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Evidence for unusually feldspathic liquids in the Nain complex, Labrador

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ABSTRACT

A variety of field evidence in the Nain complex of Labrador, supported by petrography, geochemistry, new insights into the fluid dynamics of magmas, and models for the crystallization of basaltic magma, indicates that some massif-type anorthosites require the existence of unusually feldspathic liquids at the level of their final emplacement. Fine-grained anorthositic dikes have hypidiomorphic textures and strongly zoned plagioclase that indicate liquids contained on the order of 30% excess plagioclase relative to a cotectic with pyroxene. Similar estimates of liquid compositions can be made by considering the crystallization of the Paul Island intrusion, a typical massif-type anorthosite with a stratigraphy developed partly through bottom accumulation and periodic replenishment. These liquids are too feldspathic to have formed on a cotectic with a mafic phase at any depth. They were probably initiated by remelting of suspended plagioclase in periodically replenished basaltic magma chambers near the base of the crust. The geochemical and isotopic character of these liquids suggests that crustal contamination was also an important process.

INTRODUCTION

There has been a growing consensus that mantle-derived basaltic magmas are parental to anorthosites (Morse, 1982; Emslie, 1985) even though the relatively low $100[Mg/(Mg + Fe_T)]$ values of anorthosites appear to require extensive fractionation of mafic phases at depth (Emslie, 1985; Wiebe, 1986). Earlier models of anorthosite genesis invoking intermediate (andesitic to monzonoritic) parental magmas (e.g., Ryder, 1974; de Waard et al., 1974) have largely been discredited, although models that derive a parental magma by partial melting of a mafic lower crust remain a minority view (Simmons and Hanson, 1978; Taylor et al., 1984).

Many field studies of anorthosites in recent years have confirmed that most massif anorthosites are greatly enriched in plagioclase relative to basalt and greatly deficient in associated mafic rocks at their final level of emplacement. Geophysical studies also indicate, for most anorthosites, a deficiency in closely associated mafic rocks but do permit their occurrence in the lower crust or upper mantle (Morse, 1982). If one accepts that basaltic magmas are parental to anorthosite, then, either the basaltic magmas carried abundant plagioclase crystals up to the final level of emplacement or the basaltic liquid subsequently became strongly hyperfeldspathic, perhaps by delayed nucleation of plagioclase (Morse, 1982) or by resorption of suspended plagioclase (Wiebe, 1988a).

The issue of whether the magma carried much of its excess plagioclase component as suspended crystals or dissolved within the liquid is important in that it should strongly affect the style of emplacement and solidification of anorthosite. Simply put, a crystal-rich mush will intrude and solidify differently than a liquid. The purpose of this paper is to present field and petrographic evidence from the Nain complex for the existence of unusually feldspathic (hyperfeldspathic) liquids and for their role in the production of typical Proterozoic massif-type anorthosites. Hyperfeldspathic liquids are defined here, for convenience, as liquids with more than 75 to 80 wt% normative plagioclase. They appear to lie well within the plagioclase liquidus field at any pressures relevant to their origin.

There are two main lines of evidence for such liquids. The first consists of chilled margins and dikes: some of the younger anorthositic plutons in the Nain complex have portions of their intrusive margins that consist of relatively fine-grained hypidiomorphic anorthositic rocks; fine-grained anorthositic dikes are commonly associated with these plutons and also occur elsewhere in the Nain complex. Several dikes have major- and trace-element compositions that indicate a comagmatic relationship to nearby coarse-grained anorthositic plutons. A second line of evidence emerges from the stratigraphic sequence and crystallization history of a typical anorthositic pluton, the Paul Island intrusion. It will be argued that the fine-grained dikes and this large pluton could only have been produced by liquids that resided well within the plagioclase field.

DIKES AND CHILLED MARGINS OF ANORTHOSITE

Introduction

The Nain anorthosite complex is located along the central coast of Labrador (Fig. 1). It consists of many differ-

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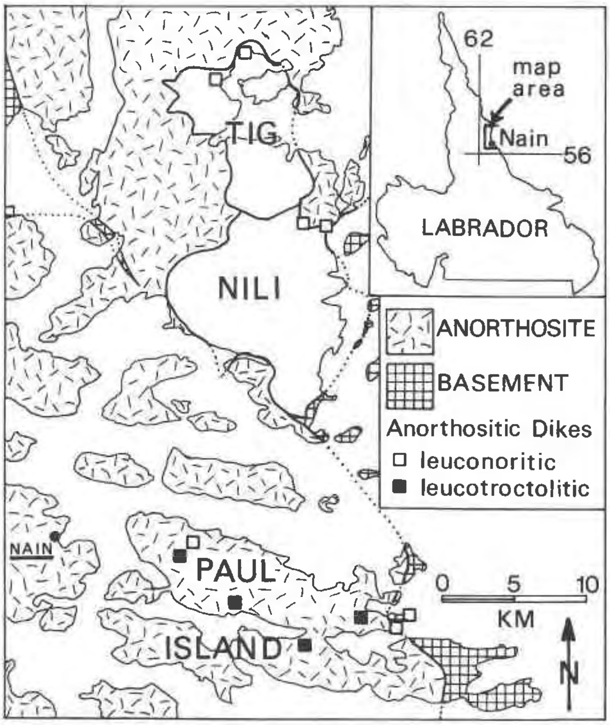

Fig. 1. Index map and simplified geologic map of a portion of the Nain complex. TIG = Tigalak layered intrusion (Wiebe and Wild, 1983). NILI = Newark Island layered intrusion (Wiebe, 1988b).

ent anorthositic, mafic, and granitic plutons. Recent age determinations (Simmons et al., 1986; DePaolo, 1985; Krogh and Davis, 1973) suggest that all of these plutons were emplaced relatively rapidly at about 1300 ± 10 Ma. Dikes and chilled margins of anorthosite, leuconorite, and leucotroctolite (CI = 10–20) are relatively common within the Nain complex and appear to be associated only with the younger and least deformed of the anorthositic plutons; a few have been described previously and interpreted as possible liquids (Wiebe, 1979, 1980). The recent discovery of several other occurrences has extended the range of known compositions and reopened the question of how closely they approach liquid compositions. In addition to the occurrences described previously (Tunungayualuk Island, Kheovik, and Uivakh—Wiebe, 1979, 1980) several anorthositic dikes have been found on Paul Island, cutting both anorthositic rocks and metamorphic basement near the eastern margin of the Paul Island intrusion (see below), and several thin dikes cut various igneous units within and around the Tigalak layered intrusion (Wiebe and Wild, 1983) (Fig. 1). These dikes range between 2 and 50 cm thick.

Petrography

The dikes typically have plagioclase grain sizes between 0.5 and 2 mm and generally lack chilled margins. Coarser-grained dikes commonly show crystal-deformation textures. Although some dikes have strongly annealed textures, many retain primary hypidiomorphic textures and display strong compositional zoning in the plagioclase. They typically contain between 80% and 95% plagioclase along with minor interstitial pyroxenes (orthopyroxene, inverted pigeonite, and augite), ilmenite, magnetite, and apatite. Many dikes contain a few percent of interstitial alkali feldspar and quartz and traces of biotite. In some, plagioclase crystals have one or two patches of alkali feldspar too large to represent exsolution; as in some mafic hybrid rocks (Wiebe, 1988b), these patches may represent relicts of alkali feldspar xenocrysts. Interstitial pyroxenes and oxides commonly contain many small (0.1 to 0.5 mm) randomly oriented plagioclase crystals.

The dikes on Tunungayualuk Island have exceptionally pristine textures that are similar in style to most other unannealed dikes and preserve strong zoning in the plagioclase (Wiebe, 1979, Plate 2). Reconnaissance microprobe studies demonstrated a minimum zoning range from An_{55} to An_{35}. Plagioclase has irregular cores (An_{55-50}) with patches of more sodic plagioclase and small inclusions of most phases found in the interstitial areas. These patches appear to truncate zoning in the cores and hence probably formed by infilling after an episode of resorption; inclusions of other phases in these patches probably crystallized from trapped liquid (Vance, 1965). Broad rims and patches typically range from An_{45} to An_{35}.

Geochemistry

Chemical analyses and partial norms of anorthositic dikes are given in Table 1. The dikes typically have between 80% and 95% normative plagioclase. They vary widely in normative An and in trace-element abundances. Their widely scattered occurrences suggest that much of their variation is due to local processes such as generation from distinct batches of magma, fractionation, and contamination. Although dikes from the different areas are compositionally distinct, taken as a whole, they form a relatively coherent group that shows $100[Mg/(Mg + Fe_T)]$ and normative An decreasing together (Fig. 2); olivine-bearing dikes (leucotroctolites) typically have higher normative An and $100[Mg/(Mg + Fe_T)]$. Within leuconoritic dikes, the distribution of interstitial mafic silicate and oxide minerals is commonly very irregular so that individual samples from the same dike may show wide variation in $100[Mg/(Mg + Fe_T)]$ with essentially constant An (Fig. 2). Those dikes with $100[Mg/(Mg + Fe_T)]$ values less than 20 contain from 0% to 0.33% MgO; their low $100[Mg/(Mg + Fe_T)]$ values are probably caused by the very low $100[Mg/(Mg + Fe_T)]$ values of plagioclase. The overall trend in Figure 2 suggests that cotectic crystallization of plagioclase and a mafic phase played a role in producing the variation even though the dike compositions are far removed from any cotectic. The entire group of dikes also tends to have Sr/Ca increasing with decreasing normative An (Fig. 3). If the dikes are related through fractionation of similar magmas, this increase in Sr/Ca

TABLE 1. Chemical compositions and partial norms of anorthositic dikes from the Nain complex

	Leucotroctolitic dikes*				Leuconoritic dikes*									
Specimen:	B-73	P-114C	B-161B	B-152	8-7A	B-20	B-80	P-53	P-48L	P-48K	P-48M	4716	4717	4718
SiO_2	47.77	49.32	47.14	50.45	52.92	54.42	52.80	55.50	54.27	55.34	57.81	55.21	51.85	56.89
TiO_2	0.08	0.20	0.12	0.09	0.13	0.09	0.17	0.11	0.10	0.08	0.09	0.06	0.11	0.04
Al_2O_3	18.93	20.37	23.43	25.07	21.96	21.60	22.46	23.17	23.51	24.61	25.55	24.97	23.05	25.06
Fe_2O_3	1.30	5.18	0.55	0.06	1.09	1.06	1.64	0.21	2.15	0.02	0.19	0.80	3.87	0.05
FeO	9.10	5.32	5.72	3.98	4.36	2.94	2.89	3.04	2.10	2.09	0.62	1.21	1.79	0.54
MnO	0.12	0.11	0.08	0.05	0.08	0.08	0.07	0.07	0.05	0.04	0.01	0.04	0.12	0.00
MgO	10.74	8.43	8.59	5.50	4.54	3.16	6.07	1.72	1.23	1.25	0.39	1.39	4.19	0.12
CaO	8.04	8.77	11.09	11.00	9.45	10.07	9.37	8.10	8.49	9.42	8.23	9.72	10.09	8.72
Na_2O	2.94	2.51	2.05	3.35	3.84	4.68	3.39	5.62	5.85	5.42	6.05	5.02	3.43	5.84
K_2O	0.26	0.20	0.13	0.19	0.26	0.43	0.24	0.58	0.26	0.50	0.84	0.16	0.19	0.28
P_2O_5	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.48	0.00	0.34	0.02	0.03	0.02	0.03
LOI	1.07	0.66	0.40	0.88	1.12	0.79	0.71	0.60	0.75	0.56	0.83	0.62	0.69	0.55
Total	100.38	101.10	99.32	100.64	99.76	99.41	99.82	99.20	98.76	99.67	100.63	99.23	99.40	98.12
Trace elements (ppm)														
Rb	dl	dl	dl	dl	dl	dl	dl	13	dl	dl	5	dl	3	5
Sr	498	466	355	433	806	624	574	551	415	511	906	360	265	760
Ba	177	136	103	109	176	454	148	277	136	185	544	87	64	209
V	20	81	23	12	70	36	48	34	26	23	12	21	53	7
Ni	184	105	191	112	30	60	47	13	8	13	10	18	41	4
Plag**	62.6	65.4	72.9	84.9	81.9	80.9	81.4	88.5	90.0	91.0	96.4	89.8	78.1	94.7
An†	58.8	65.9	75.0	63.1	55.2	46.5	60.1	41.6	42.1	45.9	41.6	51.0	60.9	44.7
Mg#§	65.1	60.1	71.1	69.2	60.3	59.0	71.2	48.7	35.2	51.4	46.8	56.2	58.6	26.8

	Tunungayualuk Island									Tigalak area				
Specimen:	500B	500C	500D	500G	715A	715B	718A	718B	719A	1022A	1022C	1184	1528	1563
SiO_2	56.13	56.31	55.54	55.02	55.18	54.38	56.47	56.46	55.05	57.15	54.38	58.49	54.43	55.60
TiO_2	0.53	0.36	0.50	0.18	0.80	0.97	0.54	0.48	0.53	0.26	0.26	0.17	0.12	0.74
Al_2O_3	23.42	24.43	23.81	26.44	21.42	22.32	23.65	24.31	23.18	26.09	27.47	24.89	26.31	24.24
Fe_2O_3	0.86	0.88	0.89	0.36	1.91	2.26	1.63	1.30	1.61	0.50	0.80	0.38	0.38	2.01
FeO	2.86	1.19	2.54	0.90	4.09	3.83	1.59	1.83	2.90	0.94	0.75	0.77	1.08	2.09
MnO	0.05	0.02	0.05	0.01	0.09	0.08	0.03	0.03	0.06	0.00	0.00	0.01	0.03	0.04
MgO	1.17	0.10	0.93	0.00	1.72	1.22	0.33	0.33	0.91	0.05	0.03	0.04	0.88	0.58
CaO	9.52	8.84	9.23	9.74	9.43	9.02	8.54	8.74	9.51	8.43	10.30	7.53	11.26	8.28
Na_2O	4.72	5.39	5.06	5.47	4.62	4.84	5.09	5.36	5.09	6.06	5.56	6.84	5.21	5.67
K_2O	0.89	1.04	0.88	0.76	0.73	0.75	0.92	0.90	0.82	0.49	0.38	0.40	0.13	1.01
P_2O_5	0.19	0.22	0.18	0.08	0.15	0.13	0.20	0.16	0.23	0.01	0.03	0.07	0.08	0.08
LOI	0.36	0.43	0.43	0.80	0.59	0.70	0.34	0.35	0.51	0.36	0.27	0.21	0.14	0.36
Total	00.70	99.21	100.04	99.76	100.73	00.50	99.33	100.25	100.40	100.34	100.23	99.80	100.05	100.70
Trace elements (ppm)														
Rb	16	14	7	3	6	8	12	8	31	dl	dl	dl	dl	5
Sr	495	522	514	592	538	529	558	564	537	974	635	869	443	770
Ba	420	480	447	396	403	412	454	460	432	798	186	533	87	990
V	35	15	27	8	87	99	33	27	29	20	312	5	32	67
Ni	24	19	20	15	32	28	13	13	27	9	dl	3	16	14
Plag**	85.0	92.3	88.0	96.4	78.8	82.9	88.4	90.4	86.0	96.0	95.7	96.7	91.9	91.4
An†	47.0	43.2	45.2	47.5	45.0	44.9	44.5	43.9	44.2	43.5	51.1	37.4	52.3	41.1
Mg#§	36.5	8.2	33.2	0.0	34.5	27.0	16.1	16.4	27.2	6.0	3.5	6.0	52.4	21.0

Note: dl = less than detection limit.
* Paul Island.
** Plag = An + Ab + Or (weight normative).
† An = 100[An/(An + Ab + Or)] (weight normative).
§ Mg# = 100[Mg/(Mg + Fe_T)] (cation).

suggests the influence of clinopyroxene fractionation at some stage in their evolution.

The degree of local homogeneity varies in different areas. The Tunungayualuk dikes, which form relatively tight groups in Figures 2 and 3, were sampled in an area less than 200 m in diameter. In contrast, several small dikes from a single outcrop in the eastern contact zone of the Paul Island intrusion vary widely in normative An. Dikes sampled in widely scattered outcrops from the Tigalak and Paul Island areas are highly variable in composition. The Tunungayualuk Island dikes have higher concentrations of incompatible elements than dikes from the other areas (Fig. 4) and presumably contained higher proportions of liquid. The Paul Island dikes show an overall increase in K_2O and a decrease in TiO_2 with decreasing normative An that may reflect contamination by granitic melts.

Isotopes

E. C. Simmons (personal communication, 1989) has acquired Sr- and Nd-isotope data that suggest the Tunungayualuk Island dikes are more affected than the nearby

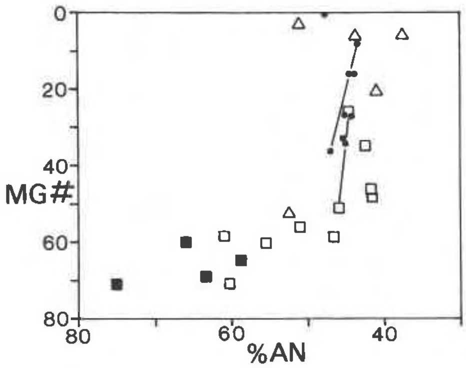

Fig. 2. 100[An/(An + Ab + Or)] (weight normative values; %An) vs. 100[Mg/(Mg + Fe_T)] (cations; Mg#) for anorthosite dikes. Paul Island dikes: solid squares (leuctroctolitic), open squares (leuconoritic). Tunungayualuk Island dikes: small solid circles. Tigalak dikes: open triangles. Tie-lines join samples from the same dikes.

coarse-grained anorthosites by crustal contamination. Initial $^{87}Sr/^{86}Sr$ (t = 1.3 Ga) ranges from 0.7091 to 0.7072 for the dikes and from 0.7059 to 0.7051 for the coarse-grained anorthosites. There is, however, no correlation between initial ratio and the abundance of interstitial quartz and alkali feldspar. The fact that mantle-derived basaltic dikes in the Nain complex, as little as 25 million years younger than the anorthosites, have much lower initial $^{87}Sr/^{86}Sr$ (0.7027 to 0.7031; R. W. Carlson, R. A. Wiebe, and R. I. Kalamarides, manuscript in preparation) lends further support to the importance of crustal contamination in the generation of the Nain anorthosites.

Discussion

The fundamental question relating to the dikes is, How closely do their compositions approach liquid compositions? The nature of the problem can be clarified by using the algorithm of Ghiorso (1985) to model the crystallization of a typical dike from the Tunungayualuk suite as if it were a liquid (Table 2). At the appropriate conditions (listed in Table 2), sample 500B has an anhydrous liquidus temperature of about 1280 °C; the initial plagioclase composition is An_{64}, somewhat more calcic than the most calcic cores in 500B. Fractional crystallization of plagioclase (An_{64-53}), removing about 63% of the original liquid, occurs before a cotectic with clinopyroxene is reached at about 1175 °C. The composition of this calculated cotectic liquid is not basaltic and does not resemble any dikes in the area. As an alternative approach, one can subtract 20% of the original liquid as plagioclase (An_{55}) from 500B and model the crystallization of the remaining liquid (Table 3). This creates an initial liquid that is still anorthositic with a lower liquidus temperature of 1250 °C. This liquid crystallizes about 56% plagioclase before it reaches a cotectic with clinopyroxene at 1175 °C. In this model, only about 35% [$=100 - 20 - (0.8 \times 56)$] of the original 500B composition will remain as liquid when a cotectic with pyroxene is reached.

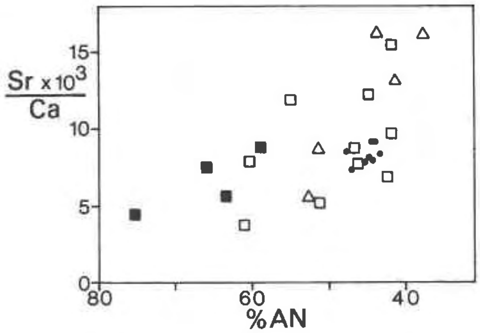

Fig. 3. Weight percent An vs. 1000(Sr/Ca) for all anorthositic dikes. Symbols as in Fig. 2.

The above calculations suggest that if the dikes were injected as cotectic liquids, these liquids must have carried roughly 65% suspended plagioclase crystals. On the basis of the experimental deformation of partially melted granite, van der Molen and Paterson (1979) suggested that magma with as much as 60% to 65% crystals could behave as a crystal-liquid suspension. However, they produced no more than 10% strain in their experiments and suggested that mobility of the mixture is dependent on an increase in the range of grain sizes due to crystal fracturing. Most anorthositic chilled margins and these dikes lack evidence of protoclasis that should be expected had they been emplaced as crystal-rich mushes. In small dikes of magmas carrying even 25% crystals, the wall and Bagnold effects (Marsh and Maxey, 1985) should cause crystal fractionation during flow and produce significant compositional variation. With the exception of dike 500G, which is coarser grained and annealed, the small variation in the Tunungayualuk Island leuconoritic dikes suggests that the intruding magmas carried a relatively small proportion of plagioclase crystals. The fact that REEs are essentially constant (Wiebe, 1980) also suggests that plagioclase fractionation within the dikes was not effective.

The crystallization history of plagioclase within these dikes permits a rough quantitative estimate of the percent of suspended plagioclase at the time of injection. The larger plagioclase crystals have cores that commonly preserve complex oscillatory zoning. These cores subsequently were partially resorbed and then filled in and surrounded by normally zoned plagioclase. The calcic cores almost certainly existed prior to injection; the resorption event, possibly due to mixing of magmas or to reduction of pressure, could have happened either prior to or during injection. In either event, the magma emplaced into the dike most likely consisted of these partially resorbed cores and liquid. Because of complex twinning and the variable sensitivity of extinction angles to composition in different sections, it has not been possible to obtain precise estimates of the modal abundances of these patchy cores. Estimates of their abundance in different thin sections range between 10% and 30%. If 20% is taken as an estimate of suspended plagioclase, it can be seen from the

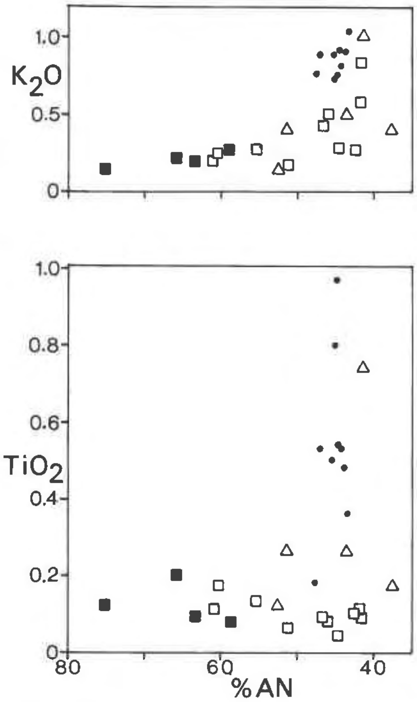

Fig. 4. Weight percent An vs. TiO_2 and K_2O for all anorthositic dikes. Symbols as in Fig. 2.

Table 2. Crystallization of an anorthosite dike (500B) using the model of Ghiorso (1985; SILMIN, version 2)

	Starting liquid*	Ending liquid**
SiO_2	55.94	57.79
TiO_2	0.53	1.42
Al_2O_3	23.34	14.60
Fe_2O_3	0.86	1.53
FeO	2.85	8.18
MnO	0.05	0.13
MgO	1.17	2.98
CaO	9.49	6.99
Na_2O	4.70	3.75
K_2O	0.89	2.11
P_2O_5	0.19	0.51

Note: Conditions during crystallization: oxygen fugacity, QFM; pressure, 3.50 kbar; temperature increment, 5 K. Results: From 1284 to 1280 °C, plagioclase in ($An_{64}Ab_{35}Or_{01}$); from 1179 to 1175 °C, clinopyroxene in ($An_{53}Ab_{46}Or_{01}$; $Wo_{46}En_{43}Fs_{11}$).

* Composition of sample 500B.

** F_L = 37.36%.

model crystallization that about 45% "excess" plagioclase component must have resided in the liquid.

The liquidus temperatures of these hyperfeldspathic liquids may not be unreasonable. Although pure plagioclase liquids surely require excessive temperatures (Lindsley, 1968), the liquidus temperatures (e.g., 1285 °C) of feldspathic liquids similar in composition to the leuconorite dikes may be approachable and would be significantly lowered if 10% to 30% plagioclase was suspended. Evidence of high temperatures for anorthosite-producing liquids is provided by lower-crustal noritic nodules thought to be related to the Nain anorthosites: they appear to have crystallized at temperatures well in excess of 1250 °C (Wiebe, 1986).

The Paul Island intrusion

Geologic setting and petrography

Paul Island is located in the middle of the coastal section of the Nain anorthositic complex (Fig. 1). It provides a representative section, roughly 20 by 10 km in area, through a composite anorthositic intrusion that apparently extends several kilometers to the north, west, and south (Fig. 5). This part of the intrusion can be subdivided into five major units, four of which define a section roughly 10 km thick consisting, from bottom to top, of a lower leuconorite unit (LLN), a mafic layered lens previously named the Bridges layered intrusion (BLI), a dominantly leucotroctolitic unit (LTR), and an upper leuconorite (ULN) (Fig. 6). Field studies in 1989 suggest that the BLI is the oldest unit. The LLN appears to have been emplaced diapirically into the BLI and clearly truncates that lens on its northern end (Fig. 5). Cumulus mafic minerals occur only in the BLI and in a few minor troctolitic lenses within the LTR. The two areas of leuconoritic rocks occurring to the north and east of this section have been tentatively grouped together as the northern leuconorite (NLN). In the northwestern area, these rocks were emplaced diapirically into the LLN after the deposition of the BLI. Leuconoritic rocks in the northeastern area of the NLN are sharply cut by the LTR.

The eastern intrusive contact of the Paul Island anorthosites with metamorphic country rock is well exposed. Fine-grained noritic rocks occur as a marginal phase of the NLN along most of its contact with the basement; their widely varying 100[Mg/(Mg + Fe_T)] values suggest that they represent residual differentiates rather than parental magmas. Along this portion of the contact, anorthositic dikes are common in the adjacent country rock. Farther south, where the higher-level ULN unit comes into contact with the country rock (Fig. 5), fine-grained anorthositic rocks occur along the contact and as irregular dikes and veins in the country rock, locally producing migmatites with anorthositic rather than granitic veins.

The LLN is dominantly anorthosite and leuconorite (CI = 0–15). Cumulus mafic minerals are absent. Plagioclase is typically 1–5 cm, commonly iridescent (pale blue, rarely greenish blue), and weakly zoned. Lamination is common; modal layering is scarce and, where present, typically weak and discontinuous. Scarce cross-cutting noritic veins that probably formed from residual liquid commonly have a weak mineral foliation oblique to the vein walls and parallel to the lamination in adjacent rocks. The occurrence of this fabric suggests that some compaction may have occurred. Structures developed near the contact with the NLN indicate slumping and soft-sediment deformation of LLN plagioclase cumulates. The LLN contains locally abundant inclusions of coarse-grained anorthosite and associated high-Al orthopyrox-

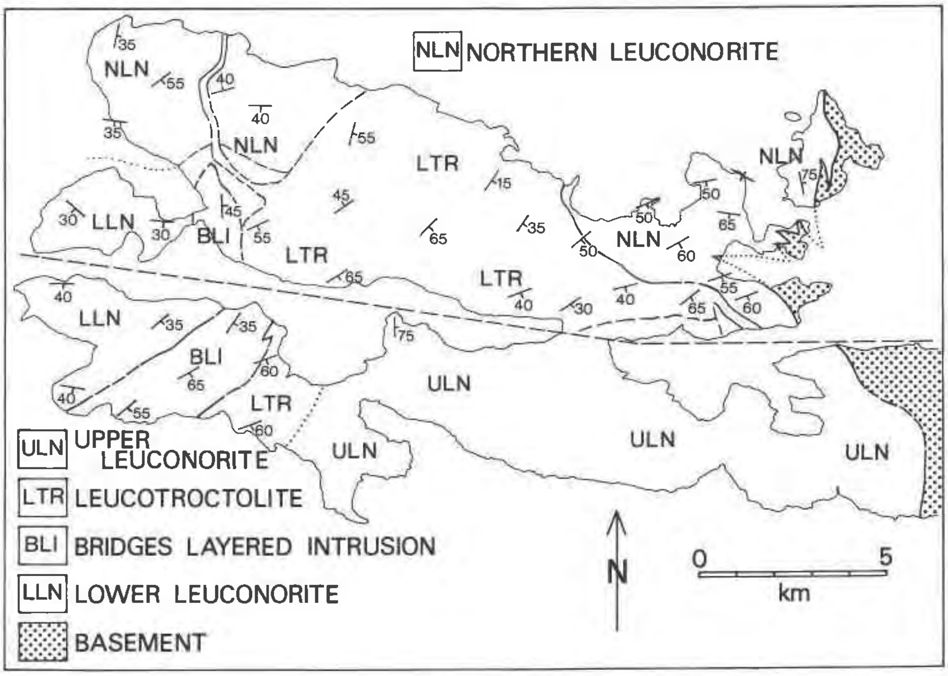

Fig. 5. Geologic map of the Paul Island intrusion.

ene megacrysts with exsolved plagioclase lamellae (HAOM).

The BLI is a relatively fine-grained, strongly layered mafic lens about 1.5 km thick and at least 8 km long. It is dominated by cumulus olivine, augite, and plagioclase. Modal layering and slump structures are nearly ubiquitous. The BLI has an abrupt lower depositional contact with the underlying LLN, and it appears to grade upward to the overlying LTR by veining and interlayering of coarse-grained anorthositic rocks with decreasing proportions of well-layered mafic cumulates. This anorthositic material probably represents injections into the BLI.

Table 3. Crystallization of an anorthosite dike (500B) after removal of 20% plagioclase (An_{55}) using the model of Ghiorso (1985; SILMIN, version 2)

	Starting liquid*	Ending liquid**
SiO_2	56.30	57.55
TiO_2	0.64	1.45
Al_2O_3	22.07	14.57
Fe_2O_3	1.00	1.56
FeO	3.54	8.43
MnO	0.06	0.14
MgO	1.45	3.06
CaO	9.04	7.01
Na_2O	4.65	3.63
K_2O	1.01	2.06
P_2O_5	0.24	0.54

Note: Conditions during crystallization: oxygen fugacity, QFM; pressure, 3.5 kbar; temperature increment, 5 K. Results: From 1269 to 1265 °C: plagioclase in ($An_{60}Ab_{39}Or_{01}$); from 1179 to 1175 °C: clinopyroxene in ($An_{51}Ab_{48}Or_{01}$; $Wo_{46}En_{44}Fs_{11}$).

* Composition of sample 500B, less 20% An_{55}.

** F_L = 44.19%.

The LTR unit consists dominantly of olivine-bearing anorthosite with subordinate leucotroctolite and has an average CI of about 10–15. Except for minor lenses with cumulus olivine in its upper half, plagioclase is the only cumulus phase. Along its western contact with the NLN, field relations appear to indicate an irregular to gradational contact with the underlying NLN. Because plagioclase is the only cumulus phase near this contact, the boundary can be mapped only on the basis of an upward change from interstitial orthopyroxene to interstitial olivine. A large troctolitic dike, possibly a feeder for the LTR, passes upward through the LLN and the NLN and disappears at the base of the LTR (Fig. 5). The LTR is clearly transgressive to the eastern area of NLN.

Rocks in the upper half of the LTR are characterized by many lenses and layers up to tens of meters thick and up to a few kilometers long of modally graded olivine-plagioclase cumulates intercalated with massive to weakly laminated olivine-bearing anorthosite. Olivine-rich layers show increases in normative An content and $100[Mg/(Mg + Fe_T)]$ and, hence, appear to represent episodes of replenishment. At many levels in the LTR there is abundant evidence for soft-sediment deformation and redeposition of plagioclase cumulate material. The LTR grades upward through olivine- and orthopyroxene-bearing massive anorthosites to the overlying ULN.

The ULN consists of massive, coarse-grained anorthositic rocks with about 15% interstitial orthopyroxene, augite, ilmenite, magnetite, apatite, and scarce alkali feldspar and quartz. It differs from the other units in lacking layering, lamination, and slump structures. This unit is characterized by 15% to 25% of complexly zoned seriate

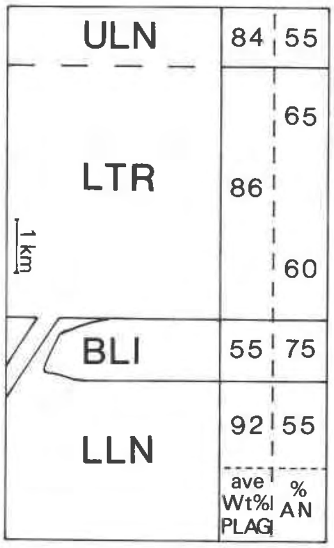

Fig. 6. Schematic cross section of the Paul Island intrusion. Average weight percent plagioclase = averages of the sums of weight normative An + Ab + Or for all samples analyzed in each unit. Number of samples: LLN (25), BLI (42), LTR (38), ULN (25). Normative An is based on similar averages of 100[An/(An + Ab + Or)].

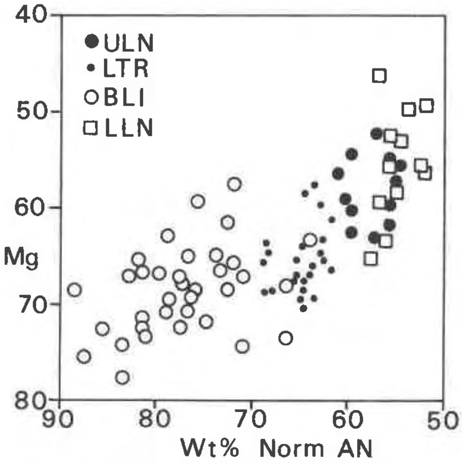

Fig. 7. 100[Mg/(Mg + Fe$_T$)] vs. normative An (defined in Fig. 2) of representative samples from the Paul Island intrusion.

plagioclase phenocrysts up to 20 cm long. These phenocrysts are iridescent, and variably colored zones typically show up to three major cycles of normal zoning separated by abrupt reversals of 10% to 15% normative An that commonly truncate inner zones and record episodes of partial resorption of the plagioclase. A few percent of similar crystals occur within the upper portions of the LTR. At its highest-level exposures and near its southeastern contact with metamorphic country rock, the ULN contains many blocks, up to tens of meters in diameter, of fine-grained anorthosite and leuconorite (CI = 5–20). Similar rocks form a discrete intrusive facies along the contact with metamorphic country rocks and also occur as dikes and veins within the country rock. Some blocks of fine-grained anorthositic rocks up to several kilometers from the exposed contact are composite and include portions of basic granulite. These blocks were probably spalled from the chamber roof and suggest that ULN formed near the top of the chamber.

Geochemistry

Whole-rock XRF analyses have been used to estimate the compositions of the anorthositic rocks because their coarse grain size and very irregular distribution of interstitial phases make it impractical to obtain valid compositional estimates from modal data. Representative analyses are given in Table 4. The data shown in Figure 7 provide a relatively complete view of the compositional ranges of the units in terms of normative An and 100[Mg/(Mg + Fe$_T$)]. The LLN and the ULN are compositionally similar, but there is little overlap between the other units. Differences between all units can be seen clearly in the compositions of plagioclase mineral separates (Fig. 8). Overall, Sr increases rather strongly as CaO decreases in plagioclase. Plagioclases from the LLN have distinctly higher Sr.

Figure 9 shows the compositional variation of plagioclase separates within a section through the Paul Island intrusion. The significance of small variations in composition is doubtful because mineral separates must consist of different proportions of cumulus plagioclase and intercumulus overgrowths. In spite of field relations that support a gradational depositional transition from LTR to ULN, there appears to be a relatively abrupt change in composition and the occurrence of one sample with abnormally low Sr.

Some significant variation can be seen within units. Beneath the BLI, the LLN contains an unusually large proportion of intercumulus material, and plagioclase from the uppermost samples is significantly lower in An and Sr. The LTR shows an overall upward increase in An and an apparent decrease in Sr that probably reflects the periodic replenishment episodes in the LTR.

High-Al orthopyroxene megacrysts (HAOM) in inclusions within the LLN have compositions similar to HAOM reported from other areas (Table 5). Although some workers believe similar megacrysts in other intrusions have crystallized at the level of final emplacement (Morse, 1975; Dymek and Gromet, 1984), the occurrences of HAOM here are more consistent with the view that they crystallized at depth and were carried up in partly crystallized anorthositic magmas (Emslie, 1975; Wiebe, 1986). The fact that plagioclase from both the inclusions and the host LLN has comparable An and Sr suggests that the inclusions represent early-crystallized material from the LLN magma.

There is a wide variety of dikes on Paul Island, and their locations and thicknesses strongly suggested in the field that some were feeders for various replenishments recorded in the cumulate stratigraphy on Paul Island. Of

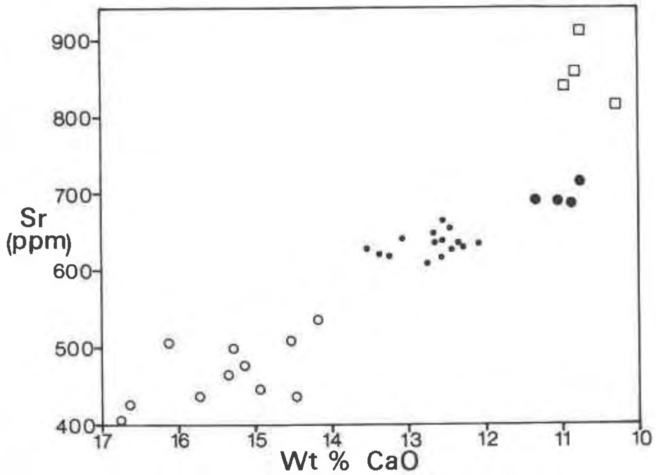

Fig. 8. CaO (wt%) vs. Sr (ppm) for representative samples of plagioclase separates from the Paul Island intrusion. Symbols as in Fig. 7.

the anorthositic and troctolitic dikes analyzed to date (see Table 1), many have compositional characteristics (e.g., normative An, Sr, Ba) that suggest a close relationship to some anorthositic and leucotroctolitic cumulates. On the basis of their major- and trace-element compositions, two leuconoritic dikes (8-7A and B-80) may approximate liquids related to the LLN and the NLN. Compositional variation within the large LTR-related dike suggests extensive olivine accumulation. In terms of low incompatible elements and the near-absence of interstitial augite, samples from this and other troctolitic dikes appear to be cumulates. Anorthositic dikes (mainly seen and sampled within the country rock) vary widely in their percent of plagioclase and in normative An content. Erratic variations in incompatible elements suggest variable contamination from metamorphic country rock or crustal melts.

Crystallization of the LTR and ULN units of the Paul Island intrusion

The LTR appears to have formed by accumulation of crystals on the floor of an actively convecting magma chamber. The widespread occurrence of slump structures within this unit indicates that much of the material was initially deposited on oversteepened slopes that were, or

Table 4. Representative analyses of rocks from the Paul Island intrusion

	LLN		BLI		LTR		ULN	
	4	51	8	22B	33	125	184	189
SiO_2	53.45	53.66	48.13	45.89	50.30	49.12	52.46	53.66
TiO_2	0.22	0.10	0.20	0.40	0.11	0.11	0.31	0.19
Al_2O_3	24.11	26.84	17.73	5.64	23.77	25.26	22.31	24.50
Fe_2O_3	0.62	0.81	1.23	2.39	2.22	1.20	1.18	1.13
FeO	3.01	0.82	3.82	10.20	2.85	3.42	3.93	2.45
MnO	0.06	0.02	0.09	0.21	0.07	0.05	0.08	0.06
MgO	2.50	1.23	9.58	18.48	5.46	5.48	3.42	2.86
CaO	9.76	10.62	16.28	14.41	10.40	11.28	9.79	10.15
Na_2O	4.49	4.71	1.04	0.28	3.20	2.99	3.80	4.30
K_2O	0.45	0.37	0.00	0.00	0.24	0.18	0.38	0.44
P_2O_5	0.03	0.03	0.02	0.01	0.02	0.02	0.03	0.03
LOI	0.88	0.73	1.29	1.62	0.82	0.84	0.82	0.28
Total	99.58	99.94	99.41	99.53	99.46	99.72	98.51	100.05
Trace elements (ppm)								
Sr	746	798	268	64	553	520	599	603
Ba	306	222	21	19	148	120	252	230
V	32	7	108	213	16	10	38	24
Ni	19	16	197	349	85	138	33	27
Plag*	88.2	94.1	52.4	15.5	82.2	81.8	82.5	88.5
An†	52.1	54.8	83.2	85.6	63.6	67.6	55.4	54.3
Mg#§	55.6	58.4	77.6	72.7	66.8	68.5	55.0	59.5

* Plag = An + Ab + Or (weight normative).
† An = 100[An/(An + Ab + Or)] (weight normative).
§ Mg# = 100[Mg/(Mg + Fe_T)] (cation).

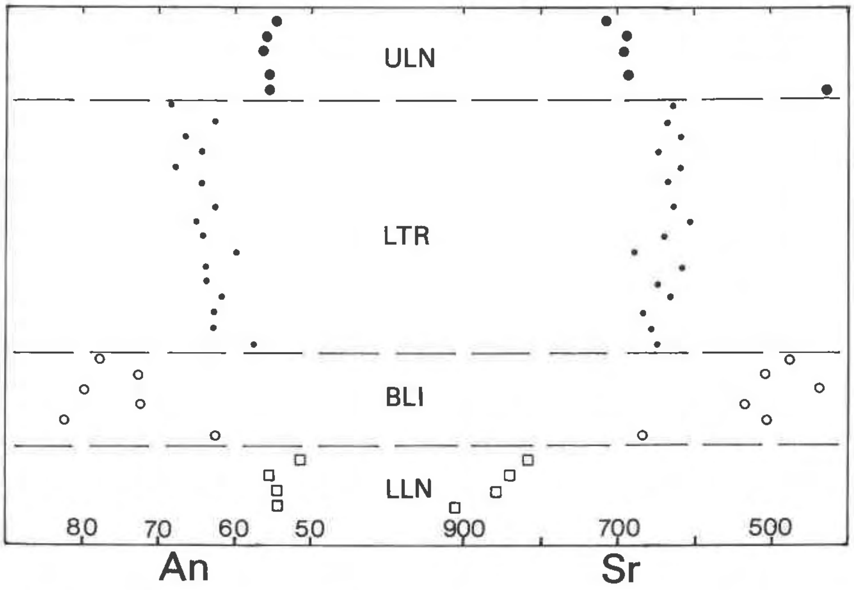

Fig. 9. Variation in An (wt%) vs. Sr (ppm) in plagioclase separates from a representative section through the Paul Island intrusion. Vertical distance between samples is only approximate. Symbols as in Fig. 7.

became, unstable. The cumulates of the LTR represent several replenishments of troctolitic or olivine-bearing anorthositic magma into a floored chamber. Some of the later replenishments led to local and temporary accumulation of olivine, but cumulus olivine consistently disappears upward, and rocks grade back to massive anorthosites and leuconorites that lack any cumulus mafic phases. These relationships strongly suggest that both resident magma (even after extensive plagioclase crystallization) and new magma emplaced into the chamber were hyperfeldspathic in character. Short-lived olivine accumulation might be related to strong supercooling of new magma on entry or crystallization of a portion of the new magma prior to mixing of the rest of the new magma with resident magma.

The ULN represents the highest major unit beneath an apparent roof of basic granulite. This upper contact is marked by the occurrence of finer-grained varieties of massive anorthosite and leuconorite. The complex zoning of plagioclase phenocrysts in the ULN records several episodes of normal growth interrupted by episodes of resorption and abrupt reversals in An content similar to those recorded in volcanic plagioclase (Nixon and Pearce, 1987). These phenocrysts must have remained suspended within a convecting magma chamber during episodes of replenishment by hotter magma. Because of the stratigraphic position and compositions of these phenocrysts, it is likely that their zoning records replenishment events seen in the underlying LTR. The periodic resorption recorded by these crystals may have enhanced or at least maintained the hyperfeldspathic character of resident magma near the top of the chamber. Continued crystallization of this magma within the upper part of the chamber led to convective stagnation beneath the chamber roof well before the onset of pyroxene nucleation and growth and produced the characteristic poikilitic texture of the massive ULN.

The correlation of resorption events in the complexly zoned phenocrysts of the ULN with at least some of the replenishment events in the underlying LTR floor cumulates is the major reason for asserting that the magma chamber that produced these units was capable of convection and stirring during replenishment events and was not simply a stagnant mush. The existence of an actively convecting magma chamber is also consistent with the clear evidence for bottom accumulation and periodic slumping of the floor cumulates.

TABLE 5. Analyses of high-Al orthopyroxene megacrysts

	1	2	3	4	5
SiO_2	50.10	49.72	50.04	49.19	50.04
TiO_2	0.55	0.45	0.70	0.62	0.52
Al_2O_3	4.67	7.25	5.20	7.28	6.17
FeO_T	18.15	15.34	18.20	16.45	15.85
MnO	0.29	0.25	0.24	0.28	0.30
MgO	22.72	23.35	23.99	22.48	24.92
CaO	1.78	2.33	1.38	2.15	1.78
Na_2O	0.04	0.09	0.10	0.29	0.04
K_2O	0.01	0.01	—	0.02	—
P_2O_5	0.01	0.01	—	0.01	—
LOI	1.34	1.14	—		—
Total	99.66	99.94	99.85	98.77	99.58
Cr	933	1291	616	547	1026
Mg#*	69.3	73.3	70.1	70.9	73.9

Note: Columns are as follows: (1) Paul Island—LLN; specimen 5. (2) Paul Island—LLN; specimen 57. (3) Dymek and Gromet (1984, Table 6, no. 3). (4) Emslie (1975, Table 2, no. 3). (5) Wiebe (1986, Table 1, no. 3).
* Mg# = 100[Mg/(Mg + Fe_T)].

Implications for liquid compositions

The fact that plagioclase remained the only cumulus phase throughout cycles of magma-chamber replenishment provides a strong argument for the existence of hyperfeldspathic liquids. This is true even though the actual volume of the chamber at any time can not be determined. Undoubtedly, "parental" liquids emplaced into the chamber lay within the plagioclase field; the question is how far within the field did they lie? Continued fractionation of plagioclase must have caused resident liquid to become more mafic and its density to increase (Sparks and Huppert, 1984) so that new replenishments of "parental" liquids were less dense than resident liquid and formed plumes that rose toward the top of the chamber (Turner and Campbell, 1986). Relatively thorough mixing was likely because viscosities were probably similar (Huppert et al., 1986), but if mixing were incomplete, a stratified magma chamber could have developed temporarily with cooler, more mafic resident magma beneath hotter, more feldspathic magma. If the chamber were stratified, crystallization of plagioclase and cooling within the upper magma would increase its density and probably lead to homogenization of the chamber (Turner and Campbell, 1986). If this analysis is correct, then resident liquids cannot be expelled from the chamber (at least not from its top), and, eventually, mafic cumulates should form on the chamber floor—as is seen in intrusions like the Bjerkrem-Sogndal lopolith (Duchesne, 1972).

Emslie (1980), recognizing the significance of bottom accumulation in massif-type anorthosites, has suggested that resident magmas nearing saturation in a mafic phase could be expelled during replenishment of anorthositic chambers by liquids residing barely in the plagioclase field, thereby maintaining plagioclase as the only cumulus phase. Replenishment by light inputs should, however, hinder expulsion of relatively mafic resident magma and eventually force saturation in a mafic phase. The general absence of mafic floor cumulates between the LTR and the ULN, which appears to have been deposited beneath the chamber roof, indicates that resident liquids within the Paul Island magma chamber continued to lie well within the plagioclase field even after extensive crystallization of plagioclase and that "parental" liquids emplaced into the chamber must also have been hyperfeldspathic.

The composition of the ULN can provide a rough estimate of liquid composition at a late stage in the crystallization. This unit appears to have evolved into a stagnant mush in the upper part of an anorthositic magma chamber (beneath a roof of country rock containing basic granulite). The complexly zoned plagioclase phenocrysts, however, record an earlier stage of convective mixing. If crystal suspension by convection ceased when the magma became about 25% crystallized (the approximate volume percent of the zoned phenocrysts), and if the remaining liquid was retained within the unit (as field relations suggest), then subtraction of 25% plagioclase from the average composition of the ULN approximates a late liquid in the chamber. The average of 22 ULN samples contains 84% plagioclase; subtraction of 25% plagioclase leaves 59% plagioclase component and 16% other components in the remaining 75% liquid. This normalizes to a liquid that still has nearly 80% plagioclase component and clearly lies well within the plagioclase field. Even if stagnation did not occur until after 50% crystallization, the remaining liquid would still have had nearly 70% plagioclase component.

DISCUSSION

Anorthositic dikes throughout the Nain complex and the anorthositic rocks of the Paul Island intrusion appear to require the existence of liquids that contain at least 30% plagioclase in excess of a cotectic with pyroxene. These liquids are not simply parental basalts with excess plagioclase dissolved in them; continued subtraction of plagioclase from them produces liquids that are highly variable in composition, relatively evolved in terms of $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$, and much higher in SiO_2. Trace-element abundances and ratios are also highly variable. The dikes vary widely in terms of normative An and show an increase rather than a decrease in Sr with decreasing An. The $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$ value decreases along with normative An. In the Nain complex, most anorthositic rocks analyzed to date have Sr-isotope ratios that suggest some involvement of crustal melts; the few anorthositic dikes analyzed to date have exceptionally high $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$. These characteristics of the highly feldspathic liquids require a complex origin that probably involves all of the following: (1) open-system fractional crystallization of different batches of magmas within different chambers, (2) remelting of plagioclase, and (3) crustal contamination.

These three processes clearly operate even at the level of final emplacement—roughly 3.5 kbar in this part of the Nain complex (Berg, 1977, 1979). Different massif-type anorthosite plutons in the Nain complex have different geochemical signatures that require the existence of different batches of magma (Wiebe, 1978), and the Paul Island intrusion, described here, demonstrates open-system behavior. Complexly zoned plagioclase phenocrysts of the ULN remained suspended within an actively convecting, periodically replenished magma chamber; their zoning demonstrates that they underwent multiple episodes of resorption, most probably in that chamber, and the stratigraphy of the LTR provides a record of multiple replenishment. Partial melting of the metamorphic country rock is common along the margins of the large anorthositic plutons, and some of these locally generated granitic liquids have mixed into partially crystallized anorthositic magma in the contact zones (Wiebe, 1978).

Although these processes do operate in the middle to upper crust, they should be much more effective at greater depth. At the level of emplacement observed in the Nain complex, their effectiveness must be limited because of relatively rapid heat loss and crystallization of the anorthositic magmas. Another reason to suspect a deeper origin is the lack of evidence at the final level of emplacement for the cotectic crystallization implied by sympathetic variation in $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$ and normative An and by the increase of Sr with decreasing normative An. For these reasons, it is most likely that the dominant characteristics of the highly feldspathic liquids originated in magma chambers near the base of the crust. It is noteworthy that only the younger plutons appear to require the involvement of hyperfeldspathic liquids. Protoclastic deformation, consistent with emplacement of crystal-rich mushes, is much more common in the older plutons.

MODEL FOR THE GENERATION OF ANORTHOSITIC LIQUIDS

1. Assume that basaltic to picritic magmas pond at the base of the crust and fractionate olivine and pyroxenes in a manner similar to that described by Emslie (1978, 1985). Extensive fractionation produces ultramafic floor cumulates and drives the resident liquid to lower $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$ and higher Al. This fractionation is strongly suggested by the relatively low $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$ values of nearly all magmas associated with massif-type anorthosites. The maximum $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$ in anorthosites and in lower-crustal nodules thought to be related to the anorthosites (Wiebe, 1986) is about 75. Because the most magnesian orthopyroxenes are in equilibrium with intermediate plagioclase, the low $100[\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe_T})]$ value is much more likely to reflect fractional crystallization than an unusually Fe-rich mantle source as suggested by Morse (1982). When the cotectic with plagioclase is reached, the liquid will be somewhat richer in plagioclase components than it would have been at low pressures (Emslie, 1971).

2. Plagioclase (of intermediate composition at this depth) will begin to crystallize along with the mafic phases and should float readily in basaltic magma at the base of the crust (Kushiro, 1980). The effect of high pressure in shifting the equilibrium composition of plagioclase toward albite (Green, 1969) removes the need to hypothesize the presence of large volumes of liquids having very low An that would have been in equilibrium with An_{50} plagioclase at low pressures.

3. If the ponded chamber is long lived, then there should be many replenishment events, each of which could cause some remelting of earlier-formed plagioclase crystals suspended within the chamber. Through time, there could evolve a stratified magma chamber in which the uppermost liquids become enriched in plagioclase components (become hyperfeldspathic) and still contain suspended plagioclase crystals. Similar resorption of plagioclase on a much smaller scale also has been suggested to explain the increasing Sr contents of evolved ocean-ridge basalts (Flower, 1984; Elthon, 1984); resorption is likely to be more effective in a chamber at depth beneath a stable craton because heat would be lost from the chamber much more slowly.

4. When hyperfeldspathic, evolved magmas with suspended plagioclase move upward from these lower-crustal chambers, they will initially lose heat relatively rapidly, heating the crust they pass through and crystallizing more plagioclase. Because of extensive crystallization, these intrusions may eventually rise mainly as diapiric mushes. Nonetheless, because the magmas are apparently low in H_2O, a decrease in pressure will lower the liquidus temperature of the magma. If very little heat is lost to the crust from the rising anorthositic magmas, some of the suspended plagioclase could melt during upward movement and cause the liquid to become even more hyperfeldspathic. Although early intrusions would tend to crystallize during upward movement, later ones will probably follow previously heated paths, rise more rapidly, and may more nearly approach an adiabatic path that would permit melting of some suspended plagioclase. These later intrusions are also more likely to be contaminated by granitic melts derived from the crust. This model is supported by the fact that only the younger plutons appear to require the existence of hyperfeldspathic liquids.

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