EVOLUTION OF SUB-CONTINTENTAL MANTLE AND CRUST: ECLOGITES FROM SOUTHERN AFRICA

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INTRODUCTION

Eclogites are essentially bimineralic garnet + clinopyroxene rocks with basaltic bulk compositions that crystallized (or re-crystallized) at relatively high pressures in the lower crust or upper mantle. Eclogites with omphachitic pyroxene and Ca, Fe-rich garnet found in blueschist terranes are thought to represent metamorphosed oceanic crust. In contrast, eclogite xenoliths in kimberlites and alkali basalts are more magnesian and are generally interpreted as high pressure cumulates that form dikes within the upper mantle. Eclogites that occur in kimberlites vary greatly in texture, mineral compositions, and isotopic characteristics, however, and there is increasing evidence that some of these nodules may also represent metamorphosed oceanic crust. In order to distinguish between these contrasting hypotheses, we have selected a suite of six African eclogites, from the collections of Dr. F.R. Boyd, for detailed petrologic, trace element, and isotopic study.

PETROLOGY AND GEOCHEMISTRY OF THE ECLOGITES

Petrography: The six eclogite xenoliths chosen are from four African kimberlites: three from Bellsbank (FRB-437-1, 438-2, 438-7), and one each from Kao, Lesotho (PHN-1850), Deutsche Erde, Namibia (DE-15), Vale do Queve, Angola (FRB-340). All consist of subequal proportions of garnet and clinopyroxene, with traces of rutile and phlogopite. FRB-437 samples also contain olivine (Fo92) and enstatite (En 95); FRB-340 contains plagioclase (An15) and sanidine (Or40-60). All have coarse granular or granoblastic textures.

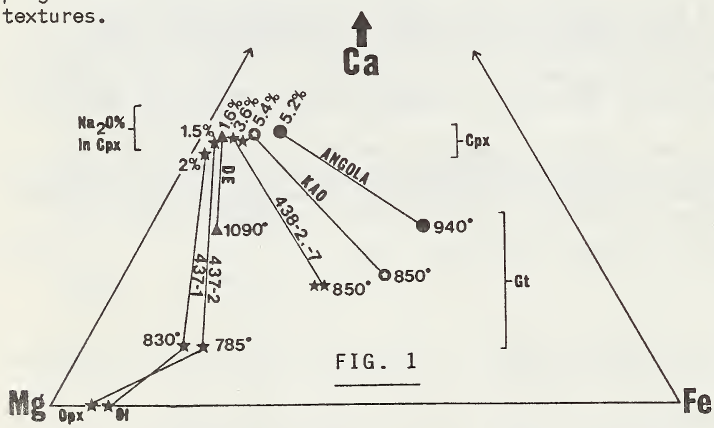

FIG. 1

Mineral Chemistry: Three groups of eclogite are recognized from major element compositions. Group A (Kao and Angola): High Fe/Mg ratios in both pyroxene and garnet (Pyroxene MG# = 77-84, Garnet MG#s = 36-46), K_D's of 5-6, and jadeite-rich pyroxene ($Na_2O \cong 5.5\%$); Group B (438-1, 438-7): Intermediate Fe/Mg ratios (Pyroxene MG# = 86-89, Garnet MG# = 57-59), K_D's of 4.8-5.8, moderate jadeite contents in pyroxene ($Na_2O \cong 3.75\%$); Group C (437-1,2; DE-15): Low Fe/Mg ratios (Pyroxene MG# = 95.0-95.5, Olivine Fo 92.5, Garnet MG# = 79-83), K_D's of 3.5-5.0, and jadeite-poor pyroxene (Na20 ≅ 1-2%). These relationships are illustrated in Figure 1. The Trace element analyses by INAA of hand-picked mineral separates support the three groups defined above by major element chemistry and provide further constraints on their origin (Fig. 2). The most LREE-enriched pyroxenes are those of Group C, with Ce/Tb ratios of 600-1200 (30-70 x chondrite). Pyroxenes from the Group A and Group B eclogites have Ce/Tb ratios which range from 9-90 (0.5-5.3 x chondrite). Group A garnets have flat or slightly postive HREE slopes that turn down at Sm (Yb/Sm = 0.7-2.2 x chondrite) and distinct positive Eu anomalies (Figure 2). These characteristics strongly suggest recrystallization of a plagioclase enriched protolith. Group B garnets feature extreme depletion of the LREE and enrichment of the HREE (Yb/Sm = 50-60 x chondrite) which suggest a refractory origin for the Group B eclogites. Group C garnets have intermediate characteristics and feature smooth positive slopes from La to Yb (Yb/Sm = 3-7 x chondrite).

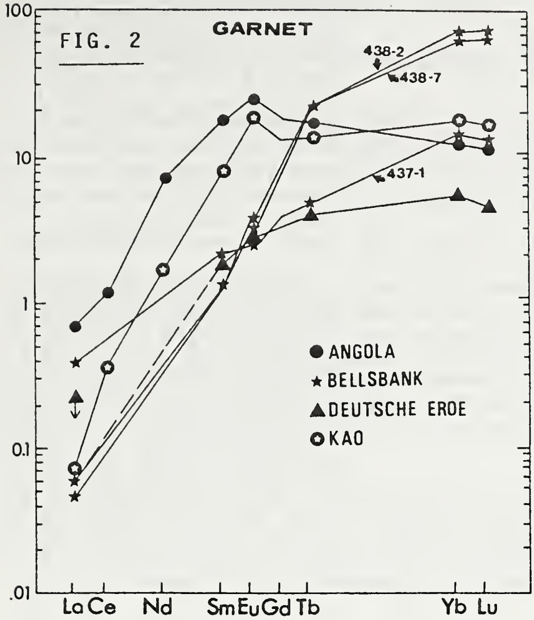

FIG. 2

Whole Rock Geochemistry: All of the eclogites studied here are approximately "basaltic" in the sense that they contain 45-51% SiO_2; however, only the Group A eclogites could represent realistic liquid compositions. The other eclogites are too low in TiO_2, and too high in CaO (DE), MgO (437-1,2), or MG# (=100*Mg/[Mg+Fe]). Concentrations of the REE in whole rock samples of eclogite have been determined by modal recombination. The Group A eclogites have REE concentrations similar to `normal' depleted MORB, but with a large positive Eu anomaly (Figure 3). This suggests that the Group A eclogites had anorthositic protoliths (Jagoutz et al 1985). The Group B eclogites and 437-1 have HREE slopes that are dominated by garnet and LREE enrichments that reflect modal pyroxene. DE-15-1 has a relatively unfractionated REE pattern with concentrations 2-3x chondrite.

Isotope Geochemistry: The results of our isotopic analyses are presented in Table 1. The Group B and C eclogites define a whole rock error-chron of 2.4 b.y. with an initial ϵ Nd of +28. If these eclogites formed at this time, their precursor was already highly differentiated (LREE depleted). De-coupling of the Sr and Nd systems is evident in the Group B eclogites. The high $^{87}Sr/^{86}Sr$ and low ϵ Nd of these eclogites suggests hydrothermal exchange with a seawater. The isotopic composition of oxygen in the eclogites studied here is listed in Table 1. These data suggest that hydrothermal exchange with seawater is a required in the petrogenetic history of the Group B eclogites and that this process may have affected the progenitors of the Group A and Group C eclogites as well.

DISCUSSION

The data presented in the preceeding sections show that the eclogites studied here can be divided into three distinct groups based on the major element composition of their silicate phases. We have shown further that these distinctions are supported by (a) whole rock major and trace element data, (b) trace element analyses of the silicate phases, (c) the isotopic composition of Sr and Nd in garnet and pyroxene, and (d) the isotopic composition of oxygen in the same phases. The petrologic and geochemical characteristics of these groups are:

Group A (Kao and Angola): Group A eclogites are characterized by high Fe/Mg ratios (MG#s = 77-84 Cpx; 36-46 Gt; 62-76 whole rock), jadeite-rich pyroxene ($Na_2O \cong 5.5\%$), extremely low Cr_2O_3 (< 0.1%), variable ϵ Nd (-16 to +24) and $^{87}Sr/^{86}Sr$ (0.704-0.707), $\delta^{18}O$ = +4 to +6, and positive Eu anomalies in garnet and possibly pyroxene; Plagioclase and sanidine may be present.

Group B (438-1,438-7): Group B eclogites are characterized by moderate to low Fe/Mg ratios (MG#s = 86-89 Cpx; 57-59 Gt; 79-82 whole rock), moderately jadeite-rich pyroxene ($Na_2O \cong 3.75\%$), extremely low Cr_2O_3 (< 0.1%), high ϵ Nd (+100 to +250) and $^{87}Sr/^{86}Sr$ (0.709-0.710), $\delta^{18}O$ = +3 to +3.4, and extremely LREE-depleted/HREE-enriched garnets with no Eu anomalies.

Group C (437-1,437-2,DE-15-1): Group C eclogites are characterized by very low Fe/Mg ratios

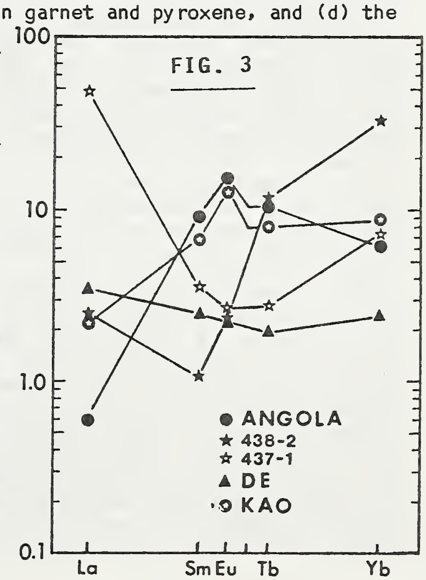

FIG. 3

TABLE 1. Isotopic Data for African Eclogites.

Type	Sample	Phase	Sm ppm	Nd ppm	$^{143}Nd/^{144}Nd$	ϵ Nd	$^{87}Sr/^{86}Sr$	$\delta^{18}O$
"A"	KAO	Cpx	1.148	4.6820	0.512761	3.80	0.704264	4.72
		Gt*	1.351	1.1070	0.513781	23.70	----	4.12
		Gt**	1.543	1.2500	0.513421	16.68	----	4.03
"A"	Angola	Cpx	0.1736	0.6157	0.511771	-15.51	0.707376	---
		Gt	3.1160	4.659	0.512665	1.93	----	6.07
"B"	438-2	Cpx	0.1945	0.4380	0.518733	120.32	0.709359	3.42
		Gt	0.2257	0.1174	0.518923	124.02	----	3.25
"B"	438-7	Cpx	0.201	0.2410	0.524274	228.42	0.710022	---
		Gt	0.2137	0.0557	0.525428	250.93	----	3.04
"C"	437-1	Cpx	1.4660	22.140	0.511594	-18.96	0.704197	5.25
		Gt	0.3596	0.8358	0.512008	-10.89	----	5.02
"C"	DE	Cpx	0.5841	4.240	0.512853	5.60	0.703326	4.87
		Gt	0.3309	0.385	0.513382	15.92	----	4.76

* Garnet with rutile exsolution.
** Garnet without rutile exsolution.

(MG#s = 95-96 Cpx,Opx; 92-93 Ol; 79-83 Gt; 91-94 whole rock), low jadeite pyroxene ($Na_2O \cong$ 1-2%), Cr_2O_3 = 0.1-1.0% bulk, low ϵ Nd (-20 to +16) and $^{87}Sr/^{86}Sr$ (0.7033-0.7042), $\delta^{18}O$ = +4.7 to +5.3, and extremely LREE-enriched pyroxene. Olivine and enstatite are commonly present, Eu anomalies are absent.

The Group A and Group B eclogites defined here correlate well with the Roberts Victor Type A and Type B eclogites, resp., described by Jagoutz _et al_ (1985) -- the similarity in our terminology is intentional. The close similarity between the groups defined here and correlative eclogite types from the Roberts Victor kimberlite suggests that these eclogites formed by the same processes. The areal distribution of these eclogite groups -- from Angola in the North to Lesotho in the South) supports the hypothesis that these groups are fundemental petrologic units that have widespread petrogenetic significance.

PETROGENESIS

The Group A eclogites are the most easily interpreted. The positive Eu anomaly that is superimposed on both the garnet and pyroxene REE patterns is characteristic of plagioclase accumulation and requires an anorthositic protolith for these eclogites. The re-constructed whole rock REE patterns are similar to normal MORB, with flat HREE-MREE at approximately 10x chondrite and slightly depleted LREE (Figure 3). A Positive Eu anomaly is also superimposed on these whole rock patterns. The $^{87}Sr/^{86}Sr$ ratios are consistent with the ϵ Nd (-1.3 to +7.0) and lie on or near the trend of ocean island basalts in a Sr-Nd correlation diagram.Both eclogites contain jadeite-rich pyroxene, consistent with a "spilitized" protolith.We conclude that the Group A eclogites represent anorthositic ocean crust, as proposed by Jagoutz _et al_ (1985) for Roberts Victor Type A eclogites. Our analyses suggest that anorthositic gabbro is the most likely protolith. The felsic portion of the crust contains less water than the overlying basaltic portion and is less affected by dehydration and partial melting.

The Group B eclogites are characterized by extremely depleted LREE and C Nd values 10x to 20x MORB. The high $^{87}Sr/^{86}Sr$ of these eclogites is not consistent with their strongly depleted LREE and high C Nd, and cannot be a primary feature of the protolith. Similarly,the extremely low $\delta^{18}O$ of the Group B eclogites cannot form by mantle fractionation processes. Both the low $\delta^{18}O$ and high $^{87}Sr/^{86}Sr$ are consistent with high temperature seawater alteration of a basaltic protolith.The low concentrations of incompatible trace elements in the whole rocks and the extreme LREE- depleted/HREE-enriched character of the garnets, are most consistent with a refractory origin for the Group B eclogites. Because of its high water content, the mafic portion of the oceanic crust will be affected more strongly by dehydration and partial melting than the less hydrous felsic poriton (= Group A eclogites).

The Group C eclogites are the only eclogites studied here whose geochemical characteristics are consistent with an origin as cumulate dike rocks in the upper mantle. They have high MG#s that are similar to the refractory peridotites thought to comprise most of the upper mantle, low concentrations of incompatible elements, and Sr-Nd systematics that are similar to ocean island basalts. The reconstructed REE patterns for these eclogites are consistent with the accumulation of pyroxene and garnet in these dikes, along with minor trapped liquid, and the values for K_{Sm} and K_{Nd} are consistent empirical pyroxene/garnet partition coefficients. The slightly low $\delta^{18}O$ values in these eclogites are inherited from the source region of the partial melts, which may correspond to the subducted ocean crust that formed eclogites of Groups A and B.

Reference: Jagoutz E., Dawson J., Hoernes S., Spettel B.,Wänke H. 1985. Anonthositic oceanic crust in the Archean Earth. The Early Earth, LPI Tech Rept. 85-01, 40-41.