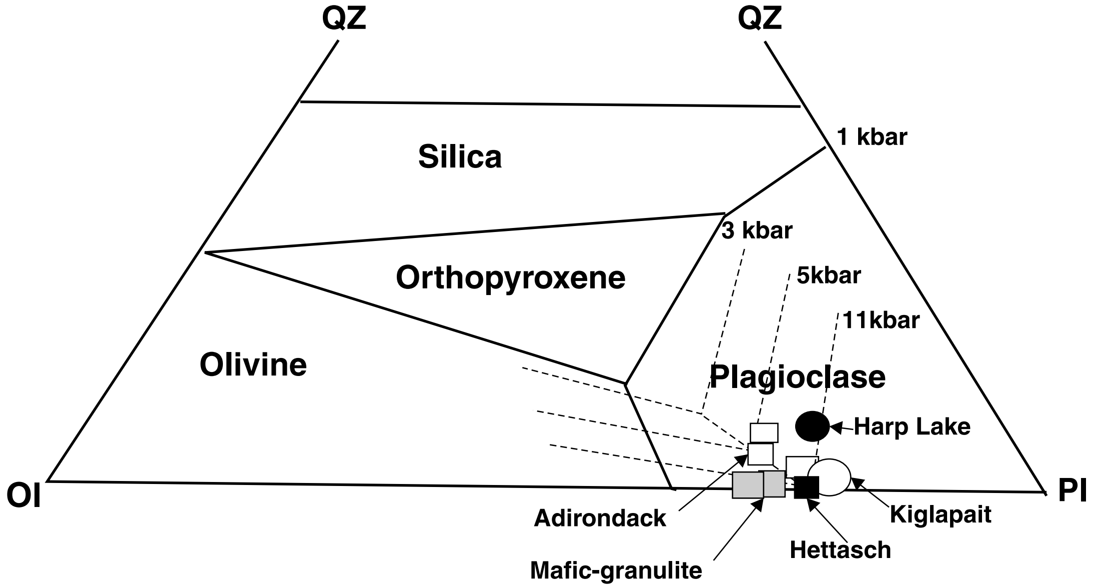


Fig. 6. Phase diagram of the mafic granulites and Al–Fe-rich gabbros found in other massif-type anorthosite terrains. It is noteworthy that all their bulk compositions cluster near the point of multiple saturation with olivine, plagioclase, and orthopyroxene. All projected from wollastonite onto the olivine–plagioclase–silica plane (Longhi 1991).



of Sr with a high ε_{Sr} available is biotite from the country rocks, particularly the ca. 2.5 Ga schlieric granitoid gneisses (Ryan 1992, 1993). The biotite is likely to have experienced breakdown during high-temperature pyroxene-hornfels facies contact metamorphism associated with NPS intrusion. The biotite in the gneisses would have developed a high ε_{Sr} signature relative to the host gneiss between the late Archaean and the time of NPS intrusion because of its high Rb/Sr ratio. Breakdown of biotite during metamorphism would result in the release of Rb and Sr which would then be available to the mafic granulites, possibly via a metamorphic fluid phase derived from the gneisses. The Sm–Nd characteristics of the marginal mafic granulites would not have been influenced because Sm and Nd are not major components of biotite. Plagioclase crystallizing in the mafic granulites adjacent to the gneisses would have been a sink for Sr from biotite breakdown, but no mineral phase crystallized to accept Rb. As a consequence, Rb would have become decoupled from Sr and the marginal rocks would have been progressively enriched in apparently unsupported radiogenic Sr. Biotite is sufficiently enriched in Sr such that only volumetrically small amounts (up to 15 wt.%) of biotite Sr would have been required to produce the observed increase in Sr within the marginal mafic granulites (Fig. 5). A similar scenario has been proposed for dykes in the Saglek Block (Collerson et al. 1984) and could also apply to those NPS anorthositic rocks (Higher Bight and the anorthosite dykes; Hamilton 1993) and the Nain dykes which have particularly high ε_{Sr} and $\varepsilon_{Nd} \approx 0$. It is possible that this effect occurred in other NPS anorthosites and associated ferrodiorites, but their more negative ε_{Nd} values makes the detection of anomalously elevated ε_{Sr} values difficult.

Implications to petrogenesis of the NPS

Olson and Morse (1990) have noted that many anorthosite complexes contain rocks with unusually high Al_2O_3 (5–15 wt.%) and Fe_2O_3 (11.6–18 wt.%). Most of the Al_2O_3 and Fe_2O_3 contents for the marginal mafic granulites and Nain dykes fall within these ranges. The bulk compositions of the marginal mafic granulites are tightly clustered near the point of multiple saturation with plagioclase, olivine, and orthopyroxene between 11.5 and 15 kbar (1 kbar = 100 MPa) on an olivine–silica–plagioclase phase diagram (Fig. 6) (after Longhi 1991). It is noteworthy that Al–Fe-rich gabbros found in the Laramie, Harp Lake, Adirondacks, and Kiglapait intrusions all plot in broadly the same area (Fig. 6) (Olson and Morse 1990).

It has long been suspected that high-Al–Fe mafic magmas have an important connection with massif-type anorthosites and their parental magmas (Emslie 1978*a*, 1978*b*, 1980; Morse 1982; Olson and Morse 1990). Fram and Longhi (1992) indicated it is not possible for high-Al–Fe mafic magmas to directly produce the amounts of plagioclase in anorthosite by fractional crystallization, thus implying mechanical enrichment of plagioclase. Alternatively, polybaric crystallization (cf. Longhi and Ashwal 1985; Emslie et al. 1994) could account for the large amounts of plagioclase. For instance, at 10 kbar olivine, plagioclase, and orthopyroxene coexist at the eutectic point. However, at 15 kbar a peritectic exists between olivine, orthopyroxene, and spinel such that the plagioclase component in the remaining liquid will increase as crystallization proceeds. If the liquid intruded upwards, pressure decreases and plagioclase is the sole liquidus phase (Morse 1979). The parental liquids of anorthositic intrusions would therefore have lower normative plagioclase compositions than would be calculated for the anorthositic intrusions (Morse 1979).

Conclusions

The marginal mafic granulites from the NPS exposed on Nukasusutok Island and Jonathon Island are interpreted to be an integral part of the NPS on the basis of their field relationships (diffuse contacts with NPS anorthosites, distinct nature compared to Archaean hornblende-bearing granulites), their major element characteristics, and their Sr–Nd-isotope systematics. The phase relationships of the marginal mafic granulites are similar to Al–Fe-rich gabbros from the Laramie, Harp Lake, and Adirondack anorthosite massifs. It is suggested that the marginal mafic granulites may be a reasonable approximation to the parental magma to the NPS.

The marginal mafic granulites, as well as the 1328–1317 Ma Nain dykes, possess a wide range of initial Sr and Nd signatures that generally overlap with those observed in the margins of the NPS anorthosites (Hamilton 1993; Emslie et al. 1994). The isotope characteristics of many of the dykes and marginal mafic granulites can be adequately accounted for by contamination with gneisses of the Nain Province as proposed for NPS anorthosites by Hamilton (1993). Some marginal mafic granulites, however, possess very high ε_{Sr} values but do not have correspondingly negative ε_{Nd} ratios typical of crustally contaminated mafic magmas. It is proposed that their Sr-isotope signatures are the result of the selective introduction of Sr derived from the breakdown of biotite in the host Archaean gneisses during pyroxene-hornfels facies contact metamorphism.

Acknowledgments

K.R.R. gratefully acknowledges support from a Natural Environment Research Council studentship and logistical support in the field provided by the Newfoundland Department of Mines and Energy. K.R.R. would particularly like to thank Bruce Ryan and field assistants John Royse and Ed Brown. We are indebted to J.N. Connelly and D.J. Scott for their incisive and helpful reviews.

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