UPPER MANTLE COMPOSITION BENEATH THE EASTERN BERING SEA

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ABSTRACT

Pyroxene granulites and fine-grained, granuloblastic equant lherzolites occur together in alkalic basalts from Nunivak Island, Alaska. The granulites are mafic to ultramafic in composition, with low abundances of incompatible elements, positive Eu anomalies and isotopic (Sr and Nd) ratios similar to MORB. The geochemistry of these inclusions is consistent with a plagioclase-olivine cumulate as a protolith. The lherzolites are Mg-rich but fertile with respect to basaltic components, with LREE/HREE $<$ chondrites, and Sr and Nd isotopic ratios similar to MORB. A petrogenetic relationship with MORB is inferred for these granuloblastic lherzolites. Their geochemical characteristics distinguish the granuloblastic lherzolites from associated relatively LREE-enriched, coarse-grained metasomatized peridotites. We infer that beneath Nunivak Island oceanic lithosphere has been extended and intruded by asthenospheric diapirs; the granulites and coarse peridotites are derived from the former domain and the granuloblastic equant peridotites from the latter.

INTRODUCTION

Nunivak Island is a predominantly basaltic island, 90 x 70 km, located 50 km west of the Yukon delta on the Alaskan coast and 600 km north of the Aleutian trench. The island is largely composed of Cenozoic basalts ranging in age from 6.2 to 0.9 Ma (Hoare et al., 1968; ages recalculated following Steiger and Jager, 1977). Thus the volcanic rocks are part of the Bering Sea volcanic province described in Moll-Stalcup (1994). The basalts range from tholeiites to basanites and are isotopically similar to mid-ocean ridge basalts (MORB; Menzies and Murthy, 1980; Roden, 1982; Hart, 1988). The youngest alkaline basalts contain a diverse suite of ultramafic and mafic xenoliths (Hoare et al., 1968). Xenolith lithologies include: (1) pyroxene granulites thought to be metamorphosed troctolitic cumulates which equilibrated at temperatures of approximately 950°C and pressures greater than 9 kbar (Francis, 1976a); (2) amphibole pyroxenites with complex textural relations suggesting reaction between anhydrous phases and an aqueous fluid (Francis, 1976b). Trace element and isotopic characteristics of these pyroxenites are consistent with formation as precipitates from an alkaline magma isotopically similar to the host basalts (Roden et al., 1984); and (3) magnesium-rich spinel harzburgites and lherzolites which are divided into coarse and fine-grained types with no transitional lithologies (Francis, 1978). The coarse-grained inclusions commonly contain amphibole or its breakdown products (Francis, 1976c) and were recently ($<$200 Ma) metasomatized (i.e., enriched in incompatible elements) by a fluid or melt probably related to the host basalts (Menzies and Murthy, 1980; Roden et al., 1984).

Here we focus on the petrogenesis of pyroxene granulite and fine-grained spinel lherzolite xenoliths. Specifically, we tested the cumulate model for the origin of the granulites by analyzing certain key trace elements which should show strong correlations with modal proportions of inferred cumulate phases. Isotopic ratios of Sr and Nd were used to infer the nature of the parent magma. We also investigated the petrogenesis of fine-grained lherzolites by determining trace element abundances and isotopic compositions of bulk rocks and clinopyroxene separates. Our data suggest that these inclusions are suitable source materials of MORB and thus have a distinct origin from that of the associated coarse-grained peridotites.

SAMPLE DESCRIPTION

The xenoliths were collected from vents near and including Nanwaksjiak maar near the center of the island. The data of Hoare et al. (1968) indicate that eruptions on this portion of the island are younger than 0.73 Ma. The *pyroxene granulites* are the corona-bearing metamorphic rocksstudied by Francis (1976a). In these inclusions olivine and plagioclase occur but are separated by orthopyroxene mantles and spinel-clinopyroxene symplectites. These coronas record the reaction of primary olivine (Fo_{72-87}) with plagioclase (estimated to be An_{65-73}). Remnants of the primary olivine and plagioclase are commonly preserved as small grains surrounded by the coronas. *Granuloblastic equant lherzolites* are fine-grained, anhydrous rocks characterized by the assemblage spinel + olivine + orthopyroxene + clinopyroxene. The olivine is Mg-rich (Fo_{88-90}), although not as magnesian as olivine in associated coarse-grained peridotites, and the spinel is Cr-poor (Cr/[Cr+Al] $<$ 0.1; Francis, 1978).

RESULTS

Representative data are presented in Tables 1 and 2; more complete data sets are in Roden (1982) and Moll-Stalcup et al., (in preparation). The *pyroxene granulites* are generally poor in incompatible trace elements (e.g., Rb, 0.05-0.15 ppm, Ba, 5-18 ppm; La 0.1-0.9 ppm) and even K (60-489 ppm) is a trace element in these rocks. In contrast, Sr is relatively abundant, 58-340 ppm. The REE element abundances are low and all the granulites have positive Eu anomalies (Fig. 1). Strontium and Nd isotopic compositions are quite unradiogenic and radiogenic respectively (0.7024-0.7026 and 0.51305-0.51314) and thus, similar to those of MORB (Fig. 2).

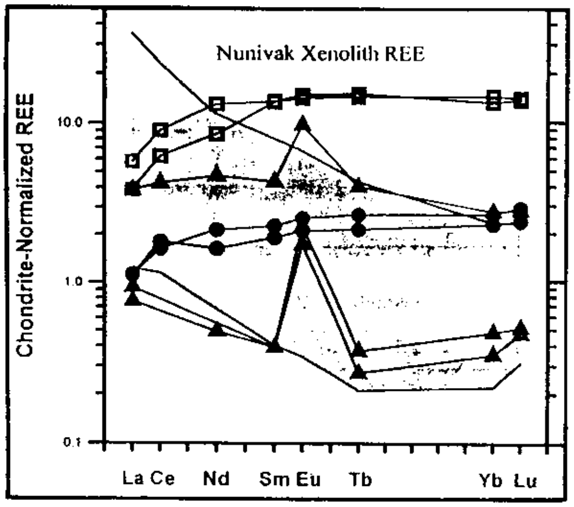

Fig. 1. Chondrite normalized REE paterns (data from Table 1 and Roden, 1982) for pyroxene granulites (triangles), and granuloblastic lherzolite whole rocks (circles) and clinopyroxenes (squares) compared to the range (shaded) of REE abundances in coarse grained peridotites (Roden et al., 1984). Chondrite values from Sun and McDonough (1989).

Although fertile with respect to basaltic components (modal clinopyroxene of the four samples is 11-13%, Table 3), the *granuloblastic-equant lherzolites* are poor in incompatible trace elements: Rb, 0.011-0.11 ppm; Ba, 0.56-1.7 ppm, Sr, 12 - 16 ppm; La, 0.20-0.27 ppm and K is also a trace element in these rocks with abundances of 9-102 ppm. Chondrite-normalized REE patterns are LREE-depleted and similar to those of "normal" MORB but displaced to lower abundances (Fig. 1). No Eu anomalies are present. Mass balance calculations show that most of the Sr and the REE are concentrated in clinopyroxene (Roden, 1982). Thus, the REE patterns of the clinopyroxene are similar to that of the bulk rock but displaced to higher concentrations. Isotopic compositions of the clinopyroxenes ($^{87}Sr/^{86}Sr$ = 0.7020-0.7026 and $^{143}Nd/^{144}Nd$ = 0.51321-0.51330) are similar to those of MORB (Fig. 2).

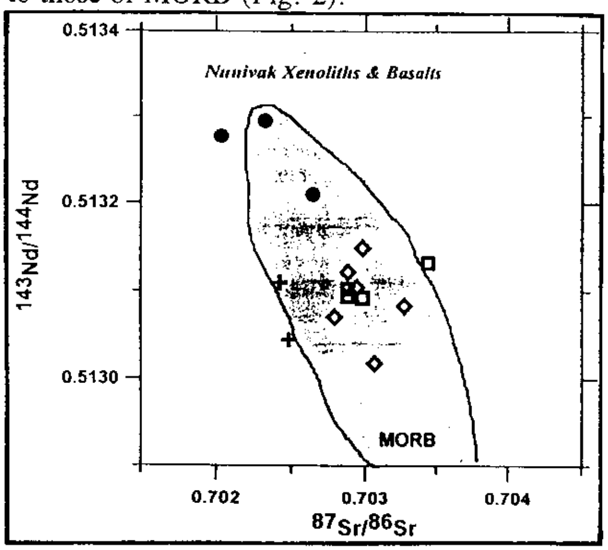

Fig. 2. Nd-Sr isotope correlation diagram for Nunivak xenoliths (circles - clinopyroxenes from granuloblastic lherzolites, crosses - pyroxene granulites, squares - amphibole pyroxenites or clinopyroxenes from coarse grained peridotites) and basalts (diamonds). Data are taken from Table 2, Roden (1982) or Roden et al. (1984). MORB field (shaded) is from Zindler and Hart (1986).

PETROGENESIS

(A) Pyroxene Granulites

Our data substantiate the inference of Francis (1976a) that the original protolith of the granulites were troctolitic cumulates which ranged in lithology from feldspathic dunites through true troctolites to olivine gabbros. Furthermore, the isotopic data require a parental magma isotopically similar to modern MORB.

Cumulate xenoliths, or xenoliths that have formed by mechanical separation of crystals from liquids (not necessarily under the force of gravity), are characterized by bulk compositions controlled by cumulate or the physically separated phases. In the case of the Nunivak inclusions, Francis (1976a) inferred that these phases were olivine and plagioclase. If the cumulate model is correct, then there should be correlations between element abundances and inferred modes of cumulate phases (bearing in mind that the current mode reflects metamorphic equilibration). As is shown in Figure 3, elements excluded from olivine (K, Sr, La, Eu, e.g., Henderson, 1984) correlate inversely with the calculated abundance of primary olivine; moreover, Co, which is concentrated in olivine, correlates positively with the calculated amount of primary olivine. Chromium also correlates positively with calculated olivine abundance; although Cr is not strongly partitioned into olivine, olivine commonly coprecipitates with chromite and Francis (1976a) inferred the presence of small amounts of primary spinel in the more Mg-rich samples. Hence, the positive correlation between calculated olivine and Cr content can be plausibly related to coprecipitation of olivine and spinel. Finally, the chondrite-normalized REE patterns of the granulites (Fig. 2) are unlike any magmatic liquid or sedimentary rock; however, the patterns are similar to those predicted for and observed in plagioclase-rich cumulate rocks (e.g., Hanson, 1980; Simmons and Hanson, 1978). The large positive Eu anomaly and low REE abundances strongly support the cumulate interpretation because both olivine and plagioclase exclude the REE exception for the preferential incorporation of Eu in plagioclase.

Table 1. Trace Element Abundances (ppm) of Representative Samples

Sample	12000	12013	10070	10070	10068	10068
Lithology	PG	PG	GE	GE cpx	GE	GE cpx
K	489	111	9.01	28.8	16.5	22.0
Rb	0.154	-	0.011	0.021	0.107	0.0603
Cs	0.0045	-	0.0006	0.0045	0.013	0.0081
Ba	17.7	5.10	0.834	-	0.559	0.37
Sr	338	136	15.8	93.2	12.9	72.2
La	0.91	0.18	0.267	1.37	0.26	0.92
Ce	2.6	-	0.99	5.5	1.1	3.8
Nd	2.2	0.23*	0.99	6.1	0.76	4.0
Sm	0.66	0.060*	0.345	2.07	0.29	2.05
Eu	0.56	0.10	0.146	0.859	0.121	0.823
Tb	0.15	0.010	0.099	0.56	0.080	0.54
Yb	0.47	0.060	0.455	2.26	0.39	2.46
Lu	0.071	0.012	0.074	0.35	0.061	0.36
Sc	20.5	4.93	15.9	-	16.0	-
Cr	415	1460	2370	-	2799	-
Co	29.0	112	112	-	110	-

Note: PG = Pyroxene Granulites, GE = Granuloblastic Equant Lherzolites, cpx = clinopyroxene
K, Rb, Cs, Ba and Sr concentrations measured by isotope dilution; REE elements measured by radiochemical neutron activation; Sc, Cr and Co measured by instrumental neutron activation; further discussion can be found in Roden et al., 1984.
*Measured by isotope dilution

Table 2. Isotopic Compositions of Representative Samples

Sample	12000	12013	10070	10070	10068
Lithology	PG	PG	GE	GEcpx	GEcpx
$^{87}Rb/^{86}Sr$	0.00132	$\leq$ 0.0035	0.0020	0.00066	0.00242
$^{87}Sr/^{86}Sr$	0.70242	0.70248	0.70262	0.70264	0.70232
$^{147}Sm/^{144}Nd$	0.205	0.156	-	0.245	0.257
$^{143}Nd/^{144}Nd$	0.51311	0.51305	-	0.51321	0.51330

Note: PG = Pyroxene Granulite; GE = Granuloblastic Equant Lherzolite; cpx = clinopyroxene
All parent-daughter ratios calculated from concentrations measured by isotope dilution; Sr and Nd isotopic ratios reported relative to Eimer and Amend = 0.70800 and BCR-1 = 0.51264 respectively. Further analytical details can be found in Roden et al., 1984

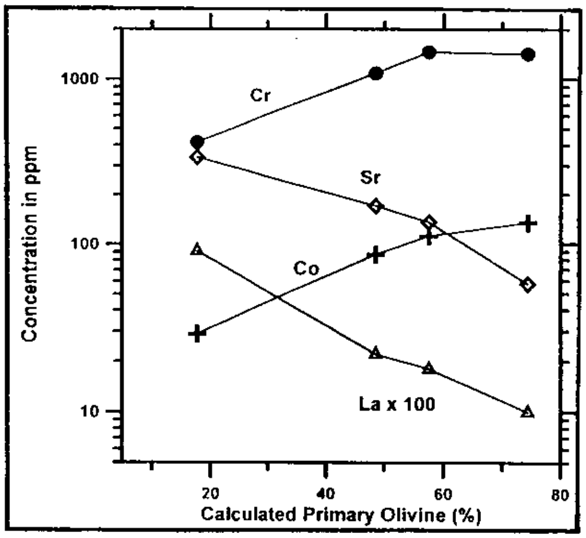

Fig. 3. Concentrations of trace elements in pyroxene granulites plotted versus calculated primary olivine. Data are from Table 1 or Roden (1982); olivine abundances are from Francis (1976a).

The isotopic compositions of the granulites constrain the composition of the parent magma provided that the isotopic and parent/daughter element ratios have not been affected by processes such as metasomatism subsequent to precipitation. The systematic correlations of trace element abundances with the inferred abundance of primary phases supports the assumption that elemental abundances have not been disturbed by metamorphism or during entrainment in and ascent of the host magma. In particular the systematic behavior of K (Fig. 3), an element which normally is very mobile, strongly supports closed system behavior of the xenoliths. Strontium isotopic ratios are very unradiogenic, and the very low $^{87}Rb/^{86}Sr$ ratios (<0.004) require that the present-day $^{87}Sr/^{86}Sr$ ratios of the xenoliths are essentially indistinguishable from the isotopic ratio of the parental magma. Two samples analyzed for Sm-Nd have nearly identical $^{143}Nd/^{144}Nd$ ratios (0.51311 and 0.51305) but quite distinct $^{147}Sm/^{144}Nd$ ratios (0.205 and 0.156). Given closed system behavior, these latter data constrain the age of crystallization to be younger than approximately 0.4 Ma (Roden, 1982). The relatively low $^{87}Sr/^{86}Sr$ ratios preclude precipitation from the host magmas (Fig. 2). Modelling of the in-situ growth of ^{87}Sr and ^{143}Nd in the granulites over the last 0.5 Ma (Roden, 1982) shows that the parent magma was isotopically similar to MORB. Moreover, the inferred primary cumulate phases in the xenoliths, olivine and plagioclase, are identical with those found as phenocrysts in MORB (e.g., Basaltic Volcanism Study Project, 1981). Thus, we conclude that the pyroxene granulites formed by crystal segregation from a parental magma similar to MORB. These xenoliths are probably accidental fragments from oceanic lithosphere beneath Nunivak Island.

Table 3. Modal Abundances of Representative Samples

Pyroxene Granulites		
Inferred Primary Mode*	12000	12013
olivine	17.6	57.4
plagioclase	70.6	36.6
clinopyroxene	11.9	5.6
spinel	0.0	0.4

Granuloblastic Equant Lherzolites		
Measured Mode	10068	10070
olivine	52	57
orthopyroxene	35	27
clinopyroxene	11	13
spinel	2.1	2.9

* from Francis (1976a)

(B) Granuloblastic-equant lherzolites

Key characteristics of the granuloblastic equant inclusions are (1) LREE/HREE ratios less than chondrites, (2) Sr and Nd isotopic compositions similar to MORB, and (3) very low abundances of incompatible elements (e.g., K, Ba, Rb) normally excluded from the four constituent phases, spinel, olivine, clinopyroxene and orthopyroxene. The granuloblastic inclusions from Nunivak are similar to the "primitive" inclusions recognized by Jagoutz et al. (1979) which occur throughout the world in alkaline basalts (e.g., Roden et al., 1988). The LREE depletion combined with low $^{8}7S^{r/86}Sr$ and high $^{14}3N^{d/}144Nd$ link these inclusions to "normal" MORB (e.g., Sun and McDonough, 1989). Melting of lherzolite in the upper mantle preferentially consumes the phases, clinopyroxene or clinopyroxene and garnet (e.g., Baker and Stolper, 1994; Takahashi, 1986), in which the REE are concentrated. Thus a melt produced from a granuloblastic lherzolite will be LREE-depleted and isotopically similar to MORB; however, the elements K, Rb and Ba must be concentrated in the melt by other means. The worldwide distribution of such "primitive" inclusions, their petrogenetic and compositional links to MORB and their source in the upper mantle suggests that they are samples of the convecting upper mantle. Moreover their common occurrence in alkaline basalts of extensional provinces supports models in which Nunivak volcanism is related to extension (Moll-Stalcup, 1994).

(C) Conceptual Model for the Lower Crust and Upper Mantle

Figure 4 is a sketch of possible lithologic domains in the crust and upper mantle beneath Nunivak Island. The relationships are deduced from the geochemical characteristics of the xenoliths. The lack of transitional peridotite lithologies between the coarse-grained and fine-grained peridotites suggests that these inclusions are derived from distinct domains juxtaposed in the upper mantle. We portray these domains as oceanic lithosphere intruded by asthenospheric diapirs - an expected relationship in a rifting environment. The oceanic nature of the lithosphere is inferred from the inferred geochemistry of the protoliths of the pyroxene granulites (Fig. 4). These protoliths are presumed to be derived from layered cumulates in the lower crust or upper mantle. Based on the geochemical similarity to convecting upper mantle, the source of the fine grained lherzolites is inferred to be in the asthenospheric diapirs. Although the source of the coarse-grained, metasomatized inclusions is not well constrained by their geochemistry, we place them in the oceanic lithosphere due to their refractory nature (e.g., Francis, 1978). In this environment, these inclusions were metasomatized by melts or fluids that were isotopically similar to the host basalts (Fig. 2). Amphibole pyroxenites crosscut these coarse-grained peridotites and are also isotopically similar to the peridotites and the basalts (Francis, 1976b; Roden et al., 1984). These data suggest a close petrogenetic relationship between the coarse lherzolites, the pyroxenites, and the basalts. We show a relationship in which basalts have intruded the coarse peridotites, precipitated pyroxene-rich lithologies on conduit walls, and equilibrated with the wall rock (Roden et al., 1984). Subsequent entrainment of conduit walls and wall rock in the basalts resulted in an assemblage of basalt, coarse peridotite, and amphibole pyroxenite, all of which are in (or nearly in) isotopic equilibrium.

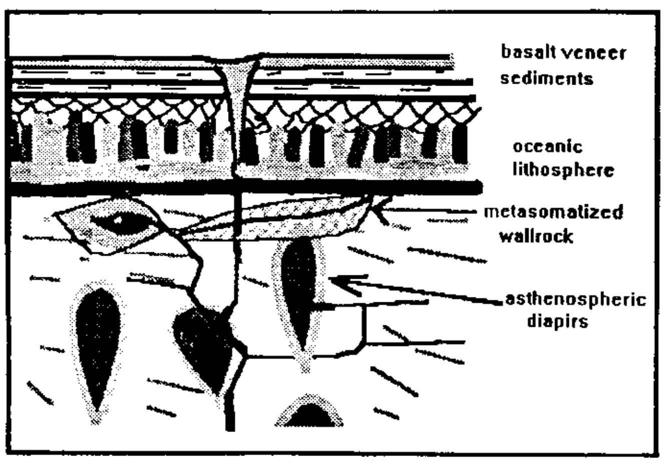

Fig. 4. Sketch of inferred lithologic relationships in the approximately upper 60 km of crust and upper mantle beneath Nunivak Island.

The ultimate source of the basalts must be at least as deep as the included spinel lherzolites. However, these basalts have the relatively high La/Yb ratios (Roden, 1982) consistent with the presence of residual garnet in their source region. Thus, the basalts are derived from greater depths than any of the included rocks.

CONCLUSIONS

Pyroxene granulites and fine-grained, granuloblastic equant lherzolite xenoliths from Nunivak Island, Alaska, are petrogenetically related to normal MORB. Based on their major and trace element chemistry, mineralogy and isotopic composition we infer that the former xenoliths are olivine- to plagioclase-rich cumulates (or crystal segregations) from a magma identical to or very similar to MORB, and that the latter inclusions are potential source materials for MORB. Although both inclusion types are MORB-related according to our model, they are derived from distinct domains. The granulites as well as coarse-grained peridotites discussed elsewhere

(Francis, 1978; Roden et al., 1984) are fragments from oceanic lithosphere beneath the island. This lithosphere was rifted and intruded by asthenospheric diapirs of granuloblastic lherzolite. During the course of the volcanism, magmas intruded, metasomatized and equilibrated with the coarse peridotites of the shallow lithosphere. As a consequence, these coarse peridotites, crosscutting amphibole pyroxenites which precipitated from the alkaline magmas, and the host basalts are isotopically similar.

The intimate intermingling of distinct mantle domains is probably common beneath continental rifts; sampling of these domains by the alkaline lavas typical of such rifts can lead to lithologically heterogeneous xenolith populations such as at Nunivak Island.

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