

# ECLOGITES WITH OCEANIC CRUSTAL AND MANTLE SIGNATURES FROM THE BELLSBANK KIMBERLITE, SOUTH AFRICA, PART I: MINERALOGY, PETROGRAPHY, AND WHOLE ROCK CHEMISTRY<sup>1</sup>

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## ABSTRACT

Three groups of eclogite xenoliths have been identified from the DeBruyn and Martin Mine of the Bellsbank kimberlite, South Africa. These eclogites are divided into the three groups on the basis of petrography, clinopyroxene and garnet mineral chemistry, and rare earth element (REE) contents of the whole rocks, clinopyroxenes, and garnets. Abundances of the REE and garnet-clinopyroxene Kd's are consistent with a petrogenesis by fractional crystallization for Group A eclogites, but not Groups B and C. We suggest, on the basis of bulk-rock major-element and REE analyses and reconstructed REE patterns, that eclogites from Groups B and C are the metamorphosed products of ancient subducted oceanic crust. Group B eclogites have major element chemistry similar to Archean basalts, and Group C eclogites have high  $Al_2O_3$  abundances. Metasomatism has affected all groups of eclogites, producing phlogopite, feldspar, amphibole, and a breakdown of primary clinopyroxene. On the basis of large ion lithophile (LIL) elements, this metasomatism can be traced to the host kimberlite. Our study demonstrates that petrogenesis by fractional crystallization cannot account for all eclogite xenolith compositions found in kimberlite.

## INTRODUCTION

The origin of eclogite xenoliths in kimberlites and alkali basalts is at present the subject of much controversy. Eclogites are garnet + clinopyroxene rocks generally with basaltic bulk compositions that crystallized (or re-crystallized) at relatively high pressures in the lower crust or upper mantle. Kyanite, rutile, orthopyroxene, plagioclase, and amphibole are common accessory phases (Coleman et al. 1965). Eclogites with omphacitic pyroxene and Ca-, Fe-rich garnet found in *blueschist terranes*, are considered to represent metamorphosed oceanic crust (Coleman et al. 1965). In fact, basaltic material is converted to eclogite at pressures >10 kb (e.g., Yoder and Tilley 1962; Wyllie 1971; Ringwood 1975).

In contrast to those found in blueschist terranes, most eclogite xenoliths in kimberlites and alkali basalts are more magnesian and vary greatly in texture, mineral compositions, and isotopic characteristics. There are three contrasting petrogeneses proposed for these "mantle-derived" eclogites: (1) as high-pressure igneous cumulates (garnet pyroxenites) that formed as dikes within the upper

mantle (O'Hara and Yoder 1967; MacGregor and Carter 1970; Hatton 1978; Smyth and Caporuscio 1984; Smyth et al. 1984); (2) as the metamorphic products of a subducted oceanic crustal protolith (Helmstaedt and Doig 1975; Helmstaedt and Schulze 1979; Ater et al. 1984; Jagoutz et al. 1984; Haggerty 1986; Schulze 1986; MacGregor and Manton 1986; Shervais et al. 1985, 1986, 1988); and (3) as relicts of the earth's primary differentiation shortly after accretion (Anderson 1981a, 1981b; McCulloch 1982, 1987).

The present investigation is based on the premise that differences in the progenitors (i.e., crustal vs. mantle) can impart eclogites with various distinguishing characteristics. The goal of this paper is to characterize kimberlitic eclogites in order to determine their petrogenesis.

## PREVIOUS WORK

The theory that some eclogite xenoliths in kimberlite represent metamorphosed oceanic crust—first postulated by Helmstaedt and Doig (1975)—received its first solid support with the isotopic study presented by Jagoutz et al. (1984). As a result of this work, we at the University of Tennessee initiated an investigation of representative suites of eclogite nodules from four kimberlites (Shervais et al. 1985, 1986, 1988), within or on the margins of the Kaapvaal craton (an approximately 3 b.y. old continental nucleus in southern Africa). These kimberlites included

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Deutsche Erde (Gibeon, Namibia); Kao (Lesotho); Vale de Queve (Angola); and Bellsbank (South Africa).

Based on numerous data (isotopes, major and trace elements, and mineral chemistry), these eclogites were divided into three distinct groups (see Shervais et al. 1988), using the mineralogical and chemical classification of eclogites by Coleman et al. (1965) to be consistent with the three-fold eclogite classification already prevalent in the literature. They were:

*Group A.*—This group is characterized by: low jadeite moles in clinopyroxene, Mg- and Cr-rich garnets, Cr-rich clinopyroxene, high whole-rock MG#’s, and mantle-type  $\delta^{18}\text{O}$  (4.8 to 5.1‰).

*Group B.*—In this group one finds moderate jadeite moles in clinopyroxene, Fe-rich garnets, extremely high  $\epsilon_{\text{Nd}}$  (+120 to 235), LREE-depleted clinopyroxenes, low  $\delta^{18}\text{O}$  (3.0 to 3.3‰), highly radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (0.710), extreme LREE-depleted/HREE-enriched garnets, and low concentrations of incompatible trace elements in the whole-rocks.

*Group C.*—These eclogites are characterized by high jadeite moles in clinopyroxene, CaO-rich garnets, positive Eu anomaly present in REE from both garnet and clinopyroxene, low  $\delta^{18}\text{O}$  (4.3 to 4.9‰), and low REE abundances.

The major-element mineral chemistry of these three eclogite groups is consistent with a petrogenesis by fractionation from an evolving magma. The isotope and REE data, however, are inconsistent with such a petrogenesis. The isotope and REE data from this preliminary study have been tentatively interpreted as being signatures of subducted oceanic crust for the Groups B and C eclogites, with Group A being “true” mantle-cumulate eclogite (Shervais et al. 1988). These conclusions, similar to those from Jagoutz et al. (1984) and MacGregor and Manton (1986), clearly question the long accepted idea of a high-pressure fractionation origin for all mantle-derived eclogites (e.g., O’Hara and Yoder (1967)). However, the tentative conclusions have been based upon samples from widely separate localities in southern Africa. The small number of samples taken from each locality does not rule out the possibility that each of these localities

may have a separate and unique geochemical signature associated with it. With our present limited data base, definitive statements on alternative, possibly crustal origins cannot be made.

#### BELLSBANK ECLOGITES

In order to test the conclusions made in our preliminary study (Shervais et al. 1988), we have concentrated our recent efforts on eclogites from the DeBruyn and Martin Mine at the Bellsbank kimberlite. We have included the three Bellsbank xenoliths reported by Shervais et al. (1988) (437-1, 438-2, 438-7) in our present study. These three samples fall into two groups with mantle and oceanic crustal heritage (i.e., Groups A and B). Because some of the data has already been presented, and the figures eloquently illustrate observed compositional differences, the majority of tables referred to in the text have not been printed. However, these are available upon request from *The Journal of Geology* at no charge. This present paper forms part I of a two-part contribution dealing with mineralogy, petrography, and whole-rock geochemistry. Part 2 involves an analysis of the Sr, Nd, and O isotope results.

A large suite (60) of eclogite xenoliths from the DeBruyn and Martin Mines was assembled through the kind donations of Drs. F. R. Boyd (Geophysical Lab) and P. H. Nixon (University of Leeds). Clinopyroxene and garnet grain mounts of 28 of the megascopically freshest eclogites from the assembled Bellsbank suite were examined by electron microprobe. Of these, polished thin sections were made from nine of the microscopically freshest samples. Based upon this initial mineral chemistry, an attempt was made to pick representatives of the three groups. These samples were also chosen for whole-rock analyses, by XRF and INAA, and for mineral separation of garnet and clinopyroxene. The pervasive effects of *metasomatic enrichment* prior to and/or after entrainment of the xenoliths in the host kimberlite require special measures to distinguish between primary and secondary geochemical characteristics. It was essential that ultrapure garnet and clinopyroxene separates be prepared in order to determine (a) the unadulterated compositions of the primary phases and (b) the contribution to the whole-rock

from any secondary processes, such as metasomatic effects.

The chemistry of the primary minerals (i.e., clinopyroxene and garnet) permits the eclogites to be divided into three groups (c.f., Shervais et al. 1988). Therefore, the clinopyroxene and garnet mineral chemistries will be discussed before the petrography, in order to classify the eclogites into groups. The analytic data of tables 1-3 and 5-7 are on file with *The Journal of Geology*.

#### MAJOR-ELEMENT CHEMISTRY OF PRIMARY MINERALS

The compositions of constituent minerals were determined using a CAMECA SX-50 electron microprobe at the University of Tennessee. Accelerating voltage was 15kV with a filament current of 100uA. Beam current used for all phases was 30nA, except for feldspars and glasses, when 20nA was employed (beam current was measured by a Faraday cup); counting times were 20 seconds. All data were corrected using ZAF procedures.

Both garnets and clinopyroxenes from the nine eclogites studied in detail and homogeneous. There is no substantial core-to-rim or intergrain variation, except where clinopyroxenes have "crinkled" or "spongy" margins (secondary alteration; see Petrography below). Average compositions (from a minimum of 20 individual analyses) of both garnet and clinopyroxene are presented in tables 1 and 2. It is apparent that the garnet compositions exhibit significant variation between samples. We place these into the A, B, and C chemical groups of Coleman et al. (1965), as used in our preliminary studies: (Group A) Mg-rich (up to 21.0% MgO); (Group B) Fe-rich (up to 16.4% FeO); and (Group C) Ca-rich (up to 18.8% CaO) (fig. 1). TiO<sub>2</sub> is present only in small quantities (<0.15 wt %), and groups cannot be distinguished on this basis.

The Na<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub> contents (jadeite mole) of the clinopyroxenes show systematic variance with garnet composition (tables 1 and 2). Three eclogite groups are again defined: (A) low jadeite mole; (B) moderate jadeite mole; and (C) high jadeite mole. Furthermore, Group A clinopyroxenes (table 2) contain the highest MgO and CaO contents (≅ 21 wt % and ≅ 16 wt %, respectively), followed by Group B (18-19 wt % and 12-13

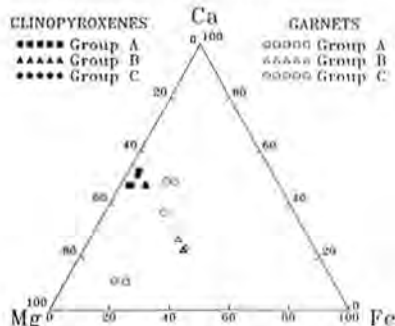


FIG. 1.—Garnet and primary clinopyroxene compositions represented on a Ca, Mg, Fe triangular plot. Note that the garnets most readily distinguish the three eclogite groups in terms of Ca, Mg, and Fe.

wt %, respectively), with Group C containing the lowest MgO and CaO contents (7-8 wt % and 12-13 wt %, respectively). Group B clinopyroxenes contain the highest FeO abundances (≅ 4 wt %), with Group C containing the least (≅ 1 wt %), and Group A clinopyroxenes having intermediate values of ≅ 2 wt % FeO. These compositional variations are shown in figure 1. Group A clinopyroxenes also contain significant amounts of Cr<sub>2</sub>O<sub>3</sub> (0.7-1.3 wt %), unlike those in Groups B and C (<0.1 wt % Cr<sub>2</sub>O<sub>3</sub>). TiO<sub>2</sub> is usually present in abundances of <0.2 wt %.

Group A eclogites are also distinguished by containing primary olivine (FRB437-1) and orthopyroxene (FRB437-2). These are both Mg-rich (MG# 92 and Fo 91; table 2), in keeping with the garnet and clinopyroxene chemistry of Group A eclogites. The orthopyroxene contains little Al<sub>2</sub>O<sub>3</sub> (0.42 wt %), and the olivine contains 0.15 wt % NiO (table 2).

*Geothermometry and Geobarometry.*—Eclogite mineralogy permits the estimation of equilibrium temperatures, but rarely equilibrium pressures. The garnet and clinopyroxene compositions are used to estimate temperatures (Ellis and Green 1979), and where orthopyroxene occurs in Group A eclogites, the Wells (1977) geothermometer was used. The presence of orthopyroxene in a Group A eclogite allows an equilibrium pressure to be estimated, using the Al<sub>2</sub>O<sub>3</sub> content of orthopyroxene (Wood and Banno 1973). Results are presented in table 3. The Group A eclogites yield lower equilibrium tempera-

tures (834–852°C) than Groups B and C. Although temperatures overlap, Group C eclogites yield generally higher temperatures (921–1001°C) than Group B (915–930°C). In 437-2, where orthopyroxene is present, the Wells (1977) thermometer (851°C) yields an almost identical result to the Ellis and Green (1979) method (852°C). The pressure derived from this eclogite, using garnet-orthopyroxene equilibria (Wood and Banno 1973), is 45.5 Kbar.

#### PETROGRAPHY

The eclogite xenoliths are 3–5 cm in diameter. Because of the coarse-grained nature of these rocks (e.g., 2–10 mm), two thin sections of each eclogite were examined by point counting methods ( $\approx 1000$  points per thin section), in order to obtain representative modes. Even here, these modes lack the precision possible with finer-grained samples. The modal mineralogies of the eclogite prior to metasomatism and alteration have been calculated by allocating the secondary minerals with either garnet or clinopyroxene (or kyanite in Group C eclogites). Serpentine is

the last mineral to form, primarily as an alteration product of the other minerals present.

Two distinct suites of eclogites can be distinguished megascopically. One suite contains minor olivine or enstatite (Group A) and are technically garnet pyroxenites rather than eclogites *sensu stricto*, but, conversely, eclogites are technically garnet websterites and garnet clinopyroxenites (Boctor et al. 1983). For the purposes of our two presentations, however, these *garnet pyroxenites are regarded as varietal eclogites*. As will become apparent, inclusion of these garnet websterites and garnet clinopyroxenites as varietal eclogites allows the distinctive petrogenesis of true eclogites to be highlighted. These rocks consist of blocky, sub-equant grains of lavender garnet (8–12 mm across) intergrown with bright apple-green clinopyroxene of similar size. Phlogopite is rare.

Microscopically, large clinopyroxenes (up to 1 cm) dominate the Group A eclogites, containing orthopyroxene exsolution lamellae (<0.1 mm wide). Garnets of similar size are fresher than the clinopyroxenes, the main alteration being serpentine along grain boundaries and cracks. Table 4 contains the

TABLE 4

MODAL MINERALOGY OF THE BELLSBANK ECLOGITES, CALCULATED FROM  $\approx 1000$  POINTS PER THIN SECTION

	PRIMARY					SECONDARY					
	Garnet	Cpxl	Opx	Ol	Ky	Cor	Serp	Phlog	Amph	Cpx2	Feld
Group A											
437-1*	43.7	35.7	...	.8	...	...	16.9	2.8	...	...	...
437-2	7.7	44.0	5.6	...	...	...	38.8	2.5	...	...	...
437-2A	14.6	41.3	3.9	...	...	...	36.1	1.7	...	...	...
Group B											
438-2*	48.4	21.4	...	...	...	...	3.2	5.6	5.0	15.4	.7
438-3	32.4	28.0	...	...	...	...	2.0	9.4	1.3	26.9	...
438-3A	63.9	8.4	...	...	...	...	.6	3.4	2.4	21.3	...
438-7*	39.9	18.7	...	...	...	...	2.9	3.4	1.7	33.4	...
2791-21	51.9	21.4	...	...	...	...	4.0	2.0	1.4	19.1	.2
2791-21A	61.3	19.4	...	...	...	...	2.4	.4	1.7	14.5	.3
Group C											
437-5	51.3	15.3	...	...	.9	1.4	2.3	5.7	2.6	20.0	.5
437-5A	43.7	17.1	...	...	1.4	1.6	1.7	4.0	3.7	26.4	.4
437-7	55.4	12.3	...	...	...	1.2	2.2	11.4	1.4	15.5	.6
437-7A	56.0	14.9	...	...	.4	.6	3.9	3.3	2.3	18.3	.3
2791-34	38.9	20.9	...	...	...	...	2.1	9.1	2.9	26.1	...
2791-34A	41.1	11.6	...	...	...	...	1.1	13.0	.6	32.6	...
Reconstructed primary modal mineralogy											
Group A											
437-1*	48.1	50.4	...	1.5	...	...	...	...	...	...	...
437-2	14.7	76.6	8.7	...	...	...	...	...	...	...	...
Group B											
438-2*	60.4	39.6	...	...	...	...	...	...	...	...	...
438-3	61.2	38.8	...	...	...	...	...	...	...	...	...
438-7*	62.3	37.7	...	...	...	...	...	...	...	...	...
2791-21	66.7	33.3	...	...	...	...	...	...	...	...	...
Group C											
437-5	59.9	37.5	...	...	2.6	...	...	...	...	...	...
437-7	69.7	29.2	...	...	1.1	...	...	...	...	...	...
2791-34	54.8	45.2	...	...	...	...	...	...	...	...	...

\* Sample also reported by Shervais et al. (1988).

modal mineralogy of each nodule. The overall texture is coarse-equant, with many triple junctions present between grains. Minor, un-oriented phlogopite masses (1–2 mm) occur with serpentine along grain boundaries and cracks. Amphibole is not present in this group. Olivine (FRB437-1) and orthopyroxene (FRB437-2) occur as primary minerals (up to 4 mm), also forming triple junctions with garnet and clinopyroxene.

The second megascopically distinguishable suite of eclogites encompasses both Groups B and C. They consist of blocky or rounded orange garnets 5–10 mm across, surrounded by smaller (2–5 mm) dark gray-green clinopyroxene grains.

In thin section, Groups B and C can be separated. Group B eclogites contain garnet and clinopyroxene as primary minerals. Clinopyroxenes exhibit "crinkled" or "spongy" margins (fig. 2A) with a massive, unaltered core with "crinkled" reaction rims, appearing to consist of hundreds of discrete clinopyroxenes and interstitial glass. However, these pyroxenes are in optical continuity with the core. In extreme cases, the entire clinopyroxene has been "crinkled." Phlogopite and amphibole are usually adjacent to the "crinkled" or "spongy" clinopyroxenes (fig. 2A). Rare exsolution lamellae are present in the unaltered cores of clinopyroxenes. Garnet is usually fresher than the clinopyroxene, exhibiting no alteration around its margins. However, garnets do exhibit embayed grain boundaries, where phlogopite and amphibole development has occurred. In extreme cases, small ( $\approx 2$  mm) garnets with deeply embayed grain boundaries are present in a sea of phlogopite and amphibole (fig. 2B). These two secondary phases are also found on the walls of veins and fractures and can occur as grains up to  $0.5 \times 1.0$  mm in size. In addition, interstitial sanidine ( $<0.5$  mm) is present. However, PHN2791-21 contains only minor amphibole and phlogopite development. These minerals are present only as a thin veneer along garnet and clinopyroxene grain boundaries. As in group A eclogites, the overall texture is coarse-equant, with many triple junctions present between the primary minerals.

Group C eclogites are the only type which contain primary kyanite (0.5–2 mm) mantled by 0.1–1 mm long needles of corundum (fig. 2C) (although these are not seen in PHN2791-

34). These minerals are usually interstitial, but kyanite inclusions in garnet are present in FRB437-5 (fig. 2D). These eclogites are dominated by large clinopyroxenes and garnets (both up to 1 cm). As in Group B, the clinopyroxenes exhibit "crinkled" or "spongy" margins, but these are not generally as extensively developed. Again, phlogopite and amphibole generally border these crinkled clinopyroxenes. Minor exsolution lamellae occur in the clinopyroxenes. Phlogopite and amphibole are present along fractures ( $\approx 0.5$  mm wide) but are most extensively developed around garnet, which exhibits embayed grain boundaries. Interstitial sanidine ( $<0.1$  mm), Ba feldspar or celsian ( $<0.1$  mm), and a possible Ba zeolite ( $<0.05$  mm) are present in FRB437-5 and FRB437-7.

#### MAJOR ELEMENT CHEMISTRY OF SECONDARY MINERALS

Secondary minerals present in these Bellsbank eclogites are phlogopite, amphibole, sanidine, celsian, and Ba zeolite. Sanidine or K-feldspar is present in some, but not all, Groups B and C eclogites (i.e., FRB438-2, PHN2791-21, and FRB437-5). Compositions are very similar in these different eclogite samples (table 7); all contain significant concentrations of barium (0.1–1.7 wt % BaO) with Na<sub>2</sub>O reaching 0.6 wt %. Celsian or Ba-feldspar is also an interstitial phase, as reported by Smyth et al. (1984), but only in Group C eclogite FRB437-7. It is compositionally variable, BaO ranging from 9–12 wt %. Also present in this xenolith is a Ba-zeolite (table 7) containing  $\approx 23$  wt % BaO. Good microprobe analysis of this phase was not possible due to decrepitation of the mineral, even at EMP conditions of 15 kV and  $<1$  nA specimen current.

Phlogopite is the only mineral found in these eclogites which exhibits core-to-rim zonation (table 5). In all groups, phlogopite displays a general decrease in SiO<sub>2</sub> and MgO and a general increase in Al<sub>2</sub>O<sub>3</sub>, FeO, Na<sub>2</sub>O, and BaO from core-to-rim. The phlogopites from Group A eclogites contain the most Cr<sub>2</sub>O<sub>3</sub> ( $>0.2$  wt %), and MgO ( $>20$  wt %), reflecting the primary mineral compositions. The phlogopites from Group C eclogites are the most aluminous, usually containing  $>20$  wt % Al<sub>2</sub>O<sub>3</sub>, whereas those from Group B contain the most iron (generally 8–13 wt % FeO:

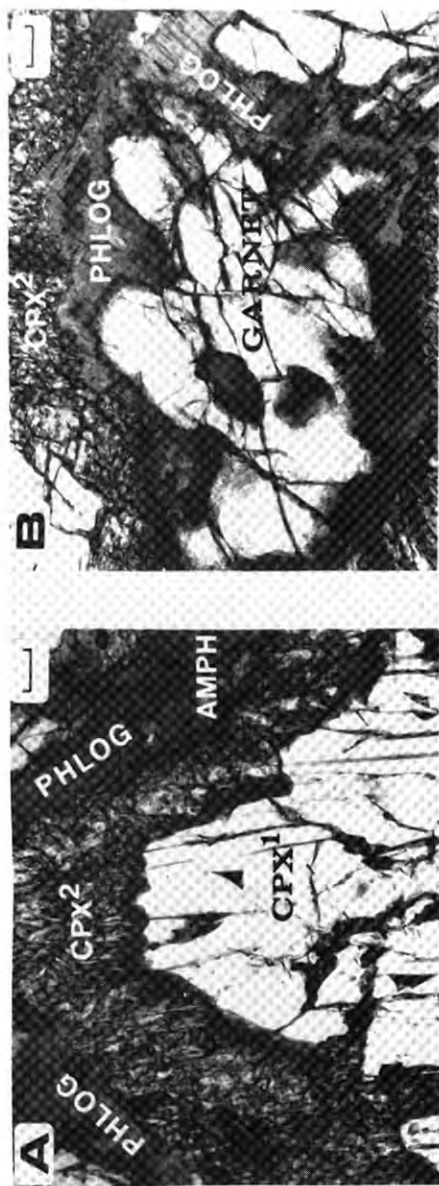


FIG. 2.—A: "Crimkled" or "spongy" margin (Cpx<sup>2</sup>) to primary clinopyroxenes (Cpx<sup>1</sup>) in FRB438-2. Phlogopite and amphibole border this spongy rind. This texture is found only in Group B and C eclogites. Scale bar represents 0.2 mm. B: Garnet with embayed grain boundaries surrounded by phlogopite in FRB438-3. Scale bar represents 0.2 mm. C: Inclusions of kyanite in garnet from FRB437-5. Scale bar represents 0.2 mm. D: Primary kyanite with embayed grain boundaries surrounded by secondary needles of corundum. Scale bar represents 0.05 mm.

table 5), also mirroring the primary mineral compositions.

Amphiboles are present only in Group B and C eclogites. They are unzoned, although limited compositional variations exist between different grains. As with the phlogopites, the amphibole compositions reflect the broad compositions of the primary minerals (table 6). Amphiboles from the different eclogite groups are compositionally distinct (table 6): those from Group B are iron-rich (11–14 wt % FeO), whereas those from Group C are the most aluminous (20–22 wt %  $Al_2O_3$ ).

We include the crinkled margins of primary clinopyroxenes in this section as they are due to secondary alteration and their compositions are distinct. These secondary clinopyroxene rims in Group B and C eclogites contain less Na and Al (jadeite mole) and more Mg, Fe and Ca (table 2) relative to the fresh

cores. However, the MG# of both the primary and secondary clinopyroxenes are similar (table 2). Between these small, secondary clinopyroxenes are areas (<0.05 mm) of glass, which are best developed in Group B eclogites. These have compositions similar to albite and sanidine (table 7). The Na-rich glass contains higher  $Al_2O_3$  (24–26 wt %) than the K-rich glass ( $\approx$  18 wt %). Barium is present in both glasses, although higher abundances are usually found in the Na-rich type. Appreciable quantities of MgO (up to 2.82 wt %) and FeO (up to 1.87 wt %) are present in both glass types.

#### WHOLE-ROCK CHEMISTRY

Whole-rock chemistry of the eclogite samples was determined by XRF and INAA (table 8). Preparation for bulk-rock analyses by X-ray fluorescence involved crushing of

TABLE 8  
WHOLE ROCK ANALYSES OF BELLSBANK ECLOGITES

		A		B				C			±%
		437-1 <sup>a</sup>	437-2	438-2 <sup>a</sup>	438-3	438-7	2791-21	437-5	437-7	2791-34	
SiO <sub>2</sub>	X	47.1	50.7	45.2	45.6	45.5	43.3	44.2	44.6	44.4	
TiO <sub>2</sub>	X	.10	.06	.27	.25	.35	.15	.32	.19	.29	
Al <sub>2</sub> O <sub>3</sub>	X	10.6	6.06	14.3	13.5	12.1	16.7	20.1	20.0	17.1	
Fe <sub>2</sub> O <sub>3</sub>	X	7.37	6.14	12.8	12.4	11.8	13.3	7.09	5.80	7.31	.01–1.1
FeO	N	7.13	5.33	13.7	12.1	12.2	12.7	7.19	5.66	7.44	.01–.6
MnO	X	.37	.20	.20	.18	.22	.21	.03	.02	.04	
MgO	X	18.8	22.7	12.2	13.7	13.3	13.5	10.5	11.1	14.3	
CaO	X	8.49	10.3	11.2	12.0	11.2	11.3	14.5	15.1	12.1	
Na <sub>2</sub> O	X	1.28	1.01	1.24	1.06	1.59	.67	1.31	1.39	1.35	8–16
Na <sub>2</sub> O	N	.45	.95	.85	1.29	.99	.87	1.70	1.92	1.69	1–2
K <sub>2</sub> O	X	.24	.25	.60	.54	.93	.19	.77	.60	.78	
P <sub>2</sub> O <sub>5</sub>	X	.12	.12	.11	.04	.37	<.01	.09	.04	.05	
Cr	X	5268	6226	342	821	342	616	547	684	753	.01–1
Cr	N	9442	7800	684	958	479	616	821	1163	1095	.01–11
Sc	N	65.2	34.7	68.3	62.1	66.4	62.2	35.6	28.4	26.0	2–3
V	X	190	157	400	282	473	231	306	237	216	1–2
Co	N	51.6	38.6	60.3	57.2	58.6	57.7	45.0	41.3	55.5	5–9
Ni	X	493	659	201	255	248	159	229	180	436	1–3
Ni	N	620	208	240	169	315	<150	112	161	304	40–50
Rb	X	12	14.5	20	16.1	37	5.4	27.8	29.1	30.1	3–11
Rb	N	<10	8.9	<10	22.5	<10	7.4	26.6	23.8	22.1	13–24
Sr	X	160	184	61	78	198	46	271	172	116	1–3
Sr	N	180	155	<150	119	350	170	260	223	145	38–50
Cs	N	2.64	1.43	2.19	2.63	8.48	.51	3.49	3.60	2.30	10–17
Ba	N	390	247	570	595	1090	485	1826	1506	1316	6–8
La	N	15.4	14.3	5.11	5.52	26.0	4.41	5.69	5.03	5.69	7–1
Ce	N	33.0	39.7	10.0	14.0	46.0	11.7	10.9	10.6	11.4	2–7
Nd	N	9.00	11.4	2.90	7.88	14.0	4.41	5.56	6.50	7.65	31–50
Sm	N	.80	.99	.56	.64	1.68	.48	.60	.57	.63	1–4
Eu	N	.21	.23	.27	.28	.50	.24	.24	.22	.28	4–5
Tb	N	.10	.07	.70	.37	.65	.30	.10	.09	.08	10–43
Yb	N	1.15	.64	9.40	7.25	8.15	5.90	.86	.72	.70	2–7
Lu	N	.23	.11	1.48	1.22	1.25	1.06	.15	.12	.11	2–9
Y	X	8	11	46	48	44	41	10.5	10.1	11.2	1–3
Zr	X	38	42	30	31	68	24	60	48	39	2–3
Nb	X	3.0	3.5	14	7.5	22	6.2	6.8	2.7	4.4	9–20
Hf	N	.21	<.1	.48	.67	1.86	.26	.88	.61	.63	13–27
Ta	N	.12	.17	.26	.27	.92	.17	.37	.36	.36	13–17
Th	N	.40	.93	.49	.63	3.25	0.58	.77	.62	.76	9–17
U	N	<.8	.44	<.5	<.5	1.8	<.5	.79	.60	.54	20–27

NOTE.—N = analysis by INA; X = analysis by XRF. Oxides in wt %; all other elements in ppm.

<sup>a</sup>Sample also reported by Shervais et al. (1988).

the eclogites in a ceramic grinding mill, with the preparation of pressed pellets using boric acid as the flux. Analyses of the nine eclogites were performed with an EG&G ORTEC X-ray fluorescence spectrometer at the University of Tennessee. Average errors from the XRF analyses can be found in table 8. The INA analyses were performed at the Johnson Space Center, Houston, using the procedure of Lindstrom et al. (1989). Although many of the data from the different eclogite groups overlap (table 8), significant distinctions can be made. These differences are not only highlighted by elements found predominantly in the primary minerals, but also in elements found exclusively in the secondary or metasomatic phases.

**Major Elements.**—Group A eclogites are characterized by high MgO, Cr<sub>2</sub>O<sub>3</sub>, and SiO<sub>2</sub> contents (18–23 wt %, 0.8–0.9 wt %; 47–51 wt %, respectively; table 8). Furthermore, bulk Al<sub>2</sub>O<sub>3</sub>, CaO, and TiO<sub>2</sub> contents (6–11 wt %, 8–10 wt %, and <0.1 wt %, respectively) are the lowest reported in this study. Group B eclogites are characterized by high FeO, moderate MgO, Al<sub>2</sub>O<sub>3</sub>, and CaO, and low Cr<sub>2</sub>O<sub>3</sub> contents (12–14 wt %, 12–14 wt %, 12–17 wt %, 11–12 wt % and <0.1 wt %, respectively). Group C eclogites contain the highest reported Al<sub>2</sub>O<sub>3</sub> and CaO contents (17–20 wt % and 12–15 wt %, respectively). They also contain low MgO, Cr<sub>2</sub>O<sub>3</sub>, and FeO contents (11–14 wt %, ≈ 0.1 wt %, and 6–7 wt %, respectively). Magnesium number is highest in Group A (82–87), lowest in Group B (62–67), with Group C eclogites being intermediate (MG# = 72–78).

**Trace Elements.**—As with the major elements, trace elements can be used to identify three groups of eclogites. Group A eclogites contain the highest abundances of Ni (493–659 ppm) and the lowest abundances of V (157–190 ppm), K (1992–2075 ppm), and Ba (247–390 ppm). Group B and C eclogites contain similar abundances of V, Ni, and K (table 8) but differ from values for Group A in that K and V are higher and Ni lower. Group C eclogites contain the highest Ba abundances (1505–1826 ppm). Other reported trace elements (table 8) do not appear to distinguish between any groups of eclogites.

The presence of amphibole, phlogopite, sanidine, and celsian indicates that these ec-

logites have been metasomatized (e.g., Dawson 1984; Menzies and Hawkesworth 1987). Therefore, care is required in the interpretation of the trace element abundances. To reduce the effects of metasomatic/kimberlitic contamination, we prepared ultrapure mineral separates of clinopyroxene and garnet by crushing each sample in the stainless steel impact mortar and hand-picking under a binocular microscope to produce grain concentrates. Further hand-picking in alcohol under the binocular microscope was conducted using a fiber-optics light device. After each hand-picking, the mineral separates were further cleaned by etching in a solution of HCl, followed by HF/HNO<sub>3</sub>. The acid washes were performed during the picking process to assist removal of surface contamination. Analyses using K-spikes were performed to monitor the possible presence of any contamination from secondary metasomatic material (typically high in K). Results of these K-spikes demonstrate the ultrapure nature of these separates, as both garnet and clinopyroxene contain <0.5 ppm K.

The ultrapure mineral separates were each split into three portions for analysis: (1) by INA; (2) for oxygen isotopes; and (3) Sr, Nd, and Pb isotopes. The INAA (table 9) determined that the Na<sub>2</sub>O and FeO contents of clinopyroxenes and FeO contents of garnets analyzed by INA compare well with the microprobe results (tables 1 and 2). Only the compatible elements, Sc and Co, and the REE gave results with low errors. Some high-field-strength element (HFS) abundances (Hf, Ta, Th) have been determined only in the clinopyroxene separates. Clinopyroxenes from Group A eclogites contain the highest Ta and Th abundances (≈ 0.13–0.16 ppm and 1.4–2.5 ppm), whereas Group B clinopyroxenes contain the highest Hf abundances (0.28–0.37 ppm; table 9). Group C clinopyroxenes generally contain HFS elements below detectability limits. The compatible element abundances generally overlap between the three groups. However, Group B clinopyroxenes contain the highest Co (29–36 ppm) and those in Group C the lowest Sc abundances (3–5 ppm). A similar scenario is witnessed for the garnet compositions (table 9).

**Rare Earth Elements (REE).**—The major distinctions between the eclogite groups are seen in the rare earth elements. The whole-



TABLE 9  
RESULTS OF INA ANALYSES OF ULTRAPURE MINERAL SEPARATES FROM BELLSBANK ECLOGITES

	Clinopyroxenes												Garnets											
	A				B				C				A				B				C			
	437-1	437-2	438-2*	438-3	438-7	2791-21	437-5	437-5	0.93	1.21	8.65	11.0	16.8	438-2	438-3	438-7	2791-21	437-5	437-7	2791-34				
FeO	1.57	2.13	3.68	3.91	3.78	3.60	1.19	0.93	1.21	8.65	11.0	16.8	438-2	438-3	438-7	2791-21	437-5	437-7	2791-34					
±	.02	.04	.04	.02	.04	.02	.01	.01	.01	.01	.01	.01	.02	.05	.04	.05	.04	.06	.06	.05				
Na <sub>2</sub> O	1.86	1.86	3.87	3.87	3.82	4.99	8.00	7.69	7.38	.02	.04	.04	.001	.01	.001	.001	.01	.01	.01					
±	.02	.001	.001	.001	.001	.001	.01	.01	.01	.001	.01	.01	.001	.01	.001	.001	.01	.01	.01					
Cr <sub>2</sub> O <sub>3</sub>	2.31	.58	.13	.11	.08	.10	.16	.16	.16	4.09	2.10	.11	.10	.10	.13	.08	.10	.15	.13					
±	.08	.01	.04	.01	.04	.03	.03	.03	.03	.04	.01	.001	.001	.001	.001	.001	.001	.02	.001					
Sc	26.2	26.7	27.2	28.5	28.8	22.4	5.21	2.99	3.69	11.4	89.4	88.0	88.0	85.8	90.0	78.5	47.3	39.2	33.4					
±	.3	.01	.3	.01	.3	.1	.01	.02	.01	.1	.2	.1	.2	.2	.1	.2	.1	.1	.1					
Co	15.7	21.1	34.6	35.4	35.5	29.4	17.1	15.9	21.4	45.0	53.0	73.0	71.2	74.0	67.6	56.3	51.7	75.1	75.1					
±	.2	.1	.4	.2	.4	.3	.1	.1	.1	.1	.4	.1	.6	.1	.5	.4	.3	.6	.6					
Sr	490	375	...	144	...	...	106	...	172	...	...	...	...	...	...	...	...	...	...					
±	30	85	...	32	...	...	26	...	33	...	...	...	...	...	...	...	...	...	...					
La	44.5	25.6	1.46	1.94	1.19	2.89	23	30	34	...	...	...	...	...	...	...	...	...	...					
±	.5	.1	.03	.03	.03	.06	.02	.03	.03	...	...	...	...	...	...	...	...	...	...					
Ce	95	78	3.1	4.3	1.8	5.3	62	77	46	...	...	...	...	...	...	...	...	...	...					
±	2	1.1	.2	.35	.2	.4	.27	.24	.2	...	...	...	...	...	...	...	...	...	...					
Nd	24	20	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...					
±	1.0	3.9	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...					
Sm	1.42	1.35	.19	.24	.19	.12	.04	.03	.05	...	...	...	...	...	...	...	...	...	...					
±	.02	.01	.001	.01	.001	.01	.01	.01	.01	...	...	...	...	...	...	...	...	...	...					
Eu	30	27	.11	.12	.11	.05	.03	.07	.03	...	...	...	...	...	...	...	...	...	...					
±	.01	.01	.01	.01	.01	.01	.01	.01	.01	...	...	...	...	...	...	...	...	...	...					
Tb	.08	.06	.10	.07	.09	.06	.08	...	...	...	...	...	...	...	...	...	...	...	...					
±	.001	.002	.01	.02	.01	.03	.04	...	...	...	...	...	...	...	...	...	...	...	...					
Yb	11	14	12	14	13	.09	.06	.08	.04	...	...	...	...	...	...	...	...	...	...					
±	.001	.02	.02	.03	.02	.04	.02	.02	.02	...	...	...	...	...	...	...	...	...	...					
Lu	.01	.01	.01	.03	.02	.01	...	...	...	...	...	...	...	...	...	...	...	...	...					
±	.01	.01	.01	.01	.01	.001	...	...	...	...	...	...	...	...	...	...	...	...	...					
Hf	.17	.16	.32	.37	.28	...	...	...	.11	...	...	...	...	...	...	...	...	...	...					
±	.03	.05	.03	.05	.03	...	...	...	.02	...	...	...	...	...	...	...	...	...	...					
Ta	.16	.13	<.05	...	<.04	...	...	...	...	...	...	...	...	...	...	...	...	...	...					
±	.01	.05	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...					
Th	2.5	1.4	.10	...	.10	.35	...	...	...	...	...	...	...	...	...	...	...	...	...					
±	.3	.19	.02	...	.02	.07	...	...	...	...	...	...	...	...	...	...	...	...	...					

NOTE:—... = not detected and no upper limit calculated. Oxides in wt %; all other elements in ppm.  
\* Sample also reported by Shervais et al. (1988).

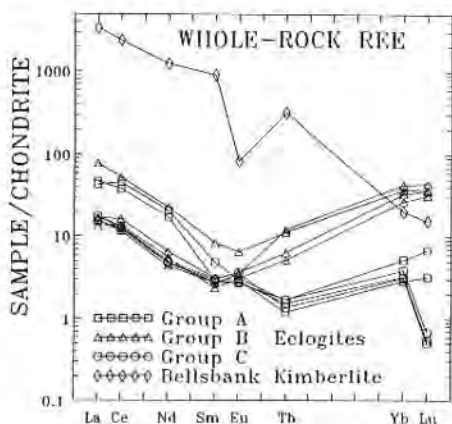
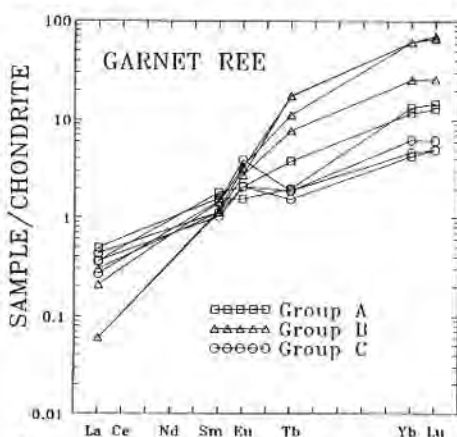


FIG. 3.—Eclogite whole-rock REE represented on a chondrite-normalized plot. Although three groups cannot be distinguished, note the positive Eu anomaly exhibited by all Group C eclogites and the HREE enrichment of Group B eclogites. The REE profile of the Bellsbank kimberlite (data from Fesq et al. 1975 and Mitchell 1986) is shown for reference.

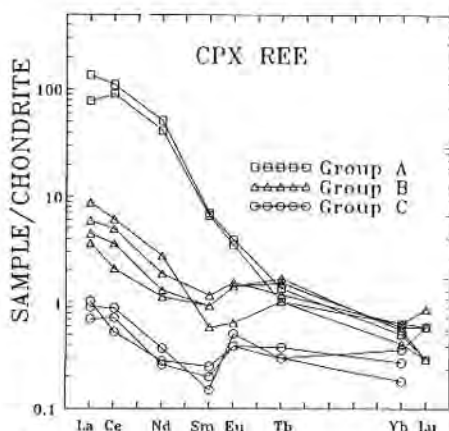
rock REE abundances, largely dominated by the chemistry of the secondary phases, are all LREE-enriched (table 8 and fig. 3). No groups can be distinguished on the basis of the LREE due to metasomatic effects and/or kimberlite infiltration. The Bellsbank kimberlite (fig. 3) is a Group II micaceous kimberlite (Smith 1983) containing  $\approx 1100$  ppm La (Fesq et al. 1975; Mitchell 1986). However, Group B eclogites contain enriched HREE abundances ( $Yb = 5.9\text{--}9.4$  ppm;  $La_N/Yb_N = 0.36\text{--}2.13$ ) over Groups A and C. Furthermore, Group C eclogites all display positive Eu anomalies (fig. 3) with  $Eu/Eu^* \approx 1.3$ .

The effects of metasomatic/kimberlite contamination have been reduced by preparation of ultrapure garnet and clinopyroxene mineral separates (fig. 4A,B; table 9). The garnets from Group B are enriched in the HREE ( $Yb = 25\text{--}70 \times$  chondrite) relative to those from Groups A and B (fig. 4A). Group A garnets exhibit a smooth increase from the La to Lu, whereas garnets from Group C exhibit pronounced positive Eu anomalies (fig. 4A) with  $Eu/Eu^* \approx 1.6$ .

The clinopyroxenes from Group A are highly LREE-enriched ( $La \approx 100 \times$  chondrite;  $La_N/Yb_N = 130\text{--}270$ ; fig. 4B). Those from Group B are again LREE-enriched (fig. 4B), but this enrichment is not as pronounced



A



B

FIG. 4.—A: Garnet REE abundances represented on a chondrite-normalized plot. Three eclogite groups are defined by HREE abundances, with Group C garnets possessing a positive Eu anomaly. B: Clinopyroxene REE abundances represented on a chondrite-normalized plot. Three eclogite groups are defined by the LREE. Group C clinopyroxenes contain a poorly defined positive Eu anomaly.

as in Group A ( $La = 3\text{--}9 \times$  chondrite;  $La_N/Yb_N = 6\text{--}22$ ). The MREE of Group B clinopyroxenes (Eu and Tb) exhibit a slight enrichment over Sm (fig. 4B), but no Eu anomaly is defined. Group C clinopyroxenes contain very low abundances of the REE, which has made their analysis problematical. There is a slight LREE-enrichment ( $La \approx 0.9 \times$  chondrite;  $La_N/Yb_N = 2\text{--}5$ ) and a slight positive Eu anomaly may be present (fig. 4B) with  $Eu/Eu^* \approx 1.4$ . Definition of this Eu

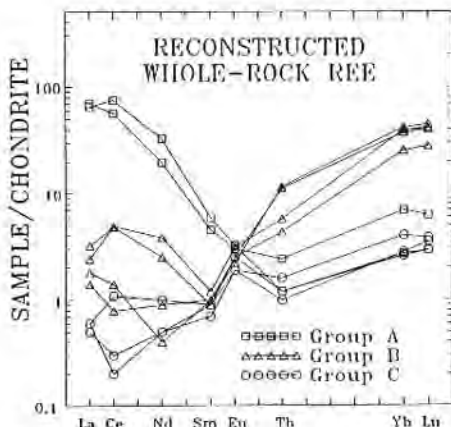


FIG. 5.—Reconstructed whole-rock REE profiles, calculated from modal analyses and clinopyroxene and garnet REE abundances. Three eclogite groups are distinguished on the basis of LREE abundances, and Group C eclogites possess a positive Eu anomaly.

anomaly is difficult because of the errors associated with the Tb analyses.

The *reconstructed* primary modal mineralogy of the eclogites (table 4), in conjunction with the REE abundances of the ultrapure clinopyroxene and garnet mineral separates, may be used to reconstruct whole-rock REE patterns (fig. 5). Such whole-rock patterns demonstrate profoundly that three groups can be distinguished on the basis of LREE, as the effect of metasomatism/kimberlite infiltration is removed. Group A eclogites are the most LREE-enriched ( $La \approx 70 \times$  chondrite;  $La_N/Yb_N = 10-24$ ), Group B are intermediate ( $La = 1.5-3.0 \times$  chondrite), and Group C are LREE-depleted ( $La = 0.5-0.6 \times$  chondrite;  $La_N/Yb_N = 0.1-0.2$ ). Group B eclogites are highly HREE-enriched ( $La_N/Yb_N = 0.03-0.13$ ), with Group C eclogites possessing a positive Eu anomaly ( $Eu/Eu^* \approx 1.3$ ).

#### DISCUSSION

The petrogenesis of eclogite xenoliths from the Bellsbank kimberlite requires careful examination of all available mineralogical, petrographic, and geochemical data. The picture is complicated because these eclogite xenoliths have experienced a later metasomatic event, or events, which has overprinted the primary eclogite signature. Our study, however, has allowed an insight into eclogite pet-

rogenesis by careful preparation of ultrapure mineral separates and the effective removal of secondary, metasomatic effects by identifying elements that have been introduced solely by metasomatism. The following discussion addresses the origin of both the metasomatic fluid(s) that affected the eclogites and the ultimate petrogenesis of these xenoliths.

#### METASOMATISM

The analyses of amphiboles and phlogopites (tables 5 and 6) reflect three eclogite groups defined by the primary minerals. These distinctive correlations suggest formation at the expense of the primary minerals. This suggestion is supported by petrography, where phlogopite develops around clinopyroxene and especially garnet, ultimately leading to garnets with ragged, embayed margins in a sea of phlogopite (fig. 2B). We envisage the metasomatic fluid percolating through the eclogites, reacting with the primary minerals to form amphibole and phlogopite.

The most obvious source for the metasomatic fluid is the host kimberlite. In order to evaluate this supposition, the nature of the primary eclogite composition must be considered. This will contain little, if any, K and Ba. Therefore, we assume that all K and Ba present in the whole-rock eclogites (table 8) must have been introduced by metasomatism. We have plotted K (ppm) against Ba (ppm) (fig. 6)

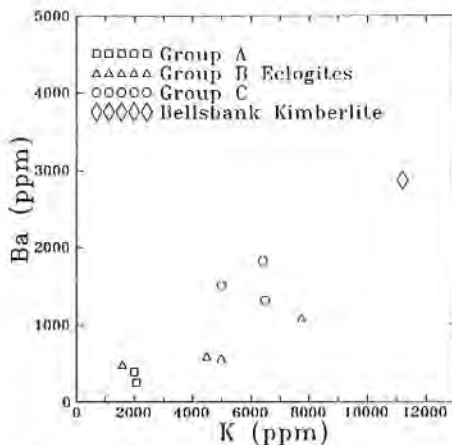


FIG. 6.—Whole-rock K and Ba abundances of the three eclogite groups and Bellsbank kimberlite (data from Fesq et al. 1975).

for our three eclogite groups and the Bellsbank kimberlite (data from Fesq et al. 1975). Note that the positive correlation between K and Ba is evidence for the infiltration of the host kimberlite, and further, that the kimberlite itself was the source of the metasomatic fluid which affected these eclogites.

Supporting evidence for kimberlite infiltration is obtained from comparing the whole-rock REE signatures (fig. 3) with reconstructed REE profiles (fig. 5). Note that the LREE in Groups B and C are significantly reduced in the reconstructed profiles. As the Bellsbank kimberlite is highly LREE-enriched (fig. 3), even small amounts of kimberlitic contamination would dramatically alter the REE profile of a relatively LREE-depleted xenolith, further emphasizing the importance of "ultrapure" mineral separates.

*Metasomatic Clinopyroxene.*—Crinkled or spongy margins of primary clinopyroxene (fig. 2A) are present only in Group B and C eclogites. These are similar to the spongy clinopyroxene texture described by Donaldson (1978) in mantle xenoliths from central England. Spongy-textured clinopyroxenes are common in spinel lherzolites (e.g., Ernst 1936; Wilshire and Binns 1961; Frey and Green 1974; Neilson-Pike and Schwarzman 1977). It was concluded that these spongy or crinkled textures resulted from the decomposition of a jadeite-rich diopside to a jadeite-poor diopside + feldspar (e.g., Carswell 1975), whereas Donaldson (1978) suggested that incongruent melting of the clinopyroxene was the cause of this texture. Mysen and Griffin (1973) noted the breakdown of omphacitic pyroxenes in eclogites from gneiss terrains and suggested that this occurred in response to an increase in  $fO_2$ . However, their breakdown formed diopside-plagioclase symplectites, which are not seen in the Bellsbank eclogites, but a change in  $fO_2$  probably occurred during metasomatism. The feldspar present in Group B and C eclogites contains substantial quantities of K and Ba (table 6), which must have been derived from a metasomatic fluid. Indeed, Jin and Taylor (1987, 1988) have invoked breakdown of jadeite-rich clinopyroxene in xenoliths from eastern China as a result of metasomatic influx.

We consider these crinkled or spongy

clinopyroxene margins to be a result of a reaction with the metasomatic fluid. The reaction between clinopyroxene and kimberlitic fluid produced clinopyroxene (reduced in jadeite) and feldspathic glass rich in K and Na (c.f., Jin and Taylor 1987, 1988). Significantly, feldspar (sanidine and celsian) and K- and Na-rich glass is only found in Group B and C eclogites, where spongy clinopyroxenes are present. The reduction in jadeite mole from core-to-rim is in response to a "leaching" of Na and Al from the clinopyroxene into the metasomatic fluid during clinopyroxene breakdown. This will produce a volume decrease resulting in the cracking of the affected clinopyroxene but will not disrupt the optical continuity of the margins with the core. Feldspar crystallization and the formation of K- and Na-rich glass could possibly have been promoted because of the contribution of Na and Al from clinopyroxene breakdown (the host kimberlite contains low abundances of Na— $<0.1$  wt %—and  $Al_2O_3$ —1.6–2.5 wt %). The presence of K requires a metasomatic input. This process does not occur in Group A eclogites, primarily because they have experienced less reaction with the metasomatic fluid than those in Groups B and C. A possible contributory factor is the low jadeite component present in Group A clinopyroxenes (table 2). If there is nothing to be leached out, no cracking of the clinopyroxene margins will occur.

In summary, the metasomatic fluid which has interacted with the eclogites was derived from the host kimberlite. The effect of this metasomatism has been in the breakdown of garnet and clinopyroxene to form phlogopite and amphibole. This fluid also interacted with clinopyroxene to produce crinkled or spongy margins with the formation of glass. The crystallization of Ba- and K-feldspar is additional evidence of metasomatism. The serpentinization that affects all xenoliths, and the Ba-zeolite present in FRB437-7, occurred as a result of near-surface alteration or weathering after kimberlite eruption. The zeolite resulted from the breakdown of celsian. Serpentine occurs as an alteration product of all minerals present, and probably formed after kimberlite eruption. All these metasomatic effects need to be recognized before the petrogenesis of the eclogites can be addressed.

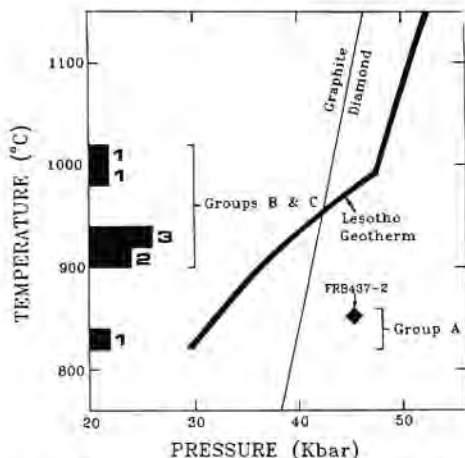


FIG. 7.—Pressure (Kbar) vs. Temperature ( $^{\circ}\text{C}$ ) plot for the Bellsbank eclogites. Only equilibrium temperatures can be estimated for the majority of the eclogites and are represented as black boxes. The numbers next to these black boxes represent the number of eclogite samples which fall into this temperature zone. Note that the temperatures calculated from Group B and C eclogites straddle the inflection in the Lesotho geotherm. Lesotho geotherm from Finnerty and Boyd (1987); the diamond-graphite boundary from Kennedy and Kennedy (1976).

#### ECLOGITE PETROGENESIS

As stated in the introduction, there are three contrasting petrogeneses for eclogite xenoliths in kimberlite. By using the data from the primary minerals and whole-rock analyses (ensuring that the metasomatism is not included), the petrogenesis of these eclogites can be evaluated.

The estimated equilibrium temperatures (assuming 30 Kbar pressure) and the sole pressure calculation (table 3 and fig. 7), put these eclogites slightly below the Lesotho geotherm (and shield geotherm—Boyd and Nixon 1975; Finnerty and Boyd 1987) but in the diamond stability field (Kennedy and Kennedy 1976). These temperatures and one pressure are similar to those reported by Bocror et al. (1983) for garnet clinopyroxenites, garnet websterites, and eclogites from the Bellsbank kimberlite. Equilibration temperatures from Groups B and C eclogites straddle the inflection in the Lesotho geotherm (fig. 7), which agrees with MacGregor and Manton's (1986) suggestion that the inflection is the result of underplating of the Kaapvaal craton

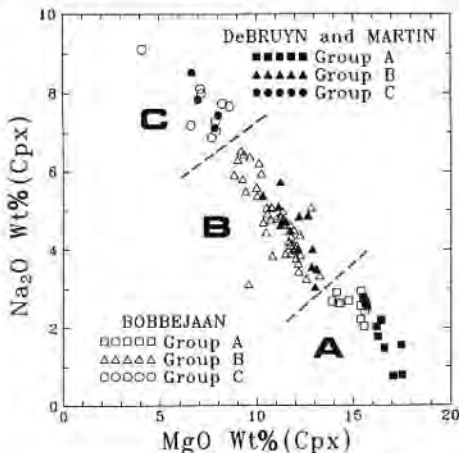


FIG. 8.— $\text{Na}_2\text{O}$  vs.  $\text{MgO}$  in eclogite clinopyroxenes from Bobbejaan (Smyth and Caporuscio 1984) and the DeBruyn and Martin Mine (this study).

by eclogitic material. Furthermore, in another study of Roberts Victor eclogites, Basu et al. (1986) suggested that eclogitic material formed the boundary layer between lithosphere and convecting asthenosphere, as they yield equilibrium temperatures that also straddle the inflection point on the Lesotho geotherm.

J. R. Smyth and co-workers at the University of Colorado are studying eclogites from the Bobbejaan kimberlite (note that, although this occurrence is from the general Bellsbank locality, our samples are from the DeBruyn and Martin Mine on the Main Fissure, over 1 km away). The garnet and clinopyroxene compositions are probably all part of the same eclogite suite. Figure 8 shows the  $\text{Na}_2\text{O}$  vs.  $\text{MgO}$  contents of the Bobbejaan clinopyroxenes (Smyth and Caporuscio 1984) along with 28 from our eclogites, nine of which we have studied in detail here. We have placed all the analyses within our three-fold classification. Although it could be argued that compositional breaks exist along this negative correlation, an alternative explanation for these data would be one of fractional crystallization. The major, minor, and REE analyses by Smyth's group of the Bobbejaan eclogitic pyroxenes and garnets (e.g., Smyth and Caporuscio 1984) would seem to indicate a continuum in their respective compositions, including our Group A varietal eclogites. In fact, Smyth (1984) and Caporuscio

and Smyth (1986, p. 1253) have considered this evidence for "crystallization from a primitive eclogitic liquid at pressures of 30 to 50 kbar" and also representing a "continuous fractionation sequence consistent with a high pressure model." However, our whole-rock and mineral trace-element data conflict with this interpretation. Furthermore, isotope results on three Bellsbank eclogites (from two groups—B and C) reported by Shervais et al. (1988) demonstrate that these groups cannot be related by fractional crystallization.

The major element compositions of the eclogites have been only slightly affected by metasomatism, as there is no correlation between the whole-rock MG# and either K (ppm) or Ba (ppm). The metasomatism introduces primarily K, Rb, Ba, LREE, and the high field strength (HFS) elements. Comparison of tables 8 and 9 shows that the HFS elements are metasomatic in origin. The HFS elements are in very low abundance in both the garnet and clinopyroxenes separates, yet in somewhat higher abundance in the whole rocks. Therefore, the major element whole-rock compositions of the eclogites may be considered uncontaminated (except for  $K_2O$  concentrations).

The whole-rock MG# exhibits a decrease from Group A to Group B eclogites, with Group C being intermediate. To test the high pressure fractionation hypothesis, we have taken the MG# as a fractionation index and plotted it against reconstructed whole-rock trace-element data (fig. 9A,B). We assume that clinopyroxene and garnet were the fractionating phases. In figure 9A, whole-rock MG# is plotted against reconstructed whole-rock Co abundances. Although there is quite a tight, negative correlation, this is the opposite of the anticipated result. If clinopyroxene and garnet are fractionating, a positive correlation between MG# and Co should be observed. The somewhat diffuse negative correlation between whole-rock MG# and reconstructed whole-rock Yb is again the opposite of what would be expected from a petrogenesis by fractional crystallization for these eclogites (fig. 9B). With garnet as a fractionating phase, Yb should decrease in the residual magma. Therefore, we conclude that a petrogenesis by fractional crystallization cannot explain all eclogite xenolith compositions from the Bellsbank kimberlite.

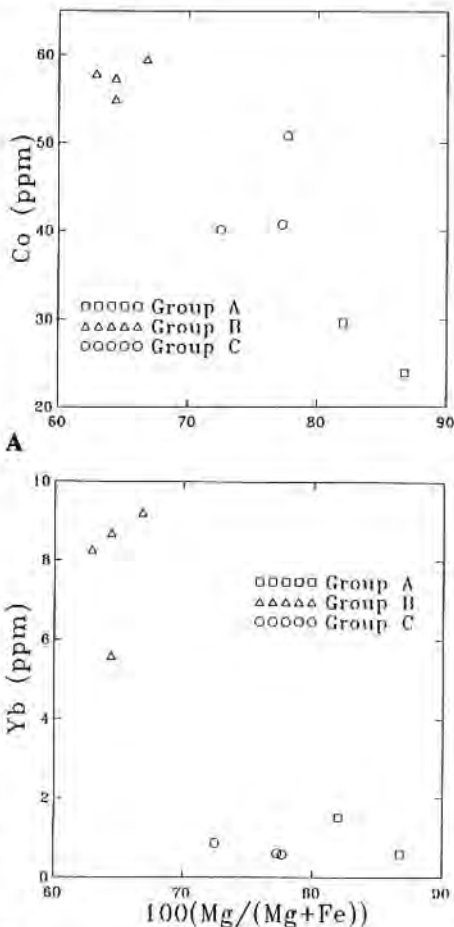


FIG. 9.—A: Whole-rock MG# vs. reconstructed whole-rock Co abundances, denoting three eclogite groups. B: Whole-rock MG# vs. reconstructed whole-rock Yb abundances, denoting three eclogite groups.

However, the high MG# of Group A eclogites is most consistent with a cumulate origin, rather than representing any known magma composition. Furthermore, Cr abundances are too high and Ni too low for these to represent primary Mg-rich liquids. Also, the values for clinopyroxene/garnet REE partition coefficients are within empirical values, suggesting crystallization from a basaltic magma. The calculated clinopyroxene/garnet REE partition coefficients from Group B and C demonstrate that these eclogites did not form by fractional crystallization, consistent

with whole-rock data. The LREE-enriched nature of the clinopyroxene and reconstructed whole-rock is probably a function of garnet-clinopyroxene equilibria.

An alternative petrogenesis for Group B and C eclogites involves a crustal progenitor. The major element compositions of Group B eclogites are similar to Archean basalts (BSVP 1981). The extreme HREE-enriched nature of these eclogites is consistent with a refractory origin, possibly as the basaltic portion of an ancient oceanic crust. When subducted, the hydrated basaltic portion will be more susceptible to partial melting, which fractionates the LREE (to the melt) from the HREE (left in the residue) and may also account for reduced Na contents relative to Group C eclogites.

The high  $Al_2O_3$  contents of Group C eclogites indicate that they may have originated as a plagioclase-rich cumulate. Although plagioclase is not present in Group C eclogites, it is thought that, at some stage during the petrogenesis of these eclogites, plagioclase accumulation was involved. This is supported by the presence of a positive Eu anomaly in the whole-rock mineral separates (especially the garnets) and reconstructed whole-rock REE patterns. We suggest that Group C eclogites represent the remnants of the plutonic portion (i.e., anorthositic gabbro) of an ancient, subducted oceanic crust.

#### CONCLUSIONS

The mineral and whole-rock data presented above indicate that our three eclogite groups represent both mantle and crustal protoliths. Compositions of Group A eclogites are consistent with a high pressure (mantle) cumulate origin. However, whole-rock compositions demonstrate that such a petrogenesis cannot account for the compositions of Group B and C eclogites. Group B and C eclogites are probably the metamorphosed products of oceanic crust. Group B represents the basaltic portion, and Group C the (plagioclase-rich) cumulate portion (cf., Sleep and Windley 1982), as proposed by Jagoutz et al. (1984, 1985) and recently confirmed by MacGregor and Manton (1986) for Roberts Victor Type II and Type I eclogites, respectively, and Shervais et al. (1986, 1988) for Group B and C Bellsbank eclogites. The role of plagioclase accumulation is wit-

nessed in the positive Eu anomaly in all Group C variants.

The importance of this interpretation for subducted oceanic protoliths cannot be over-emphasized, since it suggests: (a) the preservation of ancient oceanic crust beneath the Kaapvaal craton and (b) the possible presence of a stratified mantle in this region due to the preservation of ancient oceanic crust by underplating of the Kaapvaal craton. The estimated temperatures and pressures suggest that these eclogites equilibrated at, or near, the point of inflection on the Lesotho geotherm. This supports the contention of MacGregor and Manton (1986) and Basu et al. (1986), who alluded to an underplating phenomenon as an explanation of the inflection (Boyd and Nixon 1975; Finnerty and Boyd 1987).

The petrogenesis of Group A eclogites (or garnet pyroxenites) by cumulate processes is in marked contrast to the petrogenesis of Groups B and C. This may explain why there was less reaction between Group A eclogites and the metasomatic fluid, there being less "disequilibrium" between the two. Although Boctor et al. (1983) classified our Group A eclogites as garnet websterites and garnet clinopyroxenites, inclusion of these in our study allows two points to be highlighted: (1) the crustal origins of Group B and C eclogites; (2) that the range in eclogite compositions cannot be generated by fractional crystallization (or cumulate) processes.

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TABLE 1

## AVERAGE GARNET ANALYSES

	A			B			C		
	437-1 <sup>e</sup>	437-2	438-2 <sup>e</sup>	438-3	438-7 <sup>e</sup>	2791-21	437-5	437-7	2791-34
SiO <sub>2</sub>	42.0	41.7	40.0	39.8	40.1	39.5	40.1	40.5	40.6
TiO <sub>2</sub>	0.07	0.05	0.13	0.12	0.12	0.08	0.12	0.08	0.10
Al <sub>2</sub> O <sub>3</sub>	21.9	22.7	22.5	22.5	22.5	22.6	22.9	23.0	23.2
Cr <sub>2</sub> O <sub>3</sub>	1.89	1.03	0.04	0.07	0.07	0.05	0.05	0.07	0.06
FeO*	8.30	10.3	<b>16.4</b>	<b>16.3</b>	<b>16.2</b>	<b>14.6</b>	8.62	7.17	9.71
MnO	0.41	0.46	0.40	0.41	0.41	0.38	0.18	0.16	0.17
MgO	<b>21.0</b>	<b>19.9</b>	11.8	12.2	12.0	12.2	9.53	10.3	12.3
CaO	4.37	4.25	9.00	8.91	8.80	10.3	<b>18.5</b>	<b>18.8</b>	<b>14.2</b>
TOTAL	99.94	100.39	100.27	100.31	100.20	99.71	100.00	100.08	100.34
Formula Moles based on 12 Oxygens									
Si	2.470	2.475	2.497	2.475	2.498	2.465	2.497	2.499	2.498
Ti	0.003	0.002	0.006	0.006	0.006	0.004	0.006	0.004	0.005
Al	2.915	2.920	2.943	2.932	2.945	2.930	2.944	2.945	2.944
Cr	0.088	0.048	0.002	0.003	0.003	0.002	0.002	0.003	0.003
Fe	0.408	0.510	0.855	0.845	0.845	0.761	0.449	0.37	0.500
Mn	0.020	0.023	0.021	0.022	0.022	0.020	0.009	0.008	0.009
Mg	1.835	1.766	1.099	1.139	1.116	1.136	0.885	0.952	1.125
Ca	0.275	0.271	0.603	0.597	0.587	0.692	1.232	1.241	0.940
TOTAL	8.015	8.016	8.025	8.019	8.022	8.010	8.024	8.023	8.024
Mg#	81.8	77.5	56.2	57.2	56.9	59.8	66.3	72.0	69.3
CA#	13.0	13.3	35.4	34.4	34.5	37.7	58.2	56.6	45.5

Mg# = 100\*(Mg/(Mg+Fe)); CA# = 100\*(Ca/(Ca+Mg)); @ = sample also reported in Shervais et al. (1988); \* = total iron as FeO.

TABLE 2

## AVERAGE CLINOPYROXENE, OLIVINE AND ORTHOPYROXENE ANALYSES

	A			B			C		
	437-1 <sup>e</sup>	437-2	438-2 <sup>e</sup>	438-3	438-7 <sup>e</sup>	2791-21	437-5	437-7	2791-34
SiO <sub>2</sub>	55.5	55.0	54.1	54.8	54.1	53.8	55.3	54.8	56.0
TiO <sub>2</sub>	0.10	0.07	0.18	0.18	0.17	0.13	0.12	0.08	0.13
Al <sub>2</sub> O <sub>3</sub>	2.56	2.55	5.61	5.85	5.44	7.25	16.7	15.8	14.8
Cr <sub>2</sub> O <sub>3</sub>	1.28	0.72	0.07	0.07	0.07	0.07	0.06	0.09	0.08
FeO*	1.51	2.11	4.33	4.30	4.26	4.13	1.03	1.02	1.21
MnO	0.04	0.06	0.07	0.06	0.06	0.05	<0.02	<0.02	<0.02
MgO	16.2	16.3	13.0	12.9	13.1	12.2	6.98	7.84	8.02
CaO	20.8	21.4	19.4	18.6	19.5	18.0	11.5	12.9	12.4
Na <sub>2</sub> O	2.03	1.77	3.05	3.56	3.08	4.00	7.83	7.12	7.43
TOTAL	100.02	99.98	99.81	100.32	99.78	99.63	99.53	99.66	100.08
Formula Moles based on 6 Oxygens									
Si	1.995	1.987	1.964	1.975	1.965	1.951	1.934	1.922	1.955
Ti	0.003	0.002	0.005	0.005	0.005	0.004	0.003	0.002	0.003
Al	0.108	0.108	0.240	0.248	0.233	0.310	0.687	0.655	0.609
Cr	0.036	0.021	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Fe	0.045	0.064	0.131	0.129	0.129	0.125	0.030	0.030	0.035
Mn	0.001	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001
Mg	0.868	0.875	0.705	0.691	0.710	0.657	0.364	0.410	0.417
Ca	0.802	0.827	0.753	0.719	0.759	0.698	0.432	0.484	0.463
Na	0.142	0.124	0.215	0.249	0.217	0.281	0.531	0.484	0.503
TOTAL	4.000	4.009	4.017	4.019	4.022	4.030	3.984	3.990	3.987
MG#	95.0	93.2	84.4	84.3	84.7	84.1	92.4	93.3	92.2
CA#	48.0	48.6	51.6	51.0	51.7	51.5	54.3	54.1	52.6

TABLE 2 (Cont.)

	A		B				C		
	437-1 <sup>e</sup>	437-2	438-2 <sup>e</sup>	438-3	438-7 <sup>e</sup>	2791-21	437-5	437-7	2791-34
	OLIVINE	OPX	SECONDARY CLINOPYROXENE						
SiO <sub>2</sub>	40.5	57.6	53.6	54.1	53.3	53.1	52.2	50.2	51.2
TiO <sub>2</sub>	<0.02	0.03	0.13	0.16	0.27	0.16	0.16	0.15	0.12
Al <sub>2</sub> O <sub>3</sub>	<0.03	0.42	2.91	4.11	3.24	4.02	7.07	12.6	10.2
Cr <sub>2</sub> O <sub>3</sub>	<0.02	0.07	0.03	0.09	0.11	0.08	0.15	0.14	0.18
FeO*	7.69	6.21	4.66	4.51	4.79	4.50	2.26	2.33	1.61
MnO	0.08	0.12	0.08	0.09	0.04	<0.02	0.07	0.03	<0.02
MgO	51.3	35.7	15.0	14.3	14.9	14.5	14.3	11.6	13.1
CaO	<0.03	0.21	21.8	20.5	21.6	21.1	21.8	19.8	20.6
Na <sub>2</sub> O	na	0.04	1.49	2.05	1.50	1.90	1.34	2.76	2.35
Ni	0.15	na	na	na	na	na	na	na	na
TOTAL	99.76	100.40	99.70	99.91	99.75	99.37	99.35	99.69	99.43
Si	0.988	1.977	1.965	1.969	1.953	1.950	1.896	1.812	1.849
Ti	0.000	0.001	0.004	0.004	0.007	0.004	0.004	0.004	0.003
Al	0.000	0.017	0.126	0.176	0.140	0.174	0.303	0.537	0.437
Cr	0.000	0.002	0.001	0.003	0.003	0.002	0.004	0.004	0.005
Fe	0.157	0.178	0.143	0.137	0.147	0.138	0.069	0.070	0.049
Mn	0.002	0.003	0.002	0.003	0.001	0.000	0.002	0.001	0.000
Mg	1.863	1.826	0.819	0.774	0.814	0.791	0.773	0.622	0.703
Ca	0.000	0.008	0.855	0.798	0.849	0.829	0.848	0.766	0.798
Na	na	0.001	0.106	0.145	0.107	0.135	0.094	0.193	0.165
Ni	0.003	na	na	na	na	na	na	na	na
TOTAL	3.012	4.013	4.021	4.009	4.021	4.025	3.993	4.010	4.009
MG#	92.2	90.8	85.1	84.9	84.7	85.1	91.8	89.8	93.5
CA#	----	0.4	51.1	50.8	51.0	51.2	52.3	55.2	53.2

MG# = 100\*(Mg/(Mg+Fe)); CA# = 100\*(Ca/(Ca+Mg)); \* = total iron as FeO;  
na = not analyzed; @ = sample also reported by Shervais et al. (1988).  
Formula moles based on 6 oxygens for cpx and opx and 4 oxygens for olivine.

TABLE 3

## ESTIMATED EQUILIBRATION TEMPERATURES AND PRESSURES

	<u>Temp. °C</u>		<u>Pressure (Kb)</u>
	1	2	3
<b>Group A</b>			
437-1 <sup>@</sup>	834	---	---
437-2	852	851	45.5
<b>Group B</b>			
438-2 <sup>@</sup>	916	---	---
438-3	930	---	---
438-7 <sup>@</sup>	915	---	---
2791-21	1001	---	---
<b>Group C</b>			
437-5	934	---	---
437-7	986	---	---
2791-34	921	---	---

Refs: 1 = Ellis and Green, 1979; 2 = Wells, 1977;  
 3 = Wood and Banno, 1973. @ = sample also reported  
 by Shervais et al. (1988).

TABLE 5

## REPRESENTATIVE CORE AND RIM ANALYSES OF PHLOGOPITES

	A						B					
	437-1 <sup>a</sup>		437-2		438-2 <sup>a</sup>		438-3		438-7 <sup>a</sup>			
	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO <sub>2</sub>	39.7	37.7	41.3	37.7	38.7	37.7	39.4	36.1	39.1	39.1	35.8	
TiO <sub>2</sub>	0.08	0.06	0.51	0.10	1.47	1.08	1.01	0.48	0.94	0.94	0.85	
Al <sub>2</sub> O <sub>3</sub>	14.8	18.2	12.7	18.9	16.3	17.3	15.7	18.5	14.8	14.8	18.1	
Cr <sub>2</sub> O <sub>3</sub>	1.04	1.15	0.24	0.93	0.09	0.04	0.04	0.05	0.06	0.06	0.09	
FeO*	5.26	5.48	4.43	6.38	8.79	11.6	8.83	12.3	11.0	11.0	13.1	
MnO	0.04	0.05	<0.02	0.10	0.06	0.17	0.03	0.13	0.11	0.11	0.13	
MgO	25.5	21.8	24.1	20.3	19.3	17.2	19.5	16.4	18.3	18.3	16.4	
CaO	0.03	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	1.02	0.04	0.04	0.06	
BaO	0.60	0.57	0.38	0.55	0.38	0.33	0.22	0.51	<0.02	<0.02	0.23	
Na <sub>2</sub> O	0.58	0.53	0.17	0.55	0.31	0.55	0.18	1.14	0.21	0.21	1.11	
K <sub>2</sub> O	7.20	9.07	9.92	9.66	10.0	9.71	10.5	7.89	10.1	10.1	8.60	
F	<0.02	0.04	0.16	0.06	0.34	0.37	0.22	0.09	0.06	0.06	0.10	
Cl	0.10	0.13	1.41	0.26	0.04	0.04	0.08	0.03	0.04	0.04	0.04	
H <sub>2</sub> O	4.12	4.11	3.72	4.07	3.97	3.91	4.01	3.98	4.03	4.03	3.96	
TOTAL	99.07	98.91	99.07	99.58	99.77	100.03	99.74	98.62	98.80	98.80	98.57	
MG#	89.6	87.7	90.6	85.0	79.7	72.5	79.7	70.5	74.8	74.8	69.0	

TABLE 5: (Cont.)

	B				C			
	2791-21		437-5		437-7		2791-34	
	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO <sub>2</sub>	37.7	35.7	38.9	36.7	37.7	36.4	39.9	36.4
TiO <sub>2</sub>	1.09	0.22	1.31	1.42	1.14	0.59	1.59	0.62
Al <sub>2</sub> O <sub>3</sub>	17.2	20.9	21.3	21.9	19.0	20.5	16.9	20.5
Cr <sub>2</sub> O <sub>3</sub>	0.08	0.04	0.10	0.07	0.09	0.15	0.06	0.03
FeO*	9.26	12.0	5.59	7.28	6.31	7.36	6.59	8.40
MnO	0.09	0.14	0.06	0.04	0.03	0.04	0.03	0.04
MgO	19.4	16.7	17.7	16.8	19.7	18.4	19.7	18.0
CaO	<0.02	0.07	0.18	<0.02	<0.02	0.09	<0.02	0.07
BaO	0.84	0.41	0.55	0.66	0.26	0.60	0.32	0.65
Na <sub>2</sub> O	0.95	1.16	1.14	0.48	0.34	0.40	0.20	0.59
K <sub>2</sub> O	9.14	8.69	8.57	10.0	10.2	9.99	10.4	9.74
F	0.11	<0.02	0.07	0.06	0.23	0.04	0.32	0.12
Cl	0.04	<0.02	0.04	<0.02	0.04	0.03	0.05	0.03
H <sub>2</sub> O	4.06	4.09	4.20	4.14	4.04	4.08	4.03	4.05
TOTAL	99.97	100.16	99.71	99.59	99.19	98.67	100.11	99.24
MG#	78.8	71.3	84.9	80.5	84.8	81.6	84.2	79.2

MG# = 100\*(Mg/(Mg+Fe)); \* = total iron as FeO; @ = sample also reported by Shervais et al. (1988).

TABLE 6  
AVERAGE AMPHIBOLE ANALYSES

	B			C			
	438-2 <sup>ⓐ</sup>	438-5	438-7 <sup>ⓐ</sup>	2791-21	437-5	437-7	2791-34
SiO <sub>2</sub>	38.6	38.4	38.9	39.2	38.2	38.7	39.5
TiO <sub>2</sub>	0.12	0.20	0.30	0.19	0.15	0.17	0.38
Al <sub>2</sub> O <sub>3</sub>	20.4	19.6	17.8	19.4	21.9	21.4	20.6
FeO*	13.4	13.4	11.6	12.2	9.79	7.82	8.50
MnO	0.34	0.31	0.26	0.29	0.16	0.15	0.14
MgO	11.0	11.0	12.1	11.2	11.0	12.1	12.2
CaO	8.48	10.2	11.4	10.7	11.2	12.7	11.1
Na <sub>2</sub> O	3.84	2.85	2.62	3.08	2.85	2.14	3.12
K <sub>2</sub> O	0.81	1.26	1.60	1.35	1.60	1.65	1.60
H <sub>2</sub> O	2.00	2.01	2.00	2.03	2.03	2.03	2.00
TOTAL	98.99	99.23	98.58	99.64	98.88	98.86	99.14
MG#	59.3	59.3	64.9	61.9	66.7	73.4	71.9
CA#	35.7	40.1	40.6	40.9	42.1	42.9	39.5

MG# = 100\*(Mg/(Mg+Fe)); CA# = 100\*(Ca/(Ca+Mg)); \* = total iron as FeO;

ⓐ = sample also reported by Shervais et al. (1988).



TABLE 7  
REPRESENTATIVE FELDSPAR ANALYSES

	B		C		
	438-2 <sup>e</sup>	2791-21	437-5	437-7	437-7 Zeolite
SiO <sub>2</sub>	62.9	63.6	64.7	54.9	46.8
TiO <sub>2</sub>	<0.02	<0.02	0.02	0.07	1.05
Al <sub>2</sub> O <sub>3</sub>	17.9	19.3	18.3	20.5	19.9
FeO	1.65	0.22	0.03	0.02	0.46
MgO	0.74	0.16	<0.02	0.28	0.24
CaO	0.12	<0.03	<0.03	<0.03	0.23
BaO	0.13	0.99	0.12	11.9	22.9
Na <sub>2</sub> O	0.15	0.36	0.24	0.15	2.54
K <sub>2</sub> O	16.3	14.5	16.6	11.8	1.12
TOTAL	99.90	99.15	100.04	99.63	95.24

Representative Glass Analyses

	B			
	438-2 <sup>e</sup>	438-2 <sup>e</sup>	438-7 <sup>e</sup>	438-7 <sup>e</sup>
	K-rich	Na-rich	K-rich	Na-rich
SiO <sub>2</sub>	62.8	61.2	65.6	57.1
TiO <sub>2</sub>	0.05	0.04	0.04	0.13
Al <sub>2</sub> O <sub>3</sub>	18.4	23.7	17.5	25.9
FeO	1.33	1.23	0.98	1.87
MgO	2.82	0.12	0.03	0.49
CaO	0.22	0.32	<0.03	0.92
BaO	0.86	1.89	0.03	1.99
Na <sub>2</sub> O	0.18	10.6	1.47	11.3
K <sub>2</sub> O	13.3	0.68	14.8	0.73
TOTAL	99.96	99.78	100.45	100.43

@ = sample also reported by Shervais et al. (1988).