

KIMBERLITES AND ASSOCIATED INCLUSIONS OF BASUTOLAND: A MINERALOGICAL AND GEOCHEMICAL STUDY

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ABSTRACT

Mineralogical and chemical data of some Basutoland (South Africa) kimberlites are presented. The minerals fall into three groups, *viz.*, those belonging to kimberlite proper, those of the ultrabasic nodules and those of the eclogite-granulite-amphibolite group of nodules. The kimberlite minerals include ilmenite, pyrope, diopside (with probably omphacitic varieties) and the more ferriferous olivines and orthopyroxenes. They are found as discrete grains and pebbles and, more rarely, as "clots" or segregations in the serpentinous kimberlite matrix. The ultrabasic nodules consist essentially of chrome pyrope, chrome diopside, enstatite and forsteritic olivine. Significant proportions of the hanléite "molecule," $Mg_3 Cr_2 (SiO_4)_3$, in the chrome pyropes and the chrome acmite "molecule," $NaCrSi_2O_6$, in the chrome diopsides were recorded. The eclogite-granulite-amphibolite nodule group is characterised by pyrope-almandine, omphacitic clinopyroxene, rutile, plagioclase and hornblende.

The ultrabasic nodules are similar to some of the peridotite "bombs" in basalts and probably represent mantle material. Such mineralogical differences as occur between the two types are attributed to differences in depths of origin.

The eclogite, granulite and amphibolite types of nodule are mineralogically similar to rocks observed in metamorphic terrains and are, therefore, crustal xenoliths. The occasional presence of diamond, described by earlier writers, in eclogite nodules is contributory evidence in favor of a deep-seated eclogite zone in "shield areas" of the earth's crust (where kimberlites usually occur).

Certain garnet-bearing nodules (griquaïtes) which are similar in appearance to eclogites are considered to be cognate with kimberlite.

INTRODUCTION

The term "kimberlite" was proposed by Lewis (1888) for the brecciated, serpentinized, peridotitic rocks occurring in the Kimberley area of South Africa. Similar rocks are found elsewhere in Africa, *e.g.*, South-West Africa, Northern Angola, Belgian Congo, Southern Rhodesia, Tanganyika and French Sudan, and also in other parts of the world, *e.g.*, Siberia, Brazil, Central India, Western Australia and Western North America. Typically they occur in the Precambrian "shield" areas of the earth's crust.

The form of the kimberlite bodies, revealed by diamond mining (Wagner, 1914; Williams, 1932), is that of a downward-tapering volcanic plug or pipe which in cross section is irregularly rounded and lobed, often

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being adjoined by one or more dikes. The pipes, varying in mean diameter from tens of yards to about half a mile, may contain several kimberlite rock types, each with a distinctive diamond content. Such intrusions are considered to be products of several distinct eruptions (Wagner, 1914, p. 36). Contact metamorphic effects in the adjacent country rocks or inclusions within the kimberlite are remarkably slight, in spite of the fact that it is commonly believed (mainly on evidence provided by the presence of diamond) that kimberlite originated at great depth.

In addition to inclusions of country rock (accidental xenoliths), varying greatly in shape and size, there occur rounded garnet-bearing ultrabasic and eclogitic nodules, referred to by Williams (1932, II, p. 354) as "cognate xenoliths," thus implying a genetic connection with kimberlite. Bonney (1899, 1901) and Davidson (1943), however, maintain that such nodules, including diamond-bearing types, have been derived from the Precambrian basement during intrusion of kimberlite.

A mineralogical and geochemical study of kimberlite mineral concentrates and of a representative selection of "cognate" nodules mainly from Basutoland, forms the basis of the present work. Our aim is to determine the origin of these nodules and their role in kimberlite genesis, and to assess the evidence they provide on the nature of the earth's outer layers in "shield" areas.

BASUTOLAND FIELD OCCURRENCES

The country rocks consist, in the western lowland areas and in river sections in the south, of alternating Karroo sandstones, mudstones and shales (mainly Triassic age) with numerous dolerite dikes. Predominant, however, are the overlying near-horizontal, deeply dissected, amygdaloidal Drakensberg lavas, which form the highlands of eastern Basutoland and are several thousands of feet thick.

The kimberlite intrusions (Fig. 1) have been described by Stockley (1947), Dawson (1960, 1962) and Nixon (1960). Those in the western lowlands contain country-rock xenoliths of sandstone and shale as well as more rounded basaltic boulders of the Drakensberg type, suggesting that the eastern volcanics occupied an area much further west at the time of kimberlite intrusion (probably Upper Cretaceous). Conversely, the eastern highland kimberlites contain local nodules of shale and sandstone, carried through the Drakensberg lavas from the underlying sedimentary rocks.

The pipes are invariably located on kimberlite dykes having a regional trend of about WNW-ESE. Within the lavas (where most contacts with kimberlite have been observed) there is little evidence of tectonic dis-

turbance or contact metamorphism even in the larger intrusions, for example, the $\frac{1}{4}$ mile diameter Kao pipe.

PETROGRAPHY

Kimberlites. The three well known kimberlite types, defined on their degree of weathering as Yellow Ground, Blue Ground and Hardebank, are all found in Basutoland, but in the highlands the topmost Yellow Ground is typically absent, since physical rather than chemical weathering predominates.

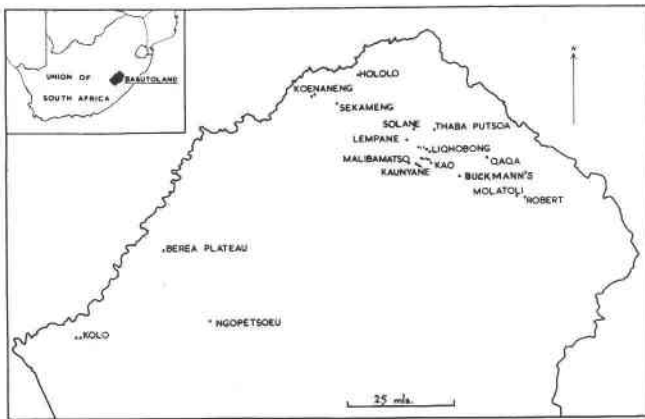


FIG. 1. Map of Basutoland (southern part omitted) showing position of kimberlite localities.

Yellow Ground is a soft, yellow, friable or clayey rock consisting of decomposed olivine pseudomorphs and rotted phlogopite flakes held together with a zeolitic, calcitic and limonitic secondary mineral aggregate. Ilmenite, pyrope and chrome diopside may be conspicuous in this highly oxidized and hydrous rock. The less altered Blue Ground contains a high proportion of serpentine minerals; structures such as joints and small shear zones with slickensiding are found.

Hardebank, the fresh hard kimberlite, is a carbonated, serpentinized, micaceous peridotite containing garnet, pyroxene and ilmenite. Chemically (anal. 1, 2, Table 1) it is characterized by high magnesia, a high K_2O/Na_2O ratio and low alumina. Two main varieties have been recognized (Wagner, 1914), (a) basaltic kimberlite, (b) lamprophyric or micaceous kimberlite.

In (a) phenocrysts of olivine or its serpentine pseudomorphs usually form 50–70% of the rock; the groundmass is rich in serpentine, perovskite, calcite and iron ores. Phlogopite is usually present but is not so

TABLE 1. ANALYSES OF KIMBERLITES, ULTRABASIC AND ECLOGITIC ROCKS

	1	2	E3	E11	3	4	E4	5	6
SiO ₂	35.02	36.33	45.15	42.30	42.42	44.35	46.98	46.26	50.24
TiO ₂	1.22	1.89	0.15	0.18	0.30	0.14	1.22	0.28	0.16
Al ₂ O ₃	3.90	5.09	2.27	2.87	1.32	2.97	15.26	14.45	7.71
Cr ₂ O ₃	—	—	0.21	—	0.40	0.41	0.00	—	0.54
Fe ₂ O ₃	5.15	7.43	0.27	2.46	4.27	0.67	1.42	4.41	1.02
FeO	4.14	3.40	6.35	5.25	6.96	7.59	9.76	5.82	4.64
MnO	0.06	0.10	0.12	0.12	n.d.	0.13	0.18	n.d.	0.11
MgO	31.29	26.63	42.21	40.01	40.80	40.80	11.51	11.99	17.79
CaO	6.80	6.78	2.08	1.75	1.19	2.55	11.34	11.66	16.66
Na ₂ O	0.34	0.37	0.24	0.18	0.72	0.20	2.30	2.45	0.97
K ₂ O	1.05	2.43	0.00	0.06	0.45	0.01	0.03	1.51	0.11
H ₂ O ⁺	7.43	7.25	0.65	4.49	0.70	0.06	—	1.10	—
H ₂ O ⁻	—	—	0.12	0.44		0.03	—		—
P ₂ O ₅	0.87	0.66	0.03	0.04	0.10	0.02	—	—	0.05
NiO	—	—	—	—	—	0.31	—	—	—
CO ₂	2.73	1.64	—	—	—	0.00	—	—	—
S	—	—	—	—	0.04	—	—	—	—
	—	—	99.85	100.15	99.67	100.24	100.00	99.93	100.00
G	—	—	3.25	—	3.255	—	3.62 (calc.)	—	3.41

1. Average chemical composition of basaltic kimberlite, 10 analyses (Nockolds, 1954).

2. Average chemical composition of micaceous kimberlite, 4 analyses (Nockolds, 1954).

E3. Lherzolite nodule, kimberlite, Thaba Putsoa. Analyst: M. H. Kerr.

E11. Lherzolite nodule, kimberlite, Fm. Lourwencia, S. W. Africa. Analyst: M. H. Kerr.

3. Lherzolite dunite bomb, basaltic rock, Parto Moniz, Madeira (Gagel, 1912).

4. Peridotite xenolith, basalt, Ludlow, San Bernardino Co., California (Hess, 1960, p. 179).

E4. Eclogite nodule, kimberlite, Kao, calculated from mineral analyses; pyrope-almundine, 49.5%; omphacite, 49.5%; rutile, TiO₂, 1%; minus water, recalculated to 100%. Analyst: M. H. Kerr.

5. Eclogite, Burgstein, Otztal, Tirol (Hezner, 1903).

6. Griquaite, Roberts Victor Diamond Mine, S. Africa, recalculated to exclude calcite and water (Wagner, 1928).

conspicuous as in (b) where it may form 50% of the rock (hence the higher K₂O content; Table 1, anal. 2). Wagner (1914) states that perovskite and iron ores are relatively scarce in the micaceous variety.

The trace elements in fourteen Basutoland kimberlites have been discussed in detail by Dawson (1960). A wide variety is present including

Rb, alkaline earths (Sr, Ba), group III elements (Y, La) and groups IV and V elements (Ti, Zr, Nb, V, and P). As in other ultrabasic rocks the Ni to Co ratio is high.

Kimberlite mineral concentrates. Heavy minerals ($G > 2.9$) constitute varying proportions of the kimberlite rock, but probably the 7% deter-

TABLE 2. RELATIVE PROPORTIONS OF MINERALS IN KIMBERLITE CONCENTRATES
(x=rare; xxxxx=abundant)

Locality	Ilmenite	Garnet	Ortho- pyroxene	Olivine	Phlogo- pite	Other notable minerals
Kao No. 1	xxxxx	xxx	xxxx	x	xx	Diamond, chrome diopside
Lighobong No. 1	xx	x	x	xxxxx	x	Diamond, chromite
Thaba Putsoa	xxxx	xxxx	x	xxx	xxx	Dark green diopside
Solane	xxxxx	xxxxx	x	xx	x	
Hololo	xxx	x	x	xxxxx	x	Diamond
Louwrencia, nr. Gibeon, S.W. Africa	xx	xxx	xxx	xxx	xxx	Chrome diopside (xxx)
Sekameng	xxxx	xxx	xx		xxx	
Molibi's (Berea Plateau) ¹	xxxx	xxxx	xx		xxxxx	Chrome diopside
Ngopetsoeu ¹	x	x	xxx		x	Chrome diopside

¹ Adopted from Stockley (1947)

mined for hardebank from Kao pipe represents an average. Kimberlite washings typically contain minerals, for example chrome-diopside, derived from "cognate" xenoliths which have been disrupted during intrusion of the kimberlite; hence a wide variety of garnet, clinopyroxenes, etc., is present. The relative proportions of the major heavy minerals in some Basutoland kimberlites are shown in Table 2.

Dull metallic, bluish-black, flattened ellipsoids of *ilmenite*, up to 2 inches across, are present in all Basutoland kimberlites. They may have striations, "pluck" marks and flat "soles" which are indications of the abrasions inflicted during kimberlite intrusion. Some pebbles contain narrow cylindrical channels and spherical cavities (about 1 mm in diameter), lined with secondary perovskite, leucoxene, goethite, haematite and calcite; these appear to have been formed by the escape of gas.

Garnet (pyrope)—excluding the garnet constituent of the "cognate" xenoliths—occurs as discrete, reddish-brown, rounded nodules with numerous irregular kelyphitised fractures. A kelyphite rind may be present but it has commonly been stripped off during kimberlite intrusion. The garnets vary from a few millimeters to more than several centimeters across, as in Solane and Thaba Putsoa pipes; Williams (1932, II, p. 368) illustrates a six-inch diameter nodule.

Rounded dark bottle-green *clinopyroxene (diopside)* nodules, consisting of single crystals, are also common in the Solane and Thaba Putsoa pipes. They are fractured and show a size range similar to that of the pyropes. Scattered minute spherical inclusions of nickel-bearing sulfides of the pentlandite type are observed. Similar clinopyroxenes, some euhedral, are present in the groundmass of less heavily serpentinized Basutoland kimberlites. These appear to be the "augites" described from South African kimberlites by Bonney and Raisin (1895), Wagner (1914, p. 68) and Williams (1932, I, p. 125). Du Toit (1934) distinguished between this type of clinopyroxene and at least one other kimberlitic variety, as is seen from his statement ". . . I have referred some of the diopside—but not the green chrome diopside—to the magma, and perhaps a little of the enstatite also."

Distinct from the above is a diopside (S89, from the Premier Mine) which occurs as an off-white nodule, consisting of finely fibrous sheaves of radiating crystals and bounded peripherally by a pale green porcelainoid layer of serpentine. From its texture there is little doubt that it formed in kimberlite at a relatively shallow level.

The "cognate" xenolithic clinopyroxenes are described further on.

Few *orthopyroxenes*, unless patently fragments of ultrabasic nodules, have been observed in Basutoland kimberlites or their heavy mineral concentrates, presumably because of their extensive alteration to serpentine. However, certain olive green and grey bronzite fragments from Kao, Lighobong No. 2 and Thaba Putsoa kimberlite washings must at present be assigned to the kimberlite rock, for this mineral has not been observed in the compound inclusions.

Olivine, according to Williams (1932, II, p. 365), has three modes of occurrence in kimberlite rock:

1. Megascopic olivine phenocrysts of the type found in peridotite and pyroxenite nodules.
2. (a) Porphyritic crystals of the first generation.
(b) Smaller serpentinized groundmass crystals of the second generation.

Owing to heavy serpentinization of Basutoland kimberlites, most of the olivine phenocrysts probably belong to group 1, having been derived by fragmentation from comparatively fresh ultrabasic nodules. However, the available data are insufficient for one to say with certainty that group 2 (a) differs petrographically or mineralogically from group 1 and the extent to which it is represented.

Olivines of group 2 (b) have been observed in several kimberlites, particularly in dikes as at Molatoli, where the euhedral crystals are up to 2 mm long, partially serpentinized, and show conspicuous 001 parting. They undoubtedly crystallized within the kimberlite itself.

Other minerals from Basutoland kimberlites include *phlogopite*, occurring in hexagonal plates up to 1 cm across or as nodular aggregates accompanied by other kimberlitic minerals. Alteration to friable, inelastic, metallic blue green or dull bronze *vermiculite* is common.

Perovskite is an invariable constituent of the kimberlite groundmass; in some cases at least, peripheral alteration of ilmenite has given rise to the mineral. Typically, it occurs as resinous, dark smoky-brown, semi-opaque cubes (<0.2 mm across), modified by a development of octahedral faces. Re-entrant angles, due to lamellar twinning, occur along the cube edges. The larger crystals especially are anisotropic, apart from opaque patches of ilmenite (?).

Apatite, although not detected in Basutoland kimberlites, is probably present as minute crystals, chemical analyses showing the presence of P_2O_5 . Wagner (1914, pp. 70, 83) and Williams (1932, II, p. 391) have described kimberlitic apatites.

Zircon exhibits golden fluorescence in ultraviolet light, and has by this method been detected in 25 out of 55 hand sieve concentrates from Kao pipe. It occurs as short rounded, colorless prisms with frosted surfaces; a specimen from Kao pipe No. 2 had a cream-colored skin of *baddeleyite*. The common occurrence of zircons in South African kimberlites has led to the belief that they are genetically connected with kimberlite rather than derived from accidental inclusions; however some have doubtless originated in this way, for example from basement granites.

Ultrabasic nodules. This is the commonest type of "cognate" xenolith in Basutoland kimberlites. The nodules, ovoid and up to 2 feet in diameter, are sharply demarcated from the enclosing kimberlite (Fig. 2). They have a coarse holocrystalline equigranular texture with a grain size of about 2–3 mm and comparatively fresh appearance. The marginal parts of nodules may be serpentinized or replaced by a hard compact "shell" of kimberlite which apparently protected the inside from alteration. The



FIG. 2. Ultrabasic nodule, Lighobong, Basutoland.

minerals in some nodules, *e.g.* E3 lherzolite from Thaba Putsoa, have granulated margins, irregular extinction and translation lamellae, indicating that the rock has been subjected to strong shearing stress. Mylonitic textures have also been observed (Fig. 3).

Chemically the ultrabasic nodules are comparable to ultrabasic "bombs" and xenoliths in basalts (Table 1, Nos. E3, E11, 3 and 4). Compared with kimberlites, however, they are lower in Ti (ilmenite and perovskite in kimberlites), Ca (calcite), K (phlogopite), P (apatite), H_2O+ (serpentine); but they are richer in Si and Mg. Cr and Ni are also

higher (>3000 p.p.m.; Nixon, 1960), but the variety of trace elements found in kimberlites is lacking.

Modal analyses of ultrabasic nodules (Table 3) illustrate the predominance of olivine and, to a lesser extent, enstatite. Nodules, or patchy segregations within them, may however show high proportions of chrome pyrope and/or chrome diopside (G12, Table 3). Other constitu-

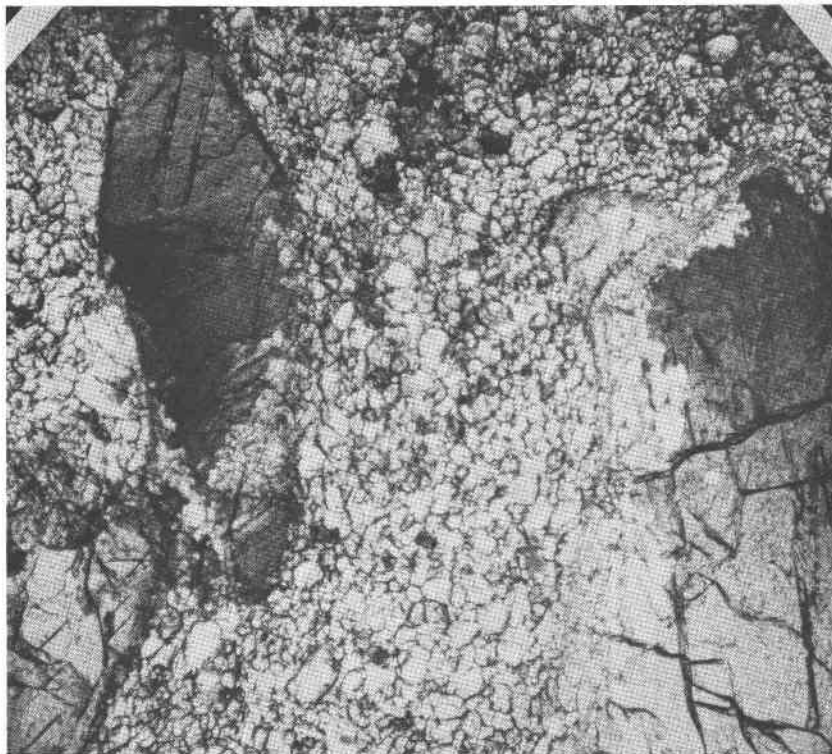


FIG. 3. Ultrabasic nodule E3 showing mortar texture. Note the irregular extinction of the well-cleaved olivine grains. Crossed polars ($\times 40$).

ents are kelyphite, rimming the garnet, and in a few nodules, chromian spinel, phlogopite and graphite.

The main mineral species are described below in the same order as for kimberlites.

Chrome pyropes, in both the kimberlite heavy mineral concentrates and the parent ultrabasic nodules, occur as near spherical, deep blood-red or purple grains. The *kelyphitic alteration rind* (normally stripped off the garnets in the concentrates) consists of a sharply demarcated inner

TABLE 3. MINERAL COMPOSITION OF ULTRABASIC NODULES FROM KIMBERLITE

	E1	E2	E3	E5	E8 ¹	E9	E11	G12
Olivine	55	50	66	69	56	61	65	20
Enstatite	36	39	15	7	41	34	12	25
Chrome diopside	1	3	11	18	0	1	17	35
Chrome pyrope	3	3	3	1	} 2	3	5	} 20
Kelyphite	5	5	5	5		1	1	

¹ Includes 1% primary chromian spinel.

E1. Lherzolite, Kao pipe.

E2. Do., Maliba Matso pipe.

E3. Do., Thaba Putsoa pipe.

E5. Garnet wehrlite (=gordunite), Thaba Putsoa pipe.

E8. Saxonite, Thaba Putsoa pipe.

E9. Lherzolite, Lighobong dyke.

E11. Lherzolite, pipe at Farm Louwrencia, Nr. Gibeon, S.W. Africa.

G12. Garnet pyroxenite, Dutoitspan pipe, S. Africa.

zone of brown semi-opaque, optically unresolvable fibrous material clearing outwardly into a border of spinel granules, phlogopite, chlorite or amphibole (Fig. 4).

Chrome diopside is easily recognised on account of its bright emerald green color. In thin sections of ultrabasic nodules it shows an irregular

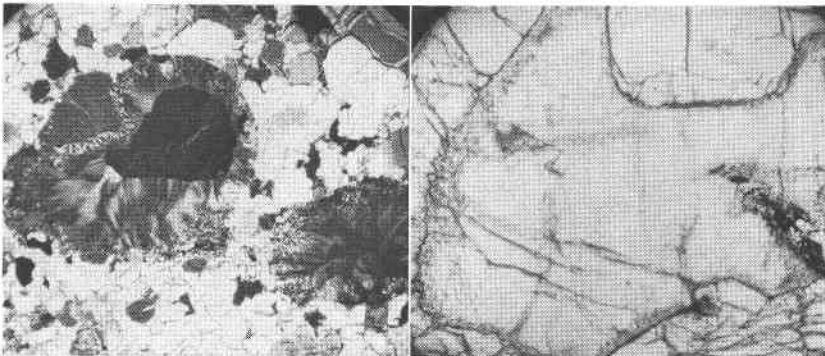


FIG. 4.

FIG. 5.

FIG. 4. Two garnets (black) surrounded by kelyphitic alteration rinds in ultrabasic nodule E30, Thaba Putsoa. The right hand garnet has almost completely broken down. Crossed polars ($\times 40$).

FIG. 5. Lobate chrome diopside with marginal turbid alteration zone. Ultrabasic nodule E32, Thaba Putsoa. Plane light ($\times 40$).

shape with lobes interfingering between accompanying minerals, suggestive of growth in a restricted environment. A marginal turbid alteration zone is typically present (Fig. 5). The chrome diopside from nodule E5 contains narrow lamellae that may be exsolved clinopyroxene; this is perhaps significant in view of Holmes' (1936) tentative identification of clinoenstatite intergrowths in a chrome diopside from Jagersfontein.

Enstatite occurs as pale green laths which are normally clear but may contain rounded olivine inclusions or secondarily formed serpentine and phlogopite. Holmes (1936) describes examples of complete metasomatic replacement of enstatite by phlogopite and even the conversion to phlogopite of complete ultrabasic nodules.

The allotriomorphic pale yellowish-green *olivine* of the ultrabasic nodules is characterized by anastomosing veinlets of fibrous serpentine. Less commonly, the olivine may be almost completely replaced by an aggregate of serpentine, chlorite and magnetite, as in nodule E11 from Sekameng. In this case the associated chrome diopside and chrome pyrope are relatively unaffected by the alteration.

Shiny, black, rounded octahedra of primary *chromian spinel*, several mm across, have been observed in some nodules, for example, saxonite nodule, E8, from Thaba Putsoa pipe and the altered nodule, E10, from Sekameng pipe. It is therefore assumed that similar chromian spinels in the kimberlite washings (some of which have a matt rather than a shiny surface) have been derived from such nodules. Individual octahedra from Qaqa pipe are brown and translucent near the margins, but black and opaque towards the centers, although the reverse condition was also observed. In polished section no intergrowth or exsolution features were detected. Spinels in the kelyphitic rims differ in being much smaller and having sharper outlines.

Graphite, like diamond, has been recorded from kimberlite and from its eclogitic and peridotitic inclusions (Wagner, 1914, pp. 72, 125, 126). The mineral makes up about 0.03% by weight of saxonite nodule E8, and occurs as slightly rounded, six-sided, striated crystals having a very bright metallic luster.

Eclogite and other nodules. These types of inclusion are relatively rare in Basutoland and, to judge from the literature, in most other kimberlites. They are similar in texture and chemical composition to non-kimberlitic rocks of high grade metamorphic terrains; compare, for example, the analyses of the eclogite nodule, E4, from Kao pipe and the eclogite from the Tyrol (Hezner, 1903) shown in Table 1. Similarly, a garnet scapolite gneiss nodule (E39) from Lighobong kimberlite dike can be matched with a gneiss from the Basement Complex of Ghana, described by von Knor-

ring and Kennedy (1958). Other nodules containing kyanite and hornblende are also similar to rocks unassociated with kimberlites. Wagner (1928, p. 138) has argued that such nodules have a common origin and form a continuous series; he states,

“The gabbroic eclogites are similarly linked by varieties containing plagioclase and cyanite with the garnet amphibolites and thus with the amphibolites occurring as xenoliths in the gneiss at the bottom of Kimberley Mine.”

TABLE 4. MINERAL COMPOSITION OF ECLOGITE AND RELATED NODULES FROM KIMBERLITE

	E4	E6	E7	E13	E39
Garnet	27	26	13	25	25
Kelyphite	2	—	—	10	—
Omphacite (clinopyroxene)	70	—	—	7	14
Rutile	0.5	2	—	1	—
Kyanite	—	22	—	—	—
Scapolite	—	—	—	—	5
Biotite	—	—	17	—	—
Natrolite	0.5	40	42	48	—
Sanidine	—	10	—	2	—
Plagioclase	—	—	—	—	56
Calcite, talc, serpentine	—	—	28	7	—

E4. Eclogite, Kao pipe.

E6. Eclogitic nodule, Qaqa pipe.

E7. Do., Kao pipe.

E13. Eclogite, Kao pipe.

E39. Scapolite gneiss nodule, Liqhobong dyke.

The eclogite nodules in particular have been susceptible to hydrothermal alteration, showing a development of natrolite, calcite, talc or serpentine (see modal analyses in Table 4), reducing the nodule to a cream colored friable mass. Sanidine (in nodules E6 and E13) and rounded, polished grains, about 0.15 mm in diameter, of both colorless zircon and honey-yellow monazite (in E6 and E7) also appear to be secondary.

The eclogitic reddish-orange or pink *pyrope-almandines* measure up to 5 mm across and may show crystal faces. There also occur inclusions of rutile and triangular arrangements of unidentified highly birefringent spicules with inclined extinction. The *kelyphitic rim*, consisting of narrow, opaque, brownish-black, finely crystalline magnetite and chlorite or distinct hornblende and chlorite crystals, is not so well developed as in the ultrabasic nodules.

The *omphacites* of the eclogites form clear dark leaf-green or greyish-

green crystals. On alteration they become paler and translucent with marginal replacement (as well as along cracks and cleavage planes, and completely in nodules E6 and E7) by secondary minerals, especially natrolite.

Tetragonal prisms of black, orange, red or yellow *rutile*, sometimes geniculately twinned, are typically found in eclogite and granulite nodules.

Other primary minerals which have been observed in eclogite, granulite and amphibolite nodules and so might be expected to occur sporadically in kimberlite mineral concentrates are: *biotite*, *kyanite*, *augite*, *plagioclase*, *sphene*, *apatite* and *magnetite*. To this list can be added *sillimanite* and *corundum* described by Williams (1932).

E16 *Pyrope-omphacite nodule, Old Kaalvallei Diamond Mine, near Welkom, Orange Free State*. This nodule is treated separately because, although superficially an eclogite, similar for example, to E4 nodule, its detailed mineralogy bears certain resemblances to the discrete kimberlitic garnet and clinopyroxene nodules described above.

It is composed of rounded, fractured, only slightly kelyphitised garnets, many exceeding 1 cm across; equally coarse, highly cleaved dark "bottle" green omphacite containing stringers of calcite forms the other major component. Other minerals, notably *rutile*, are absent.

METHODS

Being usually fairly coarse-grained the minerals in the various xenoliths were easily separated, although care had to be taken in the removal of adherent secondary alteration minerals, *e.g.*, *serpentine*, *calcite* and *kelyphite*. Hand crushing, sieving and repeated separation in methylene iodide and Clerici solutions, together with electromagnetic separation and hand-picking, enabled pure mineral products to be obtained.

The refractive indices, determined in sodium light using calibrated liquids spaced at 0.005 intervals, are accurate to within ± 0.002 . The optic angle measurements were made on a four-axis universal stage using double axis measurements supplemented with a few single axis ones. Corrections were applied for refraction and displacement of light within the central layers of the sphere (Wyllie, 1959), as well as for the refractive index of the hemispheres and the β -index of the mineral. The maximum error is $\pm 2^\circ$.

The extinction angle, in the absence of twinning, was determined by bringing the X-direction of the mineral into coincidence with the microscope axis using the universal stage and measuring $Z \wedge c$ directly (maximum error $\pm 3^\circ$).

Density was determined by the suspension method and checked by the normal pycnometer method when sufficient pure material was available. The results (given as $D^{18-25^\circ}/4^\circ/\text{air}$) are accurate to ± 0.02 .

Color is an important distinguishing feature, especially in the garnet groups, and is expressed as a formula (Rock Color Chart, 1948) which incorporates hue, light value, and chroma (vividness). The color indices are given for minerals crushed to 100 mesh size.

Measurements of the unit cube cell edge, a obtained by using Mn filtered FeK_α radiation and a calibration standard of NaCl, are accurate to $\pm 0.01 \text{ \AA}$.

Trace elements were determined by spectrographic analysis using anode excitation in a 7 amp d.c. carbon arc. Samples were diluted 1:1 with carbon powder containing indium and palladium as internal standards. Concentration calibration was by means of matching series of standards synthesized from Johnson Matthey "Specpure" materials, and working curves were established by microphotometry.

Precision varies between elements but averages $\pm 10\%$ of content. Accuracy cannot be specified in the absence of *primary* standards for the minerals under examination, but confidence in the technique has been established by reference to granite G-1 and diabase W-1 (Rooke and Fisher, 1962).

MINERALOGY AND CHEMISTRY

Garnets.

1) Pyrope. Two analyses, E15 from Thaba Putsoa pipe and Kb1 from Kimberley pipe (Table 5), of discrete, fractured, reddish-brown nodules, indicate a composition of over 70% of pyrope; a small amount of chromium is present.

Typically this garnet has a refractive index of about 1.750 with a density of 3.71 and a cell edge length averaging 11.53 \AA (Table 6). The color, especially of the finer grains, has a distinctly yellowish tinge indicated by the color indices YR (yellow red).

The garnet from the Kaalvallei nodule, E16, has a lower proportion of pyrope (57%; Table 5), but, nevertheless, in physical properties it resembles more closely the pyropes described above than the lower pyrope-bearing eclogitic pyrope-almandines. This is shown in Fig. 6.

2) Chrome pyrope. Chemical analyses of garnets (Table 5, nos. E1, E3, E11, G12 and E10) from ultrabasic nodules from Basutoland, South Africa and South-West Africa, show that 70% of the pyrope "molecule," together with subsidiary amounts of almandine, is present. About 6% of uvarovite (equivalent to about 2% Cr_2O_3) is typically present. A reddish-purple garnet sample, A79, picked from kimberlite washings at

TABLE 5. ANALYSES OF GARNETS FROM KIMBERLITES AND ASSOCIATED XENOLITHS

Analysts: M. H. Kerr (E15, E1, E3, E4), O. von Knorring (Kb1, A80, E16, E10), E. Padget (A79, G12), J. R. Baldwin (E11, E7)

	Pyropes				Chrome pyropes				Pyrope almandines			
	E15	Kb1	A80	E16	E1	E3	E11	A79	G12	E10	E7	E4
SiO ₂	42.04	42.86	42.49	41.50	41.71	42.44	42.77	42.73	42.11	41.90	39.19	40.21
TiO ₂	0.92	0.27	—	0.46	0.61	0.52	0.30	0.27	0.12	0.11	0.00	0.00
Al ₂ O ₃	21.84	23.00	23.20	21.53	21.55	22.24	21.91	19.83	22.10	16.92	21.34	22.51
Cr ₂ O ₃	0.43	0.30	0.49	0.12	2.97	1.98	1.90	2.92	1.91	7.52	0.00	0.00
Fe ₂ O ₃	1.97	7.71	8.36	1.68	0.02	1.56	1.25	0.81	0.35	1.24	1.26	1.57
FeO	7.47			13.81	7.36	4.75	6.79	7.01	8.24	6.17	25.66	17.01
MnO	0.24	0.30	0.19	0.27	0.31	0.16	0.26	0.33	0.36	0.59	0.43	0.32
MgO	20.51	20.15	20.26	15.33	20.79	21.53	20.70	21.54	19.85	19.64	8.74	11.67
CaO	4.37	5.20	5.54	5.30	5.22	4.90	4.65	4.69	4.80	6.27	3.79	6.58
H ₂ O ⁺	—	—	—	—	—	—	—	—	0.29	—	—	—
H ₂ O ⁻	0.17	—	—	—	—	—	—	—	—	—	—	—
	99.96	99.81	100.33	100.00	100.54	100.08	100.53	100.13	100.24	100.36	100.41	99.87
Percentage composition in terms of garnet end-member molecules ¹												
Spessartine	0.5	0.6	0.4	0.5	0.6	0.3	0.6	0.6	0.7	1.2	0.9	0.7
Andradite	5.3	—	—	4.8	0.1	4.2	3.3	2.1	1.0	3.3	3.6	4.5
Uvarovite	1.3	0.8	1.3	0.4	8.2	5.7	5.4	8.2	5.4	2.8	—	—
Grossularite	4.6	12.3	12.4	8.8	4.7	2.7	3.1	1.3	5.9	—	6.8	13.6
Almandine	15.0	15.3	16.1	28.5	14.3	9.6	13.9	13.6	16.4	12.4	55.2	36.6
Pyrope	73.3	71.0	69.8	57.0	72.1	77.5	73.7	74.2	70.6	61.7	33.5	44.6
										Hanléite		
										= 8.6		

¹ Calculated from cation percentages in the order listed and recalculated to 100%.

E15. Pyrope, discrete nodule, Thaba Putsoa pipe, Basutoland. Analyst: M. H. Kerr.

Kb1. Pyrope, discrete nodule, Kimberley pipe, S. Africa. Analyst: O. von Knorring.

A80. Pyrope, (pale lilac) hand picked from concentrate, Kao pipe, Basutoland. Analyst: O. von Knorring.

E16. Pyrope-rich garnet, garnet-omphacite nodule (eclogitic), Kaalvallei pipe, S. Africa. Analyst: O. von Knorring.

E1. Chrome-pyrope, lherzolite nodule, Kao pipe, Basutoland. Analyst: M. H. Kerr.

E3. Chrome-pyrope, lherzolite nodule, Maliba Matso pipe, Basutoland. Analyst: M. H. Kerr.

E11. Chrome-pyrope, lherzolite nodule, pipe at Farm Louwrencia, nr. Gibeon, S. W. Africa. Analyst: J. R. Baldwin.

A79. Chrome-pyrope, hand picked from concentrate, Kao pipe, Basutoland. Analyst: E. Padget.

G12. Chrome-pyrope, garnet pyroxenite nodule, Dutoitspan pipe, S. Africa. Analyst: E. Padget.

E10. Chrome-pyrope, Serpentinised nodule, Sekameng pipe, Basutoland. Analyst: O. von Knorring.

E7. Pyrope-almandine, eclogite nodule (altered), Kao pipe, Basutoland. Analyst: J. R. Baldwin.

E4. Pyrope-almandine, eclogite nodule, Kao pipe, Basutoland. Analyst: M. H. Kerr.

Kao, shows similar features, and is considered to have been derived from disrupted ultrabasic nodules. On the other hand, a garnet sample (A80), composed of several spherical, clear, pale purple grains from the same concentrate, is low in chromium and therefore chemically similar to the pyropes. In appearance and physical properties it can, however, be better equated with the chrome pyropes (see Fig. 6).

Chrome pyropes E9 ($\text{Cr}_2\text{O}_3 = 5.14\%$) and E10 ($\text{Cr}_2\text{O}_3 = 7.52\%$; Table 5) contain unusually high amounts of chromium. In E10, at least, there is not sufficient calcium to account for all chromium as uvarovite and another chromium "molecule," hanléite $\text{Mg}_3\text{Cr}_2(\text{SiO}_4)_3$, must be employed. The name was originally used by Fermor (1952) for a magnesia-chrome garnet found in 1864 near Hanlé Monastery, Rupshu, Kashmir. A few milligrams of a *bluish-green garnet* in a concentrate (number K47) from Kao kimberlite was seen, by spectrographic analysis, to contain a

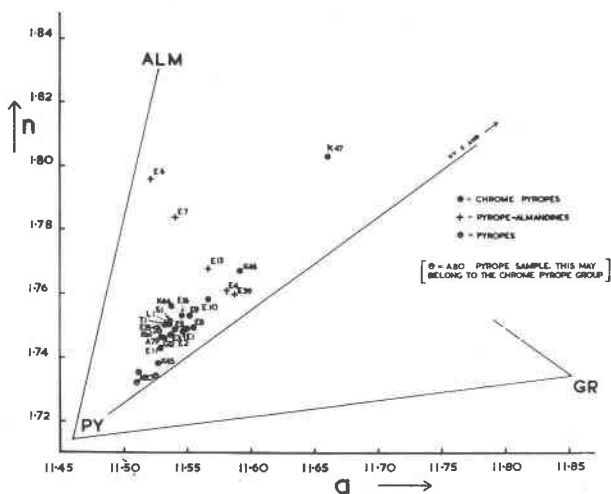


FIG. 6. Refractive index, n , plotted against cell edge length, a , of garnets from kimberlites and associated nodules. The positions of the garnet end-members (almandine, ALM, pyrope, PY; & grossularite, GR) are located according to the values given by Skinner (1956).

similar amount of calcium to E10, but even more chromium (hanléite). This is reflected in its physical properties as compared with the other chrome pyropes (Table 6). The refractive index, in particular, although usually between 1.735 and 1.750, rises above these values with increasing chromium content (Fig. 7). The chromium-rich specimen K47 shows abnormally high n , G and a values. X-ray data of K47 and of a normal chrome pyrope (E11) are compared in Table 8.

3) Pyrope-almandine. The relatively high almandine component is illustrated by analyses (Table 5) of garnets from eclogite nodule E4 (36.6% alm.) and an altered natrolite-bearing nodule E7(55.2% alm.).

The physical properties of the pyrope-almandines vary mainly according to the proportions of Fe^{2+} , Mg^{2+} and Ca^{2+} —almandine, pyrope and grossularite—as seen in Fig. 6. They can usually be distinguished from

the chrome-pyropes by their color and greater density (Table 6). X-ray powder data for garnet E4 are given in Table 8.

4) Minor and trace elements of the garnets. The discrete *pyrope* nodules exemplified by E15, Kb1 and a specimen from Thaba Putsoa T4 (quoted in Nixon, 1960)¹ have chromium at a level between the chrome pyropes and pyrope-almandines (Table 7; Fig. 8). They may contain considerable traces of Ni and Zr.

The spectrographic data for garnet E16 serves to emphasise its intermediate nature between the pyrope and pyrope-almandine groups.

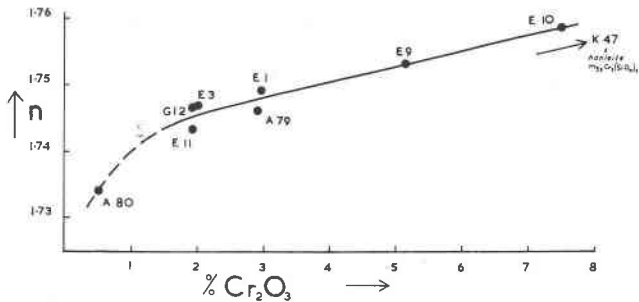


Fig. 7. Plot of refractive index against % Cr₂O₃ in chrome pyropes.

Points which favor its placing in the pyrope group are its high Ti and Ni. In its low Zr content it resembles eclogitic pyrope-almandine E4.

The *chrome-pyropes* from the ultrabasic nodules (Table 7; E1, E3, E11, A70, G12 and E10) contain relatively high amounts of Cr and V, moderate amounts of Ni and Sc, and low Co.

In the eclogitic *pyrope-almandines* Ni is comparatively low. The almandine-rich specimens E7 and E6 contain some Zn (visual comparison), and significant amounts of Y and Zr (Fig. 8). It would appear that the eightfold co-ordinated sites in the garnet lattice (occupied mainly by Fe²⁺) are able to accept the large Zr⁴⁺ in spite of its high charge. The comparatively low V in the pyrope-almandines may be due to preferential acceptance of this element by associated minerals, especially biotite or

¹ Spectrographic data (J.M.R.) of four garnets quoted from Nixon (1960); values for each element in the following sequence: E2—chrome-pyrope, lherzolite nodule, Kao pipe; E6—pyrope-almandine, altered eclogite nodule, Qaqa pipe; E39—pyrope-almandine, scapolite gneiss nodule, Lihobong dyke; T4—pyrope, discrete nodule, Thaba Putsoa pipe; (in ppm) Ga³⁺ 2, 12, 9, 9; Cr³⁺ >1000, 300, 300, —; Li⁺ <3, 10, 3, <3; Ti⁴⁺ 800, 250, 650, —; Ni²⁺ 50, 4, 15, 180; Co²⁺ 8, 45, 45, 35; V³⁺ 300, 90, 70, 300; Zr⁴⁺ 50, 130, 7, 120; Sc³⁺ 120, 95, 60, 95; Y³⁺ <30, 160, <30, 35; Pb²⁺ 5, 2, <2, 3; Ba²⁺ 10, <10, <10, <10; in all four specimens Be <3, Sr <30, Gd <30, La <100, Mo <3, Nb <30; Mn not determined.

TABLE 6. PHYSICAL PROPERTIES OF GARNETS FROM KIMBERLITES AND ASSOCIATED XENOLITHS

No.	Occurrence and locality	<i>n</i>	<i>a</i> Å	G obs.	G calc.	Color index
<i>Pyropes</i>						
T1	Discrete nodule, Thaba Putsoa pipe	1.750	11.531	3.696	—	5YR5/5
S1	Concentrate, Solane pipe	1.751	11.535	3.726	—	5YR5/5
L1	Do., Lihobong pipe	1.750	11.535	3.711	—	—
K44	Do., Kao pipe	1.756	11.537	3.762	—	5YR5/6
E15	Discrete nodule, Thaba Putsoa pipe	1.749	11.526	3.683	3.706	5YR5/5
Kb1	Do., Kimberley pipe	1.748	11.528	—	—	—
A80	Composite sample from concentrate, Kao pipe	{ 1.732 1.734 1.735	{ 11.509 11.525 11.511	{ — — —	{ — — —	{ — 3R8/2 8RP7/2
<i>Pyrope (almandine-rich)</i>						
E16	Nodule, Kaalvallei pipe, S. Africa	1.753	11.545	—	—	—
<i>Chrome pyropes</i>						
E1	Lherzolite nodule, Kao pipe	1.749	11.548	3.692	3.710	9R4/2
E2	Do., Maliba Matso pipe	1.748	11.546	3.681	—	1R4/2
E3	Do., Thaba Putsoa pipe	1.747	11.537	3.680	3.662	10R5/2
E5	Garnet wehrlite (=gordunite), Thaba Putsoa	1.749	11.538	3.679	—	1YR5/5
E8	Saxonite nodule, Thaba Putsoa pipe	1.749	11.553	—	—	—
E9	Lherzolite nodule, Lihobong dyke	1.753	11.551	3.718	—	7RP3.5/2
E10	Altered nodule, Sekameng pipe	1.758	11.565	3.715	3.748	5RP3/2
E11	Lherzolite nodule, pipe at Farm Louwrensia, nr. Gibeon, S.W. Africa	1.743	11.528	3.712	3.698	8R5/2
G12	Garnet pyroxenite nodule, Dutoitspan, South Africa	1.746	11.531	—	3.711	9RP5/2
A79	Heavy mineral washings (concentrate), Kao pipe	1.746	11.528	3.690	3.715	—
L2	Do., Lihobong pipe	1.747	—	3.68	—	—
K45	Do., Kao pipe	1.738	11.528	—	—	—
K46	Do., Kao pipe	1.767	11.590	—	—	—
K47	Do., Kao pipe	1.799- 1.807	11.659	3.756	—	6G3/2
<i>Pyrope-almandines</i>						
A78	Concentrate, Kao pipe	1.758	—	3.770	—	—
E39	Scapolite gneiss nodule, Lihobong Dyke	1.760	11.585	3.800	—	3YR6/4
E4	Eclogite nodule, Kao pipe	1.761	11.579	3.835	3.826	1YR6/4
E13	Eclogite nodule, Kao pipe	1.768	11.565	3.898	—	—
E7	Eclogitic nodule, Kao pipe	1.784	11.539	3.995	3.999	10R5/4
E6	Eclogitic nodule, Qaqa pipe	1.796	11.521	4.076	—	1YR5/4

hornblende. Relatively low values of Cr and Ti have been determined spectrochemically; the low titanium level is characteristic of eclogite garnets (Eskola, 1922).

Pb, possibly replacing Ca, is present in most garnets from the Basutoland kimberlite pipes at levels less than 10 ppm. Comparatively large amounts of Ba as in E3 (45 ppm) could be due to kelyphite impurity. Other elements detected include Cu, Ag, Na, K, Sr, Be and Sn.

The threefold division of the main Basutoland garnet types into chrome pyropes, pyrope-almandines and pyropes can be recognized in

TABLE 7. TRACE ELEMENTS IN GARNETS FROM KIMBERLITES AND ASSOCIATED XENOLITHS

Analyst: J. M. Rooke; in parts per million; occurrences and localities of specimens given in Table 6

r (Å)	S	E15	Kb1	A80	E16	E1	E3	E11	A79	G12	E10	E7	E4	
Ga ³⁺	0.62	2	8	4	2	4	3	4	5	3	3	2	8	6
Cr ³⁺	0.63	—	2950 [†]	2050 [†]	3350 [†]	820 [†]	20300 [†]	13550 [†]	13000 [†]	20000 [†]	13050 [†]	51450 [†]	350	750
Li ⁺	0.68	3	<3	<3	30	<3	<3	<3	<3	<3	<3	<3	10	<3
Ti ⁴⁺	0.68	—	5500 [†]	1600 [†]	250	2750 [†]	3650 [†]	3100 [†]	1800 [†]	1600 [†]	700 [†]	650 [†]	160	550
Ni ²⁺	0.69	10	190	70	75	140	90	160	70	35	65	70	9	30
Mo ²⁺	0.70	3	<3	<3	5	3	<3	<3	<3	<3	<3	<3	4	<3
Co ²⁺	0.72	5	50	50	70	65	9	8	30	10	50	8	70	13
V ³⁺	0.74	10	400	70	35	80	450	350	150	300	90	190	13	50
Zr ⁴⁺	0.79	3	120	110	15	15	45	35	25	20	20	45	120	3
⁵⁵ Mn ²⁺	0.80	—	1850	2300	1500	2100	2400	1250	2000	2550	2800	4550	3350	2500
Sc ³⁺	0.81	10	110	40	60	75	90	95	110	130	110	160	120	40
Y ³⁺	0.92	30	70	35	<30	30	<30	<30	<30	<30	40	<30	80	<30
Pb ²⁺	1.20	2	6	2	3	<2	10	25	3	3	4	2	<2	10
Ba ²⁺	1.34	10	<10	<10	10	<10	14	45	<10	<10	10	<10	<10	<10

In all samples Be <3, Sr <30, Ge <30, Nb <30, Ta <100 and La <100 (except E11: La=100)

N.B. Visual examination shows Zn to be present in E7 and E4.

r = ionic radii for 6 fold co-ordination (Ahrens, 1952).

S = sensitivity.

† Signifies chemical determinations.

other descriptions of kimberlites. In the Siberian kimberlite province both chrome-poor pyropes (orange) and chrome-bearing varieties (violet) occur (Burov *et al.*, 1958); the latter may contain amounts of chromium equivalent to 13% uvarovite (Milashev, 1958). Bobrievich *et al.* (1959) have given analyses of pyrope-almandines from two eclogitic nodules, one of which contains diamond. The garnets from South African kimberlites (Wagner, 1914; Williams, 1932) are pyrope-rich varieties with Cr₂O₃ varying from nil to 5.10%. Almandine-rich types are not recorded.



FIG. 8. Spectrographic and chemical data of some garnets and clinopyroxenes from kimberlites and associated xenoliths plotted to show the distribution of elements between:

- (a) chrome-pyropes ○, and chrome-diopsides ●.
- (b) pyrope-almandines □, and omphacitic pyroxenes ■.
- (c) pyropes △, and diopside ▲.

An arrow indicates that one or more specimens in the group are below the limit of detection shown.

Note: Pyrope-rich garnet E16 is plotted with the pyropes as it bears a close chemical relationship to this group. Its associated omphacite (E16) must be plotted with the omphacitic pyroxenes of the eclogite group, however, until it has been proved that the omphacites as well as relatively sodium-poor diopsides (E14) are related to the pyropes.

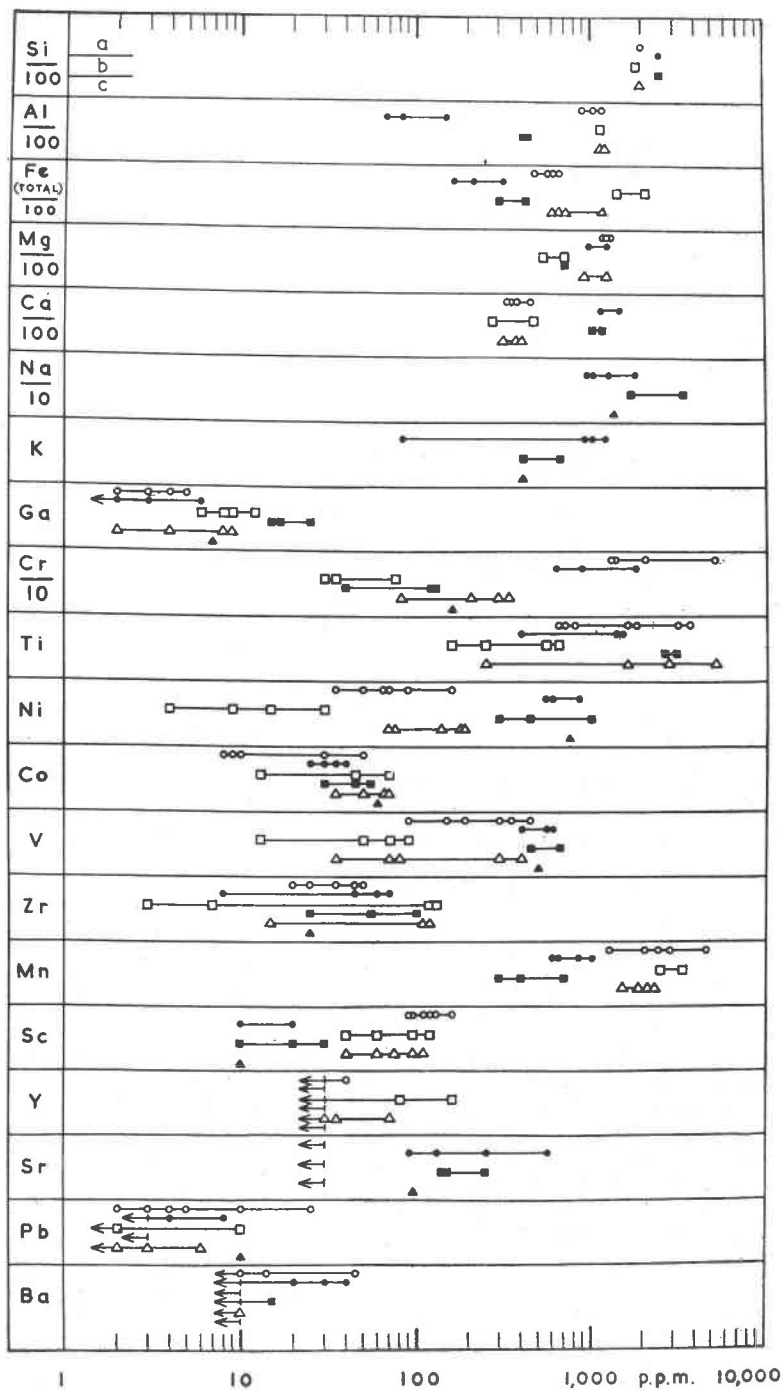


TABLE 8. X-RAY DATA OF GARNETS K47, E11 AND E4

hkl	K47 ($a=11.659$)		E11 ($a=11.528$)		E4 ($a=11.579$)	
	d	I	d	I	d	I
400	2.92	vs	2.90	vs	2.896	s
420	2.61	vs	2.59	vs	2.588	vs
332	2.489	m	2.462	m-s	2.464	w
422	2.382	s	2.364	m-s	2.364	m
510, 431	2.288	m	2.267	m-s	2.276	m
521	2.134	w	2.109	m	2.111	m
440	—	—	2.043	vw	2.045	vw
610, 532	1.894	m	1.875	m	1.876	m-s
620	1.846	w-m	1.826	w	—	—
631	—	—	—	—	1.705	w-m
444	1.684	w	1.665	m	1.671	m
640	1.618	m	1.601	s	1.605	m-s
642	1.560	s	1.543	vs	1.546	s
800	1.459	w	1.444	m	1.447	w-m
840	1.305	m	1.290	m	1.295	w-m
842	1.273	m	1.259	s	1.264	m
664	1.244	m	1.231	m	1.235	w

(vw=very weak; w=weak; m=moderate; s=strong; vs=very strong.)

K47. Hauléite pyrope from kimberlite concentrate, Kao, Basutoland.

E11. Normal chrome pyrope from lherzolite nodule, Farm Louwrencia, South West Africa.

E4. Pyrope-almandine from eclogite nodule, Kao, Basutoland.

Kelyphite. A chemical analysis of the inner fibrous zone (Table 9), together with a norm calculation based mainly on Barth's (1955) meso- and epinorms, suggests that it is composed of minerals which are observed in the kelyphitic outer borders. A similar conclusion was reached from an examination of electron micrographs prepared from diluted macerated fibrous kelyphite (Fig. 9). Three forms were observed, probably representing chrome-bearing spinel (opaque equant grains arrowed A), enstatite and/or hornblende (laths and blades arrowed B), and mica and/or chlorite (plate-like aggregates arrowed C). Enstatite and spinel have been detected in the fibrous zone optically (Wagner, 1914, p. 65) and also by x -ray methods in E1. It is interesting to note that enstatite (aluminous) is one of the breakdown products of synthetic pyrope under high pressure-temperature conditions (Boyd and England, 1959).

A chemical comparison of garnet E1 with its associated kelyphite (Table 9) shows that kelyphite contains more Cr^{3+} , Mg^{2+} and particularly OH but less Si^{4+} and Al^{3+} .

TABLE 9. CHEMICAL ANALYSES OF E1 GARNET AND ITS ASSOCIATED KELYPHITE¹

Oxides			No. of Cations/96 O (incl. OH)			
	Gt	Kel		Gt	Kel	Gain or Loss
SiO ₂	41.71	36.18	Si	23.69	20.22	-3.47
TiO ₂	0.61	—	Ti	0.26	—	?
Al ₂ O ₃	21.55	19.63	Al	14.43	12.93	-1.50
Cr ₂ O ₃	2.97	4.55	Cr	1.33	2.01	+0.68
Fe ₂ O ₃	0.02	2.38	Fe ³⁺	0.01	1.00	-0.31
FeO	7.36	4.71	Fe ²⁺	3.50	2.20	
MnO	0.31	0.25	Mn	0.15	0.12	-0.03
MgO	20.79	22.90	Mg	17.60	19.07	+1.47
CaO	5.22	4.60	Ca	3.18	2.75	-0.43
Na ₂ O	—	0.46	Na	—	0.49	+?
K ₂ O	—	0.47	K	—	0.34	+?
H ₂ O ⁺	—	3.80		—		+14.16H+(as OH)
H ₂ O ⁻	—	0.38		—		
	100.54	100.31				

¹ Analyst: O. von Knorring.

No. of O ions (incl. OH) per 100 cations = 149.63 (Garnet) and
 157.03 (Kelyphite).
 G = 3.692 (Garnet) and
 3.204 (Kelyphite).

A possible normative interpretation of E1 kelyphite data

	Si	Al	Cr	Fe+Mn+Mg	Ca	Na+K	(OH)	
Cation %	33.08	21.15	3.29	36.62	4.50	1.36	(23.16)	100.00
Enstatite	5.28			5.28				10.56
Hornblende	15.75	4.50		9.00	4.50		(4.50)	33.75
Biotite	4.08	1.36		4.08		1.36	(2.72)	10.88
Chlorite	7.97			11.96			(15.94)	19.93
Spinel		9.31	3.29	6.30				18.90
Corundum		5.98						5.98

(taken in by hornblende, biotite and enstatite)

Yoder (1952) has shown experimentally that breakdown of pyrope into kelyphite can take place simply by the addition of water at approximately 600° C. and at less than 30,000 psi.

E1 kelyphite contains 7.4 more oxygen ions per 100 cations than its associated garnet (which closely approximates to the theoretical 150 O²⁻ per 100 cations; Table 9), thus indicating an increase in volume (Barth, 1955). This is reflected in the generally lower density of kelyphite as compared with garnet and in the familiar appearance of radiating expansion cracks in the nodules immediately surrounding the kelyphitized garnets.

A spectrographic analysis (by J.M.R.) of kelyphite E1 gives the following elements (in ppm): Ga (3), Li (12), Ni (110), Co (13), V (180), Zr (15), Sc (130), Sr (35), Pb (4) and Ba (300), showing that in compari-

son with its associated garnet it is enriched in alkali- and alkaline earth metals. These are probably held in such constituent minerals as chlorite, mica and hornblende. The lower vanadium value may be due to this element being masked by Fe^{3+} in secondary chrome-bearing spinel and

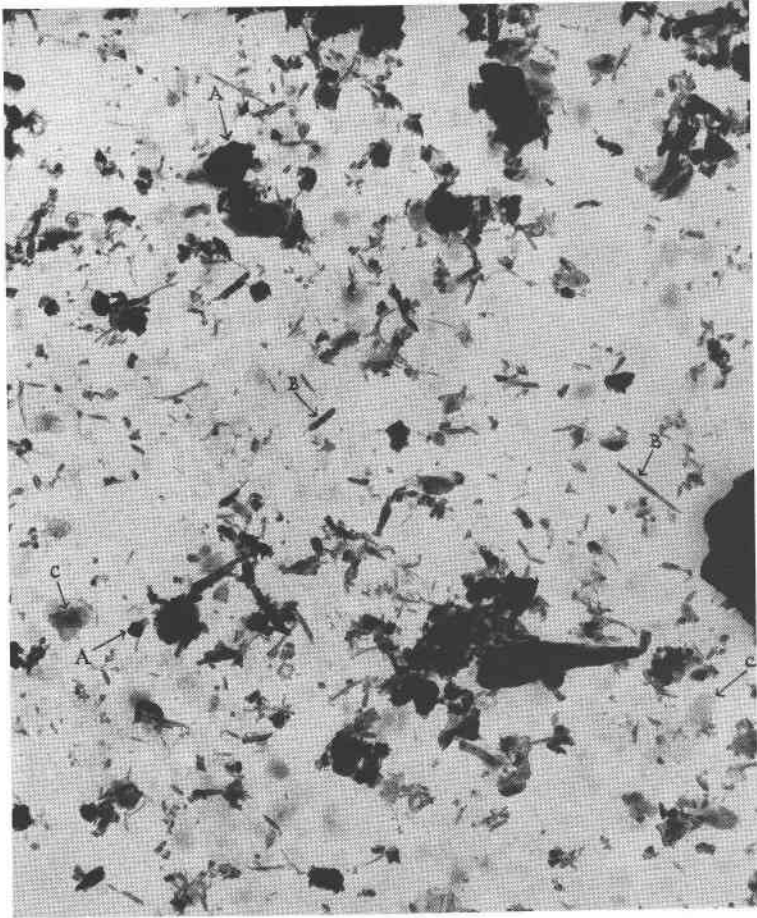


FIG. 9. Electron micrograph of E1 kelyphitic rim (fibrous inner zone).

Magnification $\times 34,200$

A=opaque equant grains (spinel).

B=narrow laths and blades (hornblende and/or enstatite).

C=plates and lamellae (mica, chlorite and/or talc, etc.)

magnetite, some of which was extracted during the purification processes.

The petrographical, mineralogical and chemical evidence suggest that in the ultrabasic nodules, at least, kelyphite formed rapidly from chrome

pyrope by the addition of water but with minor migrations of other constituents, the reaction being promoted by a decrease in pressure, probably due to kimberlite intrusion.

Clinopyroxenes.

1) Diopside. A partial analysis (M. H. Kerr) of a dark bottle-green nodule, E14 from Thaba Putsoa, gave $\text{Na}_2\text{O}=1.84\%$ and $\text{Cr}_2\text{O}_3=0.24\%$. The analysis of another seemingly nonomphacitic (but markedly subcalcic) diopside is given by Williams (1932, II, p. 379) and is quoted here in Table 10, No. 9. There is insufficient evidence to state whether these kimberlitic clinopyroxenes, including those which occur in the ground-

TABLE 10. ANALYSES OF CLINOPYROXENES FROM KIMBERLITES AND ASSOCIATED XENOLITHS

	Diopsides		Chrome diopsides			Omphacites		
	Vo. 9	S89	E3	G12	No. 7	No. 8	E4	E16
SiO_2	52.40	54.52	54.61	53.75	54.09	53.36	54.76	55.06
TiO_2	0.66	tr	0.23	0.25	0.28	0.34	0.44	0.51
Al_2O_3	1.73	0.01	1.30	2.83	1.57	9.66	8.33	7.67
Cr_2O_3	0.31	—	0.92	1.30	2.03	—	—	—
Fe_2O_3	3.68	—	1.14	1.27	0.74	1.69	1.29	1.68
FeO	4.25	1.74	3.02	1.62	1.47	5.68	2.70	4.01
MnO	tr.	0.51	0.10	0.07	0.09	tr.	0.04	0.07
MgO	21.61	17.44	20.88	16.19	16.96	9.50	11.59	11.97
CaO	13.30	25.34	16.20	20.64	21.10	12.18	16.35	14.22
Na_2O	—	0.27	1.28	1.72	1.37	6.82	4.63	4.70
K_2O	—	0.12	0.12	0.11	0.15	tr.	0.05	0.08
H_2O^+	1.20	0.26	0.41	0.24	0.22	1.05	—	—
H_2O^-	0.44	0.10	0.07	0.10	0.08	—	—	—
P_2O_5	tr.	—	—	0.07	0.00	S=0.22	—	—
	100.12 ¹	100.31	100.28	100.16	100.64 ²	100.50	100.18	99.97
atoms %								
Ca	26.9	49.3	33.4	45.5	45.0	39.3	46.0	40.2
Mg (+Ni)	61.2	47.3	59.9	49.6	51.2	42.6	45.4	47.2
$\text{Fe}^{2+} + \text{Fe}^{3+}$								
+Mn	11.9	3.4	6.7	4.9	3.8	18.1	8.6	12.6
% of Al in Z	1.8	0.0	0.6	2.0	1.4	1.0	2.3	1.9

calculated as in Hess (1949).

¹ includes 0.54% minor oxides.

² includes 0.49% minor oxides.

No. 9 Subcalcic diopside nodule of "fair average composition." Analyst: J. Parry (Williams, 1932, II, p. 379).

S89 Diopside "concretion," Premier pipe. Analyst: E. Padget.

E3 Subcalcic chrome diopside, from lherzolite nodule, Thaba Putsoa pipe. Analyst: M. H. Kerr.

G12 Chrome diopside, garnet pyroxenite nodule, Dutoitspan pipe. Analyst: E. Padget.

No. 7 Chrome diopside with lamellae of (?) clinostatite, Jagersfontein pipe. Analyst: L. S. Theobald (Holmes, 1936).

No. 8 Omphacite, Jagersfontein pipe. Analyst: J. Parry (Williams, 1932, I, p. 329).

E4 Omphacite, eclogitic nodule, Kao pipe. Analyst: M. H. Kerr.

E16 Omphacite, eclogitic nodule, Kaalvallei pipe. Analyst: O. von Knorring.

mass, embrace more sodium-rich types. However, if it is argued that the garnet of E16 "eclogite" nodule from Kaalvallei is a member of the pyrope group, then its associated omphacite (analysis in Table 10) is likely to be related to the diopside group. The pyropes and diopsides of kimberlites have already been described.

Diopside S89, consisting of radiating crystals, has a chemical composi-

TABLE 11. PHYSICAL PROPERTIES OF CLINOPYROXENES FROM KIMBERLITES AND ASSOCIATED XENOLITHS

No.	Locality	G	α	β	γ	$\gamma - \alpha$	Z/ \wedge c	2V+	Color index
	<i>Diopsides</i>								
E14	Thaba Putsoa	3.314	1.672	1.677	1.697	0.025	39°	58°	9Y 5/2
K37	Kao (average of several grains; occasional (001) twins)	—	ca. 1.678	—	ca. 1.705	ca. 0.026	—	ca. 64°	—
S89	Premier (finely fibrous)	—	1.669	—	—	—	—	54°	—
	<i>Chrome diopsides</i>								
E1	Kao	3.283	1.673	1.684	1.697	0.024	41°	62°	8GY 6/4
E2	Maliba Matso	3.253	1.674	1.682	1.696	0.022	40°	64°	10GY 6/4
E3	Thaba Putsoa	3.269	1.670	1.677	1.693	0.023	38½°	56½°	8GY 6/3
E5	Thaba Putsoa	3.295	1.672	1.678	1.692	0.020	38°	54½°	7GY 4/4
E9	Liqhobong	3.272	1.675	1.683	1.698	0.023	40°	68°	10GY 5/5
E10	Sekameng	3.302	1.676	1.685	1.701	0.025	40½°	69½°	10GY 5/6
E11	Fm. Louwrencia	3.280	1.676	1.684	1.698	0.022	—	63½°	9GY 5/4
G12	Dutoitspan	3.279	1.677	1.685	1.702	0.025	40°	71°	9GY 5/4
A	Jagersfontein, S. Africa	—	—	>1.66	—	—	50°	70°-75°	—
B	Ngopetsoe (see Fig. 1)	—	1.672	1.680	1.695	0.023	—	71°	—
C	Premier, S. Africa	—	1.671	1.681	1.699	0.028	—	69°	—
D	Zarnitsa, Siberia	—	1.680	—	1.706	0.026	—	63°	—
	<i>Omphacitic pyroxenes</i>								
E4	Kao	3.333-3.347	1.673	1.681	1.695	0.022	41°	70° mean	4GY 4/2
E13	Kao	3.337	1.672	1.679	1.693	0.021	41½°	71½°	—
E39	Liqhobong	3.332	1.686	1.693	1.710	0.024	41°	63°	—
E16	Kaalvallei	—	1.672	1.679	1.699	0.027	36°	64°	—

A, from Holmes (1936); B, Stockley (1947, p. 98); C, Partridge (1934); D, Smirnov (1959).

tion (Table 10) indicating the almost pure diopside end-member. Because of its fibrous nature and poly-synthetic twinning parallel to (100), optical properties were difficult to determine. However, the values obtained, *viz.*, 2V+ = 54° and $\alpha = 1.669$, are similar to those for skarn pyroxenes close to the diopside end-member (Hess, 1949).

2) Chrome diopside. A feature of some of the old kimberlitic chrome-diopside analyses, seen also in E3 (Table 10), is the presence of more Mg, compared with Ca, than is required to make up the diopside formula,

resulting in the appearance of appreciable enstatite in the norm. These enstatite-diopsides or subcalcic diopsides indicate, in view of the sub-solidus relations of MgSiO_3 and $\text{CaMgSi}_2\text{O}_6$ (Atlas, 1952; Boyd and Schairer, 1957) that unusually high temperatures were required for their formation. The effect of any great pressure, which may have attended their formation, is unknown.

Both the subcalcic and the normal chrome-diopsides (the latter exemplified by analyses G12 and No. 7, Table 10) are characterized by Na⁺ which is electrostatically balanced in the crystal lattice by trivalent Cr, Al and Fe³⁺. A partial analysis by O. von Knorring of an extremely vivid green chrome-diopside, accompanying the chromium-rich garnet in nodule E10 from Sekameng, showed 2.42% Na₂O and 2.68% Cr₂O₃. Thus, the rôle played by aluminium as part of the jadeite molecule in other pyroxenes (omphacites) is taken over, at least partially, by chromium (as chrome acmite, NaCrSi₂O₆) in the chrome-diopsides. The vivid emerald green of chrome-diopside E10 is an indication of the high chromium content.

The *proportion* of Al³⁺ replacing Si⁴⁺ and the *total* Al³⁺ are lower than in some other chrome-diopsides, notably those occurring in the ultrabasic nodules in basalts (Ross *et al.*, 1954).

The physical properties of chrome-diopsides from ultrabasic nodules in kimberlites, including some quoted from literature (Table 8), show significant variations. The generally high 2V, compared with the diopside end member ($2V_z = 58^\circ$), is probably due to the presence of sodic pyroxene components, especially chrome acmite ($2V_z = 140^\circ$; Roy and Tuttle, 1956). As might be expected from Bowen's (1914) optical data for the synthetic clinoenstatite-diopside solid solution series, subcalcic chrome-diopside has relatively low optic axial angle and refractive indices; probably the birefringence and extinction angle are also low.

3) Omphacitic pyroxenes. These differ from the chrome-diopsides in being dark grayish-green. They are characterized chemically (Table 10, No. 8, E4 and E16) by a high content of Na and Al (jadeite) but very limited Al-Si diadochy; and Cr is very low. They are thus chemically comparable with omphacites in regionally metamorphosed eclogites (Hezner, 1903; Alderman, 1936). The omphacites E4 and E13 in eclogite nodules from Kao, and another clinopyroxene (Na₂O = 2.31% analyst: J. R. Baldwin) in garnet-scapolite gneiss nodule E39 from Lihobong, show typically high densities (Table 8). The high optic axial angles of E4 (70°) and E13 ($71\frac{1}{2}^\circ$) are attributed to larger proportions of sodic pyroxene (jadeite) component, although omphacite E16 ($2V = 64^\circ$) seems to be an exception in this respect.

4) Minor and trace elements of the clinopyroxenes. Spectrographic

results are shown in Table 12 and Fig. 8 (which includes results given in Nixon, 1960). Of the trace elements in bottle-green *diopside*, E14, only Ga and Cr show contrasting values, being intermediate between those of the chrome-diopsides and omphacites. Diopside S89 differs from the other clino-pyroxenes in containing relatively more Sr, Ba, Co, Be, Mn and less Ni, V, Cr, Ti and Sc.

TABLE 12. TRACE ELEMENTS IN CLINOPYROXENES FROM KIMBERLITES AND ASSOCIATED XENOLITHS

Analysts: J. M. Rooke and A. M. Fisher; in parts per million; localities and occurrences given in Table 10, except for E14 (discrete nodule, Thaba Putsoa)

	r(Å)	S	E14	S89	E3	G12	No. 7	E4	E16
Be ²⁺	0.35	3	<3	7	<3	<3	—	<3	<3
Ga ³⁺	0.62	2	7	<2	3	6	—	17	15
Cr ³⁺	0.63	10	1600 ¹	<30	6300 ¹	8900 ¹	14000	1200	1300
Li ⁺	0.68	10	<10	<10	<10	<10	—	10	<10
Ti ⁴⁺	0.68	3	>1000	300	1400 ¹	1500 ¹	1700	2600 ¹	3050 ¹
Ni ²⁺	0.69	10	750	12	850	600	240	300	1000
Co ²⁺	0.72	5	60	60	40	30	—	30	45
V ³⁺	0.74	10	500	30	400	600	400	450	450
Zr ⁴⁺	0.79	3	25	40	8	45	900	55	25
Mn ²⁺	0.80	30	>1000	4000 ¹	1000	650	700	400	700
Sc ^{3+(v)}	0.81	10	10	<10	10	20	—	20	10
Sr ²⁺	1.12	10	95	450	90	550	80	250	150
Pb ²⁺	1.20	3	10	<3	<3	8	—	<3	<3
Ba ²⁺	1.34	10	<10	150	30	40	—	<10	<10

In all specimens Cu <30, Ge <30, Y <30, Mo <3, La <100, Nb <30, Ta <100.

No. 7 quoted from Holmes (1936), analyst: L. S. Theobald.

r=ionic radii, S=sensitivity, v=visual determination.

¹ Chemical determination.

The spectrographic analyses of *subcalcic chrome diopside* E3 and normal chrome diopside G12, supported by analyses of chrome diopsides E1 and E10 (Nixon, 1960),¹ show that the subcalcic variety contains relatively less Sr (occupying the Ca site), but more Ni, Mn and Co (occupying the Mg, Fe site).

¹ Spectrographic data (J.M.R.) of three clinopyroxenes quoted from Nixon (1960): E1-chrome-diopside, Iherzolite nodule, Kao pipe; E10-chrome diopside, serpentized nodule, Sekameng pipe; E39-omphacitic pyroxene, scapolite gneiss nodule, Liqhobong dike; (in p.p.m.) Ga³⁺ 2, <2, 25; Cr³⁺ >3000, 18000, † 400; Li⁺ <10, <10, 25; Ti⁴⁺ >1000, 400, >1000; Ni²⁺ 600, 550, 450; Co²⁺ 35, 25, 55; V³⁺ 550, 550, 650; Zr⁴⁺ 70, 60, 100; Mn²⁺ 850, 600, 300; Sc³⁺ 20, 20, 30; Sr²⁺ 130, 250, 140; Pb²⁺ 4, <3, <3; Ba²⁺ 20, <10, 15; in all three specimens Be <3, Cu <30, Ge <30, Y <30, Mo <3, La <100, Nb <30, Ta <100.

† Element determined chemically.

In both the *chrome-diopside series* and the *omphacites*, however, strontium is remarkably high, considering that this element is usually concentrated in the later stages of fractional crystallisation. The early clinopyroxenes of the Skaergaard intrusion, for example, contain only about 10 ppm (Wager and Mitchell, 1951), most of the strontium being concentrated in the associated plagioclase. In the rocks under consideration this mineral is usually lacking, thus resulting in a Sr-enrichment of the clinopyroxenes.

Scandium, on the other hand, is low compared with ~ 80 ppm (Wager and Mitchell, 1951) in the early Skaergaard clinopyroxenes. This is attributed to the presence in the kimberlitic rocks of garnet which accepts a greater proportion of Sc.

Orthopyroxenes and olivines. In the ultrabasic nodules of Basutoland these minerals contain over 90 per cent of the enstatite and forsterite components respectively (Table 13). They appear to show very restricted compositional ranges, a feature also characteristic of the ultrabasic inclusions in basalts (Ross *et al.*, 1954). In the latter case, however, the Fe/Mg ratios are slightly higher, as is also the aluminium in the orthopyroxenes. The orthopyroxenes of the ultrabasic nodules in kimberlites contain small but significant amounts of sodium and chromium.

In accordance with their chemistry, the physical properties of these orthopyroxenes and olivines show a narrow range (Table 14).

As might be expected, kimberlite and its washings contain mineral fragments of ultrabasic nodules with similar properties to those described above, but there are also some with optical properties indicative of higher Fe/Mg ratios (*e.g.*, orthopyroxenes, A, A', A'', A''' and olivines M3, Lo1 in Table 14). The euhedral olivines M3, at least, have crystallized within the kimberlite itself.

The minor and trace elements (Table 15) show less variety in the orthopyroxenes and olivines than in the garnets and clinopyroxenes, probably because only 4 and 6 coordinated sites are available in the mineral lattice (compared with 4, 6 and 8 in clinopyroxenes and garnets).

Of the elements not shown in the chemical analyses nickel is the most conspicuous, especially in the olivines where it is the fourth most abundant cation. The euhedral olivines M3 and T13 from kimberlite show a relatively higher proportion of Ti, as well as Fe, compared with those in the ultrabasic nodules.

Micas. The composition of phlogopite (Table 18, No. 1) in kimberlites changes on weathering to that of an oxidized, potassium-poor mica, *i.e.*, vermiculite. A dull bronze vermiculite, composed of friable inelastic

TABLE 13. ANALYSES OF ORTHOPYROXENES AND OLIVINES FROM ULTRABASIC NODULES

	Orthopyroxenes				Olivines	
	E2	E3	E8	E9	E8	E9
SiO ₂	58.48	57.11	56.61	57.70	40.94	41.03
TiO ₂	tr.	0.13	0.00	tr.	0.00	0.00
Al ₂ O ₃	0.88	1.00	0.86	0.37	0.06	0.00
Cr ₂ O ₃	0.25	0.35	0.17	0.34	0.00	0.00
Fe ₂ O ₃	0.72	1.82	1.35	1.18	0.00	1.37
FeO	3.93	3.61	3.73	3.79	7.30	6.56
MnO	0.02	0.12	0.10	0.09	0.01	0.09
MgO	34.71	34.02	35.90	35.55	50.80	51.01
CaO	0.50	1.50	0.70	0.55	tr.	0.18
Na ₂ O	0.23	0.35	0.09	0.24	0.03	0.08
K ₂ O	0.08	0.03	tr.	0.00	0.00	tr.
H ₂ O ⁺	—	} 0.28 }	} 0.44 }	} 0.43 }	} 0.38 }	—
H ₂ O ⁻	0.21					—
	100.01	100.32	99.95	100.24	99.52	100.32
Atoms%						
Ca	1.0	2.8	1.3	1.0		
Mg	92.2	89.3	91.5	91.8		
Fe ²⁺ +Fe ³⁺ +Mn	6.8	7.9	7.2	7.2		
Mg						
Mg+Fe+Mn	93.1	91.9	92.7	92.7	92.5	92.0
% Al in Z	1.1	2.0	1.8	1.0 (incl. Fe ³⁺)		

E2. Enstatite, lherzolite nodule, Maliba Matso.

(analyst: M. H. Kerr)

E3. Enstatite, lherzolite nodule, Thaba Putsoa.

(analyst: M. H. Kerr).

E8. Enstatite and olivine, saxonite nodule, Thaba Putsoa.

(analyst: M. H. Kerr)

E9. Enstatite and olivine, lherzolite nodule, Liqhobong.

(analyst: J. R. Baldwin).

lamellae, from Kao pipe compares chemically with that of a bluish-green mica from Dutoitspan pipe described by Maskelyne and Flight (1874) under the name "vaalite" (compare Nos. 2, 3 and 4, Table 18). A comparison of the calculated chemical formula of the Kao specimen with the theoretical vermiculite formula of Barshad (1948) is given below.

1) Kao vermiculite

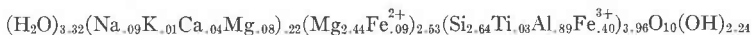
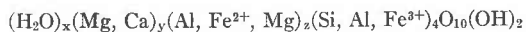


TABLE 14. PHYSICAL PROPERTIES OF ORTHOPYROXENES AND OLIVINES FROM KIMBERLITES AND ASSOCIATED XENOLITHS

No.	Occurrence	G	α	β	γ	$\gamma - \alpha$	2V	Color index
<i>Orthopyroxenes</i>								
E1	nodule, Kao	3.261	1.660	1.665	1.671	0.011	+79½°	10Y 6/3
E2	nodule, Maliba Matso	3.243	1.658	1.662	1.669	0.011	+74°	10Y 6½/2
E3	nodule, Thaba Putsoa	3.254	1.661	1.656 (6)	1.671 (2)	0.010 (1)	+78½°	10Y 6/2
E8	nodule, Thaba Putsoa	3.241	1.661	1.665	1.672 (1)	0.011 (0)	+79°	10Y 6/3
E9	nodule, Liqhobong	3.259	1.660	1.664	1.670 (1)	0.010 (1)	+77°	10Y 5/3
E11	nodule, Louwrencia, S.W.A.	3.261	1.662	1.667	1.672	0.010	+79°	9Y 6/3
B	concentrate, Kao	3.268	1.660	1.665	1.671	0.011	+77°	—
C	concentrate, Kao	3.262	1.660	1.664	1.670	0.010	+75°	—
D	concentrate, Kao	3.246	1.657	1.662	1.669	0.012	+70½°	—
E	concentrate, Kao	3.247	1.657	1.662	1.669	0.012	+71½°	—
A	concentrate, Kao	3.283	1.664	1.669	1.676	0.012	+87°	—
A'	concentrate, Loqhobong No. 2	3.306	1.666	1.672	1.678	0.012	-89°	—
A''	concentrate, Kao	3.320	1.669	1.6745	1.680	0.011	-86½°	—
A'''	concentrate, Thaba Putsoa	3.328	1.671	1.676	1.683	0.012	-83°	—
—	Mir pipe, Siberia (Smirnov, 1959)	—	1.666	—	1.676	0.010	—	—
<i>Olivines</i>								
E1	nodule, Kao	—	1.651	1.665 (6)	1.684 (5)	0.033 (4)	+87½°	—
E2	nodule, Maliba Matso	3.315	1.651	1.667	1.685	0.034	+87°	—
E3	nodule, Thaba Putsoa	3.328	1.651	1.668	1.686	0.035	+87½°	10Y 7/2
E5	nodule, Thaba Putsoa	3.332	1.653 (2)	1.669	1.687	0.034 (5)	+88½°	—
E8	nodule, Thaba Putsoa	3.303	1.649	1.664	1.683	0.034	+86½°	6Y 8/4
E9	nodule, Liqhobong	3.322	1.650	1.667	1.685 (4)	0.035 (4)	+87°	7Y 7/4
E11	nodule, Louwrencia, S.W.A.	3.331	1.652	1.668	1.686	0.034	+87½°	6Y 7/4
M3	kimberlite, Molatoli (mean)	3.362	1.656	1.674 (5)	1.694	0.038	90°	—
Ka1	kimberlite, Kaunyane	3.340	1.654	1.671	1.690	0.036	+88½°	—
Lo1	kimberlite, Liqhobong	3.378	1.660	1.678	1.697	0.037	-89½°	—
—	kimb. pipes, Siberia (Ilin <i>et al.</i> , 1959)	—	1.642	1.663	1.682	0.040	+80-83°	—
—	kimb. pipes, Siberia (Shand, 1934)	3.315	—	—	—	—	+86-87°	—
—	kimb. pipes, Siberia (Smirnov, 1959)	—	1.652	—	1.690	0.038	—	—
—	kimb. pipes, S. Africa (Partridge, 1934)	—	—	1.660	—	—	—	—
—	kimb. pipes, Tanganyika (Fozzard, 1956)	—	—	—	—	—	—	—
		Three determinations of 2V = +88.7°, +88.7°, -89°						

Figures in parentheses indicate an alternative value for the third decimal place; the true figure lies in between the two values.

2) Vermiculite, theoretical formula (Barshad, 1948)



where $x = \text{No. of mols. of water}$, $y = 0.22 - 0.36$, $z \leq 3$.

The Kao vermiculite has $G = 2.27$, $n\gamma = 1.537$, and $2V = ca. 5^\circ$.

Brown and bluish-green micas from other Basutoland kimberlites, which

also have the vermiculite property of exfoliating in a small flame, showed γ values of between 1.539 and 1.591. Cleavage along (010) is commonly developed.

The unaltered phlogopites have higher refractive indices and γ usually lies between 1.595 and 1.610. The absorption scheme is: $Z = Y > X$, with pleochroism: $X =$ pale yellow, Y and $Z =$ yellow brown. Reversed absorption and pleochroism, as described in the Bachelor Lake kimberlites by Watson (1955), also occur.

The eclogitic nodule E7 from Kao and amphibolite nodule EMB 12

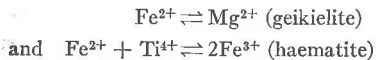
TABLE 15. QUALITATIVE SPECTROGRAPHIC DETERMINATION OF TRACE ELEMENTS IN ORTHOPYROXENES AND OLIVINES FROM KIMBERLITES AND INCLUSIONS
Analyst: A. M. Fisher

	Major	Minor ($< ca. 10\%$)	Trace (in approx. order of decreasing abundance) $< ca. 1000$ ppm
E8, Enstatite	Si, Mg.	Fe, Cr, Al, Ni, Ca, Mn.	V, Na, Co, Ti, Pb.
E9, Enstatite	Si, Mg.	Fe, Al, Cr, Ni, Ca.	Mn, Na, V, Ti, Co.
E8, Olivine	Si, Mg.	Fe, Ni.	Mn, Cr, Ca, Co, Al, Na.
E9, Olivine	Si, Mg.	Fe, Ni.	Cr, Mn, Ca, Co, Na, Al.
L8, Olivine	Si, Mg.	Fe, Ni.	Cr, Mn, Ca, Co, Bi, Na, Al, Ti.
M3, Olivine	Si, Mg, Fe	Ni.	Cr, Mn, Ca, Ti, Co, Na, Al.
T13, Olivine	Si, Mg, Fe	Ni.	Cr, Mn, Ca, Al, Ti, Co, Bi, Na, V, Pb.

Labelling as in Table 14 apart from L8 (phenocryst in kimberlite dyke, Liqobong) and T13 (euhedral phenocryst in kimberlite dyke, Thaba Putsoa).

from Dutoitspan contain brownish-black biotites having higher n_{γ} values than the phlogopites described above. Biotite E7 has: $G = 3.02$, $\gamma = 1.634$ and $2V - = ca. 5^{\circ}$; biotite EMB 12 has $G = ca. 3.0$, $\gamma = 1.614$ and $2V -$ varying between about $2-15^{\circ}$.

Ilmenite. A feature of the chemical analyses of kimberlitic ilmenite is the high proportion of magnesia and ferric oxide (Table 18, Nos. 5 and 6), corresponding to more than 30% of the geikielite ($MgTiO_3$) and haematite (Fe_2O_3) "molecules" respectively. The main substitutions in these ilmenites may therefore be written



In both cases the replacing ions are of relatively small size, thus causing

TABLE 16. X-RAY POWDER DATA FOR ILMENITE FROM KAO
(FeK α radiation)

hkl	d	I	hkl	d	I
102	3.69	m	208	1.360	vw
104	2.71	vs	1.0.10	1.321	w
110	2.52	s	220	1.260	w
113	2.21	m	128	1.195	w
204	1.84	m	2.0.10	1.171	w
116	1.700	s	134	1.144	w
108	1.610	w	226	1.109	m
214	1.487	m	2.1.10	1.064	m
030	1.454	m			

a contraction of the lattice. The x -ray measurements are given in Table 16.

Qualitative spectrographic analyses (J.M.R.) of two ilmenites from Kao and one from Thaba Putsoa show the presence, in all three samples, of the following elements: Ti, Fe, Mg, Mn, Si, Al, Cr, V, Ni, Nb, Zr, Co, Cu and Ca.

The densities of ilmenites from Liqhobong No. 2, Solane, Kao and Thaba Putsoa vary between 4.51 and 4.56 (Berman balance).

Perovskite. A chemical analysis (Table 18, No. 7) shows this mineral to be composed of over 96% CaTiO₃, with a small amount of ferrous iron. This may replace calcium in the crystal lattice or represent ilmenite (FeTiO₃) impurity. A spectrographic analysis (J.M.R.) showed traces of Mg, Si, Na, Mn, Sr, Cr, V, Nb and La. The x -ray powder data (Table 17) are similar to those of a perovskite, for which Murdoch (1951) determined $a = 15.26 \pm 0.01$.

TABLE 17. X-RAY POWDER DATA FOR PEROVSKITE FROM SOLANE
(CuK α radiation)

hkl	d	I	hkl	d	I
004	3.81	m	246	2.04	vw
024	3.41	vw	008	1.91	s
044	2.70	vs	028, 446	1.84	vw
006	2.54	vw	048	1.70	vw
026	2.42	vw	119, 357	1.67	vw
226	2.30	w	139	1.56	s
444	2.20	w	448	1.55	
046	2.12	vw			

Minor kimberlitic minerals. (See also Table 19.)

1) Chromian spinel. A chromian spinel from a concentrate at Qaqa pipe was prepared for analysis, but an *x*-ray photograph of the sample showed the presence of ilmenite impurity. This mineral proved impossible to separate (possibly because it was intergrown with the chromian spinel

TABLE 18. ANALYSES OF VARIOUS MINERALS FROM KIMBERLITES

	1	2	3	4	5	6	7	8
SiO ₂	41.20	35.25	40.77	40.83	—	0.40	—	—
TiO ₂	1.39	0.50	0.58	—	49.35	47.95	57.3	11.40
Al ₂ O ₃	10.51	10.11	11.69	9.80	0.33 ¹	—	1.5	10.68
Cr ₂ O ₃	—	—	—	—	—	0.75	—	42.42
Fe ₂ O ₃	1.68	6.32	7.31	6.84	13.71	13.15	—	—
FeO	3.82	1.41	1.63	—	27.57	28.00	1.3	23.30 ²
MnO	—	0.03	0.04	—	0.05	—	—	0.20
MgO	24.71	22.55	26.08	31.34	8.65	9.00	—	11.14
CaO	0.90	0.56	0.65	—	0.20	tr.	40.0	0.47
Na ₂ O	0.20	0.63	0.73	0.67	—	—	—	—
K ₂ O	9.50	0.15	0.17	—	—	—	—	—
H ₂ O+	4.58	8.95	10.35	9.72	—	—	—	—
H ₂ O—	1.06	13.37	0.00	—	—	—	—	—
CO ₂	0.28	—	—	—	Insol.	V ₂ O ₅ =0.20	—	—
F	tr	—	—	—	resid.	Nb ₂ O ₅ =0.13	—	—
					0.18			
	99.83	99.83	100.00	99.20	100.04	99.58	100.1	99.61

¹ Includes Nb, V, etc., oxides.

² All iron calculated as FeO.

1. Phlogopite, Driekopjes Mine, South Africa (Wagner, 1914, p. 59).
2. Vermiculite, Kao, Basutoland. Analyst: M. H. Kerr.
3. No. 2 recalculated minus H₂O—.
4. Vermiculite (vaalite), Dutoitspan pipe, South Africa. (Maskelyne and Flight, 1874).
5. Ilmenite, Kao pipe, Basutoland. Analysts: M. H. Kerr and O. von Knorring.
6. Ilmenite, Zarnitsa, Siberia (Smirnov, 1959).
7. Perovskite, Solane, Basutoland. Analyst: O. von Knorring.
8. Chromian Spinel octahedra, Qaqa pipe, Basutoland. Analyst: O von Knorring.

but on such a fine scale as to be not detected in polished section). Calculations from the chemical analysis of the sample (Table 18, anal. 8) show the chromian spinel to have the following approximate formula: (Mg_{0.55} Fe_{0.47}) (Al_{0.55} Cr_{1.45})O₄. This neglects the small amounts of calcium and manganese present and also assumes that the accompanying ilmenite

TABLE 19. PROPERTIES OF MISCELLANEOUS MINERALS IN KIMBERLITES AND ASSOCIATED NODULES

Mineral	Occurrence	Spectrographic analyses (analysts: J. M. Rooke and A. M. Fisher)			Physical properties
		major	minor <ca. 10%	trace <ca. 1000 ppm in approx. order of decreasing abundance	
Chromian spinel	concentrate, Qaqs pipe	Cr, Fe	Mg, Ti, Al	Ca, Mn, Ni, Si, V, Cu	G = 4.51, n > 2.00
Chromian spinel	kelyphite, lherzolitite nodule E9, Liqhobong	—	—	—	G = 4.02, n = ca. 1.76 (grain edges) n = 1.745 (grain centers).
Amphibole	amphibolite nodule EMB 12, Dutoitspan.	Si, Mg	Fe, Al, Ca, Na, Ti	Mn, V, Ni, Cr, Zr, Co, Y, Li, Ba, Sr, Sc, Ga	$\alpha = 1.651$, $\beta = 1.664$, $\gamma = 1.672$ Z/c = ca. 20°, 2V = 76.5°, G = 3.160 X = pale yellow brown, Y = olive green, Z = deep blue green.
Amphibole	single crystal, Kao No. 2	—	—	—	$\alpha = 1.693$, $\beta = 1.700$, $\gamma = 1.719$ Z/c = ca. 30°, 2V = ca. 60° X = pale yellow green, Y = yellow green, Z = olive green.
Zircon	concentrate, Liqhobong No. 2	Zr, Si	Hf	Mn, Ca, Mg, Na, Sc, K, Al, Nb, Fe, Ti, V, Y	
Zircon (small spherical)	nodule E6, Qaqa	Zr, Si	Hf	Ca, Sn, Mg, Sc, Na, Al, Nb, Y, Fe	
Zircon	concentrate, Kao No. 2	—	—	—	$\omega = 1.926$, $\epsilon = 1.986 \pm 0.005$ G = 4.63 \pm 0.02
Rutile (black)	eclogitic nodule E6, Qaqa	Ti	—	Fe, Al, Mg, Si, V, Mn, Ca, Cr, Li, Na	
Rutile (bright red fraction)	eclogitic nodule E13, Kao	Ti	—	Si, Al, Mg, Ca, V, Fe, Cr, Mn	G = 2.255
Graphite	saxonite nodule E8, Thaba Putsoa	C	Si, Mg, Fe	Ca, Cr, Al, Mn	
Monazite	nodule E6, Qaqa	Ce	Th, La, P	Ca, Si, Nd, Al, Mg, Pb, Zr, Fe, Bi, Sc, Y, V	$\alpha = 1.778$, $\gamma = 1.827 \pm 0.005$, 2V = 15° - 20° estim.
Kyanite	nodule E6, Qaqa	—	—	—	$\alpha = 1.714$, $\beta = 1.724$, $\alpha = 1.731$ Z/c = 30°, 2V = 81°, G = 3.677

contains $\text{Mg}:\text{Fe}^{2+}$ in the ratio 1:2 (as seems to be usual in kimberlitic ilmenites).

The brown translucent part of the chromian spinel was found to be lighter and less magnetic than the black opaque part. The refractive index and overall density are given in Table 19 together with data for the chromian spinel from kelyphite in lherzolite nodule E9. That this spinel (probably picotite) is also inhomogeneous is seen from the variation in refractive index between the centers and edges of the octahedra.

2) Amphibole. Some properties of this mineral, from an amphibolite xenolith, EMB 12, from Dutoitspan pipe, are given in Table 19. They are comparable to those of the hastingsite which Holmes (1936) has identified in amphibolite and hornblende gneiss nodules derived from the Precambrian basement, in Wesselton kimberlite pipe, South Africa. An amphibole crystal from Kao pipe No. 2 differs in having an optic positive character.

3) Zircon. In samples from kimberlite (Liqhobong No. 2) and an altered eclogitic nodule (E6), yttrium is low (Table 19) compared with the amounts found in other zircons; for example, Dennen and Shields (1956) found 1.6–4.3% Y_2O_3 in 15 zircons from various acid igneous rock, detrital sediments, etc. The E6 zircon differs from the Liqhobong sample in lacking Mn but containing Sn^{4+} (0.71) which presumably replaces Zr^{4+} (0.79).

4) Rutile. Spectrographic analyses of black rutile (maroon in powerful light) from altered eclogitic nodule E6 and a bright reddish-brown rutile fraction from eclogite nodule E13 (Table 19) are very similar considering the marked color difference. The Fe content of E6 is higher but, even so, only present in trace quantities (<ca. 1000 ppm).

5) Graphite. Spectrographic analyses of this mineral from ultrabasic nodule E8 (Table 19) and from diamond (Chesley, 1942; Raal, 1957; Bunting and Van Valkenburg, 1958) reveal that the impurities consist chiefly of some of the more common elements.

Some properties of *monazite* and *kyanite* from nodule E6 are given in Table 19.

PETROGENESIS

Ultrabasic nodules. These may be regarded either as segregations from a kimberlite magma or as xenoliths. The main objection to a cognate origin is that a suite of minerals (pyrope, diopside, ilmenite, perovskite, the more ferriferous olivines and orthopyroxenes) more obviously genetically connected with kimberlite, has been described; to add the ultrabasic nodule mineral varieties (chrome pyrope, chrome diopside, chromian spinel, olivine and enstatite) would necessitate postulating unlikely

abrupt changes in the composition of the kimberlite parent magma, particularly in its chromium content.

If the ultrabasic nodules are to be regarded as xenoliths it is probable, from the local presence of diamond (Williams, 1932, II, p. 417) and the ubiquitous occurrence of the nodules in kimberlites, that they have been derived from a deep-seated and widespread ultrabasic zone (Wagner, 1914; Holmes, 1936; du Toit, 1954) *i.e.* the earth's mantle.

A similar origin has been suggested for some ultrabasic nodules occur-

TABLE 20. MINERAL COMPOSITION OF ULTRABASIC NODULES FROM
KIMBERLITES AND DREISER WEIHER BASALTS
(FRECHEN, 1948)

	Kimberlites ¹	Basalts ²
Olivine	55	60
Enstatite	26	25
Chrome diopside	11	10
Chrome pyrope and kelyphite/spinel	8	5

¹ Mean of values given in Table 3.

² The values are the mean of the four nodules quoted in which all four constituents are present.

ring in basaltic rocks (*e.g.*, Ernst, 1936; Hess and Maxwell, 1953; Ross *et al.*, 1954; Kuno *et al.*, 1957; Ringwood, 1958; Harris and Rowell, 1960). This conclusion is based on their constant mineralogical, chemical and textural features, especially as the nodules are associated with a variety of host rocks such as basalts, limburgites and phonolites. They also constitute one of the few known rock types that yield a suitable seismic velocity (eclogite is the other well-known type). Compared with the kimberlitic ultrabasic nodules, they appear to show a similar bulk chemistry (compare analyses E3 and E11 with 3 and 4 in Table 1) and also a comparable mineralogical composition (Table 20), although more data are required to substantiate these observations. The nodules from both kimberlites and basaltic rocks (Ross, Foster and Myers, 1954) contain olivine as the dominant component, with enstatite next in abundance, though any component may in places predominate. Coarse holocrystalline texture with uncommon grain deformation and foliation features typify both occurrences.

There are a few significant mineralogical differences, outlined in Table 21. If the bulk chemical similarity of the two types of nodule be accepted, these group characteristics indicate a difference in mineral facies. The presence of pyrope-rich garnet and, rarely, diamond (Williams, 1932) in

the kimberlitic ultrabasic nodules implies crystallization under high pressure (eclogitic) conditions—*vide* the stability relations of pyrope determined by Boyd and England (1959) and those of diamond determined by Bovenkerk *et al.* (1959). The lack of these minerals in ultrabasic nodules from basalts suggests that they originated at lower pressure and/or at higher temperature.

The low proportion of Al^{IV} (occupying the z site in the crystal lattice) to Al^{VI} (y site) in the kimberlitic chrome-diopsides, is the same as that

TABLE 21. MINERALOGICAL AND CHEMICAL DIFFERENCES BETWEEN ULTRABASIC NODULES IN KIMBERLITES AND BASALTS

(a) <i>Kimberlites</i>	(b) <i>Basalts</i>
1. Garnet present (sometimes primary spinel)	1. Primary spinel present
2. Pyroxenes without much Al, most of which enters the garnet	2. Pyroxenes contain Al but usually less Cr
3. Low proportion of Al ^{IV} to Al ^{VI} in clinopyroxenes and probably the orthopyroxenes	3. Higher proportion in the clinopyroxenes of Al ^{IV} (in z position) to Al ^{VI}
4. Clinopyroxenes may be subcalcic	4. Clinopyroxenes not usually subcalcic
	5. Minerals have lower Mg/Fe ratios than corresponding minerals in (a)

recognized in eclogite omphacites by Alderman (1936)—see also values of % Al in z (Table 10)—and is probably due to the influence of high pressure. This has also been inferred by Le Bas (1962) from cell-dimension measurements of Al-bearing clinopyroxenes obtained by Kuno (1955), Sakata (1957) and Brown (1960).

By contrast with normal chrome-diopsides, the subcalcic chrome-diopsides in some ultrabasic nodules from kimberlites would seem to be a result of high temperature crystallization, although pressure must also influence their formation.

Minerals from the kimberlitic ultrabasic nodules have slightly higher Mg/Fe ratios than the corresponding minerals in the basaltic ultrabasic nodules. This does not *necessarily* mean that the Mg/Fe ratio derived from the overall composition of the ultrabasic nodules from kimberlites is higher, for only a slightly greater proportion of garnet as compared with chromian spinel in their respective nodules would be enough to equalize the Mg/Fe ratios of the two rocks. The Mg/Fe values for the

kimberlitic ultrabasic nodules E3 and E11 are 11 and 10 respectively, compared with 7 for the lherzolite-dunite bomb in basalt from Madeira and 9 for the peridotite xenolith in basalt from California (from analyses quoted in Table 1).

From the foregoing evidence it appears that the ultrabasic nodules in kimberlites are analogous to those in basalts, and have therefore probably been derived from the mantle, but have originated at greater depth.

Eclogite and other nodules. There is no doubt that amphibolite, granulite and other metamorphic rock xenoliths in kimberlite are fragments derived from the earth's crust, for they are similar to rocks exposed in metamorphic terrains, besides being totally different from the host kimberlite. A difficulty arises when eclogite nodules are considered, for they characterize (albeit sparingly) most kimberlites. Moreover, rare eclogite nodules containing diamond are known (*e.g.*, Bobrievich *et al.*, 1959). However, since du Toit (see Williams 1932, I, pp. 285-286) and Wagner (1914) have described sequences of related nodules ranging from low grade metamorphic rocks to granulites and eclogites, there is little doubt that *some eclogites at least* are true xenoliths. The main issue, therefore, concerns the *proportion* of xenolithic eclogites.

The Basutoland nodules E4, E6, E7, E13 and E39 (Table 4) contain garnets, falling naturally into a single series (Fig. 6), in which the almandine component is the main variable. Since nodules E39, E6 and E7 are clearly of xenolithic origin as they contain such non-kimberlitic minerals as scapolite, kyanite and biotite, a similar origin is inferred for the omphacite-bearing eclogites E4 and E13.

The garnet in the eclogitic nodule, E16 from Kaalvallei shows affinities with the pyropes (Fig. 6) and the rock may, therefore, be cognate.

A significant feature of the eclogitic nodules is the presence of either primary rutile, as in the xenolithic nodules E4, E6 and E13, or ilmenite, the latter being essentially a kimberlitic mineral, discussed below.

The depth from which xenolithic eclogites originated is conjectural, but the local presence of diamond in them and their widespread occurrence in kimberlites are the main reasons why they have been regarded as representatives of a primary eclogite zone within the earth (*e.g.* Fermor, 1913; Goldschmidt, 1922) possibly overlying a peridotite mantle (Wagner, 1928) or interlayered with its upper zones (Holmes, 1936). Unlike the ultrabasic nodules, true eclogite nodules are rarely found in non-kimberlitic volcanic rocks which suggests that the eclogite zone, if present, is largely restricted to regions of the earth's crust where kimberlites occur (*i.e.*, "shield" areas).

Cognate nodules. Under this heading are listed the discrete nodules and grains of ilmenite, pyrope, diopside, certain olivines and enstatites, etc. thought to have originated within the kimberlite magma. Although rarely observed in Basutoland kimberlites, local segregations of a *composite* nature containing two or more of these minerals, e.g., olivine, ilmenite and pyrope, have been recorded by Wagner (1914, p. 119). Nodules containing olivine and bronzite, with and without diopside and pyrope, are also listed by this author who regards some of them (p. 131) as having

“resulted from the clotting together under plutonic conditions of early products of the consolidation of the kimberlite magma, or from the breaking up of rock thus formed.”

If, as is generally agreed, ilmenite is mainly a primary constituent of kimberlite, the occurrence of ilmenite-diopside and ilmenite-pyrope nodules (Wagner, 1914) is strong evidence that pyrope-diopside nodules (also described by Wagner, 1914), as well as the discrete pyrope and diopside nodules, are also cognate. These particular garnet-clinopyroxene nodules may be termed “griquaite,”¹ (See anal. 6, Table 1) a name suggested by Beck (1907) who, in fact, regarded *all* the “eclogite” nodules in kimberlite as cognate segregations. Unfortunately there are insufficient mineralogical and chemical data to delimit with certainty the eclogite xenoliths and the griquaite segregations. Nodule E16 for example, although having a garnet which may be classed with the pyropes, also contains omphacite, a mineral typical of the eclogites. It must be stressed, however, that the compositional range of the kimberlitic clinopyroxenes (diopsides) is unknown.

Kimberlite. The major clues to the origin of this rock are provided by its inclusions and the nature of its field relations. As has been seen the inclusions point to sampling by the kimberlite magma of rocks occurring at all levels in the earth's crust and in the upper zones of an ultrabasic mantle. Wagner (1914), Taljaard (1936) and Holmes (1936) have emphasized the close spatial and chemical relation of kimberlites to melilite basalts in the field and considered the two genetically connected. The chemical nature of the original kimberlite magma is obscured by the fragments of rocks and minerals, both cognate and foreign, present in kimberlite. Large volumes of gases, notably H₂O and CO₂ were also probably present, as is suggested by the observed extensive hydration and carbonation of the rock.

¹ The name “griquaite” has been used to designate the igneous facies equivalent of the metamorphic eclogite facies (Eskola, 1958).

The original magma may therefore be expressed in terms of a number of variables, thus:

Parental magma = kimberlite + volatiles - accidental inclusions (ultrabasic and crustal fragments) + cognate segregations (ilmenite, pyrope, griquaite, etc.)

Holmes (1936) considered that the original magma was essentially an olivine melilitite (melilite basalt) from which "emanations" consisting mainly of water, carbon dioxide and phosphorus pentoxide had been lost and to which had been added xenolithic ultrabasic mantle material (lherzolites, etc.) thereby producing kimberlite. One of the main difficulties is to account for the low $\text{Na}_2\text{O}\%$ of kimberlites (Table 1, Nos. 1 and 2) compared with other alkalic volcanics (K_2O values are of the same order). Holmes and Harwood (1932) originally accounted for this by postulating a removal of omphacite-bearing eclogites from the magma, but rescinded this hypothesis when subsequent helium determinations demonstrated that the eclogitic nodules examined were true xenoliths (Holmes and Paneth, 1936).

The griquaite nodules and the discrete bottle-green clinopyroxene nodules on the other hand, are considered to be cognate and, if segregated from the magma, *e.g.*, by gravitational settling, would reduce its sodium content. For this to have been effective the cognate clinopyroxenes must include omphacitic varieties similar to E16 omphacite, for example.

It is significant that the amount of cognate minerals varies greatly in different kimberlites; in South Africa they may constitute more than half the kimberlitic rock (Harger, 1905; Voit, 1908). This would account for the relatively high sodium content of some kimberlites. In view of this, as well as the variation in the proportions of different types of cognate and xenolithic inclusions and the extensive secondary alteration of kimberlite, it is difficult to compute the chemical nature of the original magma. It may be noted, however, that melilitite basalt (as postulated by Holmes (1936) and others) and nepheline melilite basalt compositions can be obtained for the parental magma by substitution of chemical values in the equation given above.

On account of a lack of experimental data on rock melting under very high pressures, it can only be conjectured that the parental magma arose by partial fusion of part of the earth's (ultrabasic) mantle. The origin of the volatiles and variety of trace elements in kimberlites is equally obscure although separation of large quantities of cognate minerals from the magma (visualized as taking place under reduced temperature conditions) would effect some concentration.

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