TABLE 86 COMPOSITIONS OF TWO LESOTHO GRIQUAITES CALCULATED FROM EQUAL PROPORTIONS OF THEIR GARNET AND CLINOPYROXENE CONSTITUENTS AND TWO GRIQUAITES FROM ROBERTS VICTOR MINE (KUSHIRO AND AOKI, 1968) COMPARED WITH LESOTHO THOLEIITES (COX *et al.*, 1968)

	Roberts Victor Type					
	Estimated Griquaite		Griquaites (Kushiro and Aoki, 1968)		Lesotho tholeiites (Cox *et al.*, 1968)	
	1446	*2307*	*1*	*6*	*B67*	*Average*
SiO_2 . . .	44,63	48,56	45,67	49,49	49,0	51,8
TiO_2 . . .	0,23*	0,44*	0,42	0,52	0,89	1,13
Al_2O_3 . .	14,98	13,73	17,85	8,46	11,6	14,8
Cr_2O_3 . .	0,08	0,09	0,07	0,24	0,08	0,05
Fe_2O_3 . .	—	—	2,88	3,20	2,80	3,92
FeO . . .	12,46	9,76	8,46	5,80	9,88	7,26
MnO . .	0,27	0,24	0,17	0,24	0,16	0,17
MgO . .	10,68	14,05	11,90	16,23	11,8	7,1
CaO . . .	11,77	12,34	7,35	10,60	8,12	10,57
Na_2O . .	2,46	1,93	2,01	1,67	1,85	2,40
K_2O . . .	n.d.	n.d.	0,39	1,12	0,59	0,74
H_2O^- . .	n.d.	n.d.	1,07	0,64	—	—
H_2O^+ . .	n.d.	n.d.	2,01	1,43	3,23	—
P_2O_5 . . .	n.d.	n.d.	0,04	0,04	0,06	0,13
Totals . .	—	—	100,29	99,68	100,06	—

* Ti may be present in ore minerals which are not allowed for in the calculation of the rock composition.

Texturally, these griquaites resemble those of the Roberts Victory type. Rounded dark green diopside and orange brown garnet are interlocked in a simple mosaic, but rarely they form lamellar intergrowths (plate 24B). Accessory constituents include coarse bronzite, granulated olivine or rare ilmenite and sulphides.

In chemical composition they are richer in MgO and poorer in CaO than the Roberts Victor type of griquaite on account of the subcalcic diopside. There is no likely basaltic equivalent, unless it be picrite. Their tendency, to occur as discrete nodules suggests, however, that they are not high pressure equivalents of such a rock.

The discrete nodules are rounded but occasionally fluted or dimpled giving an impression of having been plastic perhaps having been subjected to rheid flow. In several instances the griquaite texture appears to have originated through the kneading together of such pyrope and diopside pellets. They were thought to be segregations (phenocrysts) within the kimberlite magma (Nixon *et al.*, 1963) but they are more likely to have developed as phenocrysts in the crystal-mush magmas in the sheared peridotite low-velocity zone of the earth's upper mantle (Nixon and Boyd, p. 74).

Diamonds in eclogites and other deep-seated nodules

Diamonds are relatively common in eclogites (e.g. Rickwood and Mathias, 1970) compared with other deep-seated nodules.

No ultrabasic nodules from Lesotho have been observed to contain diamonds, although about 10 granular specimens are known to contain graphite. If eclogites of the Roberts Victor type are regarded as occurring as lenses within the mantle, then diamond-bearing varieties must occur low in the granular zone (lower B zone in figure 79 – next section) or within the shear zone. This is in accordance with the diamond-graphite inversion curve (Berman, 1965) and Boyd's pyroxene geotherm data this volume, figure 70).

Bosch (1971) records diamond inclusions in pyrope nodules which are here assigned to a deeper zone (C, in figure 79, next section, p. 315).

Diamonds of unknown provenance include those with Cr-rich, Ca-poor pyrope inclusions (Meyer and Boyd, 1972) which Sobolev *et al.* (1973) relate to a dunitic paragenesis. This suite, although recognized in Lesotho and South Africa (and conjectured to comprise peridotite minus mobilized garnet pyroxenite constituents), is poorly documented. Although Ca-poor pyropes may indicate a high pressure origin on experimental grounds (Kushiro *et al.*, in Boyd, 1973) the degree of Ca solid solution in the enstatite inclusions in diamonds is small (Meyer and Boyd, 1972), indicating only moderate temperatures of formation.

Without more data from rocks of equivalent mineral composition, it can only be surmized that this mineral suite including diamond formed at greater depth than either the diamonds associated with eclogites or discrete nodules, under conditions where a normal geotherm existed, i.e., either they were erupted before the geotherm was perturbed (Boyd 1973) or they formed below the perturbed zone of the geotherm.

The Evidence of Kimberlite and its inclusions on the Constitution of the Outer Part of the Earth

P. H. NIXON, F. R. BOYD and ANNE-MARIE BOULLIER

The important role of kimberlites in providing a section, albeit a discontinuous one, of the outer layers of the earth has been long appreciated (see "Historical Survey" above).

The crust

Rocks from the crust are usually easily recognizable, even if hydrothermally altered, on account of their sialic components, e.g. felspar, quartz, hornblende, biotite, epidote, combined with (very often) metamorphic features, e.g. gneissose banding, augen, and schistosity. In Lesotho the metamorphic grade varies from amphibolite through granulite to eclogite facies (e.g. Bloomer and Nixon, p. 28, Nixon and Boyd, p. 106). Many rocks are clearly derived from the Precambrian basement at relatively shallow depth (e.g. plates 33B and 43B). As noted in the section on crustal eclogites (p. 308) the granoblastic garnet granulites are a widespread high grade metamorphic variety found in Lesotho kimberlites. They consist of equant grains, showing 120° grain boundaries in thin section, which resemble the tetrakaidecahedra of close-packed cells in plants. They are interpreted as an equilibrium texture of minimum surface energy produced by annealing under high pressure.

In addition to the pyrope-almandine and grey green omphacitic pyroxene that characterizes the eclogitic mafic bands, plagioclase (andesine) is present, and accessory rutile, apatite and sometimes kyanite and scapolite. These nodules are thought to represent the deepest crustal layer beneath Lesotho. Similar scapolite gneisses from the basement rocks of Ghana have been shown by von Knorring and Kennedy (1958) to have formed under conditions very close to those of the eclogite facies.

The mantle

The recognition of depth zones within the mantle is possible through a study of ultrabasic (lherzolite) nodule mineral chemistry based on experimental and theoretical phase studies (Boyd, 1973; Boyd and Nixon, this volume, p. 262). This is particularly so when the study is combined with fabric analysis. In table 87 are shown the PT origins deduced for a suite of ultrabasic nodules from Lesotho kimberlites, together with an *independent* classification of their fabric.

With increasing depth the ultrabasic nodules vary in texture, thus (the textures are described in detail by Boullier and Nicholas, p. 57 *et seq.*):

1 Coarse grained types with no foliation (plates 19A and B).

2 Foliated types with aligned tabular olivine and enstatite crystals (plate 20A).

3 Porphyroclastic types with large elongated olivine and enstatite crystals in an undeformed mosaic of smaller crystals (Plate 20B).

4 Mosaic types have been replaced by the smaller crystal mosaic, (plates 15B and 21A) on which a non-penetrative shear deformation may be superimposed (plate 21B).

The upper mantle can thus be tentatively divided into depth zones each characterized by a textural type. Much more work has to be done to confirm whether this pattern can be extended outside the Lesotho area and to ascertain the significance of aberrant nodules that do not conform to the normal geotherm (Boyd, 1973). However, unusual textural varieties, mentioned below, suggest that some degree of fusion, liquid migration and recrystallization has taken place. One ilmenite-bearing nodule from Matsoku and another from Thaba Putsoa have possibly been derived from above the zone represented by the highly sheared nodules (Boyd and Nixon, p. 264). Many of the Matsoku nodules show a gneissose structure and have obviously been contorted (op cit.). They do not possess, however, the deep-seated mineralogy of the highly sheared nodules from Thaba Putsoa. They are also tentatively ascribed to the porphyroclastic layer (figure 79) at the base of the African plate. To account for the gneissose structures it is conjectured that the layer was "drag" folded resulting from movement along the underlying main sub-continental shear zone (mosaic layer).

The petrological and structural evidence for this model is supplemented by a consideration of other aspects, viz., the bulk chemistry and seismic data.

The relatively depleted nature of the granular lherzolites of "basaltic" constituents, compared to the sheared lherzolites, has been demonstrated by

TABLE 87 ULTRABASIC NODULES FROM LESOTHO SHOWING THEIR CALCULATED TEMPERATURES AND PRESSURES (IN TERMS OF DEPTH) OF ORIGIN AND FABRIC ANALYSES CLASSIFICATION

No.	Macroscopic identification	Locality	T°C	Km*	Fabric analyses classification	Group
1595	Granular, with phlogopite	Thaba Putsoa	930	132	Tabular olivine and enstatite	2
1567	Granular, with phlogopite	” ”	950	134	Coarse grained	1
1592	Granular	” ”	955	134	Tabular olivine and enstatite	2
1572, 3	Granular, with phlogopite	” ”	980	142	Tabular olivine and enstatite	2
1568	Granular	” ”	985	137	Tabular olivine and enstatite	2
1559B	Granular, with phlogopite	Mothae	1025	158	Porphyroclastic	3
1654	Granular (with shear lenticles) – with phlogopite	Matsoku	1050	158	Tabular olivine and enstatite	2
1582	Intermediate ilmenite bearing	Thaba Putsoa	1115	172	Porphyroclastic	3
2001	Sheared	Mothae	1240	188	Porphyroclastic	3
1591	Sheared	Thaba Putsoa	1260	195	Porphyroclastic	3
1924	Sheared	Mothae	1345	194	Mosaic	4
1925	Sheared	”	1365	194	Mosaic	4
1611	Sheared	Thaba Putsoa	1380	199	Mosaic	4
1566	Sheared	” ”	1405	204	Mosaic	4
1596	Sheared	” ”	1415	204	Mosaic	4

* Pressure (depth) calculated from “raw” Al content of enstatite (see Boyd and Nixon, p 262) without correction for small amounts of Na, Fe and Cr. The effects of these constituents are discussed by Boyd (1973).

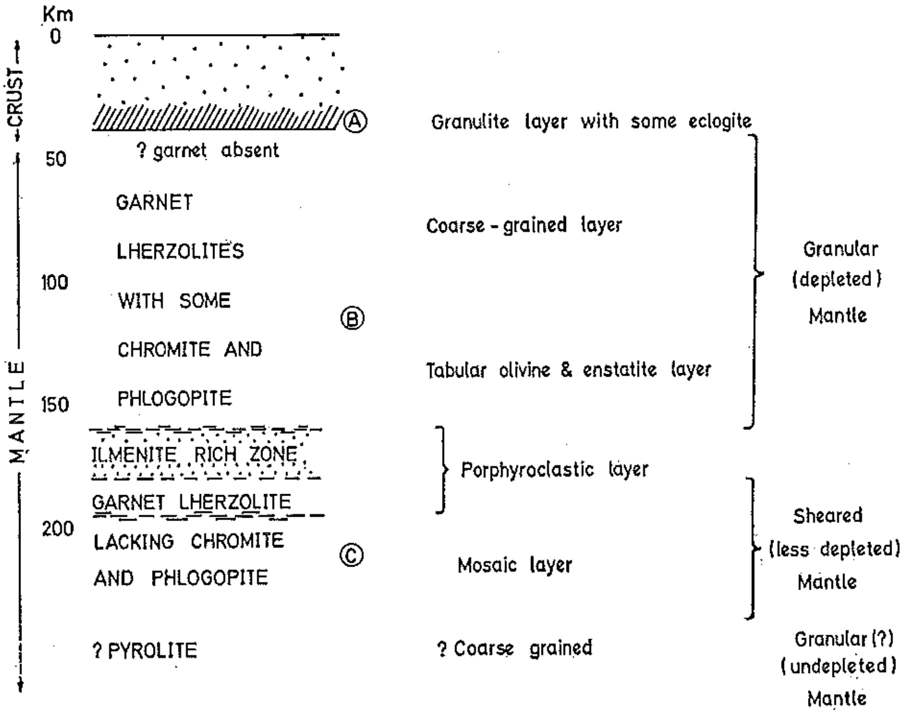

Figure 79 A schematic representation of the upper mantle and crust beneath Lesotho based on the evidence of deep-seated nodules in Cretaceous kimberlites. The points A, B, and C represent the relative levels of formation of crustal eclogites, Rödhaugen and Roberts Victor type of eclogites, and Thaba Putsoa type of eclogites respectively (see text). Whilst A is confined to the lower crust B may extend from the base of the crust (Mohorovicic discontinuity) to the ilmenite-rich zone. The depth in kilometres is calculated from pyroxene raw data (see Boyd, 1973 and Boyd and Nixon, p. 262) and the values, therefore, cannot be regarded as absolute. This does not, however, affect the relative positions of the various zones.

Nixon and Boyd (p. 49). The experimental data of Kushiro (p. 298) further argues that tholeiites, in this case the Lesotho Stormberg lavas, could have arisen from rocks similar in composition to the less depleted sheared nodules. The model conforms therefore, with a logical sequence of decreasing degree of depletion with depth, that one might expect in a mantle that had yielded a variety of magmas through geological time up until the period of kimberlite intrusion.

The coincidence of the sheared zone in the mantle with the low velocity zone (Boyd, 1973) may be explained in two ways.

Firstly, according to Holmes (1965) "The lowered velocity depends on the temperature of the material in relation to the melting point, the velocity being least where the actual temperature makes its nearest approach to the melting point". Under conditions of high P_{H_2O}, the experimental data of Mysen and Boettcher (1972) indicate that partial fusion could take place in the garnet lherzolite mantle particularly in the deeper zones. The extent to which this occurred at the time of kimberlite eruption or is operable at the present time (to account for the observed low velocities) is uncertain. However, in addition to the evidence afforded by the generation of basalt magma the following "fossilized" evidence for a liquid phase in the mantle should be noted: veinlets of clinopyroxene or pyrope (plate 23B) in ultrabasic nodules at Matsoku, Monastery (p. 220) and Letseng-la-terae (p. 29), and trails of minute pyropes and "pools" (plate 29A; Cox, Gurney and Harte, p. 86); (*b*) lamellar or rod-like intergrowths between the following lherzolitic minerals: clinopyroxene, orthopyroxene, pyrope and chromite, e.g. Letseng-la-terae (Bloomer and Nixon, p. 30); Ngopetsoeu (locality given in figure 1) and Frank Smith (South Africa, Nixon and Boyd, 1973); (*c*) glassy veinlets in peridotite nodules from an East African kimberlitic volcano (Nixon, 1973).

Secondly, there is a *gradual* wave velocity decrease with depth (Holmes, 1965, p. 949) which could correspond with the transition from the slightly foliated tabular olivine and enstatite layer to the deeper highly foliated layer, suggesting that it may be a structural effect. Certainly, vertical vibrations are transmitted through the zone more rapidly than the horizontal ones (op cit., p. 950) and this is stated to be indicative that the foliation is parallel to the low velocity zone. After passing a minimum and resuming the normal downward increase, the velocity, as it was just below the Moho, is only regained at a depth of about 250 km or higher (Holmes op. cit.). This pattern can be regarded as being "perturbed" – in the same way that the geotherm is perturbed (Boyd, 1973). Furthermore it suggests that the normal geothermal gradient may be resumed at similar depths.

The resumption of unperturbed conditions suggests that there are rocks, similar in texture to the coarse grained types immediately underlying the crust (figure 79), that also characterize the zone below the shear zone. These are presumably even less depleted chemically than the sheared types and thus even closer, or equivalent, in composition to the pyrolite of Ringwood (1966). As nodules of this type have not been found it must be assumed that kimberlite magma developed above this zone in Lesotho. This is borne out by the discrete nodules, which are regarded as phenocrysts of crystal mush magmas (if not of the kimberlite magma itself) and which have developed within the shear zone (Nixon and Boyd, p. 75). The crystal mush nature of the shear zone is regarded as an ideal vehicle for the process of zone-refining (defined by Harris, 1957 and adapted by Green and Ringwood, 1967) and this may account for the observed small chemical trends in the discrete nodules, whilst enabling upward concentration of intergranular, K-bearing, volatile-rich liquids to take place.

If the foliated ultrabasic rocks are the cause of velocity decrease within the earth's mantle, what evidence is there to support the observed rise of the velocity zone towards oceanic areas? The sheared ultrabasic nodules and their associated discrete nodules *are not everywhere formed at the same depth*. Nixon and Boyd (in preparation) show that the maximum depth indicated by the nodules at Thaba Putsoa is $>$ 200 km whereas at Letseng-la-terae it is slightly less and in S.E. Lesotho and East Griqualand it is 10–20 km less. The shear zone thus rises away from the old (1 850 ± 250 m.y.). Rhodesia-Transvaal craton (Clifford,

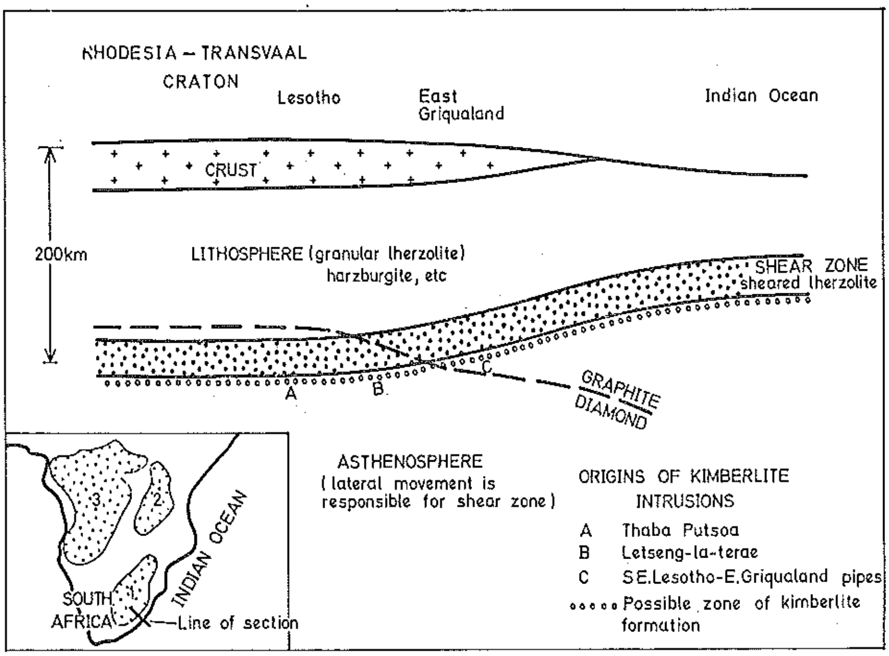

Figure 80 A schematic section through the SE portion of the Rhodesia-Transvaal craton (see inset, after Clifford, 1970) showing the shear zone at the base of the African Plate rising towards the Indian Ocean. The effect of this zone is to produce locally elevated temperatures and reduced earthquake wave velocities within the earth. Kimberlites (indicated by A, B and C) which arise in or below the shear zone may form within the graphite stability field at the edge and outside the craton. The evidence is based on the calculated depths of equilibration (Boyd, 1973) of ultrabasic nodules from Lesotho and East Griqualand kimberlites. (After Nixon and Boyd, in preparation).

1970) towards the Indian Ocean and must represent a decrease in the depth of the base of the African plate (figure 80).

In spite of the fact that the evidence applies to a Cretaceous model, and that waning Gondwana movement along the plate shear zone may have taken place since kimberlite intrusion, the structural picture has probably not changed significantly. However, the degree to which the geotherm is still perturbed depends on several factors including the present rate of stress heating in the mantle.

If kimberlites have arisen within the sub-continental shear zone through stress heating, it is reasonable to expect that other magmas, e.g., olivine melilitite, nephelinite and alkali basalt are capable of doing so at the appropriate depth of the shear zone. Thus, tectonic considerations, as recognized by Kennedy (1933) and Kennedy and Anderson (1938) are likely to provide clues to the origin of these magmas and their distribution.

An economic implication of the decrease in the depths of the shear zone and the focus of kimberlitic magmatic activity, is that conditions of diamond stability may no longer obtain, and this appears to be the case in the SE Lesotho–

East Griqualand kimberlite field which is virtually devoid of diamonds. There are other physical and chemical reasons why a kimberlite may be devoid of diamonds but over the African continent as a whole Clifford (1966) has observed that diamond-bearing kimberlites are restricted to the craton areas that have remained stable since the end of the 1850 ± 250 m.y. orogenesis.* It is concluded that only in these areas was the crust and accompanying granular mantle (i.e. the plate) sufficiently thick and, consequently, the zones of shear and kimberlite magma formation sufficiently deep for diamonds to have formed in them.

When more ultrabasic nodules have been studied from more kimberlites of different ages, it may be possible to chronicle fluctuations in the geotherm and their influence on zones of diamond stability. It should also be feasible to chart the structural evolution of the upper mantle and the sequence of magmatic depletion that has occurred (and recurred) from place to place.

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* A similar observation has been made for the diamond deposits of Brazil (Verwoerd, 1970).