Intrusion Features of Some Hypabyssal South African Kimberlites *

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Abstract

Kimberlite in certain dykes and in the deepest parts of some diatremes show textural and other features which contrast with those in the breccia diatremes. Some hypabyssal kimberlite intrusions show relatively high-temperature contact phenomena including baking of country-rock sediments and sedimentary xenoliths, and contrasting with the brecciated texture of most diatreme-facies kimberlites, in the hypabyssal kimberlites are numerous examples of preferred orientation of inequidimensional minerals (? trachytic flow texture), and rapid mineralogical gradients from the contact towards the dyke centres that may be attributable to flowage differentiation. In the Benfontein sill (Kimberley area) there is well-developed horizontal banding due to gravitational settling, and pseudo-sedimentary structures are also present. The accumulated evidence indicates that kimberlite existed as a relatively hot fluid up to depths of 2-3 km below the land-surface at the time of intrusion; above this level, gas release caused diatreme formation, brecciation and adiabatic cooling. These views are contrary to those of geologists who postulate eruption of kimberlite as a cold breccia directly from the mantle or deep within the crust, but accords with the views of many Russian geologsts who accept the existence of kimberlite magma, the extrusive equivalent of which is the ultrabasic lava meimechite.

Introduction

For many years, hypotheses about the nature and emplacement of kimberlite were influenced by observations made on the kimberlites infilling the major diamond-producing diatremes of South Africa. The two main observations, which have overshadowed less spectacular observations are that:

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1) kimberlite is essentially a brecciated rock;

2) kimberlite is essentially a « cold » rock since the kimberlite in the diatremes shows no thermal metamorphic effects even upon very sensitive wall-rocks and xenoliths (WAGNER, 1914; WILLIAMS, 1932).

The two observations have lead certain geologists to propose that kimberlite has been intruded from the mantle either as a cold mush, akin to Alpine-type peridotites (MIKHEYENKO and NENASHEV, 1962), or as a cold, fluidised system (DAVIDSON, 1964; KENNEDY and NORDLIE, 1968). These hypotheses, which deny the existence of a hot kimberlite magma at the time of the kimberlite activity, appear to conflict with the observations of Russian geologists who have found various magmatic features in the kimberlites of Yakutia, and amongst whom the term « magmatic kimberlite » is standard terminology. Moreover, the lava meimechite, which has been found in northern Siberia, is chemically similar to kimberlite and is regarded by Russian geologists as its extrusive equivalent.

There are in the sub-diatreme kimberlite dykes and sills of South Africa various contact and textural features that appear to be consistent with kimberlite being intruded as a hot liquid into the sub-diatreme dyke swarms, prior to the formation of the high level diatremes with their attendant brecciation and cooling. These intrusion features have been found in connection with what is normally termed « massive » kimberlite occurring in dykes and sills, as inclusions in brecciated kimberlite, or in the deepest parts of kimberlite diatremes where the massive kimberlite has intruded the diatreme-facies breccias. The two types of feature to which attention may be specially directed are thermal metamorphic effects and internal fluidal textures.

Thermal Metamorphic Effects

Various of the old South African geologists noted thermal effects at the contacts of kimberlite dykes. For example, DU TOIT (1908) and ROGERS and DU TOIT (1909) found that kimberlite in small pipes and dykes in the Prieska area (on the farms Riet Gat, Grenaat Kop, Markt and Kalk Put) have baked and hardened the surrounding Dwyka shales, and « limestone concretions in the shale have acquired a semi-crystalline structure » (Du Toit, *op. cit.*, p. 116). Again DU TOIT (1913) has described an occurrence on the Hlangwini location near Matatiele, Natal, where purple Karroo mudstones have been converted to a hard mass for a distance of a few inches from the contact with a micaceous kimberlite dyke, whilst small mudstone inclusions have been converted to lydianite. Furthermore, ROGERS (1910) states that in the micaceous kimberlite pipe at Eende Kuil in the Sutherland district, shale and sandstone inclusions are converted to hornstone and quartzite.

In addition to these occurrences, the writer has found evidence of thermal metamorphism in connection with a micaceous kimberlite dyke at Marakabei, in north-western Lesotho (28°42′ S 28°21′ E). The dyke is one of a group of micaceous dykes that strike WNW - ESE, which is the dominant trend of kimberlite dykes in northern Lesotho (DAWSON, 1962). The dyke in question is 3½ feet wide, and is thicker than most of the other dykes which do not exceed 9 inches. The dyke rock consists of phenocrysts of serpentinised olivine and zoned idiomorphic mica in a matrix of calcite and microcrystalline serpentine containing small crystals of magnetite and perovskite. An analysis of the rock (Table 1) underlines the calcite-rich nature of the rock, which

TABLE 1

	1	*2*	*3*	*4*
SiO_2	16.97	12.24	30.45	24.99
TiO_2	2.17	1.60	1.69	2.69
Al_2O_3	1.66	2.08	2.91	4.38
Fe_2O_3	11.29	3.28	6.08	7.12
Cr_2O_3	n.d.	n.d.	0.26	0.41
FeO	1.43	1.73	3.14	3.01
MnO	0.13	0.14	0.17	0.24
MgO	9.47	7.20	29.50	24.76
CaO	28.71	39.20	9.44	15.63
Na_2O	0.29	0.28	0.46	0.87
K_2O	0.56	1.34	1.58	1.08
H_2O^+	3.13	1.52	6.37	6.47
H_2O^-	3.68	nil	1.42	1.30
P_2O_5	0.14	2.92	0.93	1.30
CO_2	20.12	26.67	5.68	5.87
	99.75	100.25	100.08	100.12

1. Kimberlite, Marakabei dyke, Lesotho. Analyst: D. G. POWELL.
2. Kimberlite dyke, Jagersfontein mine (WILLIAMS, 1932, p. 137).
3. Porphyritic zone in layered kimberlite (S30) from the 2,500 foot level, Wesselton Mine. Analyst: J. R. BALDWIN.
4. Aphanitic zone in layered kimberlite (S30) from the 2,500 foot level, Wesselton Mine. Analyst: J. R. BALDWIN.

resembles in this way a dyke rock from the Jagersfontein mine (Williams, 1932, p. 137). The country rock is a flat-lying, red, arkosic siltstone of Stormberg (Karroo) age. For a distance of 2 feet from the contact with the dyke the red country-rock has been changed to a green colour, presumably due to reduction of the ferric iron in the siltstone, and also the siltstone has been made hard and splintery up against the contact. Small xenoliths of siltstone within the dyke have been converted to a tough, splintery, black hornstone. Despite the fact that there are very striking differences between the country-rock and the hornstone in hand specimen, in thin section there is little evidence of recrystallisation. The only effects are that the feldspars are intensely clouded, and small magnetite grains have formed. There is no sign that the induration is due to impregnation by calcite, despite the calcite-rich nature of the dyke-rock.

It is of interest that in all the cases of thermal metamorphism recorded above, the intrusion is of micaceous, rather than basaltic, kimberlite.

There are also rare recordings of thermal metamorphism of inclusions in kimberlite pipes. Wagner (1911, p. 54) has recorded metamorphism of many of shale and dolomite inclusions in the kimberlite of the Premier Mine. In the case of the former there is development of radially disposed crystals of augite, and of garnet in rounded crystals or in peculiar, elongate, worm-like growths. In the case of the dolomite inclusions, they have recrystallised to assume a very coarsely crystalline texture and, more rarely, development of grossular garnet. Whilst a certain amount of caution must be applied to the significance of an isolated recording such as this, it is to some extent confirmed by the recent finding of metamorphosed xenoliths of marly sediments in the Novinka, Komsomolskaya and Zimnyaya pipes in Siberia (Kharkiv, 1967). Some of these xenoliths are concentrically zoned, with marl in the centre and andradite garnet-cuspidine rims and an intermediate transitional zone in which monticellite is found in addition to garnet and cuspidine. Other xenoliths have a pronounced banded texture, each band having its characteristic mineralogy. Bands composed of garnet and cuspidine alternate with bands of garnet and garnet-cuspidine-monticellite, and in between these bands are strips of unaltered sedimentary carbonate-clay rock. The parts of the banded xenoliths directly in contact with the kimberlite do not show the banded texture but are composed of fine-grained aggregates of cuspidine and garnet.

Internal Textures and Structures

a) *Phenocryst distribution*

In some massive kimberlites there are considerable differences in the proportion of phenocrysts at various points within the body (¹). A particularly good example has been described by WAGNER (1914, p. 42-45) in a kimberlite dyke cutting granite gneiss on the 2,040 foot level of the De Beers mine, Kimberley (Fig. 1). To quote Wagner (*op. cit.*, p. 44) « the dyke rock appears to have been chilled at its contact with the fissure walls. It is coarsely porphyritic at the centre with phenocrysts up to one third of an inch in diameter, whereas in its peripheral portions except for occasional small flakes of phlogopite, no phenocrysts are visible. In places a tendency to a vesicular structure was noted in the marginal phase of this intrusion ». WAGNER (1911) has also noted layers of coarsely porphyritic kimberlite alternating with aphanitic kimberlite in a dyke at Franspoort, Pretoria,

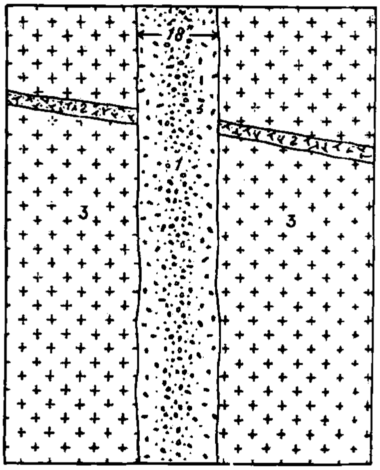

FIG. 1 - Concentration of phenocrysts in central part of a kimberlite dyke, De Beers Mine, Kimberley (from WAGNER, 1914).

(¹) In the following discussion it is not intended to enter the phenocryst *v.* xenocryst argument; the term « phenocryst » is used to denote the larger crystals or pseudomorphs and carries no genetic connotation. Most earlier geologists referred to them as « phenocryst »; the modern concepts hold them to be xenocrysts.

and he also records the two texturally contrasting types in the Zonderwater pipe and the Kleinzonderhout dyke in the same area.

A similar example of alternation of coarsely porphyritic kimberlite with aphanitic kimberlite has been found by the writer on the 2.500 foot level in the Wesselton Mine, Kimberley. In the wall of the haulageway is exposed the contact between the grey-green pipe breccia, which is full of small, angular xenoliths of granite and shale, and a later intrusion of massive, black kimberlite. In contrast to the pipe breccia, in which the olivines are serpentinised and most of the peridotite xenoliths are decomposed, the olivines in the massive black kimberlite are extremely fresh, with only small rims of serpentine. The margin of the massive kimberlite is very fine-grained, containing only rare phenocrysts of olivine, and has the appearance of a chilled margin (Fig. 2). Seven cm from the contact the fine-grained margin is succeeded by a thin zone, some 3 cm wide, in which there are abundant phenocrysts up to 8 mm of fresh olivine, marginally altered mica, kelyphitised garnet and ilmenite, along with abundant xenoliths of fresh peridotite and rare xenoliths of limestone and shale. The longer axes of the phenocrysts and xenoliths are aligned parallel to the contact with the pipe breccia. The porphyritic zone is succeeded by another thin (1.5 cm) zone in which penocrysts are comparatively few and which again runs parallel to the contact. This in turn is followed by porphyritic kimberlite which comprises the bulk of the massive kimberlite intrusion. In thin section it is apparent that the fine-grained margin is not a chill phenomenon as the grain size is no finer than that of the groundmass in the porphyritic varieties. In

FIG. 2 - Alternating layers of aphyric and phenocryst-rich massive kimberlite, 2,500 foot level, Wesselton Mine.

fact the fine-grained serpentine-magnetite-calcite assemblage of the margin is the same as the groundmass of the porphyritic variety. The only difference between these two apparently contrasting types is in the phenocryst/matrix ratio.

The writer has also seen alternation of aphanitic and porphyritic bands in the kimberlite of the Byrnes dyke, Theron area, Orange Free State, and also in a block of massive kimberlite from the Roberts Victor Mine (Fig. 3). In addition to the alternating zones the Roberts Victor specimen shows a swirling texture which is picked out by alignment of the olivine and mica phenocrysts.

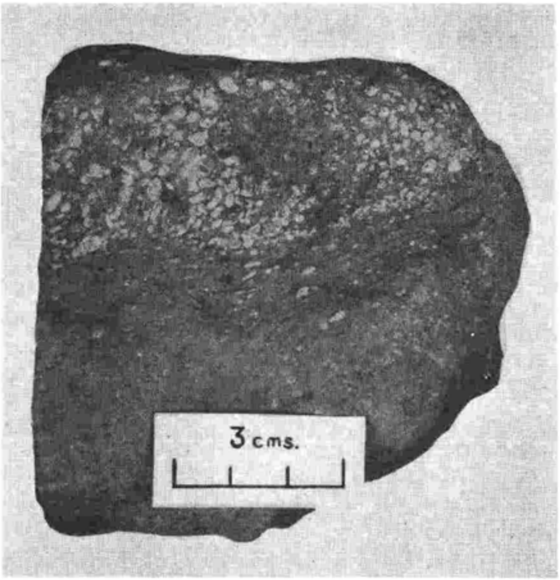

FIG. 3 - Alternating layers of aphyric and porphyritic massive kimberlite, block in yellow ground, Roberts Victor Mine.

b) *Alignment of phenocrysts*

In many intrusions of massive kimberlite there is a strong alignment of inequidimensional phenocrysts, several instances having already been mentioned above. In addition to these, the writer has seen alignment of phenocrysts in dykes in Lesotho; in the eastern Orange Free State (Monteleo and Star mines); in the Belsbank dykes, northern Cape Province; and at the Helam Mine, W. Transvaal. In addition trachytic texture has been seen in the kimberlite of the Voorspoed and Monteleo mines (O.F.S.) where aligned, *undeformed* mica crystals flow round xenoliths of basalt and shale (Fig. 4).

c) *Banding*

A type of banding which is, to the writer's knowledge, unique in kimberlite, has been found in a kimberlite sill at Benfontein, seven miles ESE of Kimberley. The sill is one of several in the Kimberley area that have been described by HAWTHORNE (in the press), and it has also been tentatively listed as a carbonatite by VERWOERD (1966). The sill, which is believed by Hawthorne (*op. cit.*), to be up to four feet thick, is intruded into Karrao shales beneath a thick dolerite sheet which apparently acted as a cap rock. The sill, which is only sporadically exposed, crops out over an area of two miles east to west, and one mile north to south.

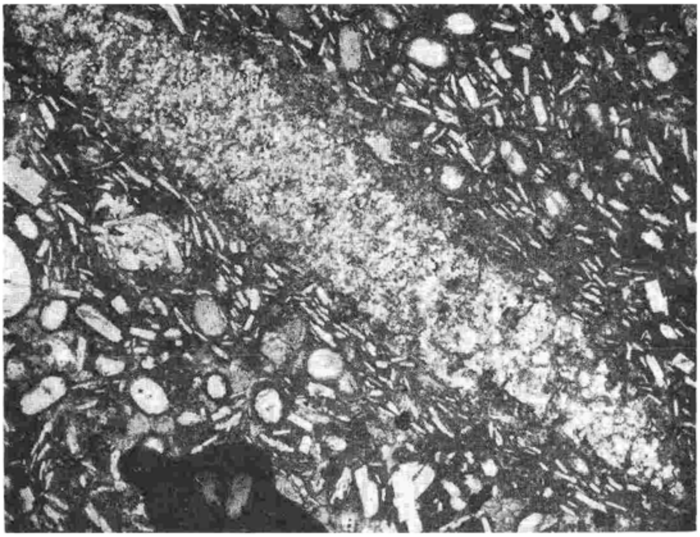

FIG. 4 - Trachytic texture of mica crystals round a shale inclusion, in micaceous kimberlite, Monteleo Mine. Ordinary light, x 15.

The first author briefly examined the sill in 1966 and made a small collection of specimens on which the present account is based. It is apparent that the sill has had a complex intrusion and cooling history, the elucidation of which will necessitate the collection of more specimens, but within the specimens already collected are a number of interesting textures which are relevant to the present discussion. The sill is noticeably layered in certain parts, particularly where it thins out, but there are other points where the kimberlite is relatively structureless, and this structureless kimberlite may be taken as a standard against which the more unusual variants may be compared. The structureless kimberlite consists of phenocrysts of olivine, up to 2 mm long, set in a matrix consisting mainly of calcite and magnetite with smaller amounts of apatite, perovskite and a lath-shaped zeolite-like mineral. The olivine phenocrysts show every transition from very fresh to completely serpentinised, though in some specimens they are remarkably fresh with only narrow rims of magnetite; these fresh olivines are very often idiomorphic, and show alignment of their long axes (Fig. 5). Olivine separated from specimen S8 has the composition of Fo_{90} (analysis 1, Table 2). There

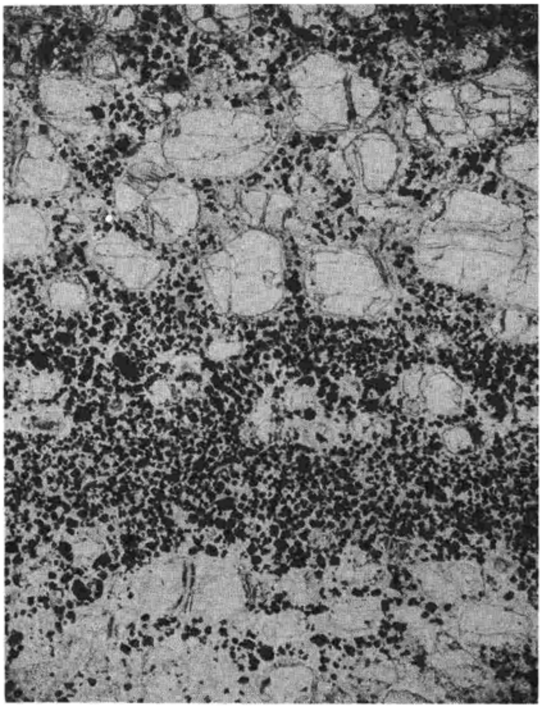

FIG. 5 - Benfontein kimberlite, showing (a) alternation of olivine-rich and ore-rich layers; and (b) parallelism of the long axes of the olivines.

are also rare phenocrysts of mica, and also small rounded aggregates or nodules of xenomorphic olivine. Also in the groundmass are patches of isotropic serpophite, and in two samples the groundmass calcite is in the form of small plates which form a trachytic texture around olivine phenocrysts (Fig. 6). These platy calcites, which are a common feature in some specimens from the sill, may possibly be pseudomorphs after some earlier, easily carbonated mineral, but on the other hand they may be primary. Pyrope, chrome-diopside and picroilmenite have not been found in the specimens in the writer's possession, but Hawthorne (*op. cit.*), notes that these min-

TABLE 2 - Analysis of Benfontein rocks and olivine.

	1	*2*	*3*	*4*	*5*
SiO_2	40.00	25.19	28.63	3.17	0.52
TiO_2	0.05	1.89	1.07	10.98	0.10
Al_2O_3	nil	2.27	—	9.21	0.48
Fe_2O_3	1.55	3.72	6.03	18.78	1.30
FeO	9.06	6.72	5.38	11.04	0.61
MnO	0.09	0.22	0.14	0.22	0.19
MgO	48.90	29.69	34.02	14.99	8.87
CaO	nil	13.59	11.92	16.49	44.07
Na_2O	nil	0.01	0.20	0.04	0.41
K_2O	nil	0.15	0.05	nil	nil
H_2O^+	nil	1.15	2.75	1.90	0.36
H_2O^-	0.05	—	0.23	0.23	0.03
P_2O_5	nil	2.20	0.27	1.67	1.42
CO_2	nil	12.83	8.99	10.91	41.24
	99.70	99.62	99.69	99.63	99.60

1. Olivine from specimen S8. Analyst: D. G. POWELL.
2. Composite sample of Benfontein kimberlite (HAWTHORNE, 1968).
3. Benfontein kimberlite S8. Analyst: D. G. POWELL.
4. Ore-rich layer, specimen S5. Analyst: D. G. POWELL.
5. Carbonate-rich layer, specimen S3. Analyst: D. G. POWELL.

erals have been found in samples milled by the De Beers Consolidated Mines. The only xenoliths yet found within the sill, are fragments of the overlying dolerite and highly carbonated fragments of country-rock shale.

The most widespread structure in the sill is layering, the layering being due to alternation of layers of contrasting mineralogical and chemical composition. The most usual type is due to interbanding of layers rich in magnetite and perovskite (with interstitial calcite) and layers rich in olivine with little ore mineral, calcite again being the groundmass mineral (Fig. 5). In other layers there is a difference in the phenocryst/groundmass ratio with relatively few olivine set in a calcite matrix. These layers in themselves are usually not greater than 1-2 cm thick.

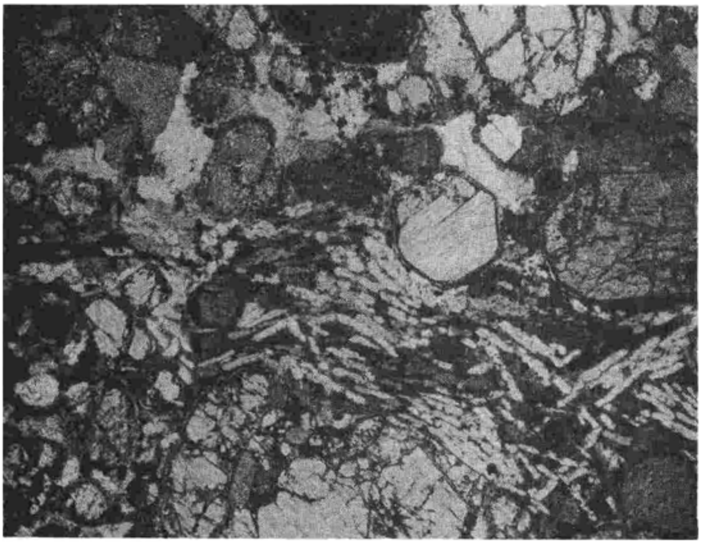

FIG. 6 - Trachytic textures of platy calcite round olivine. Note the euhedral shape of the olivines and the absence of serpentinisation. Benfontein kimberlite. Ordinary light, x 15.

Some of the most spectacular layering, combined with a number of very unusual structures are found in a small exposure on the southwest side of the sill, in rock which appears to be topographically near the lower margin of the sill. Here, interbanded with layers of well-serpentinised « normal » kimberlite are layers extremely rich in magnetite and perovskite and other layers which are extremely rich in calcite and apatite (Fig. 7). Whilst these two types of rock are mineralogically the heavy and complementary light fractions of normal kimberlite, it has not yet been found that the ore-rich layers have resulted from *in situ* settling out of the opaque minerals. In several specimens it has been found that there is a gradual vertical transition from normal kimberlite into carbonate rock which may in these instances be regarded as a differentiate. However, there are other cases where there is an extremely strong phase ratio contact between the carbonate layers and the normal kimberlite. Analyses of these rocks show that they differ markedly from the normal kimberlite (Table 2). The differentiated carbonate layers are creamy in colour and contain platy or wedge-shaped calcite crystals. In several specimens, material from the differentiated carbonate layers has penetrated the interface between the carbonate-rich layer and the overlying layer, and has migrated vertically to from amygdale-like bodies that will be referred to as « migration amygdales » (Fig. 7). Some of the

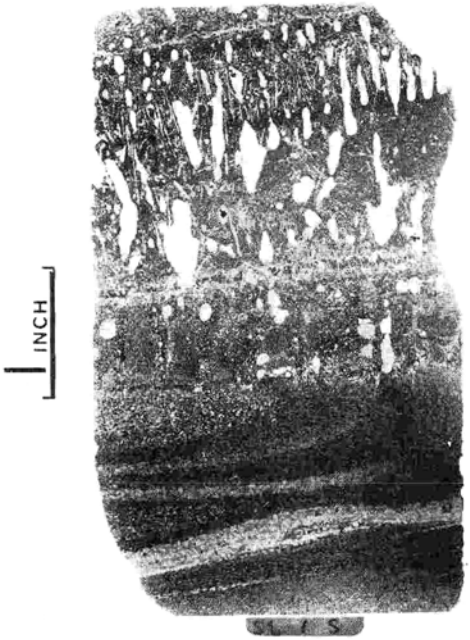

FIG. 7 - Layered Benfontein kimberlite (specimen S. 1) showing layers of contrasting composition, rooted migration amygdales and rootless amygdales consisting of calcite and, occasionally, magnetite. The lower layers show cross bedding.

migration amygdales consist of a mixture of calcite, microcrystalline serpentine and magnetite which contrast with the olivine-rich areas in between the amygdales; these amygdales invariably terminate vertically in a lobe of clear calcite. In other amygdales, the lower part consists of the creamy, platy carbonate of the differentiated carbonate layers in which the amygdales are rooted, but the upper part of the amygdale is composed of clear, white, coarsely crystalline calcite of rhombohedral habit, that shows a sharp contact with the rest of the material infilling the amygdale (Fig. 8). In other instances, the whole of the rooted amygdale may consist of clear, white, coarsely crystalline calcite. In some of the clear calcite areas are crystals of magnetite. Within the kimberlite into which migration has taken place, the olivines are invariably serpentinised or carbonated. Above the zone of rooted amygdales there are other amygdales which may be either elongated vertically or else rounded (Fig. 6). They contain

FIG. 8 - Layered Benfontein kimberlite (specimen S. 4b) showing platy calcites (lower layer), calcite-filled migration amygdales, and dendritic calcites.

either rhombohedral calcite, sometimes with magnetite, or else clear platy calcite, the latter usually being found at definite horizons. In the case of some of the larger amygdales, they have a vuggy appearance, with the centre of the amygdale being unoccupied. In the case of certain of these rootless amygdales which are vertically above rooted ones, it is possible that they were originally part of the rooted migration amygdales but they became detached during the vertical migration.

FIG. 9 - Layered Benfontein kimberlite (specimen S. 5), showing lateral thinning of layers, banding, and downward-growing calcite dendrites.

In the rocks from this locality there is another feature of great interest. There are within certain horizons, fine, feathery crystals of dentritic calcite (Figs. 8, 9, 10). Whilst a very few are found randomly oriented the vast majority grow downwards from the contacts between layers of contrasting mineralogy, and they also branch out downwards. They appear to be morphologically similar to the « Willow Lake » or crescumulate textures found in basic layered intrusions (*e.g.* TAUBENECK and POLDERVAART, 1960; WAGER and BROWN, 1968).

In some cases, downward protruding calcite dendrites have caused bifurcation of upward migrating amygdales.

In addition to these features, there are a number of pseudo-sedimentary structures such as cross-bedding (Fig. 6), rapid lateral thinning of layers (Fig. 9), and wash-out structures where layered kimberlite is truncated by a body of carbonate rock in which the platy calcites are randomly oriented and which contains rafts and fragments of the adjacent « wall » kimberlite (Fig. 11).

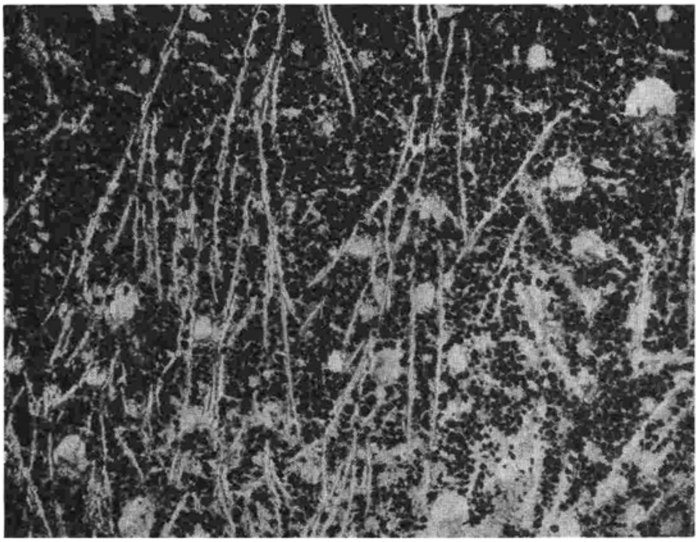

FIG. 10 - Dendritic calcite in Benfontein kimberlite (specimen S. 3). Ordinary light, x 15.

Discussion

In the case of the thermal metamorphic effects, it is apparent that the kimberlite must have been hot at the time of its emplacement. It is readily acknowledged that many kimberlites do not exhibit contact metamorphic features but this need not imply that kimberlite was cold, since the same is true for many basaltic or granitic dykes which were undoubtedly hot at the time of injection.

In the case of the internal structures, these have to be examined in the light of three possible modes of intrusion, (1) as a cold, plastic injection; (2) as a gas-solid fluidised system; and (3) as a melt containing phenocrysts, or liquid/crystal mush. Emplacement as a cold plastic mush appears to be precluded by (a) the thermal effects; (b) by the presence of vesicles in kimberlite; and (c) by the underformed nature of the fragile mica plates arranged in trachytic texture.

There is a distinct possibility that some of the features could be caused by a gas-solid fluidisation process. Features such as alignment of phenocrysts could be caused by gas-streaming, and gas velocity gradients, particularly within dykes, could produce contrasting phenocryst distribution. However, two of the most characteristic features of fluidisation — brecciation and attrition of the particles — have not been seen in the examples described.

FIG. 11 - Wash-out structure in layered Benfontein kimberlite (specimen S. 14). The layered kimberlite is truncated by structureless calcite-rich kimberlite which contains rafts of the banded kimberlite.

On the other hand most of the features described above may be matched in rocks that have crystallised from igneous melts. The pseudosedimentary structures in the Benfontein sill may be matched by similar sedimentary structures in gabbroic rocks in particular (*e.g.* Skaergaard and the Bushveld), and the alternation of aphyric and porphyritic layers attributed to flowage differentiation is known in many minor basic and ultrabasic intrusions (*e.g.* DREVER and JOHNSTON, 1958, 1968; SIMKIN, 1968; BHATTACHARJI, 1968). Alignment of phenocrysts is common in rocks that have formed by cooling of magma, as are trachytic textures. The most convincing evidence, however, for the presence of magma, at least at Benfontein, is the presence of the differentiation layers, the migration amygdales and the dendritic calcites. It is difficult to imagine how the migration amygdales could have remained as discreet units if the material into which they have migrated had not been a liquid at the time, allowing the amygdales to be confined by surface tension. In addition the dendritic calcites may be matched only with crystals that have been precipitated from supersaturated melts (SARATOVKIN, 1959; TAUBENECK and POLDERVAART, 1960; WAGNER and BROWN, 1968; KOSTOV, 1968). It is extremely doubtful if they could have grown in the solid state, or from plastic mush.

On balance it can be said that the internal structures of many hypabyssal, massive kimberlites from South Africa can best be explained if it accepted that the kimberlite was a hot liquid, probably with suspended crystals and xenoliths of deep-seated rock types, at the time of its intrusion into the crust. When account is taken of the extent of erosion since the time of emplacement, it can be said that certain kimberlites were still partially liquid at depths of as little as 2 km below the original land surface. Above these levels, gas release with attendant adiabatic cooling from the highly gas-charged melts caused the formation of diatremes with their characteristic brecciated rocks and evidence of cold emplacement.

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