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The role of subcontinental lithospheric mantle in massif-type anorthosite petrogenesis: evidence from the jotunitic Red Bay pluton, Labrador

by *John D. Greenough*[1] and *J. Victor Owen*[2]

Abstract

The Red Bay pluton (RBP) occurs near the northeastern extremity of the Grenville Province, which contains the world's most voluminous series of Middle Proterozoic (c. 1.0–1.4 Ga), massif-type anorthosites. Mineralogically, the RBP resembles jotunites associated with anorthosites: apatite and Fe–Ti oxides are abundant, plagioclase is sodic (An_{32}–An_{45}) given the Mg-rich nature of orthopyroxene (X_{Mg} = 0.58–0.78) and clinopyroxene (X_{Mg} = 0.65–0.76), and biotite and hornblende are minor phases. Furthermore, the pluton is Fe_2O_3(t)-, TiO_2-, and P_2O_5-rich (means of 8 samples = 11.7, 3.1, and 0.9 wt%, respectively). Non-layered gabbros display high Ti/V and Ga/Al ratios that overlap jotunites associated with massif anorthosites from several classic localities and that distinguish jotunites from basalts of varied tectonic affinity. The base of the intrusion (inferred from igneous cross-bedding and modal layering) is predominantly cumulus, and Mg# progressively increases upward into relatively unlayered gabbroic rocks. Mass balance and magma modelling calculations confirm that plagioclase and Fe–Ti oxide precipitation led to declining Ca and Fe contents but increasing Mg# (= Mg/(Mg + 0.9 · total Fe), atomic) as the Red Bay magma evolved. Alkalis-silica relations, elevated light REE concentrations, and high Ba concentrations indicate that the magma was mildly alkaline. Positive Ba and negative Nb and Ti anomalies (high Ba/Nb ratios) on MORB-normalized diagrams suggest magma derivation from subcontinental lithospheric mantle metasomatized by subduction-derived fluids. Magmas such as shoshonites that are associated with late-tectonic transpressional settings characteristically have geochemical signatures indicative of such mantle sources. Alternatively, jotunites may be subsurface analogues of extension-related, orogen-parallel, mafic volcanic rocks (e.g., the Basin and Range province, western U.S.A.) bearing a subcontinental lithospheric mantle signature.

Keywords: Proterozoic, anorthosite, jotunite, lithospheric mantle, tectonic setting, magma modelling, geochemistry, Red Bay pluton, Labrador.

Introduction

Philpotts (1990, p. 307) regards the origin of massif-type anorthosites and associated rocks as one of petrology's greatest puzzles. Particularly problematic issues concern the tectonic setting of these rocks, and the nature of the parent magma, its source, and the processes by which associated rocks such as jotunite and mangerite are derived. The nomenclature of the anorthosite-jotunite-mangerite suite (i.e., anorthosite, leuconorite, jotunite and (quartz-) mangerite [Philpotts, 1981]) has also been contentious. Numerous labels have been attached to what are essentially the same rocks in this suite (Owens and Dymek, 1992), and the usage of individual terms has evolved over the last two decades. For example, many petrologists presently eschew modal definitions (Streckeisen, 1976) of jotunite, and now use the term in connection with rocks enriched in Fe–Ti oxides and apatite (Owens and Dymek, 1992).

The petrogenesis of anorthosites *sensu stricto* cannot be separated from the origin of affiliated rocks. There is, however, no consensus concerning the significance of jotunitic-mangeritic-rocks (*sensu lato*) in this regard. On the one hand, Owens et al. (1993) concluded that jotunites in the Grenville Province are transitional in a large-

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ly comagmatic suite spanning anorthosite to mangerite. On the other hand, DUCHESNE (1990) and DUCHESNE et al. (1989) suggested that monzonorites from Rogaland are coeval but not comagmatic with respect to anorthosites, and are derived from the partial melting of mafic rocks in the lower crust. Despite the controversy concerning their origin and significance, many of these rocks have characteristic compositions, most notably an enrichment in Fe–Ti–P.

This paper focusses attention on a small (~ 5 km^2), jotunitic or Fe-Ti-P-rich ("FTP"), gabbroic intrusion (Red Bay pluton [RBP]) hosted by amphibolite-grade granitic gneiss in the Grenville Province of southeastern Labrador. Geochemical data are used to evaluate the genesis of this and compositionally-similar plutons in the eastern Grenville Province. Finally, we speculate on petrogenetic relationships with other rocks in the anorthosite suite, and garner clues regarding their tectonic implications.

FIELD RELATIONS

Most of the RBP lacks a tectonic fabric resulting in the preservation of primary textural features. Igneous layering is best exposed in wave-washed outcrops on the south coast of Saddle Island (Fig. 1). Layers are typically 0.1 to 1 m thick, dip moderately to steeply to the north or northeast, and are defined by (1) variations in colour index (modal layering), (2) grain size, and, in places, (3) crystal orientation (i.e., crescumulate texture involving very coarse grained plagioclase and pyroxene). Some layers show modal (but not grain size) grading.

Most layering is planar-tabular. Rare trough crossbeds generally yield equivocal "younging-direction" information, but some are clearly truncated by topsets and have tangential bottomsets; these indicate that tops in this part of the intrusion are up to the north. This observation is supported by modal grading in continuous and discontinuous (lensoid) layers, wherein ferromagnesian phases are concentrated in the inferred base of the graded layers. We acknowledge that modal grading does not constitute as definitive evidence for gravitational settling as does grain-size grading, which was not observed.

The statigraphic position of each sample from Saddle Island was determined with a tape measure; readings were corrected for the dip of the igneous layering. The position of samples from the mainland portion of the pluton was determined from an enlarged topographic map, after transposing sample locations from airphotos, and

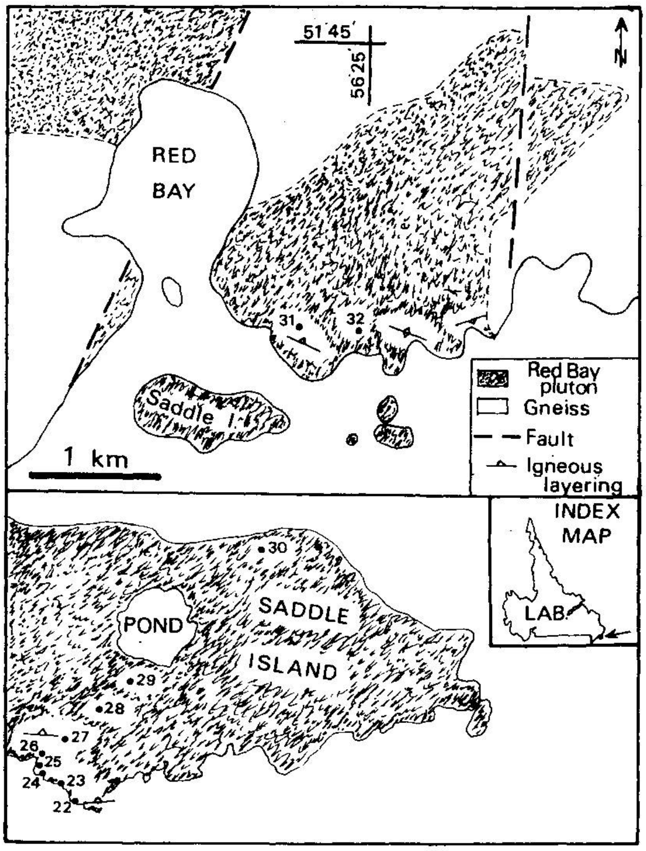

Fig. 1 Geological sketch map of the Red Bay pluton (after BOSTOCK, 1983) showing sample locations.

correcting for average foliation dips. The southern contact with the gneissic host rock is not exposed, so the thickness of the layered sequence on Saddle Island is not known. Layering becomes less pronounced and grades into massive gabbros about 40 m above the exposed base.

ANALYTICAL METHODS

Whole-rock compositions were determined by X-ray fluorescence on fused glass pellets (major elements) and pressed powder pellets (trace elements except the rare earth elements [REE], Y and Th). The REE, Y and Th were determined by a sodium peroxide sinter technique and subsequent analysis by inductively coupled plasma-mass spectrometry (LONGERICH et al., 1990). Replicate analyses of geological reference materials indicate precision and accuracy of better than 5% for the major elements, REE, Y and Th and between 5 and 10% for trace elements determined by X-ray fluorescence.

Mineral compositions were determined using a JEOL Superprobe 733 equipped with four wavelength-dispersive spectrometers and one energy-dispersive spectrometer, operated with a beam current of 15 kV at 5 nA. Data were reduced using ZAF corrections.

Mineralogy and petrography

For discussion purposes we categorized the Red Bay rocks as leucocratic cumulates, melanocratic cumulates, relatively massive gabbros, and granophyres. Cumulus phases in the layered rocks include clinopyroxene, orthopyroxene, plagioclase and apatite. Analyses of silicate minerals from samples with different whole-rock Fe/Mg ratios appear in table 1 and variations with stratigraphic level of X_{Mg} in the mafic minerals and X_{Ca} in plagioclase are portrayed in figure 2.

Clinopyroxene is an aluminous augite (Al_2O_3 ~ 3 wt%) with X_{Mg} ranging between 0.65 and 0.76. It is cumulus in the layered rocks but also locally encloses subidiomorphic (cumulus) orthopyroxene.

Orthopyroxene is a pleochroic hypersthene with X_{Mg} between 0.58 and 0.78. In some samples (e.g., 23B) it also occurs as symplectic intergrowths in plagioclase adjacent to biotite. The symplectic orthopyroxene (in sample 23B, X_{Mg} = 0.62) is compositionally similar to the medium- to coarse-grained, subidiomorphic hypersthene (X_{Mg} = 0.61) in the same sample. Both hypersthene and augite are flecked with reddish (hematite? biotite?) reaction- or exsolution-lamellae.

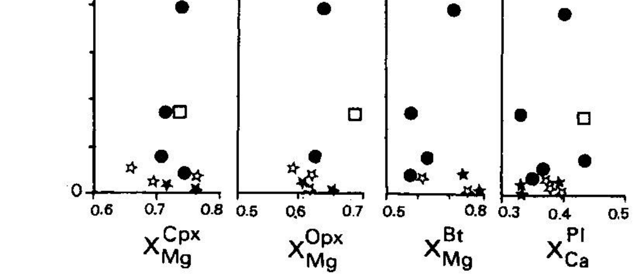

Fig. 2 Variations in X_{Mg} ratios in clinopyroxene, orthopyroxene and biotite, and Ca ratios in plagioclase, with stratigraphic level (m) in the Red Bay pluton. Symbols: dots = jotunitic gabbro; open stars = leucocratic cumulate; closed stars = melanocratic cumulate; square = granophyric pegmatite.

Tab. 1 Microprobe analyses of silicate minerals from selected samples of the Red Bay pluton, Labrador.

	VO90–22A					VO90–22B						VO90–31					
	Cpx	Opx	Bt	Pl		Cpx	Opx	Bt	Bt	Pl		Cpx	Opx	Bt	Hbl	Pl	
				core	rim			(matrix)	(inclusion)	core	rim					core	rim
SiO_2	52.32	52.95	38.36	60.62	59.22	50.63	52.18	38.59	37.74	60.07	59.06	51.72	51.31	36.38	44.79	57.69	59.13
TiO_2	0.39	0.10	4.32			0.27	0.13	4.25	6.30			0.34	0.13	4.44	1.37		
Al_2O_3	3.08	1.65	14.40	25.23	25.78	3.37	1.52	14.14	13.63	25.94	27.05	3.27	1.50	14.07	9.92	26.88	25.89
FeO_T	7.73	21.29	9.53	0.10	0.30	10.43	23.99	10.79	14.49	0.11	0.13	9.76	23.18	14.95	14.03	0.08	0.43
MnO	0.20	0.82	0.08			0.35	0.89		0.08			0.26	0.90	0.10	0.25		
MgO	13.61	21.88	18.97			13.29	21.16	18.11	14.22			13.74	22.37	14.34	12.73		
CaO	22.78	2.35		6.92	7.98	20.24	0.97			7.54	8.42	20.77	1.47	0.07	11.63	8.59	7.34
Na_2O	0.51			7.53	7.09	0.65	0.23	0.18	0.19	6.37	6.00	0.76	0.26	0.15	1.60	6.06	6.70
K_2O	0.04		9.57	0.49	0.34			9.47	9.35	0.28	0.19			9.08	0.61	0.32	0.30
Total	100.66	101.04	95.23	100.89	100.79	99.23	101.07	95.53	96.00	100.31	100.85	100.62	101.12	93.58	96.93	99.62	99.79
X_{Mg}	0.758	0.647	0.780			0.694	0.611	0.749	0.636			0.715	0.632	0.631	0.618		
X_{An}^{Pl}				0.328	0.376					0.389	0.432					0.431	0.370

Tab. 2 Mean microprobe analyses of oxide minerals in the Red Bay pluton.

	Melanocratic cumulate (sample 22A)							Jotunitic gabbro (sample 31)						
	Ilm	sd	Exsolved Ti-Hem	sd	Reintegrated ilm comp.	Hem	sd	Ilm	sd	Exsolved Ti-Hem	sd	Reintegrated ilm comp.	Hem	sd
SiO_2													0.30	0.05
TiO_2	46.86	1.08	12.15	0.60	44.08			46.94	1.04	12.53	1.13	44.77		
Al_2O_3			0.21	0.04	0.02	0.46	0.21							
Cr_2O_3										0.39	0.07	0.03	0.36	0.15
FeO_T	47.84	1.21	76.78	1.71	50.15	89.30	0.65	49.38	1.41	77.61	0.93	51.16	89.32	0.39
MnO	0.72	0.21			0.66			1.10	0.82			1.03		
MgO	1.38	0.08			1.27			0.41	0.16			0.38		
Total	96.80		89.14		96.18	89.76		97.83		90.50		97.37	89.98	
n =	10		8			10		11		11			10	

Notes: sd = one standard deviation.
Ti-Hem exsolution lamellae occupy ~ 8 vol.% of ilmenite in sample 22A, and ~ 6.3 vol.% of ilmenite in sample 31.
FeO_T = total Fe as FeO.

Biotite forms orange-brown, xenomorphic to subidiomorphic crystals that appear intercumulus in the cumulate rocks. It has up to 6.3 wt% TiO_2 and X_{Mg} falls between 0.57 and 0.78.

Amphibole generally occurs as an accessory, noncumulus phase rimming augite, but is an essential mineral in one pyroxene-free, relatively melanocratic sample (24A). The amphiboles are hornblendic (Si/Al = 3 to 6), and have overlapping X_{Mg} ratios (X_{Mg} = 0.55–0.66), but differ in their alumina contents (Al_2O_3 in matrix grains = 6–8 wt%; in coronal grains = 10–11 wt%).

Plagioclase has compositions ranging between An_{32} and An_{45}. In most samples, it shows a rimward increase in An content (by 2–5 mol.% An) with a corresponding decrease (by 30–50%) in K/Na. The calcic rims imply crystallization from vestiges of intercumulus liquid (MORSE and NOLAN, 1984) or perhaps more likely reflect plagioclase reaction with late-stage magmatic fluids (DYMEK and SCHIFFRIES, 1987).

Titano-hematite and *ilmenite* are important rock-forming minerals in all samples. Fe–Ti oxides are generally medium-grained but in some cumulus samples (e.g., 22A) they form poikilitic grains surrounding orthopyroxene and clinopyroxene. Perhaps the most important feature making leucocratic layers stand out from melanocratic layers in the field are the high-percentages (≤ 50 modal percent) of Fe–Ti oxides in the melanocratic rocks. The ilmenite contains exsolved Ti-hematite (Fig. 3) and coexists with hematite (Tab. 2). Ilmenite compositions were reintegrated using volume estimates for Ti-hematite determined by backscatter-image analysis (see OWEN and DAY, 1994). The reintegrated ilmenite contains a moderate amount of hematite (X^{Ilm}_{Hem} ~ 0.14). Other opaque accessory phases include pyrite and/or chalcopyrite. Apatite is a conspicuous accessory phase particularly in the lowermost cumulate samples.

As is apparent from the above descriptions, the pervasive preservation of primary minerals indicates that the intrusion has not suffered substantial metamorphic effects.

Major- and trace-element geochemistry

Bulk geochemical data (Tab. 3) reveal that the RBP is extremely fractionated. Silica concentrations range from 30 to 56 wt%, Mg# (= Mg/(Mg + 0.9 · total Fe) atomic) values span ~ 0.30 to ~ 0.55, and lime/alkalis ratios vary tenfold (0.7–7.1). Apatite and ilmenite are reflected by elevated concentrations of P_2O_5 (0.2–3.4 wt%) and TiO_2 (0.5–6.9 wt%). Non-layered rocks (stratigraphic positions appear in Tab. 3) are characterized by high Ti/V ratios (mean of 8 gabbros ~ 110) and high Ga/Al ratios (ppm/wt%; mean ~ 2.6).

The RBP shows a trend toward higher Mg# values upward through the 36 m of layered rocks on Saddle Island (Fig. 4). A similar trend characterizes 150 m of poorly-layered gabbro overlying the layered rocks. The three samples from above the 180 m level have compositions within the range shown by underlying rocks, but exhibit relatively scattered geochemical signatures.

Various major element geochemical parameters, particularly in the gabbros, correlate with Mg# (and stratigraphic level) in the pluton (Fig. 4). For example TiO_2, CaO and Fe_2O_3 (correla-

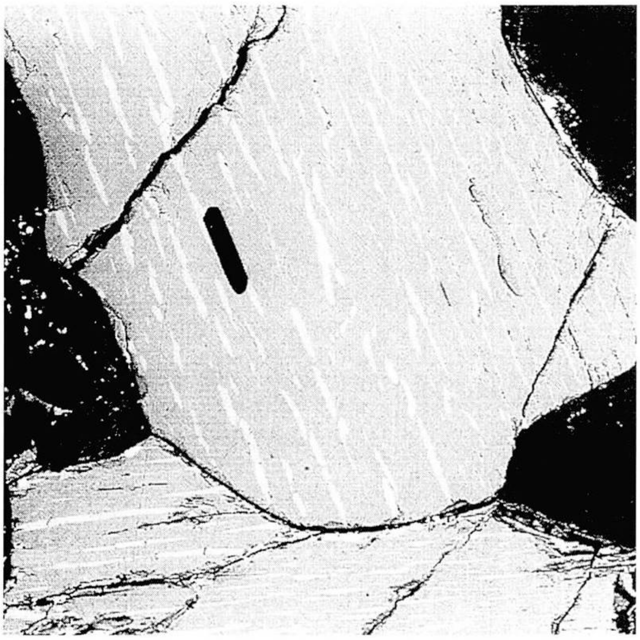

Fig. 3 Backscattered-electron image of narrow (≤ 4 μm), Ti-hematite exsolution lamellae in ilmenite from melanocratic cumulate (sample 22A).

tion coefficients, r, are –0.86, –0.81 and –0.86, respectively, for 8 gabbro samples) tend to decrease with increasing Mg# whereas SiO_2 increases (r = 0.92 for gabbros), and K_2O concentrations remain relatively constant. Many trace elements tend to show poorer correlations with Mg# (Fig. 5; r for La, Zr and Cr is –0.08, –0.31 and 0.56, respectively), even if the gabbros are considered in isolation from the other rocks. Nickel and Cu, however, correlate well (r = 0.95, all samples) with Mg#, and the sample with the highest Ni concentration (435 ppm) is also enriched in Cu (344), consistent with the presence of sulphides (Tab. 3).

Samples show three distinct chondrite-normalized REE patterns (Fig. 6): (1) those with the lowest total REE concentrations display a positive Eu anomaly; (2) those with intermediate REE concentrations have relatively straight patterns; and (3) those with the highest REE concentrations have patterns that bulge upward between Pr and Er relative to the intermediate total REE patterns. The REE correlate with P_2O_5 (e.g., r for Gd = 0.96 using all samples) suggesting that apatite controls REE concentrations. The relatively steep slopes of the REE patterns corroborate other geochemical data (e.g., elevated Ba, P and Ti concentrations) indicating mildly alkaline affinities. This is supported by the fact that fully $^1/_3$ of the samples have alkaline compositions on the basis of alkalis-silica relations (IRVINE and BARAGAR, 1971). These general characteristics distinguish the RBP from most layered mafic intrusions which typically have tholeiitic compositions.

Comparison with other jotunites

Mineralogical and geochemical criteria confirm the jotunitic character (*sensu* OWENS and DYMEK, 1992) of the RBP. Compositionally-similar rocks are associated with massif-type anorthosites elsewhere in the Grenville Province (e.g., the Labrieville, Morin and St. Urbain plutons; OWENS et al., 1993). Similar compositions of clinopyroxene and plagioclase occur in Quebec jotunites (X_{Mg}^{Cpx} = 0.58–0.73; X_{An}^{Pl} = 0.25–0.45; OWENS et al., 1993). Orthopyroxene compositions are relatively magnesian compared to the Quebec jotunites but fall in the continuum of compositions between Quebec anorthosites and jotunites so that these rocks are essentially jotunitic gabbros (Fig. 7). The plagioclase is much more sodic in rocks of the anorthosite-jotunite suite than in typical basalts (Fig. 7; ANDERSON and MORIN, 1968). Possibly oxide-silicate re-equilibration caused subsolidus Fe–Mg exchange making the ferromagnesian silicates more Mg-rich but the absence of zoning (because reequilibration would preferentially affect mineral rims) in the ferromagnesian minerals and presence of reverse zoning in plagioclase argues against this hypothesis. Regardless of its origin, clearly this is a characteristic of the anorthosite clan of rocks.

The RBP has high P and Ti contents. Similar P and Ti concentrations characterize ferrogabbroic to jotunitic FTP rocks worldwide (Fig. 8; OWENS and DYMEK, 1992). Non-layered gabbros display high Ti/V and Ga/Al ratios that overlap those of jotunites from Morin, St. Urbain and Labrieville (Quebec, Canada) and distinguish these rocks from basalts in general (DYMEK, 1990; OWENS et al., 1993). Figure 9 shows MORB-normalized trace element patterns for the mean of 8 Red Bay gabbro samples, average jotunite from three classic Quebec localities, jotunite from the Grenvillian Potato Hill pluton in western Newfoundland, and the mean composition of selected shoshonitic lamprophyres from Nova Scotia, North Carolina and England. Using this element order oceanic island basalts display relatively smooth convex-up patterns (PEARCE, 1983). Important similarities between the Quebec jotunites and the RBP include large positive Ba anomalies, high LREE concentrations and negative Nb anomalies. The three Quebec jotunites also exhibit slight to substantial negative Ti anomalies.

Tab. 3 Major, trace and rare earth element concentrations in the Red Bay pluton, Labrador.

	VO90–22A*	–22B	–23A	–23B	–24A	–24B	–25	–26	–27	–28	–29Q**	–29P**	–30	–31	–32
SiO_2(wt%)	29.68	38.07	38.92	49.75	37.47	52.66	43.68	46.58	48.50	50.47	56.52	54.16	52.29	53.88	52.64
TiO_2	6.87	4.40	5.62	2.10	4.47	2.26	5.01	3.16	4.11	2.96	0.50	2.11	2.04	1.59	2.20
Al_2O_3	5.87	10.59	10.18	16.39	11.01	18.68	14.96	15.64	15.78	17.56	21.96	20.33	18.40	16.94	18.31
Fe_2O_3(t)	32.37	22.74	26.13	13.62	21.07	8.70	15.71	14.27	12.93	11.17	3.92	6.81	8.68	8.90	8.75
MnO	0.29	0.20	0.20	0.12	0.19	0.09	0.14	0.12	0.12	0.11	0.05	0.06	0.10	0.14	0.09
MgO	7.28	5.36	6.14	3.65	5.85	3.52	3.89	3.76	4.11	4.25	2.06	1.46	3.55	5.10	3.06
CaO	11.66	11.02	9.59	8.20	11.58	6.25	7.59	8.89	7.96	6.41	6.75	5.43	7.13	6.28	7.07
Na_2O	1.27	2.62	2.26	3.53	2.52	3.94	3.60	3.47	3.37	3.64	4.35	4.76	3.64	3.40	3.78
K_2O	0.37	0.95	0.78	1.48	0.63	1.58	1.53	1.41	1.28	1.26	1.56	2.63	1.45	1.78	1.63
P_2O_5	3.22	3.30	0.47	0.51	3.41	0.27	1.64	1.65	0.47	0.26	0.20	0.34	0.85	0.52	0.64
L.O.I.	0.10	0.60	0.00	0.10	0.80	0.50	0.90	0.50	0.00	0.90	0.70	1.30	0.60	0.40	0.70
Total	98.98	99.85	100.29	99.45	99.00	98.45	98.65	99.45	98.63	98.99	98.57	99.39	98.73	98.93	98.87
Alkali and alkaline earth metals															
Rb(ppm)	5	9	10	20	< 5	14	25	14	10	9	8	34	13	18	20
Sr	734	1276	912	1458	1318	1818	1556	1616	1452	1649	1907	1701	1574	1348	1548
Ba	549	1179	915	1421	897	1591	1204	1351	1250	1248	1261	1691	1241	2070	1301
High field strength elements															
Th	0.56	0.61	0.37	0.88	0.22	0.90	0.53	0.48	0.51	0.37	0.57	0.89	0.71	0.90	1.50
Zr	128	75	141	70	42	61	94	77	130	62	36	107	94	101	93
Nb	7	5	10	< 5	< 5	< 5	5	6	7	< 5	< 5	7	6	7	5
Y	32.5	29.7	17.2	14.7	29.2	7.6	15.7	15.4	14.1	6.1	6.1	10.8	13.4	15.7	13.2
Rare earth elements															
La	35.2	35.5	15.0	20.4	34.7	16.9	23.6	22.8	17.9	11.2	14.4	25.8	24.1	27.3	25.2
Ce	95.9	94.3	40.3	48.8	95.7	35.1	57.6	55.7	42.4	24.6	30.7	54.1	55.9	60.8	57.0
Pr	14.8	14.1	6.02	6.65	14.7	4.40	8.32	7.88	5.92	3.21	3.90	6.87	7.55	7.98	7.47
Nd	73.6	69.4	30.2	30.3	72.3	18.5	39.2	36.0	27.0	13.8	15.8	28.1	32.7	34.9	32.1
Sm	15.6	15.0	6.9	6.04	15.4	3.31	7.66	7.08	5.49	2.48	2.85	4.92	6.19	6.66	6.21
Eu	3.84	3.80	2.04	2.21	3.89	2.04	2.44	2.14	1.95	1.29	1.56	2.18	2.08	2.85	2.04
Gd	13.1	12.2	6.08	5.00	12.8	2.66	6.55	6.12	4.91	2.12	2.11	4.08	4.98	5.35	4.70
Tb	1.48	1.30	0.717	0.603	1.340	0.305	0.726	0.715	0.601	0.245	0.258	0.484	0.586	0.660	0.558
Dy	8.42	7.32	4.27	3.43	7.47	1.74	3.88	3.83	3.51	1.53	1.48	2.67	3.34	3.91	3.24
Ho	1.33	1.26	0.737	0.580	1.18	0.290	0.630	0.616	0.587	0.249	0.239	0.437	0.541	0.641	0.533
Er	3.27	2.82	1.83	1.45	2.67	0.763	1.55	1.52	1.43	0.649	0.641	1.05	1.32	1.69	1.34
Tm	0.389	0.324	0.236	0.192	0.306	0.107	0.180	0.180	0.189	0.088	0.086	0.133	0.170	0.218	0.162
Yb	2.13	1.82	1.40	1.12	1.61	0.664	0.975	0.962	1.23	0.503	0.417	0.778	1.04	1.27	0.953
Lu	0.31	0.269	0.187	0.164	0.236	0.096	0.137	0.146	0.166	0.072	0.076	0.121	0.157	0.193	0.140
Siderophile and chalcophile elements															
V	634	356	671	289	418	125	291	247	228	155	33	98	112	67	129
Cr	< 5	< 5	< 5	< 5	7	5	84	10	20	94	39	15	85	191	34
Ni	18	6	435	162	60	39	61	34	55	67	14	23	45	82	38
Cu	86	51	344	178	98	23	64	42	75	54	14	55	43	46	31
Zn	404	257	231	157	232	87	166	133	114	103	49	64	101	125	96
Ga	27	26	26	26	31	19	21	23	27	25	25	26	23	23	21
Mg#	0.33	0.34	0.34	0.37	0.38	0.47	0.35	0.37	0.41	0.46	0.54	0.32	0.47	0.56	0.43
Stratigraphic level (m)***	0	0	26	26	36	36	45	58	82	131	180	180	~ 400	~ 850	~ 1000

Notes: * "A" suffix denotes relatively melanocratic layer; "B" – relatively leucocratic layer.
** Sample VO90-29Q = quartz-bearing gabbro; –29P = pegmatitic gabbro.
*** Level (rounded to nearest m) above the structurally-lowest exposed part of intrusion.

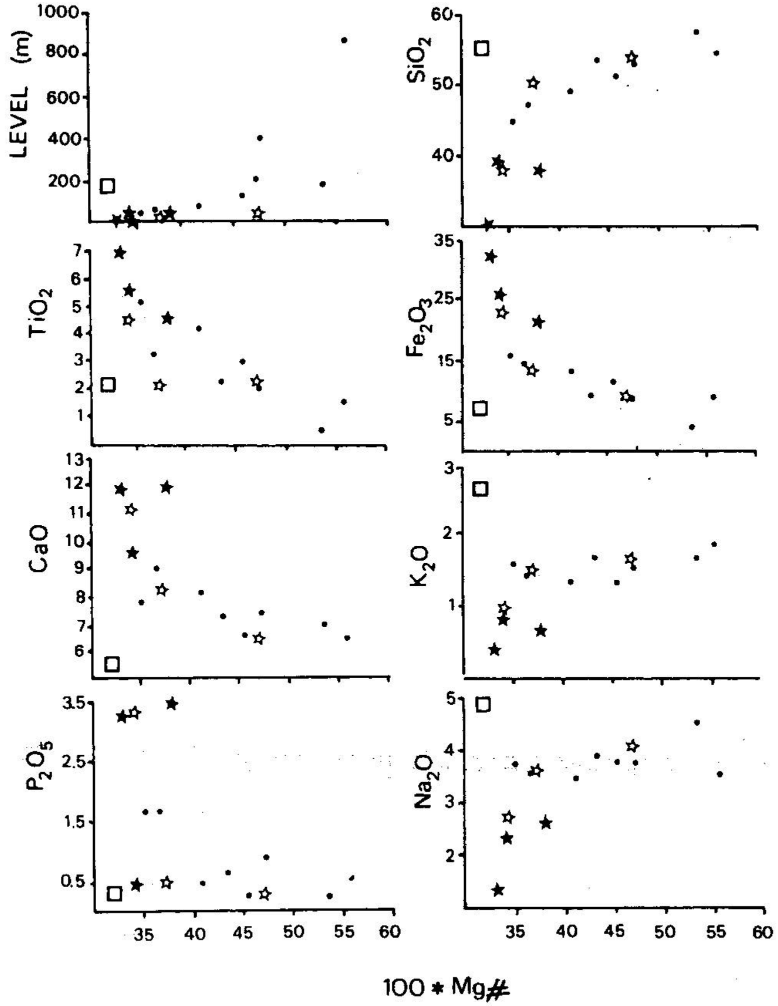

Fig. 4 Selected major elements (wt% volatile free) and stratigraphic level above the exposed base (m) plotted against Mg# (Mg# = Mg/(Mg + 0.9 · total Fe), atomic). Symbols as in figure 2.

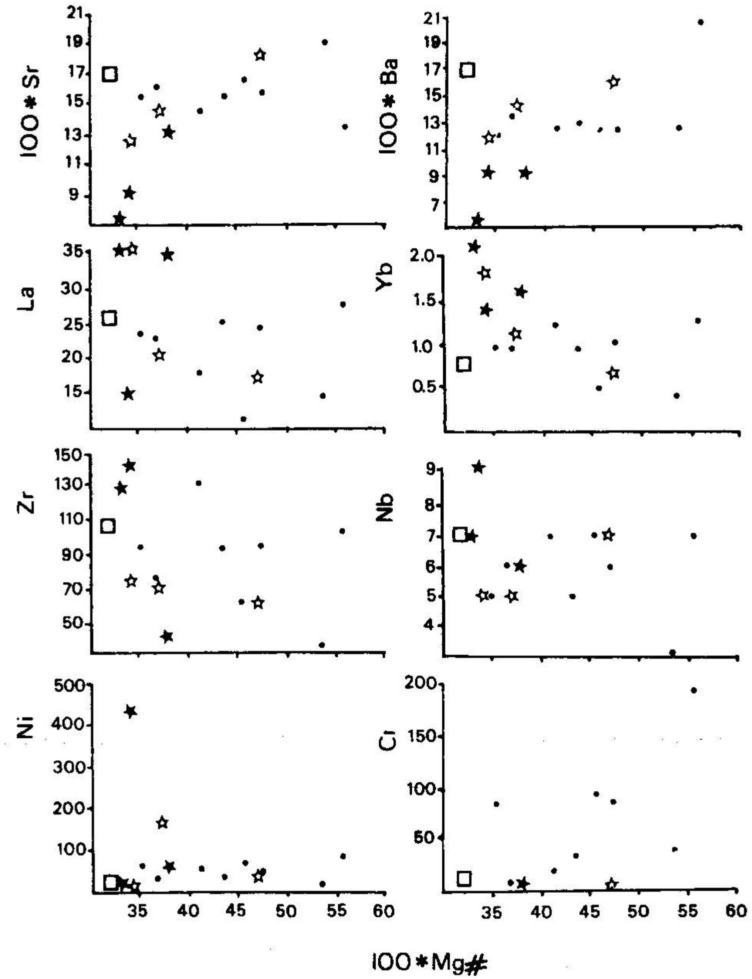

Fig. 5 Selected trace elements (ppm) plotted against Mg# (= Mg/(Mg + 0.9 · total Fe), atomic). Symbols as in figure 2.

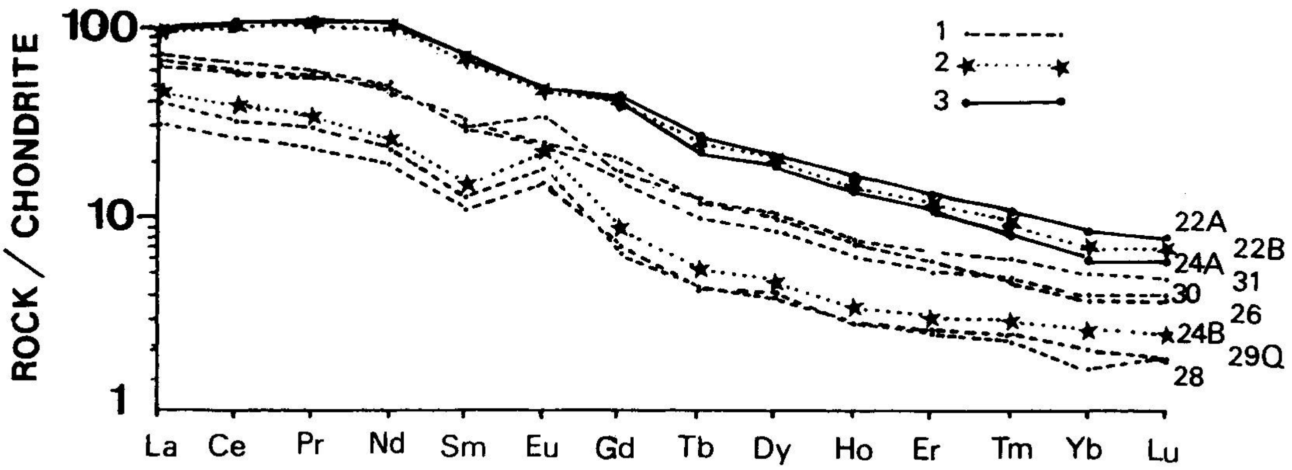

Fig. 6 Chondrite-normalized rare earth element concentrations in representative Red Bay rocks. Normalizing values from EVENSEN et al. (1978). Symbols: 1 = jotunitic gabbro; 2 = leucocratic cumulate; 3 = melanocratic cumulate.

Although overlapping the Quebec and Red Bay jotunite trace element patterns, the Potato Hill jotunite and the shoshonitic lamprophyres are depleted in both P and Ti, components which distinguish *bona fide* FTP rocks.

Red Bay magma evolution

Interpretation of the evolutionary history of the RBP is complicated by the fact that no portion of the intrusion need represent a liquid composition and some portions are clearly cumulus. Correlations between the major elements, particularly in the gabbros indicate that all samples can be treated as cogenetic. The poor correlations between some of the trace elements and major elements (e.g., Mg#), however, suggest either multiple magma emplacement, or a single magma pulse, with minor phase accumulation (harbouring minor and trace elements) not necessarily linked with the accumulation of specific major phases.

The latter interpretation is favoured by the REE data. For example, using partitioning coefficients (D values) determined by the method of NIELSEN (1992), the upward-bulging chondrite-normalized REE patterns in samples with high total REE concentrations are consistent with the presence of accumulated apatite. This is compatible with the strong positive correlation between P and the REE. Similarly, the Eu anomalies that characterize the low total-REE samples reflect the presence of accumulated plagioclase, with little or no cumulus apatite.

Mass balance calculations (BRYAN et al., 1969) were used to provide an indication of the petrogenetic relations between relatively primitive and evolved rocks within the RBP, and hence shed light on magma evolution. End-member (based on Mg#) gabbroic samples were used to approximate parent and daughter magma compositions and analysed minerals (e.g., Tab. 1) were assumed representative of fractionating phases. Low values for R^2 (sum of squared residuals, < 1) indicate that the fractionation (or accumulation) of orthopyroxene, augite, plagioclase, apatite, hematite and ilmenite can account for variations in gabbro chemistry. The calculations point to the importance of Fe–Ti oxide and plagioclase precipitation in magma evolution. This inference is consistent with the abundance of these phases in cumulus layers near the base of the intrusion. However, despite hundreds of different mixes

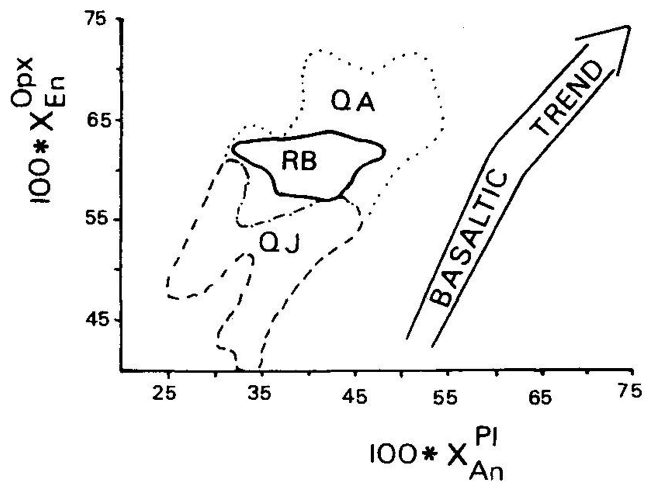

Fig. 7 Comparison of the composition of plagioclase and orthopyroxene in the Red Bay pluton (RB) with X_{Mg}^{Opx} and X_{An}^{Pl} in Quebec anorthosites (QA) and associated jotunites (QJ), and divergent basalt trends, as compiled by OWENS and DYMEK (1993). MgOp = Mg/(Mg + Fe + Ca + Ti); $X_{An}^{Pl} = X_{Ca}$ = Ca/(Ca + Na + K).

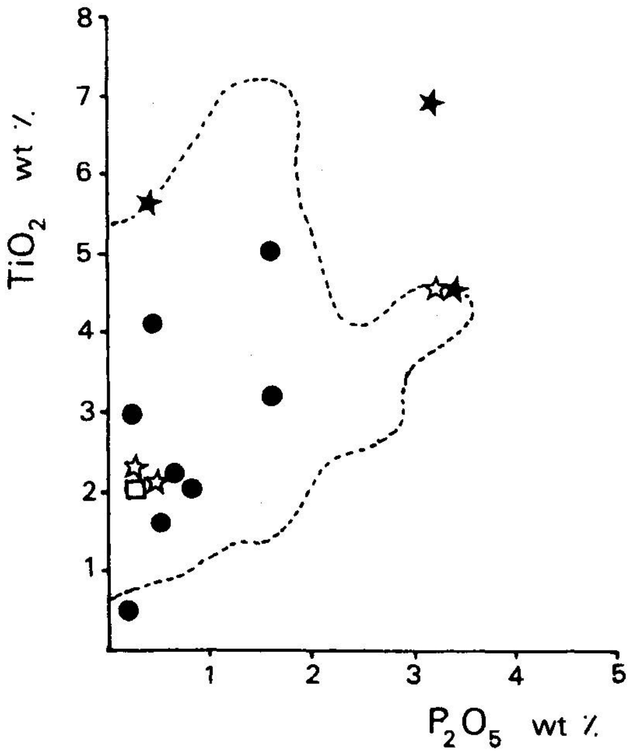

Fig. 8 Comparison of TiO_2 and P_2O_5 concentrations in the Red Bay pluton and ferrogabbroic to jotunitic rocks worldwide (dashed line, based on a compilation of 22 localities by OWENS and DYMEK [1992]). Symbols as in figure 2.

(mineral analysis combinations) during modelling runs, small amounts of one phase (usually orthopyroxene) always had to be *added* to the daughter product. Apparently the premise that the gabbros represent liquids is not strictly valid. Some cumulus phases may occur in all samples.

The hypothesis that oxide precipitation partly controlled magma evolution was tested by running gabbro compositions through a low pressure melting-experiment based computer program (NATHAN and VAN KIRK, 1978) that mathematically models the evolution of anhydrous magma. Our intent was not to use the program to predict how individual gabbro samples would evolve, but to see what liquidus phases might be expected during the first 10% of magma crystallization. That the program models anhydrous magma evolution is not considered a problem because textural relationships indicate that hydrous phases formed late in the crystallization sequence. A high Fe_2O_3/FeO ratio (= 0.2) was assumed because similar rocks from Quebec crystallized under high $f(O_2)$ conditions (OWENS et al., 1993). The program predicts that plagioclase and Fe–Ti oxides would be the dominant liquidus phases during crystallization of most gabbroic samples, consistent with the observed mineralogy of the samples.

The program also explains several enigmatic observations about the intrusion. Igneous cross-beds and modal layering indicate that the intrusion's bottom is to the south. Plagioclase is an important phase in the intrusion thus high CaO concentrations in the south are consistent with this being the base of the intrusion. However, Mg# and MgO concentrations increase toward the north which is apparently contrary to the previous two observations. The modelling experiments indicate that Mg# and MgO concentrations *increased* as the magma evolved as a result of oxide precipitation! Thus the gabbroic sample 25 with lowest Mg# was used as parent and 31 (highest Mg#) as daughter in the mass balance calculations discussed above. The program also predicts that SiO_2 concentrations should increase, and that CaO, Fe_2O_3 (total Fe) and TiO_2 should decrease. The predicted trends are the same as those shown in the variation diagrams (Fig. 4). Although inversely zoned intrusions (i.e., relatively primitive rocks overlie more evolved rocks) are not uncommon (e.g., BEARD and DAY, 1988; GASTIL et al., 1991), the inference that Mg# increased with Red Bay magma evolution indicates that the intrusion is normally zoned and that the most evolved rocks, although having the highest Mg# values, occur in the upper exposed portions of the intrusion. We were, however, unable to substantiate by two pyroxene solvus thermometry (e.g., WELLS, 1977), two-pyroxene exchange equilibria (using TWQ software; BERMAN, 1991), and amphibole-plagioclase thermometry (BLUNDY and HOLLAND, 1990) whether stratigraphically-lower rocks formed at elevated temperatures relative to higher rocks. All approaches yielded a scatter of temperatures apparently reflecting subsolidus mineral reequilibration during cooling or subsequent metamorphism.

Relationships with anorthosite and mangerite

Jotunites are nearly universally associated with massif-type anorthosite, and the tendency for a gradation from anorthosite to jotunite at higher structural levels suggests that the latter are derivative (HARGRAVES, 1962; PHILPOTTS, 1981; GOLDBERG, 1984). Apart from relatively coarse-grained (5–20 cm), plagioclase-rich layers, anorthosite has not been observed in spatial association with the RBP, but the intrusion occurs at the end of the world's most extensive belt of massif-type anorthosites, that stretches from Labrador through Quebec. Furthermore, as shown earlier, the RBP shows remarkably close compositional similarities with anorthosite-related jotunites in Quebec. Consequently, consideration of relationships between the RBP (and similar jotunitic rocks elsewhere) and anorthosite and mangerite is justified.

As expected from REE partitioning coefficient data, anorthosites show large positive Eu anomalies on chondrite normalized REE diagrams (DUCHESNE et al., 1974). Consequently, a commonly cited problem concerning jotunites is their lack of a negative Eu anomaly, which implies that these rocks cannot represent residual liquids (OWENS et al., 1993). The Red Bay jotunites (gabbros) are no exception (Fig. 6). Although high magmatic $f(O_2)$ results in plagioclase-melt Eu partitioning coefficients that are similar to D values for the other REE (DRAKE and WEILL, 1975), anorthosite consistently shows positive Eu anomalies. OWENS and DYMEK (1992) suggested that attempts to identify residual or parental magmas based mainly on Eu anomalies is fraught with problems (e.g., apatite is the primary reservoir for the REE in these rocks; EMSLIE [1985]). We concur with this view, and suggest that the problem can be put into perspective: plagioclase precipitation is undoubtedly important to the evolution of many oceanic basalts (ELTHON, 1984), but negative Eu anomalies are not common in these rocks.

PHILPOTTS (1981) proposed an immiscible origin for jotunites and associated mangerites with anorthosites representing residual material left after separation of the Fe-rich and Si-rich liquids. The hypothesis explains the Fe-, Ti- and P-rich nature of jotunites and it relates the essentially fixed composition of anorthosite plagioclase to the buffering effect of the two liquids changing relative proportions. Nevertheless, if immiscibility is involved, the separated Si-rich liquid must assimilate country rock in order to explain the Sr (EMSLIE, 1978) and Nd (BASU and PETTINGILL, 1983) isotopic composition of mangerites. The gabbroic sample data presented here (i.e., ignoring what are clearly cumulate samples) indicate that jotunite evolution does not result in K_2O enrichment (Fig. 4). This supports a role for immiscibility and/or partial melting in mangerite formation. We caution that jotunites with associated mangerites need to be examined for K_2O enrichment to determine if the RBP is typical.

The very low Rb and Th contents of the Red Bay jotunites argue against substantial crustal contamination during their formation. This supports Sr (EMSLIE, 1978), Nd (BASU and PETTINGILL, 1983) and O isotope data (DEMAIFFE and JAVOY, 1980) for anorthositic rocks indicative of a mantle source. OWEN et al. (1992) concluded on the basis of trace element, O and Nd isotopic data that highly evolved jotunites from the Potato Hill pluton, Newfoundland show little evidence for crustal contamination.

Magmatic affinities and tectonic implications

Although it may not be possible to point to modern-day equivalents of jotunitic magmas, in this section we discuss several magma types (such as shoshonitic lamprophyres) with distinctive geochemical features that overlap those of jotunites. Identification of these features and the geochemical processes that cause them makes it possible to speculate on the tectonic environment that produced the anorthosite clan of rocks.

Isotopic data (e.g., OWENS et al., 1994) suggest a mantle origin for the magma that produces anorthosites and jotunites, but models to explain their formation must account for low Mg# values and their extremely feldspathic character. Magmas formed in equilibrium with mantle lherzolite bearing Fo_{90} olivine should have an Mg# of ~ 0.70 (ROEDER and EMSLIE, 1970; GREEN, 1971), but jotunites such as those at Red Bay have very low Mg#'s (0.2–0.5; see also OWENS et al., 1993) indicating they are highly evolved. Furthermore, low Ni and Cr contents imply significant ferromagnesian mineral removal (or generation in a non-peridotitic source region). Melting experiments show that the pyroxene-anorthite eutectic moves to plagioclase-rich compositions at high pressures (PRESNALL et al., 1978). Fractionation of mafic magma near the base of the crust could lead to enrichment in feldspar components, low Mg# values and low Cr and Ni concentrations.

Tentatively concluding that massif-type anorthosites and associated rocks are products of mafic magma evolution is hardly very satisfactory. Geoscientists recognize many types of mafic magmas from numerous tectonic settings. The importance and difficulty of identifying the tectonic environment is emphasized by the observation that many anorthosites formed between 1.1 and 1.45 Ga (PHILPOTTS, 1990, p. 305) and it is dubious that they have modern-day tectonic analogues. A problem with using anorthosites to infer a tectonic setting is that they are apparently cumulates which give at best a poor indication of element patterns in their source magma. Magmas parental to anorthosites have not been identified. The discovery of fine-grained jotunite dykes (OWENS et al., 1993) demonstrates that jotunites form liquids, and the multi-phase character of

RBP "gabbros" suggests that these rocks provide some constraints on magma compositions.

Many incompatible elements resist fractionation during magma evolution. Consequently, highly evolved magmas commonly reflect the incompatible trace-element patterns of their parent magmas (THOMPSON and FOWLER, 1986; OWEN et al., 1992). It is for this reason that these elements tend to be used in discriminant diagrams. Although crustal assimilation can modify magmatic trace element patterns (e.g., THOMPSON et al., 1982; DOSTAL and DUPUY, 1984), it has already been argued that there is little evidence that these magmas were substantially contaminated.

The large positive Ba anomalies, high LREE concentrations, negative Nb anomalies, and generally slight to substantial negative Ti anomalies that characterize jotunite patterns on MORB-normalized diagrams represent some of the more important attributes of magmas such as shoshonitic lamprophyres associated directly or indirectly with subduction processes (WYMAN and KERRICH, 1989a; FITTON et al., 1991) (Fig. 9). These geochemical characteristics have been attributed to melting of sub-continental lithospheric mantle metasomatized by subducted slab-derived fluids (e.g., MACDONALD et al., 1985; MAUGER, 1988a; WYMAN and KERRICH, 1989a). The metasomatizing fluids carry the large ion lithophile elements (especially Ba) and light REE and enrich the lithospheric mantle in these elements. They are either incapable of carrying Ti and Nb, or result in stabilization of oxide phases that retain Ti and Nb during subsequent melting events.

Enrichment in Ba and depletion in Nb, relative to La, characterizes subduction-related metasomatism. Thus plots of La/Ba versus La/Nb are useful for identifying magmas whose source regions were affected by this process (FITTON et al., 1991). Figure 10 compares data for jotunites from Quebec and Red Bay, oceanic island basalts, continental "basalts" that melted previously metasomatized subcontinental lithospheric mantle, and selected shoshonitic lamprophyres. The subduction-related component of magmas increases down and to the right (low La/Ba and high La/

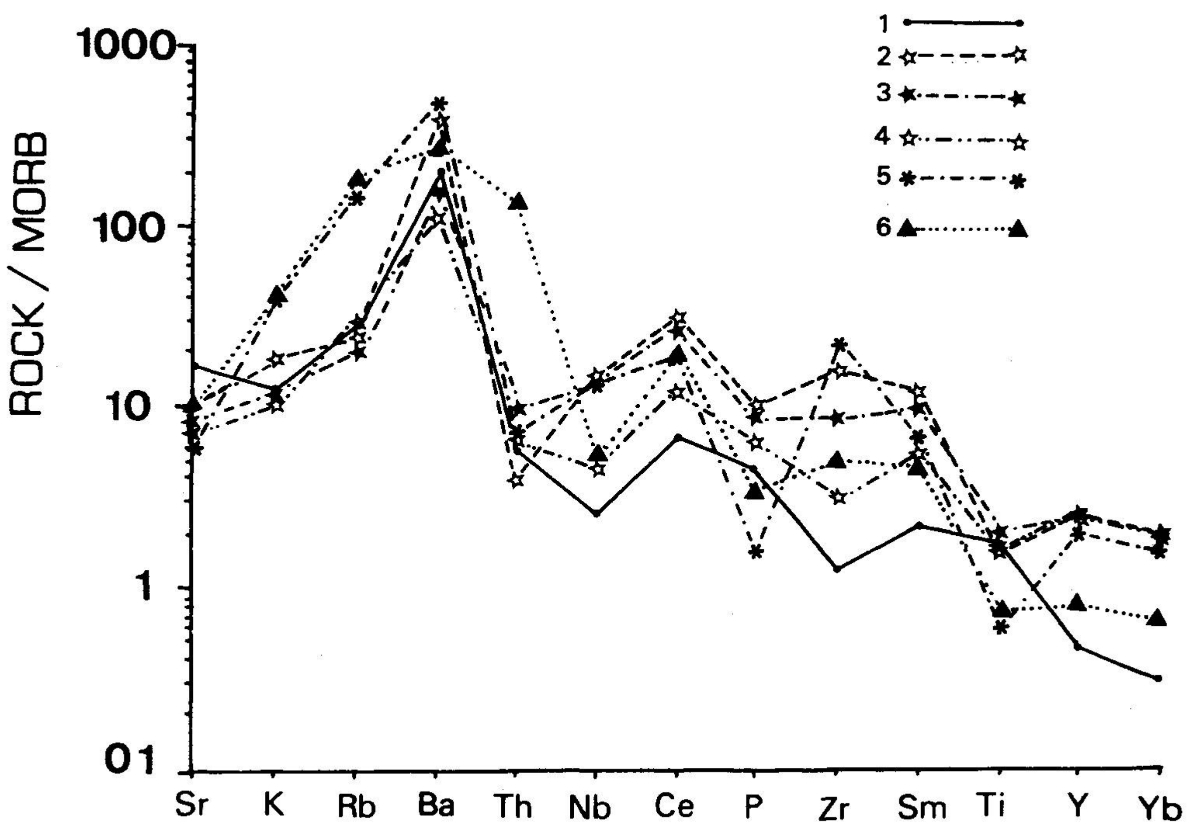

Fig. 9 MORB-normalized trace element patterns in jotunites. Shown are average patterns for the 8 "gabbro" samples reported here (symbol 1), Quebec jotunites (OWENS et al., 1993) from Labrieville (n = 5; symbol 2), St. Urbain (n = 5; symbol 3) and Morin (n = 5; symbol 4), as well as the Potato Hill jotunite in western Newfoundland (n = 2; symbol 5; OWEN et al., 1992). For comparison a composite average pattern for Palaeozoic shoshonitic lamprophyres from North Carolina (MAUGER, 1988a), Nova Scotia (GREENOUGH et al., 1993) and northern England (MACDONALD et al., 1985) is also shown (symbol 6). MORB normalizing values are from SUN and MCDONOUGH (1989) and the element order is as suggested by PEARCE (1983).

Nb; FITTON et al., 1991). The diagram indicates that subduction processes were directly or indirectly important to the formation of jotunites.

Attention has already been drawn to some of the chemical similarities between jotunites and shoshonitic lamprophyres, but there are clearly important differences between these rock types. Shoshonitic lamprophyres are very primitive rocks with a high Mg#, and normally show high K, Rb and Th (Fig. 9), and contain an abundance of hydrous phases which may indicate an elevated water content in the magma (ROCK, 1984). In contrast, jotunites are relatively depleted in K and Rb. This feature may result from liquid immiscibility (PHILPOTTS, 1981), because synthetic melting experiments indicate that these elements partition into the Si-rich liquid (WATSON, 1976; RYERSON and HESS, 1978). However, the same experiments suggest that Th would move into the Fe-rich liquid, in this case jotunite. Note that the positive Ba and negative Nb and Ti anomalies in jotunites (Fig. 9) must represent an intrinsic characteristic of the parent magma and could not be an artifact of immiscibility. The melting experiments predict that the anomalies would be at least as pronounced in the parental liquid because Ti and Nb would partition into the Fe-rich liquid, and Ba would partition into the Si-rich liquid.

As regards the apparently low volatile content of jotunitic magma, there may be problems with using the anhydrous mineralogy to make such inferences. Shoshonitic lamprophyres are heteromorphic (ROCK, 1984): the same whole-rock composition can be expressed mineralogically in different ways depending on pressure. These apparently hydrous magmas crystallize anhydrous minerals at high pressures (MAUGER, 1988b; GREENOUGH et al., 1993). Calcic myrmekite on the rims of plagioclase grains provides evidence for aqueous fluids during anorthosite crystallization (DYMEK and SCHIFFRIES, 1987).

Perhaps closer Phanerozoic analogues of jotunites include the swarms of mildly alkaline (chemically transitional between basalts and shoshonitic lamprophyres) dykes associated with Palaeozoic transpressional docking of terranes along the Appalachian mountains. They generally lack hydrous phases, commonly contain plagioclase megacrysts and have trace element characteristics bearing a subduction imprint reminiscent of the jotunites (e.g., high Ba, REE; GREENOUGH, 1984, p. 96, 234, 235; ROSS, 1986). Admittedly the limited information suggests that the plagioclase is more calcic (labradorite) than in most anorthosites and jotunites, still some massif-type anorthosites contain plagioclase of the same composition (e.g., Michikamau intrusion, Labrador; EMSLIE, 1965).

If the compositional subduction signature for these rocks is valid, then there are several possible tectonic environments in which anorthosites and kindred lithologies could form. For example, shoshonitic lamprophyres form on active continental margins where they tend to be younger, stratigraphically higher, and further from the oceanic trench than calc-alkaline magmatism (MORRISON, 1980). They also are characteristically emplaced late to post-tectonically along transcurrent fault zones (MAUGER, 1988a; ROCK et al., 1988; WYMAN and KERRICH, 1989b). For example transpressional tectonism within an assembled Pangea resulted in the middle Palaeozoic shoshonitic lamprophyres common in eastern North America and western Europe.

The fact that most massif-type anorthosite complexes in North America occur in a single belt crudely parallel to the Grenville Front leads one to suspect an association with orogenesis. However, EMSLIE (1985) associated anorthosite

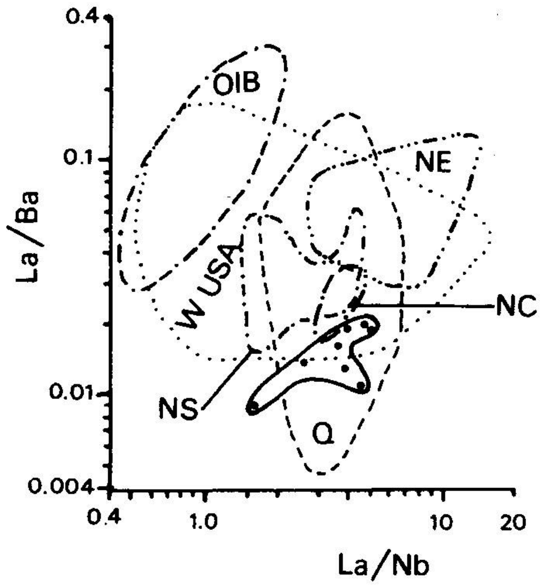

Fig. 10 Comparison of La/Ba and La/Nb ratios in jotunites, oceanic island basalts ("OIB"; FITTON et al., 1991), and selected continental "basalts" and shoshonitic lamprophyres. Jotunites are from Red Bay (solid field; data points are indicated) and Quebec ("Q"; 15 samples from the Morin, St-Urbaine and Labrieville plutons [OWENS et al., 1993]). Continental basalt data ("W-USA") are for extension-related Cenozoic mafic rocks from the western U.S.A. (FITTON et al., 1991). The shoshonitic lamprophyres are various late Palaeozoic Gondwanaland rocks, as follows: "NC" = three minettes from North Carolina (MAUGER, 1988a); "NS" = 12 spessartites from Nova Scotia (GREENOUGH et al., 1993); "NE" = 5 minettes and kersantites from northern England (MACDONALD et al., 1985, Tab. I, II and III).

formation with aborted continental rifting during a c. 1.4 Ga anorogenic event. This model is based on information that there was little deformation during the period of anorthosite formation and that magmatism ended with inception of the Grenvillian orogeny (~ 1.1 Ga). OWENS et al. (1994) point out that anorthosite formation took place pre- syn and post-tectonically.

Another setting where mildly alkaline to strongly alkaline magmas bearing a "subduction" signature occur is in western North America (Fig. 10). In this area, Cenozoic mafic magmas form a belt extending from the southern United States (FITTON et al., 1991) well up into Canada (MATHEWS, 1989). Although clearly associated with extension, it is not clear what role, if any, subduction played in creating this extensional environment. Certainly eruptions in Canada perhaps as recently as ~ 10,000 years ago took place even as subduction was occurring farther west. Nevertheless, isotopic data indicate that the "subduction" signature of United States examples resulted from melting subcontinental mantle enriched by subduction processes that occurred long before the Cenozoic basic magmatism (FITTON et al., 1988). In summary, perhaps the best Phanerozoic tectonic analogue is the Cenozoic basic magmatism in Western North America. Many of the rocks are mildly alkaline, commonly bear a subduction signature, occur parallel to an orogenic belt and are associated with extension.

Summary and conclusions

1. The RBP is mineralogically and chemically similar to jotunitic rocks associated with massif-type anorthositic intrusions.

2. Trends in major element data suggest that the RBP constitutes a cogenetic suite, but poor correlations between major and trace element data indicate that minor phase accumulation (notably apatite) was poorly linked to major phase removal, and that none of the gabbroic samples represent melts.

3. Mass balance and magma modelling calculations confirm the importance of plagioclase and Fe–Ti oxide precipitation to evolution of the Red Bay magma. These calculations also indicate that oxide precipitation led to declining Fe concentrations, causing Mg# to rise, whereas plagioclase precipitation lowered Ca concentrations. Similar evolutionary schemes have been derived for Quebec jotunites by OWENS et al. (1993).

4. Although SiO_2 concentrations increased as the Red Bay magma evolved, K_2O did not. If the RBP is typical of jotunites this could support a role for immiscibility in the origin of mangerites and jotunites as suggested by PHILPOTTS (1981).

5. Positive Ba anomalies, elevated LREE concentrations, negative Nb and Ti anomalies on MORB-normalized diagrams, and high Ba/Nb ratios indicate that the jotunitic magmas were mildly to strongly alkalic and resulted from the melting of subcontinental lithospheric mantle that had previously been metasomatized by subduction-derived fluids.

6. Although magmas bearing a subduction-induced subcontinental mantle imprint are most commonly produced in late-tectonic transpressional environments, the general lack of evidence for syn-anorthosite deformation and metamorphism suggests that anorthosites were not produced as a direct result of orogenesis.

7. Perhaps the setting for Cenozoic basic magmatism in Western North America represents the best Phanerozoic tectonic analogue for the anorthosite suite of rocks. The Cenozoic rocks tend to be mildly alkaline, commonly bear a subduction signature, occur parallel to an orogenic belt and are associated with extension.

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