

A CONTRIBUTION TO THE PETROLOGY OF KIMBERLITES

by
Floris Johan Kruger B.Sc.(Hons.) (Natal)

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I declare that this thesis

A CONTRIBUTION TO THE PETROLOGY OF KIMBERLITES

is my own original work except
where acknowledged in the text.



F.J. KRUGER.

A prima decendit origine mundi

Causarum series.

Lucan Pharsalia

ABSTRACT

The petrogenetic relationships of the different varieties of kimberlite in the De Beers Mine and Letseng-la-terai composite diatremes have been investigated using petrographic and chemical methods.

Kimberlites in the Letseng-la-terai diatreme were found to be strongly contaminated by crustal material, mainly basalt. A method to correct for the effects of the contamination has been developed and applied to these kimberlites. Using the corrected data, the four kimberlite types in each group appear to be related to each other by crystal/liquid fractionation models. However the two groups cannot be related to each other.

The De Beer Mine has two varieties of kimberlite, a monticellite, apatite and calcite rich variety which intruded first; and a phlogopite rich type forming a discrete cylindrical body within the earlier kimberlite. These two kimberlites do not appear to be related by any of the fractionation models discussed.

An examination of the data from this work and published sources, suggests that kimberlites are derived from below the low velocity zone by small degrees of partial melting involving garnet lherzolite with subordinate phlogopite and carbonate. Diamonds are probably incorporated as xenocrysts in the magma.

Upward movement and emplacement of kimberlite appears to have been very rapid. The diatremes were probably eroded and shaped by gas, derived from the kimberlite magma, escaping to surface along weak zones in the earth's crust.

Xenoliths of crustal material incorporated in the kimberlite on intrusion have also been studied and various features due to alteration by the magma are described, including the formation of natrolite and cebolite. The latter is a rare mineral that has not been described from kimberlite before.

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CHAPTER 1REVIEW OF PREVIOUS WORKIntroduction

Kimberlite was discovered in a small diatreme at Jagersfontein in 1870 (Williams, 1932), and Lewis (1877) proposed the name Kimberlite, after Kimberley, for this rock. In the original definition of kimberlite diamond is listed as an essential constituent. A great deal of research was done on this rock type between 1871 and 1932, the works of Wagner (1914), and Williams (1932) being landmarks in the literature relating to kimberlite.

From 1932 to 1954, when the Russian diamond deposits were discovered in the Yakutia (Siberia) kimberlite province, kimberlite research stagnated. A revival of interest in kimberlites was heralded by the publication of two monographs by Bobrievich et al. (1957; 1959) on the Yakutian kimberlites. Since the publication of these volumes there has been upsurge in research, especially on the inclusions of mantle material such as peridotite and eclogite.

The investigation of the mantle inclusions has influenced our understanding of, the nature of, and processes occurring in, the upper mantle. Besides the phase relationships of the major minerals such as olivine, orthopyroxene, clinopyroxene and garnet, the suggested four phase mantle assemblage (O'Hara, 1968), some attention has also been focussed on minor phases such as phlogopite (Yoder & Kushiro, 1969; Gurney & Berg, 1969) and the origin of minor elements and volatile components in the mantle.

From the study of the mantle inclusions and kimberlite two hypothesis to account for the unusual features of the kimberlite were proposed, the residual hypothesis and the partial melting hypothesis. A zone refining process has also been invoked by Harris & Middlemost (1969) to account for the kimberlite chemistry.

a) The Residual Hypothesis

O'Hara & Yoder (1967) and O'Hara et al. (1975) propose that kimberlite is the result of fractionation of biminerallitic eclogite from an initial picritic partial melt of garnet peridotite at about 30 kb which then produces the alkaline residual liquids that could eventually erupt as kimberlites. Mitchell (1973) proposes that ilmenite fractionation may also have been important in the initial stages of kimberlite formation.

Recent age determinations on kimberlitic zircon (a matrix mineral?) by Davis et al. (1976) indicate an age of about 100 m.y. for the intrusion of

some kimberlites while the age of some eclogite inclusions^{in them} is Precambrian (Allsopp et al., 1969) and therefore could not have crystallized from the initial magmas to produce kimberlite. In addition, some eclogites have lower Sr^{87}/Sr^{86} ratios than the peridotite 'parent' which should have a similar ratio (Mitchell & Crockett, 1971a).

b) The Partial Melting Hypothesis

This hypothesis is termed the 'insipient melting hypothesis' by Dawson (1971). Dawson & Davidson (1965) proposed that hydrous potassic phases in the mantle, such as phlogopite, underwent insipient fusion with some diopside, and that the liquid produced which would have high concentrations of the 'kimberlitic' elements K, Rb, Ti etc. accumulated and erupted as kimberlite. This hypothesis is very attractive as it explains many features of the kimberlite such as the higher Sr^{86}/Sr^{87} ratio (0.705-0.729) of the bulk kimberlite compared to that of the matrix (0.703 - 0.704), due to the phlogopite 'xenocrysts' in the rock (Dawson, 1971). The melt produced would also crystallize olivine, knorringite rich garnet, picro ilmenite, perovskite, diamond etc, the megacrysts often found in kimberlite.

c) The Zone Refining Hypothesis

The proposal by Harris & Middlemost (1969) that a heat front moving up from the core drives the constituents enriched in the kimberlite before it, has met with considerable opposition as considerable amounts of magma should be produced by the process, and the amount of kimberlite is volumetrically small (Dawson, 1971). Furthermore the process also works in the reverse direction depleating the liquid in Mg, Cr and possibly other constituents, and it should considerably enrich the liquid in Fe. This apparently has not occurred to a very great extent.

More recent research summarized in the Lesotho Kimberlite volume (P.H. Nixon ed., 1973), the proceedings of the Cape Town Kimberlite Conference (1975) and the Second International Kimberlite Conference (1977), have tended to reinforce the partial melting hypothesis e.g. Barrett, (1975).

Experimental work by Wyllie & Huang (1975, a,b), and Wyllie (1977), Eggler (1975; 1977) and others has emphasized the importance of CO_2 , in addition to water in the mantle and its influence on the generation of kimberlitic and carbonatitic magmas.

Few geochemical studies of kimberlite groundmass had been undertaken until recently when research by Martin et al. (1975), Kable et al. (1975), Paul et al. (1975), Gurney & Ibrahim (1973), Paul et al. (1976), Gurney & Berg (1969), Steele & Wagner (1977) and others was published.

This Study

The Letseng-la-terai and De Beers Mine kimberlites are composite bodies, the former comprising four separate intrusions and the latter two. For these, and other, multiple intrusion kimberlites relationships with respect to the origin and possible genetic links are unknown. Furthermore within composite diatremes the various kimberlites have different diamond tenor and the reasons for this are also unclear.

The aim of this investigation is to decipher the petrological relationships between the different varieties of kimberlite in the diatremes, and also to investigate the late stage metasomatic and metamorphic effects of the kimberlite magma on the country rock as an aid to understanding the cooling history of the diatreme facies kimberlite.

Interpretation of whole rock chemical data may elucidate these relationships and may indicate the nature of the source areas in the mantle and possible processes of generation and differentiation in kimberlitic magmas. The mechanisms controlling movement and intrusion from the region of origin to where the kimberlite is implaced, are also investigated. Problems such as heat sources and chemical inhomogeneity leading to the formation of these and other magmas would be better understood.

Contamination of the magma by high level wallrock material is very marked in some cases such as Letseng-la-terai and this partially obscures the chemistry of the different kimberlites and their relationships to each other. Methods for dealing with this problem have been developed in the light of crustal inclusion studies and applied to the strongly contaminated Letseng-la-terai kimberlites.

Besides the inclusions of crustal material an unknown amount of upper mantle xenoliths and xenocrysts, mainly olivine, are also included in the kimberlite and these may also obscure the chemical relationships. Simple enrichment of components that are included in matrix minerals such as Sr, Ca, Nb etc. may be due to a reduced contamination by mantle material, such as olivine, which does not contain the elements in question. Similarly elements such as Ni and Mg, which are concentrated in xenolithic and xenocrystic mantle material are strongly influenced by the ratio of matrix to mantle material. This effect is examined in Chapter 3.

Models of fractionation to explain the data are developed and tested using physical and chemical criteria. The models developed are tested in a qualitative or semi qualitative manner using the published Nernst distribution co-efficients;

$$K_D = X_{\text{liquid}} / X_{\text{solid}}$$

where X_{liquid} and X_{solid} are the concentrations of the element in the liquid and crystals, or assemblage of crystals, respectively. Distribution (partition) co-efficients are temperature, pressure and composition dependant (Mysen, 1976; O'Hara et al., 1975), and most published data refers to natural rocks of basaltic to dacitic composition. Very few data are available for systems at high pressure, or containing substantial amounts of CO_2 and H_2O . These factors are of importance as kimberlites are of unusual composition and have possibly been derived from different depths in the mantle.

Petrographic Nomenclature

The models developed and tested refer to conventional liquid/crystal differentiation, and exclude other processes that may have occurred such as gas streaming and liquid immiscibility. Data on the behaviour of trace as well as major components in such processes are too few to test models that embody them.

Petrographic description and interpretation of kimberlites is obscured by the variety of different mineral fragments and inclusions present. Besides the problem of phenocrystic and xenocrystic olivine (Mitchell, 1973b) the same problems apply to garnet, ilmenite, phlogopite, diopside and various types of intergrowths and small xenoliths or aggregates. These have variously been termed xenocrysts, phenocrysts, xenoliths, megacrysts and discrete nodules. I propose to use the neutral term "inset", a word with no genetic connotations revived by Shand (1925), for descriptive purposes. Only cryptogenetic material of mantle derivation, which in kimberlite is mainly olivine as crystals and small granular aggregates that give the rock its porphyritic appearance are included by this term, as are crystals such as garnet of unknown origin. Other extraneous material such as crustal xenocrysts and xenoliths, and large nodules of mantle material are excluded. The terms phenocryst and megacryst are retained for material of implied cognate origin.

Experimental Methods

Separate appendices on the experimental procedures (X-Ray Fluorescence and Diffraction) are given at the end of this work.

An analysis of the precision of the data is presented.

CHAPTER 2

THE LETSENG-LA-TERAI KIMBERLITES

Introduction

The Letseng-la-terai (The Swamp at the Corner) Kimberlite diatreme was discovered in 1957 and declared a government digging in 1959 (Bloomer & Nixon, 1973). After extensive sampling by various companies, De Beers Consolidated Mines (Pty) Ltd. decided to establish a mine and it was officially opened in late 1977.

The mine is unusual in that it is low grade but contains large gem quality stones, and the operation is geared to extract only these.

Early work on the intrusive by C.G.A. Marshall, J.J. Hauman & C. Hartnady define seven varieties of kimberlite in the diatreme, of which the K6 type is economically important (Bloomer & Nixon, 1973). The petrographic and other characteristics of the different kimberlite types and inclusions have been described by Bloomer & Nixon (1973).

Later extensive work by N. Lock showed that there are four varieties of kimberlite occurring as cylindrical bodies within the diatreme (Fig. 2:1). These are termed the Non-K6, K6, K5 and K4 Kimberlites in order of decreasing age (N.Lock, pers. comm.).

Samples were collected from each of the four varieties of Kimberlite and analysed using x-ray fluorescence techniques (Appendix A). The results are listed in Table 2:1. The K6 and Non-K6 varieties are chemically and petrographically similar. Garnet is however more abundant in the K6 type which serves to distinguish it in the diatreme (N. Lock pers. comm.). On the other hand the younger K4 and K5 types differ chemically as well as petrographically from each other and from the earlier Non-K6 and K6 varieties.

The amount of contamination by xenoliths of crustal origin (Karoo lavas and sedimentary rocks, and Basement metamorphics) is variable. The Non-K6, K6 and K4 Kimberlites are contaminated (up to 50%) while the K5 variety has much less xenolithic material.

Fesq et al. (1975) and Kable et al. (1975) have found that the contaminating material has acted essentially as a dilutant in the kimberlites investigated by them, and the inter element relationships had not been disturbed. This is only true for those elements which are strongly enriched in kimberlite relative to the contaminants (Kable et al., 1975) and care must therefore be exercised in the interpretation of data from contaminated kimberlites. A method to

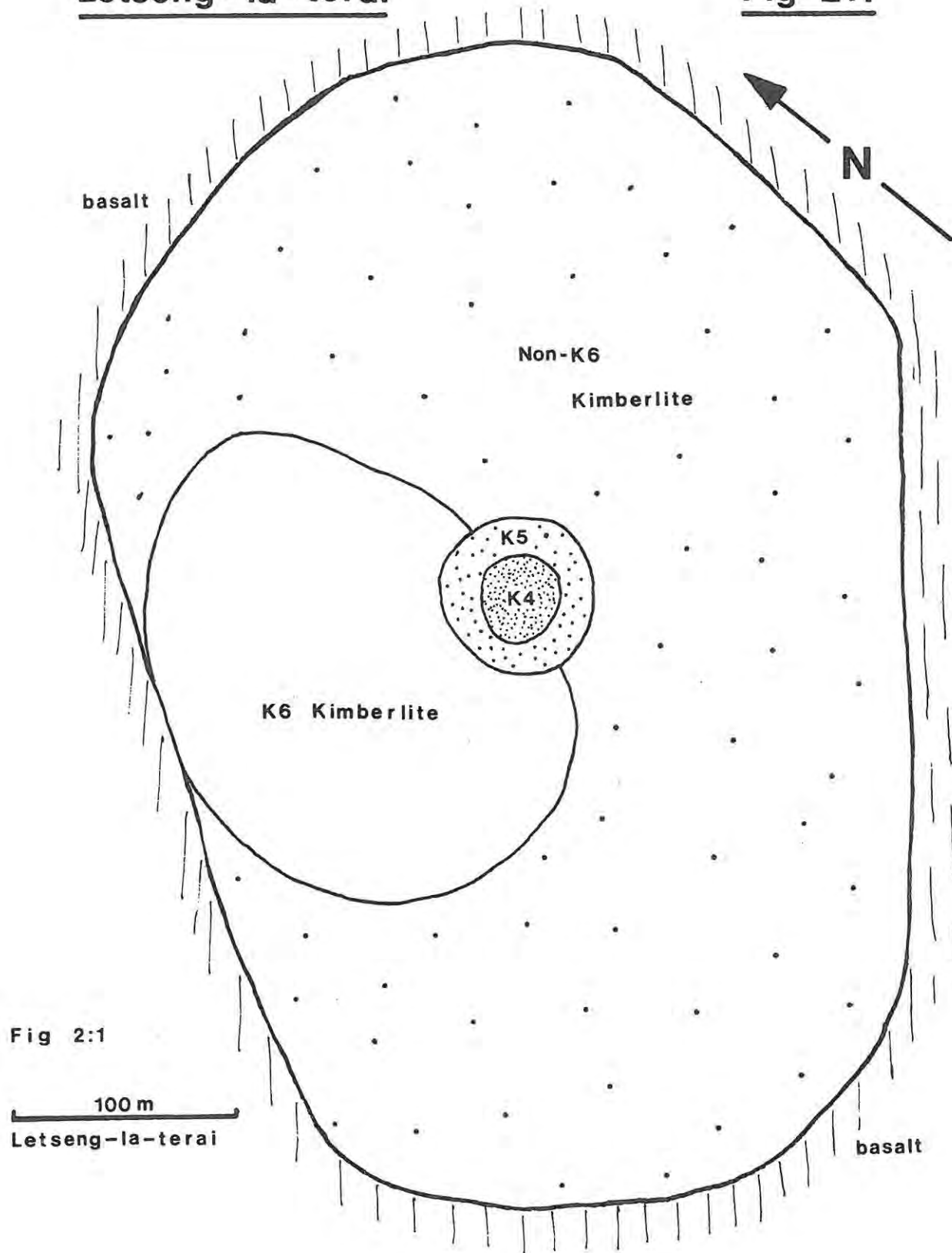
Letseng - la - teraiFig 2:1

Fig. 2:1 Sketch map of the Letseng-la-terai pipe at the 60m level. Taken from Bloomer & Nixon (1973) and N. Lock (pers. comm.). The map shows the relationships only and the boundaries of the K6, K5 and K4 Kimberlites are schematic.

TABLE 2:1

MAJOR AND TRACE ELEMENT ABUNDANCES OF SAMPLES FROM LETSENG-LA-TERAI

	<u>K6</u>							<u>K4</u>	
	L1	L5	L6	L7	L8	L9	L14	L11	L12
SiO ₂	37.58	36.35	36.29	37.97	36.77	35.96	36.56	36.91	38.65
TiO ₂	1.11	1.17	1.13	1.23	1.32	1.20	1.31	1.50	1.48
Al ₂ O ₃	5.93	4.89	6.20	6.10	6.18	5.74	6.64	6.02	5.71
Fe ₂ O ₃	10.00	9.17	9.59	9.73	10.46	9.66	9.76	10.29	9.65
MnO	0.13	0.13	0.14	0.14	0.16	0.14	0.16	0.16	0.15
MgO	21.53	22.82	20.43	22.12	21.36	21.38	18.74	23.63	23.46
CaO	6.80	7.18	7.41	7.23	8.42	7.58	8.52	8.20	8.22
Na ₂ O	0.55	0.64	1.08	0.83	0.72	0.75	1.68	0.90	1.13
K ₂ O	0.87	0.74	0.70	0.83	0.56	0.71	0.99	1.24	1.32
P ₂ O ₅	0.31	0.30	0.25	0.29	0.30	0.29	0.35	0.43	0.44
L.O.I.	8.89	9.80	10.06	8.14	9.25	10.43	8.16	9.41	8.43
H ₂ O	7.09	6.70	6.27	5.36	4.82	5.79	6.19	1.19	1.19
TOTAL	100.79	99.89	99.65	99.95	100.32	99.63	99.06	99.88	99.83

Table 2:1 continued

	TRACE ELEMENTS								
				K6					K4
	L1	L5	L6	L7	L8	L9	L14	L11	L12
SR	356	418	392	332	360	492	624	406	383
RB	38	37	32	37	33	37	38	38	44
Y	13	12	15	14	16	14	16	15	13
ZR	119	105	95	106	117	113	128	138	143
NB	49	55	34	47	48	45	52	69	76
ZN	69	61	67	68	76	65	68	73	74
CU	55	42	64	46	59	59	56	57	54
CO	103	86	64	81	82	73	74	83	82
NI	1578	1344	906	1161	1126	1082	851	1119	1182
V	135	122	158	146	165	157	84	168	139
CR	687	697	525	757	678	714	924	837	792
TH	-	5	-	-	-	-	-	5	-
LA	26	24	16	21	24	23	35	34	37
CE	56	43	32	42	45	43	67	63	71
ND	26	19	17	17	20	17	30	28	29

TABLE 2:1 continued

	<u>NK6</u>						<u>K5</u>	
	L3	L4	L15	L16	L17	L18	L10	L13
SI02	40.11	39.06	38.95	39.40	40.05	39.97	37.39	33.66
TI02	1.03	1.15	1.16	1.25	1.26	1.21	1.60	1.75
AL203	7.48	6.44	6.31	6.70	6.70	6.32	5.20	3.11
FE203	10.06	10.28	9.91	10.29	10.33	10.36	9.86	10.00
MNO	0.14	0.15	0.15	0.16	0.16	0.16	0.16	0.15
MGO	19.85	22.93	21.14	20.49	20.53	22.38	24.81	28.51
CAO	7.31	6.71	8.03	8.16	9.05	7.82	7.16	8.82
NA2O	1.36	0.83	0.87	0.48	0.94	0.81	0.40	0.45
K2O	0.60	0.65	0.90	0.66	0.78	0.77	2.00	1.65
P2O5	0.25	0.28	0.31	0.32	0.34	0.32	0.52	0.56
L.O.I.	6.03	7.40	8.05	7.32	6.25	7.32	8.05	9.96
H2O	5.84	3.88	4.64	4.52	2.66	3.01	2.71	1.02
TOTAL	100.06	99.76	100.42	99.75	99.05	100.45	99.86	99.64

Non-K6 Kimberlite is listed as NK6

Table 2 :1 continued

	<u>TRACE ELEMENTS</u>							
	<u>NK6</u>						<u>K5</u>	
	L3	L4	L15	L16	L17	L18	L10	L13
SR	413	352	490	250	261	261	589	869
RB	29	32	34	32	33	34	69	61
Y	16	14	16	16	17	16	14	14
ZR	107	113	120	141	134	124	160	205
NB	33	41	40	46	47	45	90	108
ZN	73	73	68	72	73	72	68	67
CU	56	59	55	65	57	55	53	50
CO	76	251?	75	76	75	80	83	76
NI	1056	1162	1017	991	954	1142	1172	1325
V	147	145	139	162	163	146	139	86
CR	488	537	538	578	619	611	904	952
TH	-	-	-	-	6	5	7	6
LA	20	21	22	27	27	25	45	53
CE	38	44	49	65	55	50	79	95
ND	19	18	23	27	25	22	34	53

Non-K6 Kimberlite is listed as NK6

correct for contamination by foreign material is developed and applied to the Letseng-la-terai analysis.

Petrography of the Letseng-la terai Kimberlites

The Non-K6 and K6 Kimberlites

The only observable difference between these two Kimberlites is that the K6 type contains abundant garnets with kelyphytic rims and also contains xenoliths of the previous Non-K6 variety, whereas the latter contains much less garnet and no kimberlite xenoliths.

Olivine :

Abundant pseudomorphs after olivine display a zonal structure with a rim of highly birefringent greenish talc and a core of light green to brown material with a lower birefringence - probably saponite (Kresten, 1973). The rock contains little serpentine according to Kresten (op. cit.) who used Differential Thermal Analysis (D.T.A.) to distinguish the phases within the K6 Kimberlite. No remnant olivine was observed in any of the sections studied.

Groundmass :

Perovskite, ilmenite, chromite and titanomagnetite grains are set in a groundmass consisting of a low birefringent, greenish material with a low relief, parallel extinction and a radial fibrous habit; possibly saponite, and subordinate calcite. Occasional clusters of acicular crystals around crustal inclusions have a similar appearance to cebollite but were too small for positive identification. The properties of this mineral are discussed in Chapter 5.

Calcite occurs as clear, interstitial, irregular areas and is one of the last minerals to crystallize with the greenish groundmass material.

Xenolithic Material :

An average of from 15 to 30% xenolithic crustal material, largely Karoo basalt, is present in the Kimberlite. These xenoliths are extremely variable in size and range from 1mm to several meters in diameter. The smaller inclusions, less than a centimetre in diameter, are of particular importance as they cannot be extracted when the kimberlite is crushed prior to analysis. These xenoliths are now largely altered to mixture of clay minerals, natrolite, cebollite and remnant mafic minerals. The details of

this alteration process are described in Chapter 5. The larger xenoliths are removed during crushing.

The K5 Kimberlite

This kimberlite is the third in the intrusive sequence. It is characterized by abundant phlogopite in the groundmass, and phlogopite phenocrysts are also present. Only two specimens were obtained and these show different characteristics due to variable contamination and alteration.

Olivine :

One specimen (L13) is a hard competent rock showing little alteration of the olivine inclusions which are in some cases strained, and granular aggregates are also present. A feature of this specimen is the alteration of olivine in a zone around occasional inclusions of crustal material present. This latter material is altered to the assemblage of natrolite etc. described before.

L10 has more abundant smaller inclusions and in this case alteration is complete, little if any olivine remaining.

Groundmass :

The groundmass of this kimberlite consists largely of phlogopite with some calcite and serpentinous material. Phlogopite occurs as yellow interstitial material with a high birefringence and normal pleochroism in common with all phlogopite observed in the Letseng-la-terai kimberlites. The phlogopite in the L10 specimen occurs as aggregates of small bent plates possibly due to the partial conversion to vermiculite, a mineral identified by Kresten (1973) in these kimberlites. Calcite occurs as small clear irregular patches and it is one of the last minerals to crystallize. Irregular interstitial areas of serpentinous material (?saponite) are also present.

Perovskite is more abundant in this variety of kimberlite than in the other types, and fairly large ($\pm .1\text{mm}$) crystals are quite common. These are often associated with ilmenite, euhedral chromite and titanomagnetite which are also present.

Xenoliths :

The xenoliths in this rock type consist largely of Karoo sedimentary rocks with occasional basalt xenoliths, and in general the rock is much less contaminated than the K6 and Non-K6 Kimberlites; the L13 specimen having only a few large

xenoliths and L10 having 15% of small xenoliths that could not be removed during crushing.

The K-4 Kimberlite

Two specimens of K4 have been analysed and the petrography of these differ markedly from the specimen described by Bloomer & Nixon (1973) as uncontaminated with sporadic phenocrysts of olivine and enstatite. The rock sampled in this study contains abundant inclusions of basalt ($\pm 20\%$). The originally abundant inlets of olivine are now represented by pseudomorphs consisting of talc and green (?) saponite. The K4 Kimberlite is distinguished from the K6 and Non-K6 types by a greater abundance of perovskite and phlogopite in the groundmass which also contains greenish serpentine or saponite and irregular clear areas of calcite.

Contamination by Basalt Xenoliths

Basalt xenoliths from the Karoo sequence are intimately mixed ~~in~~ with the kimberlites. These xenoliths vary in size from that of a pinhead to several meters in diameter. The smaller xenoliths are completely altered to clays, natrolite and cebolite, ~~while~~ ^{whereas} the larger ones (≥ 2 cm diam.) display alteration around rims only.

During the alteration process there is an exchange of components between the xenoliths and the surrounding magma both in the liquid and solid state. This can be observed where xenoliths are surrounded by largely uncontaminated kimberlite, e.g. L13, where alteration of the kimberlite has occurred only around the xenoliths. This is probably due to the conversion of plagioclase in the xenoliths to natrolite releasing SiO_2 which reacts with the surrounding olivine under hydrous conditions to form serpentine. Other components released by the reaction may in turn move into the xenolith.

This exchange of components therefore modified the composition of the xenoliths and the enclosing Kimberlite. The problem of contamination can thus not be solved simply by removal of the xenolithic material before analysis, especially if the xenoliths have been extensively altered.

Fesq et al. (1975) have corrected for contamination effects by assuming that the contaminant acts purely as a dilutant on the trace element chemistry. This approach is only permissible when the contaminant is almost devoid of the elements of interest as was the case in the rock investigated by these authors.

When contamination by basaltic material occurs, the effects on different elements in the kimberlite is not simply one of dilution e.g. about 90 ppm of Zr is present in basalt and approximately 110 ppm in the kimberlites analysed from Letseng-la-terai (Table 2:1). On the other hand only 4 ppm of Nb is present in the basalt and 54 ppm in the analysed kimberlite. Contamination by significant amounts of basalt may therefore significantly alter the Zr/Nb ratio of the resultant kimberlite-xenolith mixture.

To correct for these effects an estimate of the contamination of the rocks was made by point counting techniques and a correction applied using an average basalt from Cox and Hornung (1966) and J. Pemberton (unpublished data) (See Table 2:2).

Correction Procedures for Contaminated Rocks

The method here developed to correct for contamination is simple and completely general. It can be applied to major and trace elements, provided the concentration in the contaminant is known.

The contaminated rock, contaminant and uncontaminated (unknown) compositions of any rocks are related by the following equation:

$$ax + b(1-x) = c$$

where;

a- concentration of element in the contaminant.

b- concentration of element in uncontaminated material.

c- concentration of the element in the contaminated material

x- proportion of contamination.

From this it follows that:

$$b = \frac{c - ax}{1 - x}$$

Furthermore the composition of a in any multi-contaminant situation can be calculated by the following:

$$a = \sum_1^n a_n Y_n$$

where;

a_n - concentration of the element in the N^{th} component of a.

Y_n - proportion of the N^{th} component of a.

Any contamination is therefore reduced to a 'single' contaminating material for the rock in question. To illustrate the effect and the correction for contamination, four plots (Figs. 2:2, 2:3, 2:4, 2:5) for the Letseng-la-terai Kimberlites

TABLE 2:2

UNCORRECTED AND CORRECTED, LOI AND H₂O⁻-FREE, MAJOR AND TRACE ELEMENT ABUNDANCES. PROPORTION OF BASALT
LISTED AS CONT.

The L H S of each pair is uncorrected and the R H S corrected.

	L1/K6		L5/K6		L6/K6		L7/K6		L8/K6		L9/K6	
CONT	0.22	-	0.20	-	0.23	-	0.19	-	0.17	-	0.22	-
SiO ₂	44.62	42.6	43.60	41.6	43.33	40.8	43.93	42.1	42.65	40.8	43.12	40.7
TiO ₂	1.30	1.35	1.40	1.47	1.38	1.45	1.42	1.49	1.53	1.61	1.44	1.53
Al ₂ O ₃	6.98	4.8	5.87	3.6	7.56	5.4	7.05	5.2	7.17	5.6	6.88	4.6
Fe ₂ O ₃	11.87	11.9	11.00	10.8	11.61	11.5	11.25	11.1	12.12	12.2	11.59	11.5
MnO	0.16	0.16	0.15	0.15	0.18	0.18	0.16	0.16	0.18	0.18	0.17	0.17
MgO	25.51	30.7	27.37	32.4	24.61	29.8	25.66	30.0	24.77	28.4	25.64	30.9
CaO	8.05	7.3	8.61	8.1	8.89	8.4	8.36	7.8	9.77	9.6	9.09	8.7
Na ₂ O	0.65	0.16	0.77	0.40	1.31	1.00	0.96	0.60	0.83	0.50	0.91	0.49
K ₂ O	1.03	1.11	0.89	0.93	0.86	0.90	0.97	1.02	0.65	0.63	0.85	0.88
P ₂ O ₅	0.37	0.44	0.36	0.42	0.31	0.36	0.34	0.39	0.35	0.40	0.35	0.41
TOTAL	100.00	-	100.00	-	100.00	-	100.00	-	100.00	-	100.00	-

Continued

TABLE 2:2 (continued)

	L1/K6		L5/K6		L6/K6		L7/K6		L8/K6		L9/K6	
SR	356	404	418	476	393	455	332	336	360	396	492	579
RB	38	45	37	42	32	38	37	42	33	37	37	43
Y	13	10	12	8	15	13	14	11	16	14	14	11
ZR	119	127	105	109	95	96	106	110	117	122	113	119
NB	49	62	55	67	34	43	47	56	48	57	45	57
ZN	69	65	61	56	67	62	68	64	76	74	65	60
CU	55	47	42	32	64	58	46	37	59	54	59	52
CO	103	119	86	96	64	69	81	89	82	89	73	81
NI	1578	1998	1344	1658	906	1150	1161	1412	1126	1338	1082	1362
V	135	107	122	94	158	136	146	126	165	151	151	136
CR	687	804	697	791	525	601	757	871	678	761	714	839
TH	-	-	5	-	-	-	-	-	-	-	-	-
LA	26	30	24	28	16	18	21	24	24	27	23	27
CE	56	65	43	48	32	34	42	46	45	49	43	48
ND	26	29	19	20	17	18	17	17	20	21	17	18

TABLE 2:2 CONTINUED

	L14/K6		L3/NK6		L4/NK6		L15/NK6		L16/NK6		L17/NK6	
CONT	0.22	-	0.22	-	0.22	-	0.30	-	0.25	-	0.22	-
SIO2	43.17	40.7	45.51	43.7	44.17	42.0	44.42	41.3	44.83	42.5	44.44	42.4
TIO2	1.55	1.67	1.77	1.18	1.30	1.35	1.32	1.40	1.43	1.53	1.40	1.48
AL2O3	7.84	5.88	8.48	6.7	7.28	5.2	7.19	3.9	7.62	5.2	7.44	5.4
FE2O3	11.53	11.4	11.41	11.3	11.62	11.6	11.29	11.1	11.71	11.7	11.46	11.4
MNO	0.18	0.18	0.16	0.16	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.18
MGO	22.12	26.4	22.51	26.9	25.88	31.2	24.10	31.4	23.32	28.7	22.78	27.2
CAO	10.06	9.9	8.29	7.6	7.59	6.7	9.16	8.6	9.27	8.8	10.05	9.9
NA2O	1.99	1.87	1.54	1.30	0.94	0.53	1.00	0.40	0.54	0.05	1.05	0.67
K2O	1.17	1.29	0.68	0.66	0.74	0.74	1.02	1.14	0.75	0.75	0.87	0.91
P2O5	0.41	0.49	0.28	0.32	0.32	0.37	0.35	0.44	0.37	0.45	0.37	0.44
TOTAL	100.00	-	100.00	-	100.00	-	100.00	-	100.00	-	100.00	-

Continued

Non-K6 Kimberlite is listed as NK6

TABLE 2:2 (continued)

	L14/K6		L3/NK6		L4/NK6		L15/NK6		L16/NK6		L17/NK6	
SR	624	748	413	477	352	399	490	621	250	272	261	282
RB	38	45	29	33	32	36	34	43	32	38	33	39
Y	16	14	16	14	14	12	16	12	16	14	17	15
ZR	128	138	107	112	113	119	120	132	141	158	134	146
NB	52	66	33	41	41	51	40	55	46	60	47	59
ZN	68	63	73	70	73	70	68	62	72	69	73	70
CU	56	48	56	48	59	52	55	43	65	59	57	50
CO	74	82	76	84	251?	-	75	87	76	86	78	83
NI	851	1066	1056	1329	1162	1465	1017	1415	991	1292	954	1198
V	84	42	147	123	145	120	139	99	162	138	163	143
CR	924	1108	488	549	537	612	538	652	578	680	619	717
TH	-	-	-	-	-	-	-	-	-	-	6	-
LA	35	42	20	23	21	24	22	27	27	33	27	32
CE	67	79	38	42	44	49	49	59	65	78	55	63
ND	30	34	19	20	18	19	23	26	27	31	25	28

Non-K6 Kimberlite is listed as NK6

TABLE 2:2 CONTINUED (L10 dilution — for some elements only)

	L18/NK6		L10/K5		L13/K5		L11/K4		L12/K4	
CONT	0.19	-	.15	-	-	-	0.23	-	0.23	-
SIO2	44.37	42.6	41.97	-	37.97	-	41.35	38.1	42.86	40.2
TIO2	1.35	1.40	1.80	2.10	1.98	-	1.69	1.87	1.64	1.79
AL2O3	7.02	5.2	5.83	-	3.51	-	6.74	4.2	6.33	3.8
FE2O3	11.49	11.4	11.07	-	11.28	-	11.53	11.4	10.71	10.4
MNO	0.18	0.18	0.17	-	0.19	-	0.18	0.18	0.17	0.17
MGO	24.85	29.0	27.87	-	32.15	-	26.46	32.6	26.02	31.7
CAO	8.68	8.2	8.04	-	9.95	-	9.19	8.8	9.12	8.7
NA2O	0.91	0.56	0.45	-	0.51	-	1.01	0.60	1.26	0.92
K2O	0.85	0.88	2.24	2.64	1.86	-	1.39	1.60	1.46	1.68
P2O5	0.36	0.41	0.58	0.68	0.64	-	0.47	0.58	0.49	0.60
TOTAL	100.00	-	100.00	-	100.00	-	100.00	-	100.00	-

Non-K6 Kimberlite is listed as NK6

Continued

TABLE 2:2 (continued)

	L18/NK6		L10/K5		L13/K5		L11/K4		L12/K4	
SR	261	279	589	693	869	-	406	476	383	442
RB	34	38	69	82	61	-	38	46	44	53
Y	16	14	14	16	14	-	15	12	13	10
ZR	124	132	160	180	205	-	138	153	143	159
NB	45	54	90	106	108	-	69	89	76	97
ZN	72	70	68	80	67	-	73	70	74	71
CU	55	48	53	62	50	-	57	49	54	45
CO	80	88	83	98	76	-	83	95	82	93
NI	1142	1389	1172	1379	1325	-	1119	1444	1182	1442
V	146	126	139	164	86	-	168	147	139	111
CR	611	691	904	1064	952	-	837	1016	792	948
TH	5	-	7	8	6	-	5	-	-	-
LA	25	29	45	53	53	-	34	41	37	45
CE	50	56	79	93	95	-	63	75	71	85
ND	22	24	34	40	53	-	28	32	29	33

Non-K6 Kimberlite is listed as NK6

TABLE 2:3

Uncorrected average abundances for NK6, K6, K5 and K4
and associated statistical data

	<u>NK6</u>			<u>K6</u>			<u>K5</u>	<u>K4</u>
	$\bar{X}$	s	s/ $\bar{x}$	$\bar{X}$	s	s/ $\bar{x}$	AV.	AV.
SiO2	44.3	0.87	0.02	43.6	0.57	0.01	40.0	42.1
TiO2	1.35	0.13	0.09	1.42	0.08	0.06	1.88	1.67
Al2O3	7.5	0.49	0.07	7.0	0.68	0.10	4.7	6.5
Fe2O3	11.5	0.15	0.01	11.6	0.37	0.03	11.2	11.1
MNO	0.18	0.01	0.05	0.17	0.01	0.07	0.18	0.18
MGO	24.03	1.23	0.05	25.2	1.73	0.07	30.0	26.2
CAO	8.97	0.85	0.10	8.84	0.70	0.08	9.0	9.2
NA2O	0.97	0.30	0.31	1.10	0.49	0.45	0.48	1.14
K2O	0.79	0.13	0.16	0.96	0.12	0.13	2.05	1.43
P2O5	0.34	0.03	0.09	0.36	0.03	0.09	0.61	0.48
TOTAL	99.82	-	-	100.25	-	-	100.10	100.00

<u>TRACE ELEMENTS</u>								
SR	341	90	0.26	436	108	0.25	729	395
RB	32	1.9	0.06	36	2.1	0.06	65	41
Y	16	0.9	0.05	14	1.6	0.11	14	14
ZR	122	11.9	0.10	111	11.6	0.10	183	141
NB	43	5.2	0.12	47	7.0	0.15	99	73
ZN	73	2.2	0.03	66	2.9	0.04	68	74
CU	58	3.5	0.06	54	8.2	0.15	52	56
CO	79	3.7	0.05	80	13	0.17	80	83
NI	1064	81	0.08	1156	277	0.24	1249	1125
V	152	10	0.07	134	28	0.21	113	157
CR	578	63	0.11	717	128	0.18	928	815
TH	5	-	-	5	-	-	6	5
LA	24	5.8	0.24	24	3.1	0.13	49	36
GE	46	11	0.25	47	12	0.26	87	67
ND	21	5.2	0.25	22	3.4	0.15	37	29

Non-K6 Kimberlite is listed as NK6

TABLE 2:4

CORRECTED AVERAGE ABUNDANCES FOR NK6, K6, K5, AND K4 KIMBERLITES

	NK6			K6			K5	K4	AVERAGE BASALT*
	X	s	s/x	X	s	s/x			
SiO ₂	42.2	0.90	0.02	41.4	0.81	0.02	37.97	39.2	51.8
TiO ₂	1.42	0.14	0.10	1.49	0.11	0.07	1.98	1.83	1.13
Al ₂ O ₃	5.3	0.81	0.15	4.9	0.79	0.16	3.51	4.0	14.8
Fe ₂ O ₃	11.5	0.36	0.03	11.4	0.39	0.03	11.28	10.9	11.99
MnO	0.18	0.01	0.05	0.18	0.01	0.07	0.19	0.18	0.17
MgO	29.0	1.76	0.06	30.0	2.0	0.07	32.15	32.2	7.1
CaO	8.5	1.11	0.13	8.4	0.98	0.11	9.95	8.8	10.57
Na ₂ O	0.64	0.30	0.47	0.75	0.61	0.81	0.51	0.76	2.40
K ₂ O	0.82	0.18	0.22	1.02	0.16	0.15	1.86	1.64	0.74
P ₂ O ₅	0.40	0.05	0.12	0.42	0.04	0.11	0.64	0.59	0.13
TOTAL	99.96	-	-	99.96	-	-	-	100.10	100.83

TRACE ELEMENTS

SR	389	128	0.33	505	140	0.28	781	459	185
RB	38	3.0	0.08	43	2.6	0.06	72	50	14
Y	14	1.13	0.08	11	2.1	0.19	14	11	24
ZR	132	16	0.12	117	14.8	0.13	183	156	91
NB	54	6.4	0.12	59	8.8	0.15	107	93	4
ZN	69	3.6	0.05	62	3.3	0.05	74	71	84
CU	51	5.1	0.10	46	9.6	0.21	56	47	83
CO	86	2.3	0.03	89	17	0.19	87	94	46
NI	1347	87	0.06	1441	343	0.24	1352	1443	89
V	128	18.4	0.14	107	36	0.34	125	129	233
CR	666	70	0.10	836	163	0.20	1008	982	271
TH	5	-	-	5	-	-	7	5	-
LA	28	4.1	0.15	28	7.3	0.26	53	53	10
CE	57	11.8	0.21	53	16	0.30	94	94	25
ND	27	6.0	0.22	22	6.5	0.30	47	47	15

* The average basalt major element data from Cox & Hornung (1966) and trace element data from J. Pemberton (unpublished data) - Lesotho Formation.

Non-K6 Kimberlite is listed as NK6

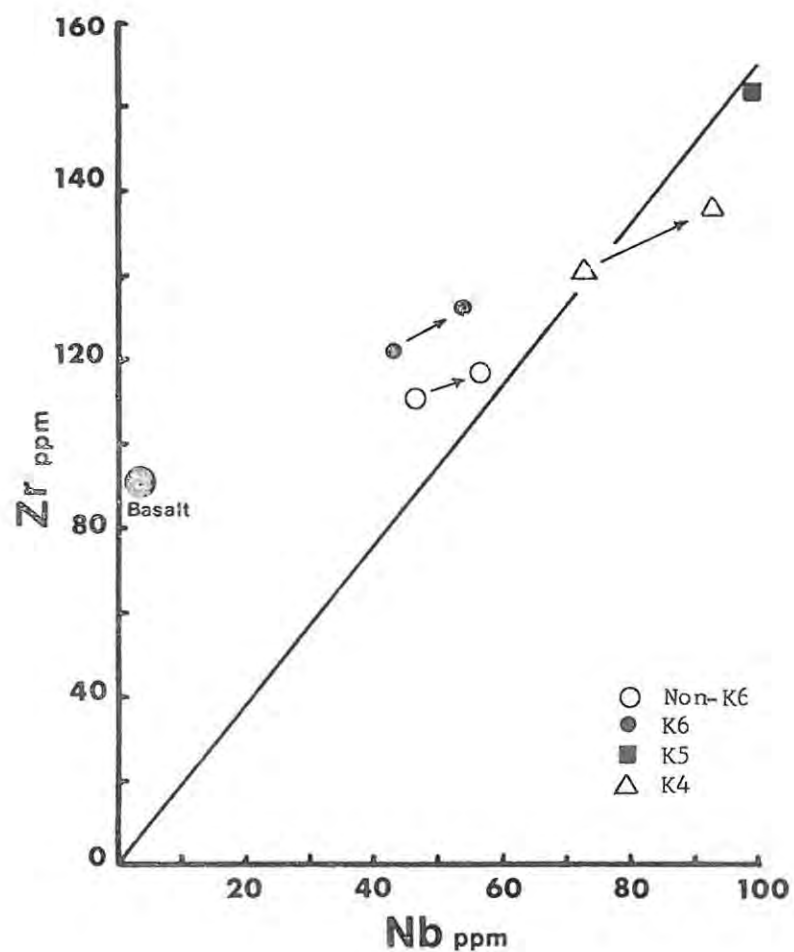


Fig. 2:2 Zr vs. Nb. (corrected & uncorrected)

The effect of the contamination on the Nb is more marked than on the Zr thus altering the Zr/Nb ratio which is closer to 2 (the black line).

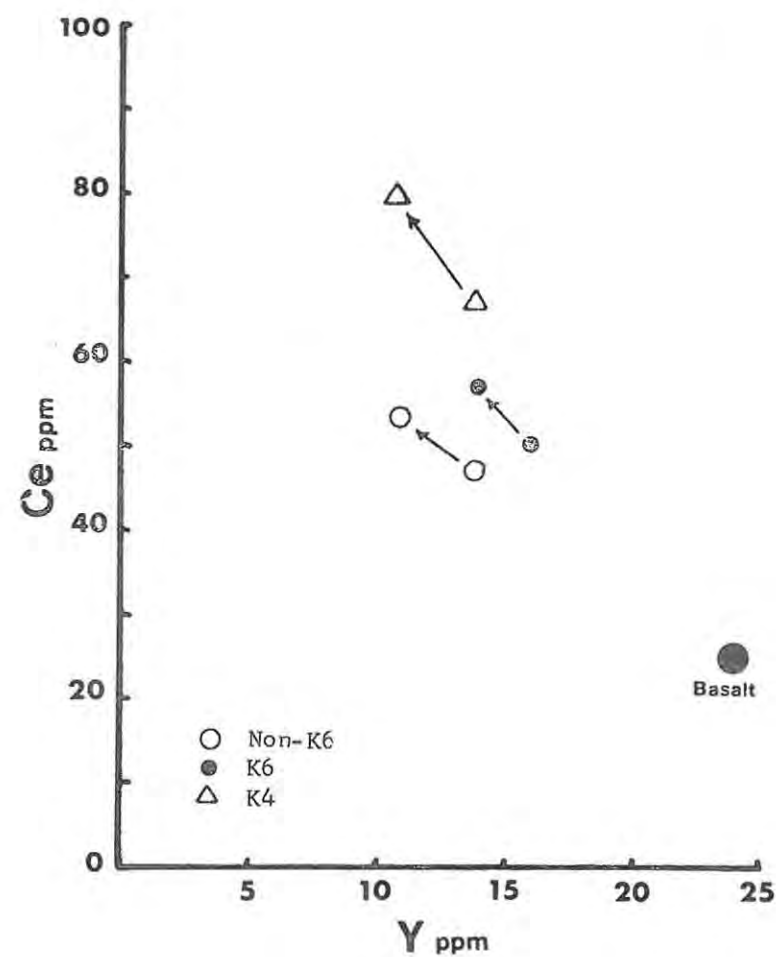


Fig. 2:3 Ce vs. Y. (corrected & uncorrected)

The correction procedure has increased the Ce concentration and decreased Y thus sharply increasing the Ce/Y ratio.

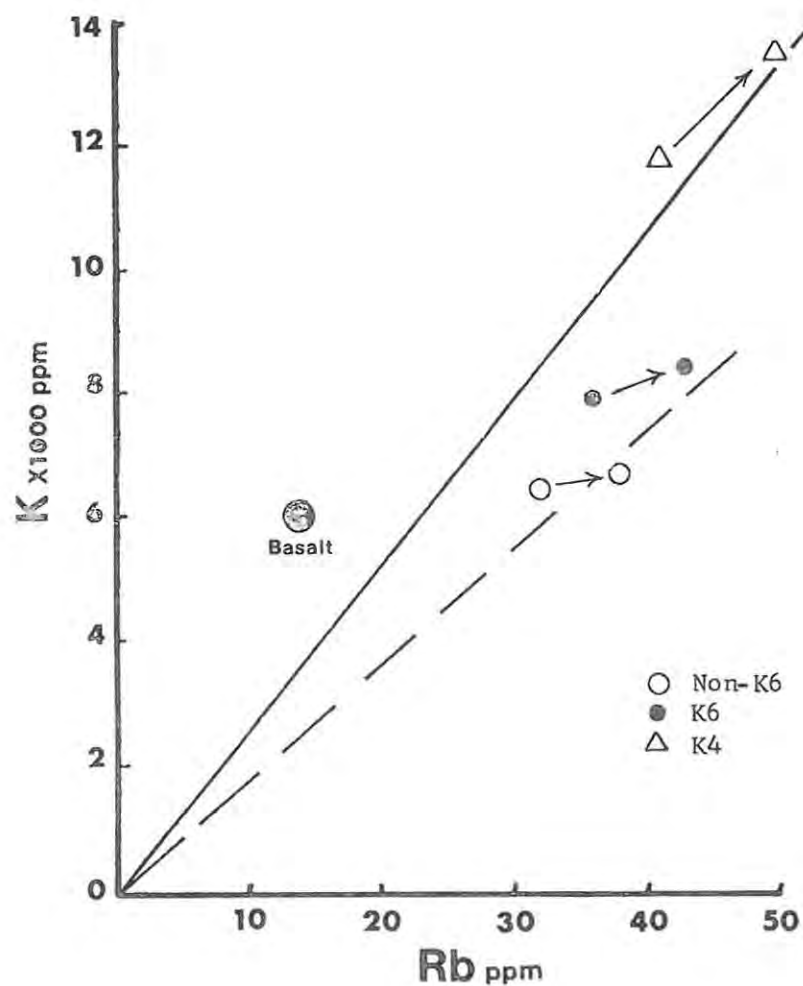


Fig. 2:4 K vs. Rb. (corrected & uncorrected)

This plot shows the dilutant effect of the basalt on the K4 Kimberlite, while the K/Rb of the Non-K6 and K6 varieties has changed.

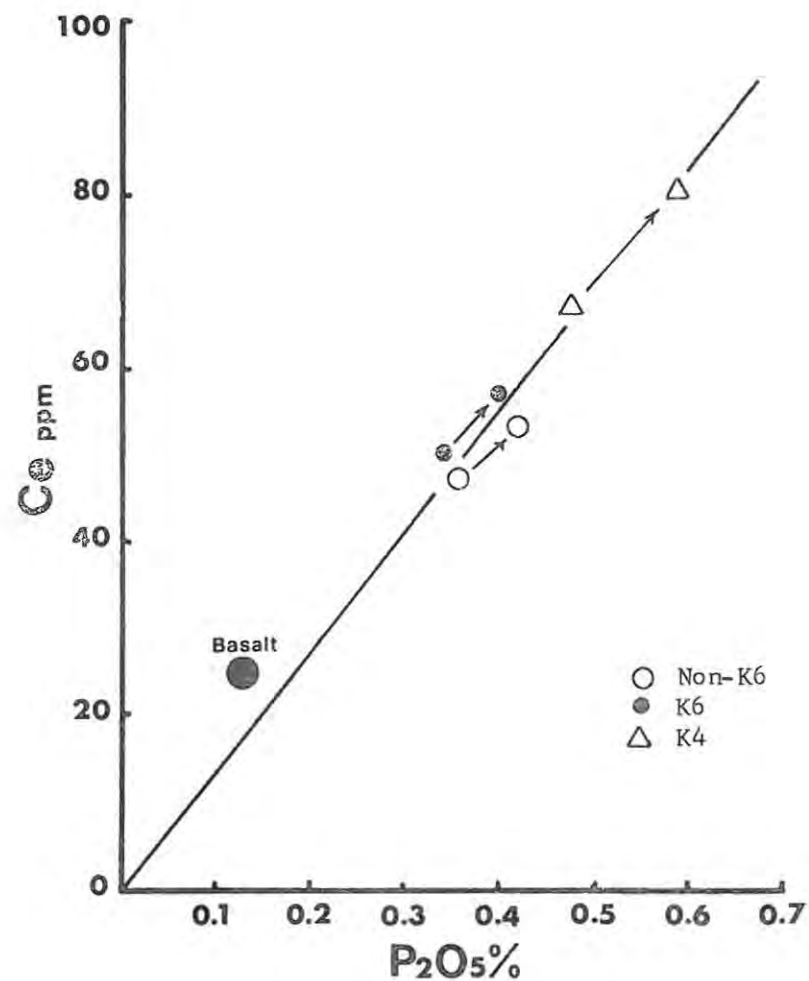


Fig. 2:5 Ce vs. P₂O₅ (corrected & uncorrected)

In all cases the basalt has acted as a dilutant. Only the absolute abundances have altered, and the Ce/P ratio has not significantly changed.

are shown. The average composition of the Non-K6, K6 and K4 Kimberlites are used. These data are taken from Table 2:3 & 2:4.

The four binary diagrams show the effects of correction for contamination on the abundances and the inter element relationships of the three contaminated Kimberlites, the Non-K6, K6 and K4 varieties. These plots show the position of the contaminant (basalt), the uncorrected and corrected analysis of the three Kimberlites. The arrows show the displacement of the corrected analysis away from the composition of the contaminant (basalt).

The (Zr vs. Nb) plot (Fig. 2:2) shows that the correction for Zr is not as great as the correction for Nb due to the very similar concentration of Zr and very much lower concentration of Nb in the contaminant compared to the kimberlite.

A plot of Ce vs. Y (Fig. 2:3) indicates that the correction procedure may increase the concentration of one component and decrease another. Ce is increased as the basalt has considerably less of this component than Kimberlite and the reverse is true for Y. It follows that the Ce/Y ratio is sharply increased by the correction.

As can be seen in the K vs. Rb plot (Fig. 2:4) the K/Rb ratio of the Non-K6 and K6 Kimberlite has been substantially altered by the correction for basalt contamination. On the other hand the K/Rb ratio of the K4 Kimberlite has not been changed to the same extent. Before correction the K/Rb ratios of the three kimberlite types may have been considered similar.

With regard to the Ce vs. P_2O_5 plot (Fig. 2:5) the basalt contamination has acted essentially as a dilutant only changing the absolute abundances of the two components but not the Ce/P ratio to any great extent.

As can be seen the relative positions of the kimberlites on the binary diagrams are considerably altered with a correction for contamination by about 20% of basalt. The greater the difference in the concentrations of the element in the contaminant and the kimberlite is, the more marked the effect of the correction is.

The Corrected Chemistry of the Letseng-la-terai Kimberlites

Introduction

In the following discussion the data used has been corrected for the contamination by crustal material (Table 2:2) by the method discussed above. Unfortunately the correction is relatively crude for the following reasons :

- a) the values taken for the trace elements are from the Lesotho Formation in the Barkly East district more than 200 km away and cannot be considered a representative average, even though the Lesotho Formation is relatively uniform in composition over a great area (J.S. Marsh, pers. comm.).
- b) Point counting was carried out on a limited number of slides, but there does appear to be a consistent contamination of about 20% by foreign material (Table 2:2). These estimates are considered conservative and there may be some undercorrection due to the positioning of the slide in the specimen to avoid xenoliths.
- c) The contamination is assumed to be basalt only, although some Karoo shales, sandstones and basement xenoliths are present. The proportion is however small compared to the basalt. (5-10% of the contaminating material; visual estimate).

The chemistry is discussed under two major headings : Major elements, and Minor and Trace elements. The former includes SiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO and Na_2O , all re-calculated to a LOI free basis; K, Ti, P (L.O.I.-free) and the trace elements are discussed in the second section.

Major Elements

Table 2:2 lists the uncorrected and corrected LOI-free analysis of the Letseng-la-terai Kimberlite. As can be seen the uncorrected major element concentrations are very similar for the different kimberlites, only the relatively uncontaminated L13 specimen having a distinctly different chemistry. The uncorrected concentrations are also very similar to those reported by Gurney and Ibrahim (1973) when these have been re-calculated LOI-free.

Correction for contamination has brought the concentration of the various components closer to that of the uncontaminated specimen, L13.

Extreme variation is found in the content of Na_2O with a single kimberlite type (Tables 2:2 and 2:4) and therefore the component cannot be used to discriminate between kimberlite varieties. The contaminating basalt has a higher concentration of sodium than the kimberlite and the correction has therefore reduced the Na_2O concentration in the kimberlites. Correction also increased the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio in the kimberlites; and the majority now have a $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio that is greater than one in common with most other kimberlites.

The Minor and Trace Elements

Unlike the major elements previously discussed the Minor and Trace elements display a variation between kimberlite types that can be used to possibly decipher the relationships between them. The corrected concentrations will be used in the following discussion:

Strontium :

There is a large overlap in the concentrations obtained for the Non-K6 and K6 samples, and although the latter has a higher average concentration, the difference is not significant as can be seen in Table 2:3. The younger K5 Kimberlite is significantly enriched in Sr compared to the other kimberlites including the K4 type which is youngest. Sr enrichment of the K5 Kimberlite is reflected in the Ca/Sr ratio of 88 which is the lowest of the four kimberlite varieties (Fig. 2:6).

Potassium and Rubidium :

Phlogopite is the major host for K and Rb in kimberlites, and these elements are therefore discussed together. A plot of K vs. Rb (Fig. 2:7) clearly indicates the following relationships:

- a) The Non-K6 and K6 Kimberlites have a similar K/Rb ratio which is different from that of the K5 and K4 types.
- b) The Non-K6 and K6 Kimberlites have similar abundances of these elements, while the K4 and K5 varieties are relatively enriched, the K5 type having the highest concentration.

K and Rb concentrations reflected in the petrography as phlogopite, is more abundant in the K4 and K5 Kimberlite types and most abundant in the latter.

Zirconium, Niobium and Titanium :

All the kimberlites have a similar Zr/Nb ratio (± 2) in common with many other kimberlites such as those of De Beers Mine (Chapter 3) and those reported by Kable et al. (1975). The Non-K6 and K6 Kimberlites have similar concentrations of both Zr and Nb, while the K4 and K5 Kimberlites are relatively enriched in these elements, the latter having the highest abundances (Table 2:2).

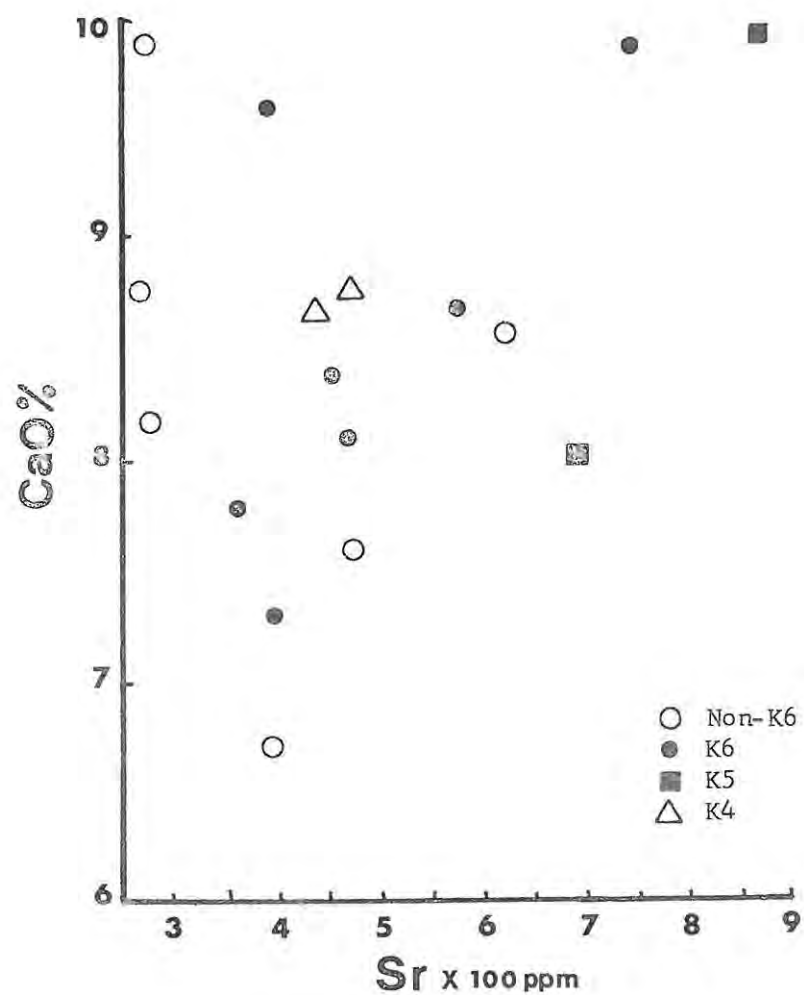


Fig. 2:6 CaO vs. Sr.

The K4 and K5 Kimberlites have distinctly different Ca/Sr ratios as shown by this diagram. (133 and 88 respectively). There is a scatter of values for the other kimberlites.

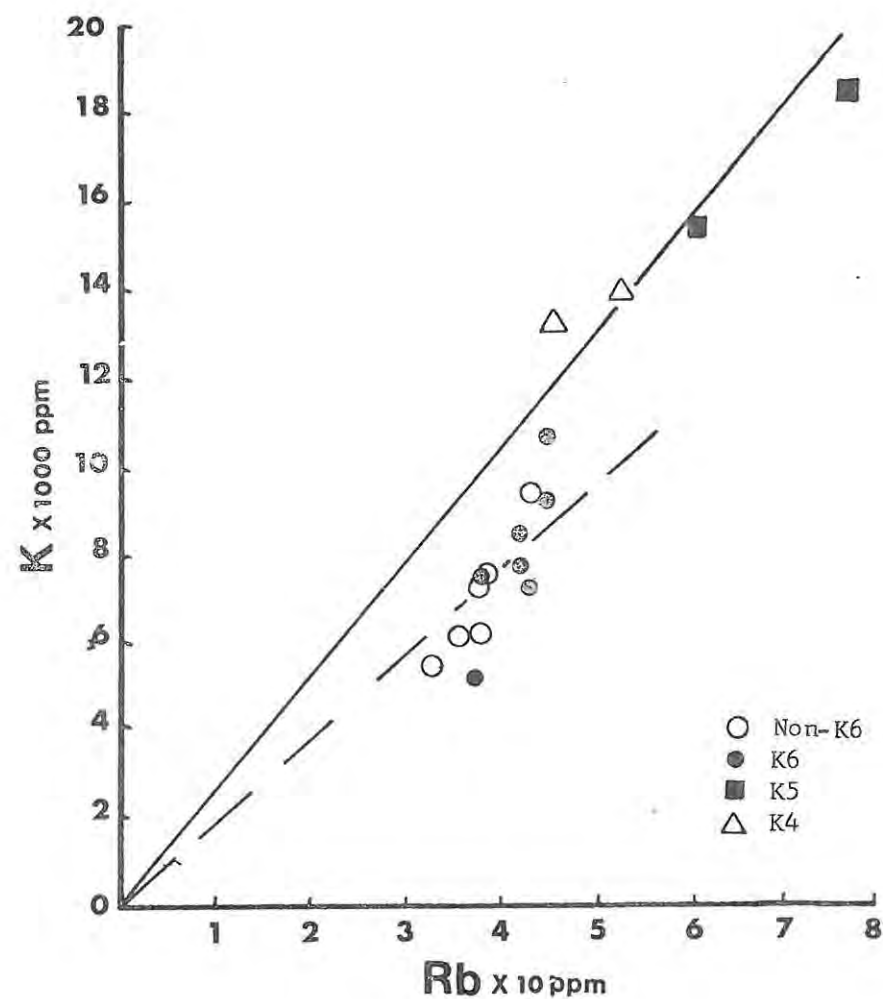


Fig. 2:7 K vs. Rb

This diagram illustrates the similarity in the K/Rb ratio of the K4 and K5 Kimberlites and the Non-K6 and K6 varieties respectively.

Ti is also lowest in the K6 and Non-K6 and more enriched in the K4 and K5 varieties. A plot of Ti vs. Nb (Fig. 2:8) also reveals that the Ti/Nb ratio is similar for the Non-K6 and K6 Kimberlites (154) and the K4 and K5 Kimberlites (113) respectively.

Ilmenite and perovskite concentrate Ti, Nb and probably Zr; the enrichment in these elements is reflected by a greater abundance of these two phases in the K4 and K5 Kimberlites.

Zinc, Copper and Vanadium :

There does not appear to be any systematic variation in the concentration of these elements. None of the four Kimberlite types are enriched in these components as a group (Table 3:3).

Cobalt and Nickel :

Ni and Co are both strongly fractionated into olivine ($D_{ol}^{Ni} = 13.1-23.5$, Leeman & Scheidegger (1977); $D_{ol}^{Co} = 3.6-6.3$, Duke (1976) and for this reason there is very little variation between the different kimberlites as the proportion of olivine is approximately constant for all kimberlites. This inference applies to the olivine crystals as a group (average). Individual grains may be enriched or depleted in the two components depending on the environment in which they crystallized, and if they are phenocrysts or xenocrysts.

Chromium :

Olivine, chromite, ilmenite and magnetite all concentrate Cr. The distribution of Cr between Olivine and the liquid is somewhat controversial and may be strongly influenced by the liquid composition. Duke (1976) found $D_{ol}^{Cr} = 1$ to 6, and taking these values a considerable amount of Cr must be concentrated in what used to be olivine inlets. However there is a positive correlation of Ti and Cr (Fig. 2:9) and picro-ilmenite is known to contain considerable amounts of Cr (Mitchell, 1977 ; Nixon and Kresten, 1973 and others). The reaction of ilmenite to perovskite, a Cr poor phase (?) may have lead to the formation of the euhedral chromite in the groundmass of the kimberlites.

As can be seen in Table 2:4 the Cr concentrations of the Non-K6 $\approx$ K6 $<$ K5 $\approx$ K4.

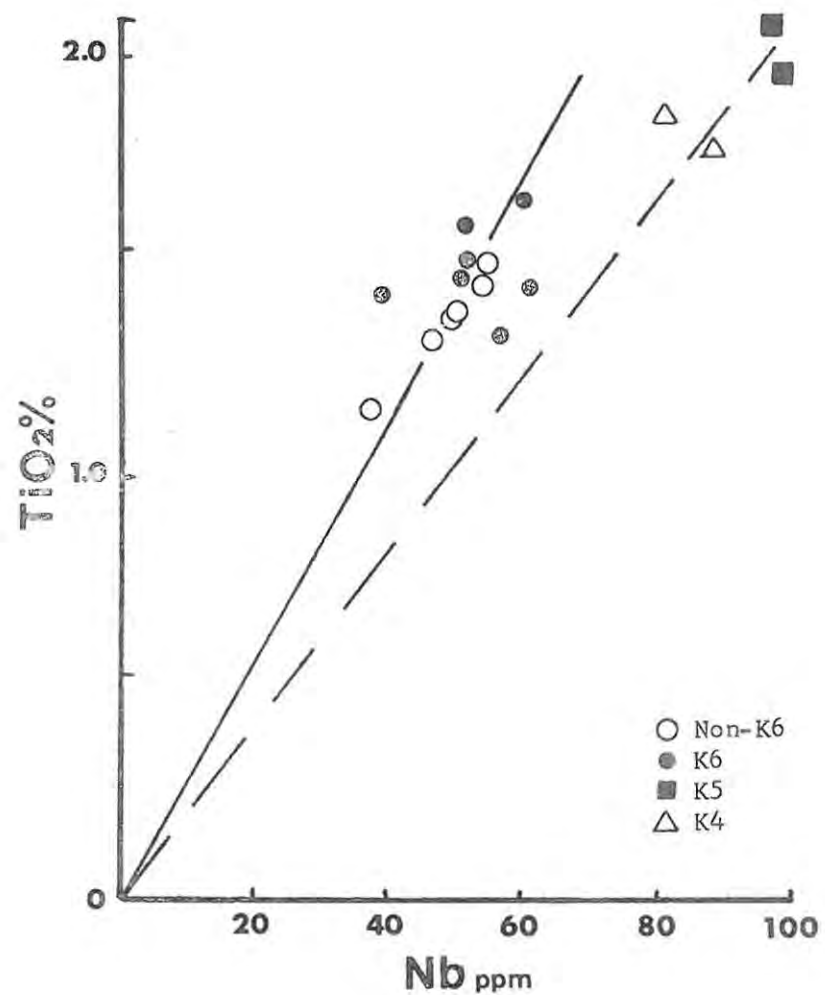


Fig. 2:8 TiO_2 vs. Nb

This shows the different Ti/Nb ratios for the Non-K6 and K6 Kimberlites (154) on the one hand and the K4 and K5 types (113) on the other.

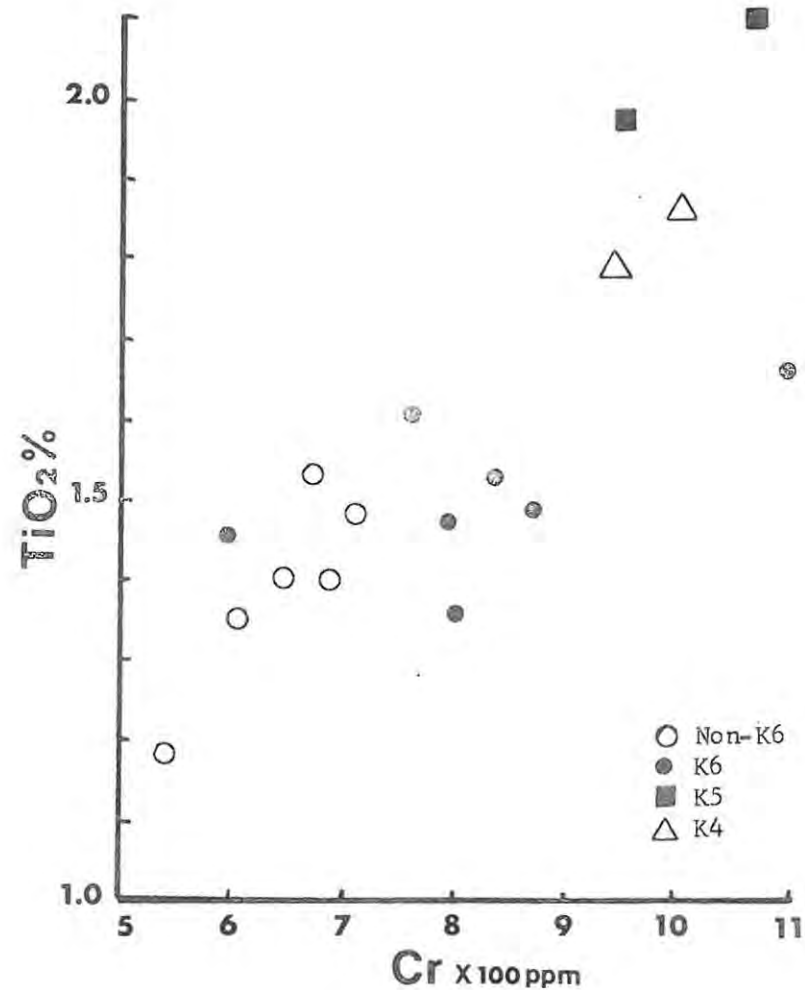


Fig. 2:9 TiO_2 vs. Cr

The plot illustrates the positive correlation of Ti and Cr.

Light Rare Earth Elements, Yttrium and Phosphorous

La, Ce and Nd are the three LREE that have been determined and Y has similar geochemical properties as the HREE (Frey et al., 1968). This is due to its similar charge, and an ionic radius which is approximately equal to that of Ho, the eleventh REE.

There is a strong enrichment in the LREE relative to the HREE in all varieties of Kimberlite (e.g. Paul et al., 1976).

Contamination by basalt has enriched the HREE represented by Y and diluted the LREE. For this reason the chondrite normalized abundance vs. atomic number plot usually used to indicate fractionation (Frey et al., 1968; Haskin et al., 1968) is considered to be unreliable in distinguishing between the different Kimberlites, as the difference may be subtle and even after correction no firm conclusions can be drawn. The effect of the correction on one Kimberlite is illustrated by Fig. 2:10.

Taking the light REE as a group there is little difference between the NK6 and K6 Kimberlites while the K4 and K5^{types} have distinctly higher LREE contents and they in turn do not differ much from each other (Table 2:2). A plot of Ce vs. P (Fig. 2:11) illustrates the enrichment of the LREE and phosphorous in the K4 and K5 Kimberlites relative to the other two types. This plot also shows that Ce/P ratio is constant in all varieties of the Letseng-la-terai Kimberlite.

The strong positive correlation and constant Ce/P ratio suggest that the LREE are associated with a phosphorous bearing mineral such as apatite.

INTERPRETATION OF RESULTS

Introduction

In the consideration of the relationships between the different varieties several models for the formation and possible fractionation of the Kimberlites will be examined in the light of the trace and minor element data previously described. All the Kimberlites have very similar major elements abundances and this has to be taken into account in any models proposed.

The mantle is assumed to consist of a four phase garnet peridotite (O'Hara, 1968) with subordinate phlogopite, carbonate and possibly apatite and other phases.

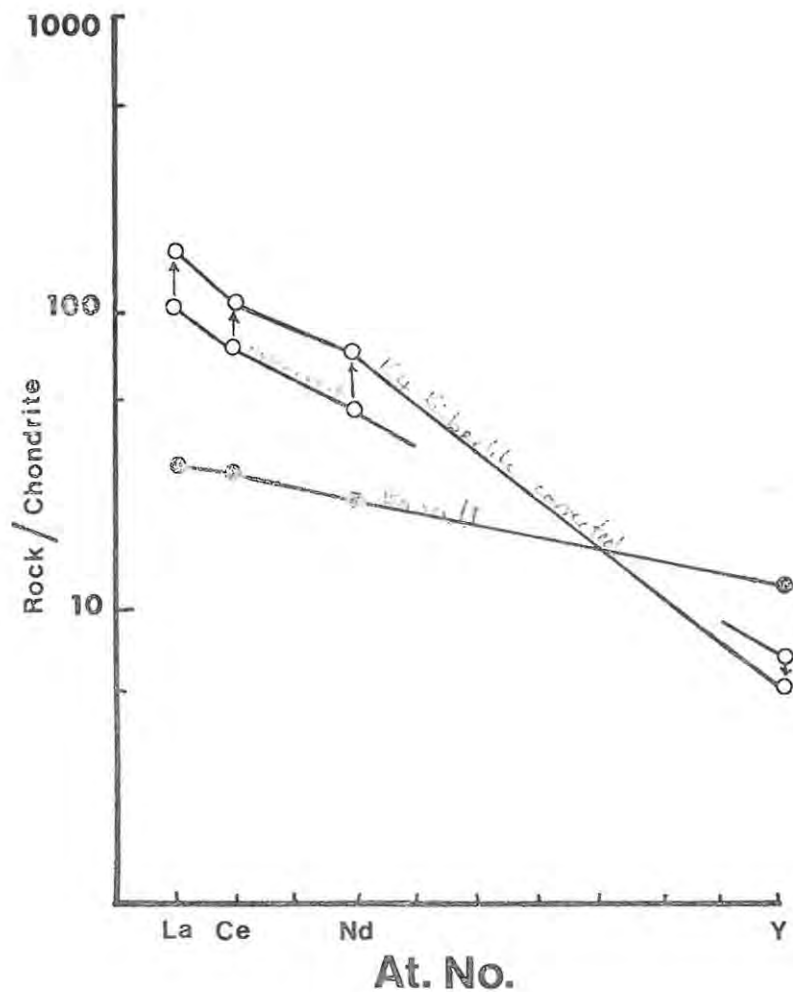


Fig. 2:10 REE plot

This diagram illustrates the effect of dilution by basalt on the K4 Kimberlite.

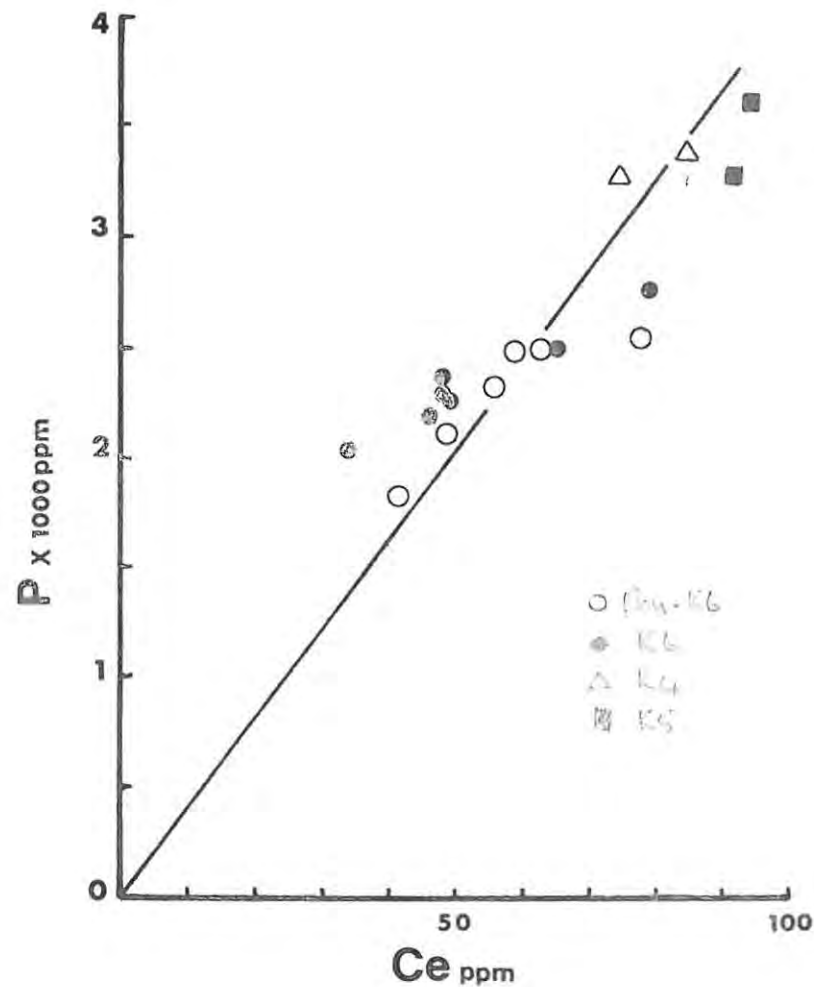


Fig. 2:11 P vs. Ce

The diagram illustrates the similarity of the P and Ce concentrations for the Non-K6 and K6 Kimberlites. The K4 and K5 types also have similar concentrations. The Ce/P ratio is the same for all the kimberlites.

Initially the Non-K6 and K6 Kimberlites will be considered because of their close chemical similarity, and then the K4 and K5 Kimberlites which are also very similar. Thirdly the relationship between these two groups of kimberlite will be examined.

The Non-K6 and K6 Kimberlites

As shown previously there is very little, if any difference in the chemistry of the Non-K6 and K6 Kimberlite varieties. However the K6 Kimberlite, the second oldest intrusion contains isolated large diamonds, and nodules of peridotite whose P.T. conditions have been determined to be in the range of 30 to 60 kb and 900 to 1400°C (Boyd & Nixon, 1975), and considerable amounts of garnet.

Since the chemistry and petrography of these kimberlites is so similar, it suggests that they are intimately related by some process. The two Kimberlites were either derived from very similar parts of the mantle or were originally part of the same liquid after partial melting.

A possible model relating the two kimberlites is as follows:

Initial partial melting produces a liquid which moves up, incorporates and brecciates diamond bearing material which sinks to the bottom of the magma chamber with the garnet and some nodules. The liquid may then form a vertically zoned magma chamber with the top deficient in diamond which then intrudes rapidly upward incorporating much olivine and mantle material on its way up. This material is then intruded as the initial Non-K6 Kimberlite. The magma at the bottom of the chamber follows the first material up but does contain diamond and garnet as it represents the cumulate portion

Garnet (and diamond) fractionation can however not be tested as the amount of garnet is volumetrically insignificant, and therefore has very little effect on the Al contents of the Kimberlites which were contaminated by Al - rich material. Similarly the expected increased REE fractionation of the Non-K6 Kimberlite can not be tested, even after the corrections have been applied.

The K6 magma also incorporates significant quantities of mantle material and it intruded the same diatreme probably very shortly after the initial intrusive. Fig. 2:12 schematically shows this model and alternative model discussed below.

The second model proposes that the two magmas come from physically different but chemically very similar parts of the mantle, possibly straddling the diamond/graphite inversion zone, and were then intruded in succession.

The two mechanisms are illustrated schematically by Fig. 2:12.

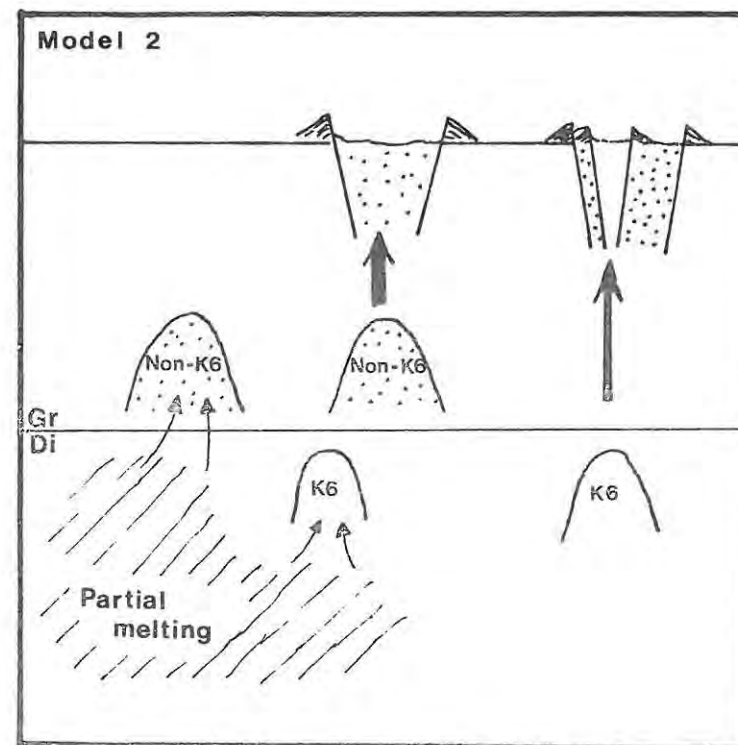
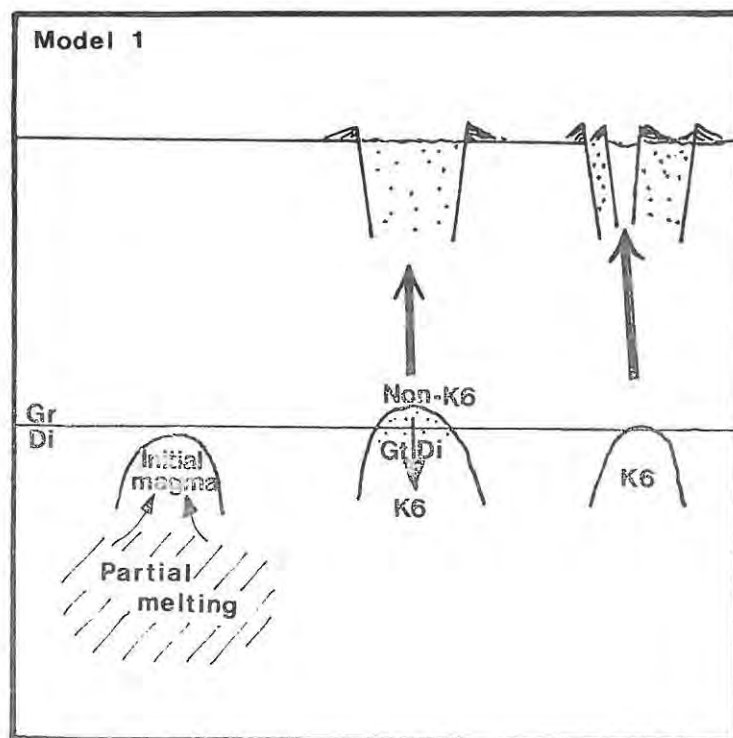


Fig. 12:12 Possible ways by which the Non-K6 and K6 Kimberlites were derived.

Model 1 : The two Kimberlites were derived from the same initial magma and there was only a small amount of differentiation involving diamond (Di) and garnet (Gt) to produce the two magmas.

Model 2 : The two Kimberlites were derived from two different parts of the mantle by partial melting.

The K4 and K5 Kimberlites

The order of intrusion is K5 and then K4. Inter element ratios such as K/Rb and Ti/Nb are similar for the two kimberlites, but different from the other two types. The K5 Kimberlite is however enriched in K, P, Ce, Ti, Nb and Zr relative to the K4 variety. These relationships, discussed previously suggest that these two kimberlites may be also related by some melting or fractionation process. Three models are examined in terms of the chemical data. Fig. 2:12 and 2:13 schematically illustrate the models.

The Melting Model :

This model requires that the first the K5 Kimberlite and then the K4 type were derived by successive melting of the same part of the mantle to produce the two liquids. This model is attractive as it explains several features.

The first melt to be derived from a particular area by a small degree of partial melting would be expected to be enriched in K, Rb, P, Ce, Zr, Nb, Sr and Ti, and this is the case with the K5 which is enriched to a greater extent than the K4 in these elements.

Carbonate is possibly an important phase in the mantle (Wyllie & Huang, 1975), and Sr is held in this phase in the unmelted material. However on partial melting the Sr is preferentially concentrated in the liquid (Koster van Groos, 1975) which therefore has a lower Ca/Sr than the residual solid. The Ca/Sr ratios of the K5 and K4 Kimberlites, which are 88 and 133 respectively also tends to lend support to this hypothesis.

Phlogopite is an important K and Rb bearing phase in the mantle (Kushiro, 1970; Yoder & Kushiro, 1969; Modreski & Boettcher, 1973; Beswick, 1976 and others). Beswick (1976) has shown that partial melting will decrease the K/Rb of the residual phlogopite as $D_{\text{phlog}}^{\text{Rb/K}} \pm 3$, and hence the K/Rb of subsequent liquids derived from the same source. The K/Rb of both the kimberlites are similar (Fig. 2:7), and the model is therefore doubtful as the K/Rb of the K5 should have been greater than the K/Rb of the K4. It seems therefore that this model is not plausible on the evidence of the K/Rb ratio.

The Parental Magma Model :

The hypothesis is that an initial magma is generated and intrudes as the K5 Kimberlite. The residual left in the magma chamber then differentiates to form a

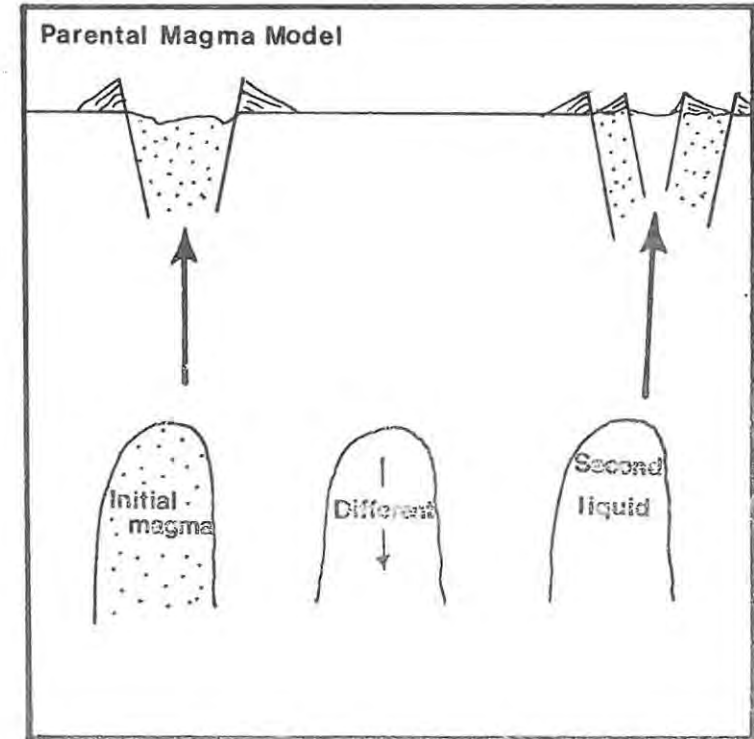
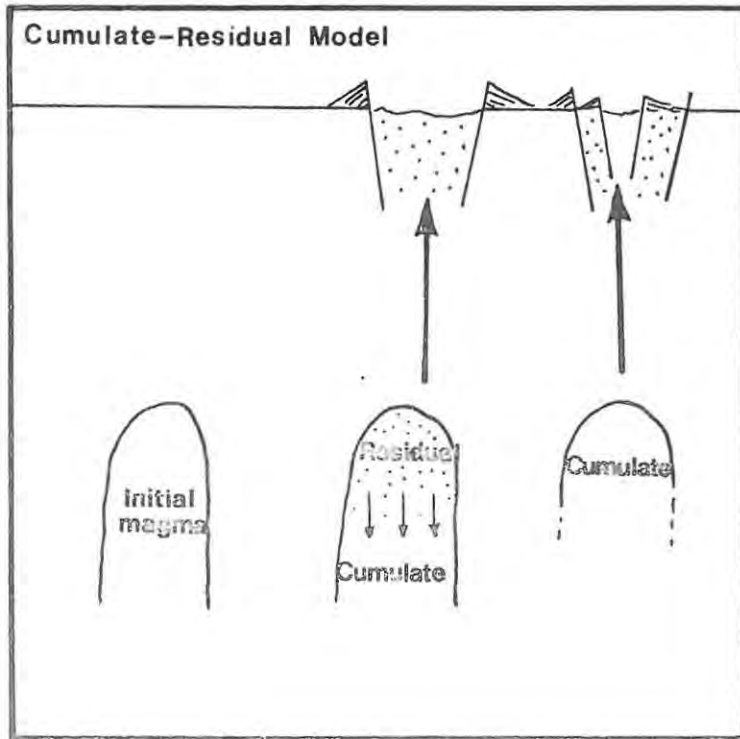


Fig. 12:13

Cumulate-Residual Model : Two magmas are derived by differentiation in a single magma chamber after the accumulation of the initial liquid. The top and bottom of the magma chamber are the residual and cumulate liquid respectively.

Parental Magma Model : An initial magma accumulates and erupts. The magma left in the magma chamber then differentiates and a second liquid (the residual liquid) then intrudes as a second Kimberlite type.

second residual liquid, which then intrudes as the K4 Kimberlite.

Possible fractioning phases in a kimberlite magma are olivine, picro-ilmenite (Mitchell, 1973 a,b). Garnet (Gurney & Switzer, 1973) clinopyroxene, orthopyroxene, carbonate (Wyllie & Huang, 1975^{a+b}), phlogopite (Dawson & Smith, 1975) and possibly apatite. Also from geochemical evidence possible fractionating phases must be phlogopite, ilmenite and some apatite. Fractionation of phlogopite will reduce the concentration of K and Rb present in the residual, however the latter should have an increased K/Rb ratio and thus has not occurred as is apparent in Fig. 2:7.

Furthermore as apatite would have to be a fractionating phase to reduce the amount of P, LREE and Y. No apatite phenocrysts were found in the kimberlites. Ilmenite or perovskite should have to fractionate from the K5 Kimberlite to deplete the residual (K4 Magma) in Ti. The former would be expected to fractionate the Zr/Nb ratio as shown in the previous discussion, and no change in the ratio is discernable. No other phases such as olivine, pyroxene or garnet can fractionate as this would counter the effects of removal of the three essential phases mentioned. The difference in the Ca/Sr ratio is also not explained by this model as carbonate cannot be a fractionating phase as the residual liquid (K4 Kimberlite) should have been enriched in Sr relative to Ca (Koster van Groos, 1975) and the reverse has in fact occurred.

The model is therefore not valid on geochemical criteria.

The Cumulate K4 and Residual K5 Kimberlite Model :

This model is similar to that proposed to relate the Non-K6 and K6 Kimberlites. An initial magma intermediate between the K4 and K5 Kimberlites is generated by small degrees of partial melting in the mantle and while moving up through the mantle some differentiation occurs, the top of the magma chamber containing the K5 Kimberlite and the base the K4 variety, which then intrudes in that order possibly as two discrete episodes.

Alternatively the magma may move up and the fractionation occurs only when the ascent is arrested at some point, possibly the base of the crust. The 'residual' K5 Kimberlite liquid at the top of the magma chamber then intrudes and is followed by the 'cumulate' K4 variety at the bottom of the chamber, the youngest kimberlite in the diatreme.

The model must be able to explain the general enrichment in elements contained in the matrix of the K5 variety and the differences in the Ca/Sr ratio.

Fractionation of some olivine in the initial liquid would cause a general enrichment in all the elements of interest and downward movement of carbonate

would decrease the Ca/Sr ratio in the liquid as Sr is enriched in the residual (Koster van Groos, op. cit.). All the other inter element ratios such as the K/Rb, Ti/Nb, Zr/Nb and Ce/P would not be disturbed and would be very similar for the two Kimberlites.

The model therefore accounts for the chemistry and order of intrusion of the K5 and K4 Kimberlites.

The Relationship of the Non-K6 and K6 to the K5 and K4 Kimberlites.

It has been shown that the Non-K6 and K6 Kimberlites are possibly closely related. The K5 and K4 varieties are also possibly linked by the cumulate residual model discussed previously. The relationship between these two groups of Kimberlite are now considered.

The following differences between the two groups of Kimberlite have to be considered in the petrogenetic models examined. The enrichment in the matrix elements (Ti, Nb, Zr, K, Rb, P, REE and Cr) in the K4 and K5 Kimberlite group; and the contrasts in the K/Rb and Ti/Nb ratios illustrated by Figs. 2:7 and 2:8 for the two groups of Kimberlite.

Three models identical to those previously discussed are examined using the chemical data. The three models proposed are the Partial Melting model, Parental Magma Model and the Cumulate/residual model. These are illustrated schematically by Fig. 2:12 and 2:13.

The Partial Melting Model :

In this model two melting episodes are envisaged, which produce protomagmas of the (Non-K6 and K6) and (K5 and K4) Kimberlites which later differentiate to give the different types of kimberlite now found in the diatrema.

There is an increase in the K/Rb ratio from the earlier (Non-K6 and K6) to the (K4 and K5) Kimberlites. In any melting episode the K/Rb ratio of the initial (Non-K6 and K6) melt should be higher than any subsequent melts as phlogopite which is residual in the mantle after melting has a lower K/Rb ratio, due to the $D_{\text{phlog}}^{\text{Rb/K}}$ being approximately 3 (Beswick, 1976). Furthermore the second melt should be less enriched in the two elements under consideration, and Zr, Nb, Ti, P etc., as it would then originate from a depleted source area.

It is therefore unlikely that the different kimberlites are related by this model.

The Parental K6 to the proto (K4 and K5) magma:

Differentiation of the K6 Kimberlite magma to form the (K4 and K5) magma as a residual liquid (Fig. 2:13) explains the enrichment of the matrix elements in the latter. The change to higher values of the K/Rb ratio can be explained by this model if phlogopite is considered a fractionating phase, as the residual liquid (K4 and K5) has a higher K/Rb ratio, possibly due to the preferential concentration of Rb over K in the fractionating phlogopite (Beswick, 1976). There would however have to be considerable fractionation of other phases that do not concentrate elements enriched in the K4 and K5 Kimberlites, probably olivine, as clinopyroxene would deplete the magma in Cr which is enriched ($D_{\text{cpx}}^{\text{Cr}}$ 8-36 (Duke, 1976)), to counter the depletion in K and Rb due to phlogopite fractionation. Olivine fractionation would therefore have to be dominant over phlogopite. This would significantly reduce the Ni and Co contents of the residual magma as $D_{\text{ol}}^{\text{Ni}}$ 13-23 (Leeman & Scheidegger, 1977) and $D_{\text{ol}}^{\text{Co}}$ 3-6 (Duke, 1976). No observable differences are present but this effect could be masked by the presence of xenocrystal olivine. Fractionation would also remove any diamond and garnet from the magma.

The greater Ti/Nb of the (Non-K6 and K6) Kimberlite group could be explained by a small amount of ilmenite fractionation if the $D_{\text{ilm}}^{\text{Ti/Nb}} > 1$. The distribution co-efficient is however not known.

This model could relate the two varieties of magma, the (Non-K6 and K6) and (K5 and K4), and must be considered a possibility. To further test this model K and Rb are plotted versus Ce on the same diagram (Fig. 2:14). Ce shows a constant enrichment in all the kimberlites with P_2O_5 , Nb, Zr etc. and is thus a convenient monitor for the behaviour of K and Rb. Fig. 2:14 shows that the Ce/Rb ratio is similar for all the kimberlites, but the Ce/K ratio is not constant and is less for the K4 and K5 Kimberlites than the Non-K6 and K6 varieties. Phlogopite fractionation removes K and Rb from the magma, the latter more than the former as $D_{\text{phlog}}^{\text{Rb/K}} \simeq 3$ (Beswick, 1976). Rb should therefore be depleted more than K and both the Ce/K and Ce/Rb ratios should have increased. Phlogopite could therefore not have been a fractionating phase and the model is therefore untenable on this chemical criterion.

The 'Residual' K6 and 'Cumulate' (K4 and K5) Kimberlite Model :

The Model proposed here is that the K6 magma fractionates phases which are host to the elements enriched in the (K4 and K5) magma combination.

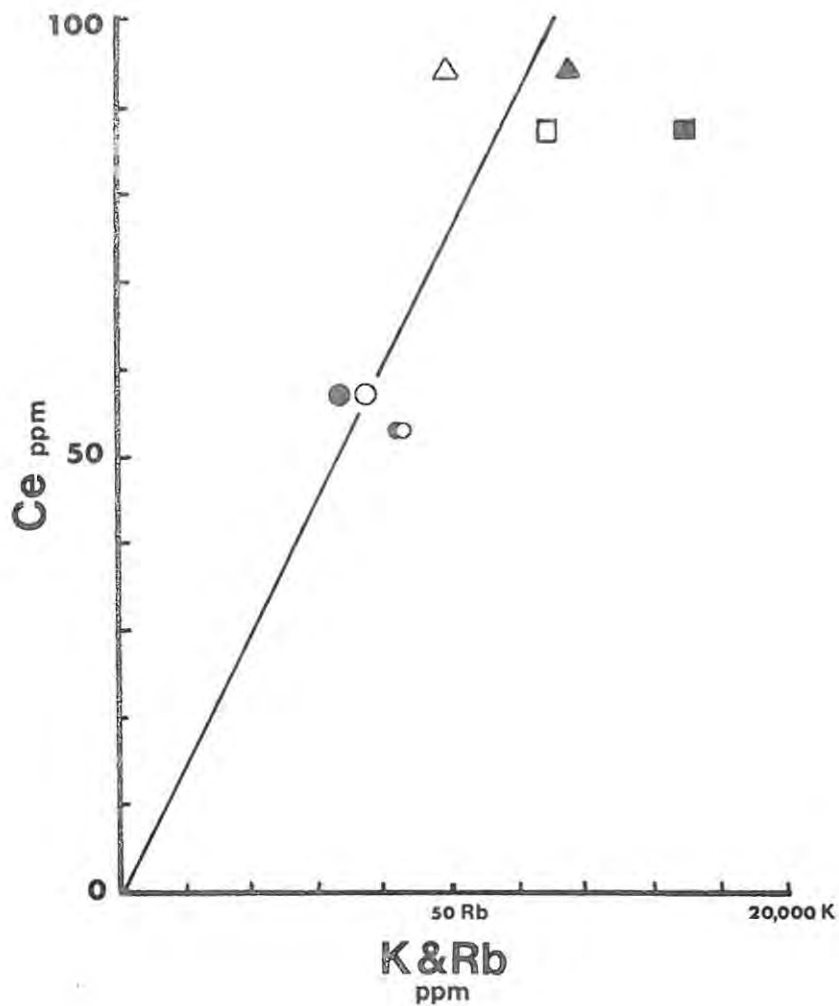


Fig. 2:14 Ce vs. K & Rb

The Rb/Ce ratio is similar for all the varieties of kimberlite (open symbols), but the K/Ce ratio is greater for the K4 & K5 Kimberlites than for the K6 & Non-K6 types. Phlogopite could thus not have been a fractionating phase (see text).

Average values are used (see Table 2:4).

These phases are apatite, ilmenite or perovskite and phlogopite. Olivine would have to be subordinate to these phases. Because the K4 and K5 magmas intruded after the K6 Kimberlite they would have to have been the cumulate at the bottom of the magma chamber. In this case one would expect the (K4 and K5) magma to be most enriched in dense constituents such as garnet, ultramafic nodules and diamond, but this has not happened. Pheno- or megacrysts of ilmenite, perovskite, apatite and phlogopite would also be expected. Apatite has not been found as a large inset. The model is therefore unlikely on physical grounds.

To maintain constant relationships between components, like Nb and Ce, concentrated in different phases such as Ti bearing minerals and apatite, specific proportions of the fractionating phases would be required and this is extremely unlikely. Furthermore the fractionation of phlogopite should decrease the K/Rb ratio of the 'Cumulate' (K4 and K5) magma as phlogopite concentrates Rb in preference to K. The K/Rb ratio of the K6 Kimberlite is lower than that of the K4 and K5 varieties and phlogopite could therefore not have been a fractionating phase.

This model is therefore also unlikely.

Conclusion

From the chemical and physical relationships discussed it appears that there were two melting episodes in different parts of the mantle and the magmas formed then differentiated to form the four separate kimberlite types in the Letseng-la-terai diatrema.

The first two intrusions, the Non-K6 and K6 Kimberlites, are very closely related chemically and a plausible physical model relating them, and explaining the lack of diamond and garnet in the Non-K6 type, has been proposed. On the other hand the last two, K4 and K5 Kimberlite intrusions, appear to be unrelated to the K6 and Non-K6 types but are in turn related to each other by the Cumulate/Residual model developed.

CHAPTER 3THE DE BEERS MINE KIMBERLITESIntroduction

The De Beers Mine diatreme facies kimberlite (Dawson, 1971) consists of two roughly co-axial intrusions, the earlier Peripheral Kimberlite and a later Core Kimberlite. Fig.3:1 illustrates the relationships between the two types, and an isometric projection of the pipe is given by Williams (1932).

The Peripheral Kimberlite is massive with little contamination by crustal material, and no xenoliths from the Karoo formations which once covered the area have been found. It therefore appears that the magma did not penetrate into, or through, these rocks to the surface (Clement, pers. comm.). The Core variety, however, is more fragmental and does contain Karoo xenoliths, and therefore probably did penetrate through to the surface.

In order to clarify the relationships between the two kimberlite types, their petrography and chemistry are examined in the following sections.

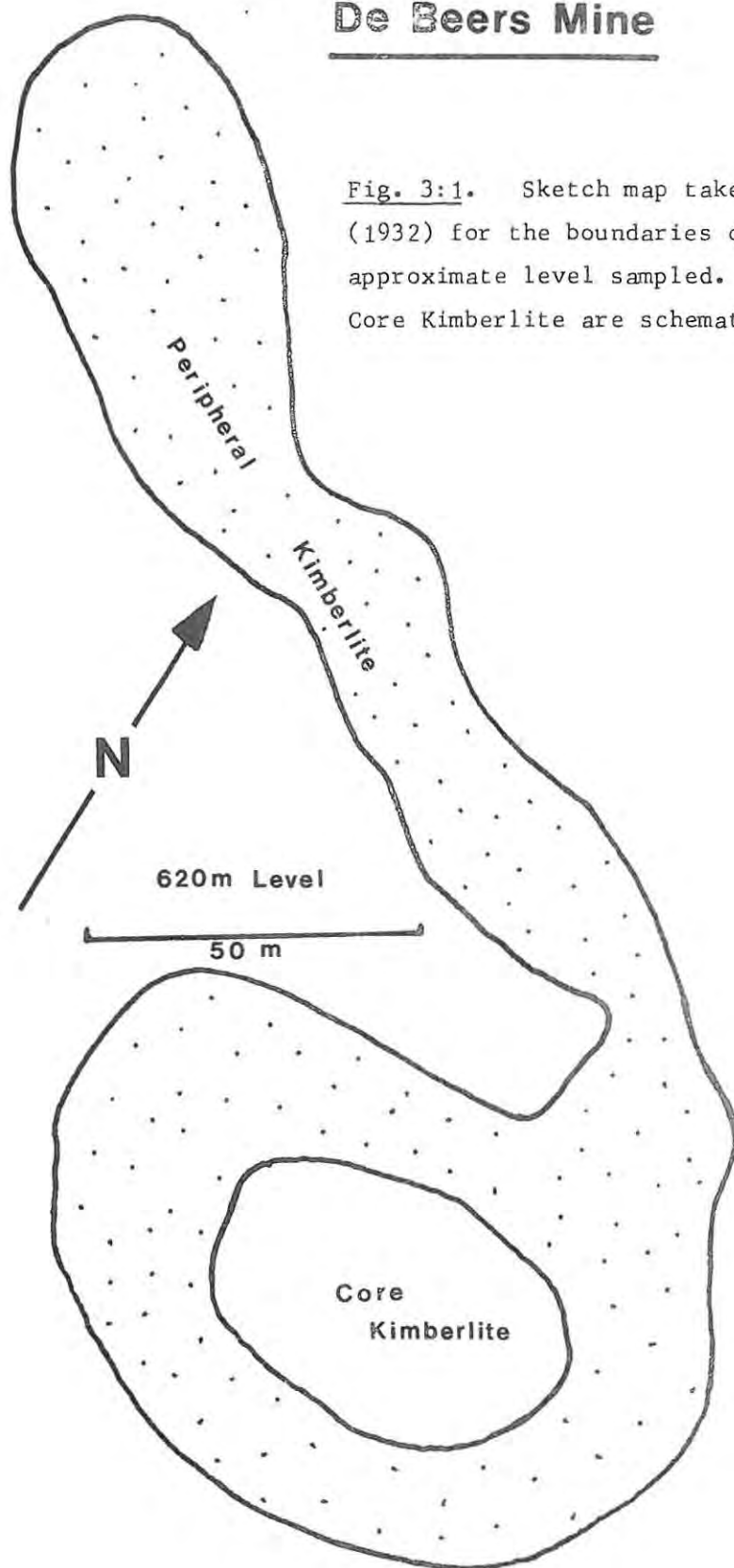
PetrographyPeripheral Kimberlite

This is a porphyritic rock with large olivine insets and granular xenoliths in a matrix consisting of smaller olivine grains, phlogopite, perovskite, ilmenite, titanomagnetite, chromite, monticellite, apatite, calcite and primary serpentine. The extent of serpentinization is extremely variable, even on the scale of a hand specimen. Olivine grains in the groundmass have been altered extensively, in common with many other kimberlites (Williams, 1932; Mitchell, 1970). Matrix phlogopite has also suffered variable amounts of alteration to chlorite.

Calcite is the dominant matrix phase, with subordinate primary serpentine. These minerals poikilitically enclose the other smaller, rounded groundmass mineral grains. In most cases the calcite crystallized prior to the serpentine, the latter where it does occur filling small interstices. Clement & Skinner (1977) have classified this kimberlite as a monticellite kimberlite, but in view of the considerable quantities of apatite, calcite and primary serpentine, it should possibly be re-classified as an apatite bearing calcite-monticellite-serpentine kimberlite.

De Beers MineFig. 3:1

Fig. 3:1. Sketch map taken from Williams (1932) for the boundaries of the pipe at the approximate level sampled. Boundaries of the Core Kimberlite are schematic.



In common with most other kimberlites, two generations (at least) of olivine are present (Mitchell, 1970). The larger rounded insets consisting of single strained and unstrained crystals, and small xenoliths consisting of granular aggregates of sheared crystals. These are therefore probably largely xenogenic material incorporated during the upward migration of the kimberlite magma. The extent of serpentinization of this olivine is variable, and the insets range from fresh to altered. Groundmass olivine crystals are much more extensively altered, complete pseudomorphs of serpentine after olivine being very common. Initially these grains were euhedral, although the form has been obscured by serpentinization, and this together with the unstrained nature of the remnant grains, suggests that most of the smaller olivine grains in the matrix crystallized from the kimberlite magma, and the main are phenocrystic, although some may indeed be xenocrystic.

Ilmenite

Large grains of picro-ilmenite occur in the rock, but are very dispersed and make up only a small proportion of the total. These usually occur as rounded and angular fragments, which may have been derived from larger crystals or aggregates, such as those described by Mitchell (1973 a), fragmented during ascent and intrusion of the magma. A rind of perovskite is often present on the outer rim of these crystals and fragments, apparently due to reaction with the kimberlite liquid. This is illustrated in Fig.3:2, and is similar to that discussed by Haggerty (1975).

Garnet

Garnet is also present as large rounded grains with kelyphytic borders. Volumetrically this mineral is also insignificant and appears not to be in equilibrium with the environment. It also occurs in association with sheared olivine xenoliths, and in this case kelyphite only occurs where the garnet has been exposed to attack by the kimberlite liquid, (Fig. 3:2).

Perovskite

Perovskite is ubiquitous in the matrix as rounded, gold to dark brown grains of small size, but isolated larger crystals are present. The larger crystals often enclose a smaller ilmenite grain. The larger ilmenite crystals are also rimmed by this phase. Perovskite crystallized after the small groundmass ilmenite but probably simultaneously with, or before, the euhedral

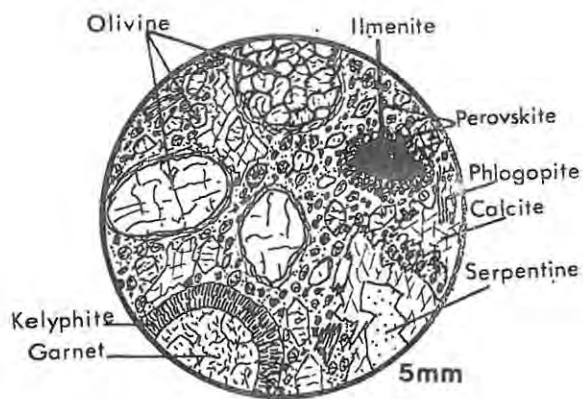


Fig. 3:2 : Peripheral Kimberlite with insets of olivine, ilmenite and garnet. The groundmass consists of perovskite, titanomagnetite, monticellite, apatite calcite & phlogopite. Reaction of garnet to kelyphite and ilmenite to perovskite can be seen.

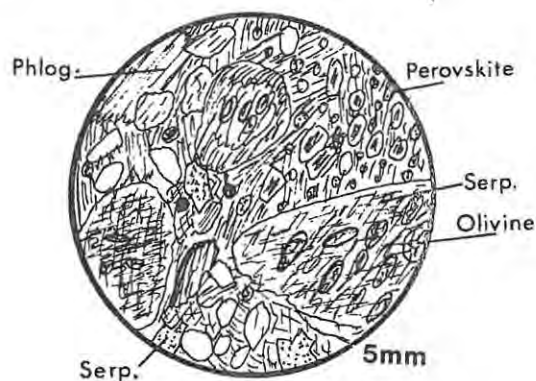


Fig. 3:3 : Core Kimberlite with large insets of olivine now almost totally altered to serpentine. The groundmass consists largely of phlogopite & smaller olivine with subordinate serpentine and calcite. Perovskite, and apatite are also present in the groundmass.

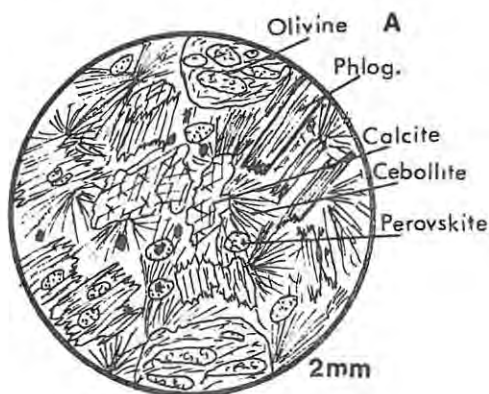


Fig. 3:4A : Core Kimberlite with abundant calcite and cebollite besides phlogopite, olivine, perovskite and ilmenite.

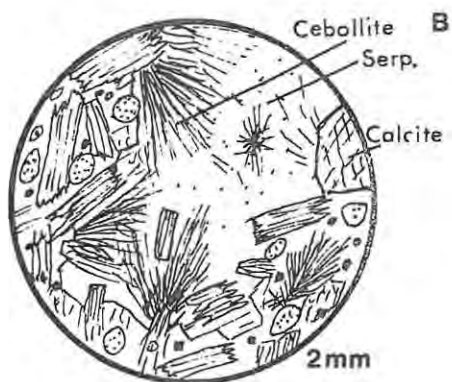


Fig. 3:4B : Similar to Fig. 3:4A above but there is a considerable amount of late stage serpentine intergrown with cebollite.

groundmass titanomagnetite which is often situated on the outer rim of the perovskite crystals.

Matrix oxides

Titanomagnetite, ilmenite and chromite occur as small grains in the groundmass. The ilmenite is generally enclosed by perovskite grains and titanomagnetite is euhedral and unaltered. Titanomagnetite appears to have formed simultaneously with or after the perovskite. Chromite occurs as small euhedral grains and is often associated with the larger ilmenite as small inclusions visible in reflected light, and detectable by scanning using the electron microprobe.

Phlogopite

Fairly large phenocrysts of yellow phlogopite displaying both normal and reversed pleochroism occur in the rock. Phlogopite is also present in the groundmass, and has reversed pleochroism with more subdued colours. Some of the larger crystals are possibly xenocrystic as phlogopite is occasionally enclosed poikilitically by larger strained olivine insets. Groundmass phlogopite appears to have crystallized after the oxide minerals including perovskite, as these phases are often enclosed within plates of mica, which are quite large (1-2 mm diameter) in some cases. Calcite sometimes encloses euhedral books of matrix phlogopite and is therefore a later crystallizing mineral.

Alteration of matrix phlogopite to greenish chlorite with a low birefringence is quite common.

Apatite

Very small grains ($< .005$ mm) of apatite with very low birefringence and high relief are extremely common and form a large proportion of the groundmass. The mineral crystallized as rounded grains, often enclosed by the matrix phlogopite or calcite and it therefore crystallized prior to these phases.

Monticellite

Monticellite has a similar appearance to apatite but is usually slightly larger and has a higher birefringence. It appears to have crystallized with apatite in the groundmass.

Calcite

This is a very common groundmass phase, poikilitically enclosing the other minerals except serpentine. Irregular clear patches occasionally enclosing euhedral phlogopite and other minerals also occur. Fig. 3:2 illustrates these relationships.

Serpentine

Primary serpentine is found as clear, greenish, interstitial patches surrounded by euhedral calcite and other minerals. It is therefore the last phase to crystallize from the kimberlite liquid, (Fig. 3:2).

Deuteric Alteration

Deuteric alteration of olivine and phlogopite to serpentine and chlorite respectively, is common. The larger insets of olivine have been serpentinized to a variable degree but less extensively than the olivine grains in the groundmass. Complete pseudomorphs of serpentine after the groundmass olivine grains are common.

In general where there is more calcite in the matrix there is less alteration of the other minerals, suggesting that this is a very late effect as calcite is the penultimate mineral to have crystallized.

Core Kimberlite

Generally the Core Kimberlite is more contaminated and fragmental than the peripheral type. The olivine, garnet and ilmenite insets are similar to those of the Peripheral variety and need not be described here. Besides these the matrix contains olivine, phlogopite, calcite, celadonite, apatite, serpentine, ilmenite, titanomagnetite and chromite. Large phenocrysts of phlogopite are abundant in the Core Kimberlite. Small autoliths (Ferguson et al., 1973 b), cored by olivine, are also commonly found; (Fig. 3:3). This kimberlite has been classified as a phlogopite kimberlite by Clement & Skinner (1977).

Olivine

Groundmass olivine grains show well developed euhedral form, and unlike the larger rounded insets show no evidence of strain. As in the Peripheral Kimberlite there is a variable, but in general much more extensive, alteration of the insets and the smaller groundmass olivine grains to serpentine.

Phlogopite

Phlogopite is common in this variety of kimberlite, occurring as phenocrysts, and in the matrix. The larger crystals show variable optical characteristics. Zoning is common and crystals often have contrasting pleochroism from Core to rim. Cores and rims may have normal or reversed pleochroic character, and the intensity of the colours is also non-uniform. Inclusions of ilmenite within the phlogopite phenocrysts are also present.

The matrix phlogopite which in the main has reversed pleochroism, is abundant and takes the form of tiny plates less than 0.05 mm in diameter and larger anhedral crystals up to 1 mm in diameter, the latter poikilitically enclosing other minerals. Groundmass phlogopite crystallized after all the minerals except calcite, cecolite and serpentine. As opposed to the Peripheral Kimberlite alteration to chlorite is rare and the phlogopite is usually well preserved. In contrast the other mafic minerals, especially the matrix olivine, are extensively altered.

Perovskite and opaque oxides

In appearance these minerals (ilmenite, titanomagnetite, chromite and perovskite), are identical to those of the Peripheral Kimberlite and display similar mutual relationships to each other. They crystallized prior to the other groundmass phases except olivine.

Apatite

Matrix apatite is quite common as very tiny grains, similar in appearance and paragenesis to those of the Peripheral kimberlite.

Calcite

Euhedral to anhedral grains and patches of primary calcite are common in the matrix of the Core Kimberlite. The calcite forms as clear patches and interstitial material enclosing perovskite, phlogopite, apatite and olivine. Crystallization occurred prior to the groundmass serpentine, and its relationship to cecolite with which it is often intergrown is problematic, but it probably crystallized after that phase as it encloses clusters of acicular cecolite crystals. This is illustrated by Fig. 3:4.

Cecolite

Cecolite is a rare mineral normally associated with the alteration of melilite by late stage aqueous solutions (Larsen & Goranson, 1932; Tilley &

Harwood, 1931; Larsen, 1942; Rodygina, 1971), and has never been described in kimberlite (Mitchell, 1970). A more detailed review together with the properties determined for this phase is given in Chapter 5.

The Core Kimberlite contains significant amounts of this mineral as a late stage primary phase that has crystallized with or before the calcite, and before the primary serpentine. It occurs as clear, fibrous, radiating clusters and patches of acicular and fibrous crystals where abundant, and as small rosettes and radiating sheaves when present in minor amounts. These relationships are illustrated in Fig. 3:4.

Serpentine

Clear, green, almost isotropic patches of primary serpentine are common in this kimberlite. This phase is clearly the last to crystallize as it is present only as interstitial material often surrounded by euhedral calcite crystals, (Fig. 3:3).

Late Stage Alteration

Serpentinization of the olivine insets and matrix grains is advanced, and in many cases complete pseudomorphs of serpentine after the large olivine insets occur. However the alteration of the groundmass olivine is generally more marked. Phlogopite is unaffected by late effects.

Conclusions

The order of crystallization appears to have been similar in the early stages of both kimberlites.

Initially the kimberlite magma crystallizes the large phenocrysts of ilmenite, phlogopite and possibly garnet. A large proportion of the olivine insets are xenocrystic and are probably incorporated after the crystallization of the ilmenite, phlogopite and garnet megacrysts, if these are phenocrystic. Dawson & Smith (1975) believe phlogopite and other megacrysts to be phenocrystic, and Mitchell (1973a;1977) believes the ilmenite megacrysts to be an essential primary phase in kimberlites crystallizing from a proto-kimberlite magma, which is modified by fractionation of this phase before intrusion.

During the later stages in the upward migration of the magma, ilmenite reacts with the liquid to form perovskite and possibly titanomagnetite. After this stage intrusion and final consolidation of the liquid takes place; the



final liquids crystallize olivine, apatite and monticellite, and then phlogopite, cebolite, calcite and serpentine, in that order.

Later fluids, which are probably deuteric, may alter the groundmass olivine and phlogopite. These fluids may be the medium from which the primary serpentine in the matrix precipitated.

The Chemistry of the De Beers Mine Kimberlites

Introduction

Eight samples from the Peripheral Kimberlite and five from the Core Kimberlite have been analysed using x-ray Fluorescence spectroscopy (See Appendix A). The abundance data are listed in Table 3:1, and the range shown by each variety, re-calculated H_2O^- and L.O.I. free, are listed in Table 3:2. The latter Table lists DB/P5 separately, as this sample from the Peripheral Kimberlite, shows some unusual features.

There is a marked contrast in the chemistry of the Peripheral and Core Kimberlite varieties respectively, as shown by Table 3:2. The petrographic contrasts are reflected in the chemistry of the two kimberlites.

The Major Elements

Core Kimberlite

The Core Kimberlite is enriched relative to the Peripheral variety in SiO_2 , Al_2O_3 , K_2O and Na_2O , (Table 3:2). This is reflected petrographically by the presence of phlogopite in the groundmass of the Core Kimberlite. Phlogopite phenocrysts are also more common in this type. However there appears to have been an enrichment of SiO_2 and Al_2O_3 in the residual liquid and cebolite therefore formed as an additional phase.

There is a positive correlation between MgO and CaO (Fig. 3:5), and minerals containing these components are common to both kimberlites; i.e. groundmass calcite and serpentine, and the groundmass and inset olivine. In general there is however a lesser amount of primary serpentine and calcite in this variety of kimberlite than in the Peripheral type, and this is illustrated by Fig. 3:5.

TABLE 3:1

MAJOR AND TRACE ELEMENT ABUNDANCES FOR DE BEERS MINE

	MAJOR ELEMENTS													
	DB/P1	DB/P2	DB/P3	DB/P4	DB/P5	DB/P6	DB/P7	DB/P8	DB/C1	DB/C3	DB/C4	DB/C5	DB/C6	
SiO ₂	30.05	27.89	32.64	31.11	26.11	30.47	32.01	29.59	32.77	32.95	38.67	38.32	36.40	
TiO ₂	1.80	1.80	1.77	1.73	2.33	1.69	1.86	1.80	1.45	1.60	1.45	1.32	1.14	
Al ₂ O ₃	2.00	2.08	2.41	2.05	2.81	1.88	2.53	2.32	3.76	3.67	5.34	4.70	4.38	
Fe ₂ O ₃	8.75	8.50	9.10	8.86	8.61	9.12	9.32	8.72	7.78	8.20	7.98	7.83	8.35	
MnO	0.16	0.16	0.24	0.19	0.25	0.23	0.15	0.16	0.13	0.17	0.17	0.17	0.19	Σ
MgO	32.33	30.74	34.26	32.53	27.63	33.75	32.21	29.67	25.96	29.10	27.47	27.72	28.09	
CaO	10.25	11.80	7.72	7.71	16.68	10.70	10.04	10.92	8.48	8.59	7.01	7.37	8.74	
Na ₂ O	0.51	0.45	0.67	0.35	0.37	0.53	0.56	0.31	0.71	0.86	0.81	1.09	1.19	
K ₂ O	0.53	0.87	1.11	1.09	0.18	0.95	0.92	1.07	2.25	1.76	3.34	2.33	2.49	
P ₂ O ₅	2.07	1.84	1.79	1.89	3.04	1.78	2.05	1.53	1.18	1.51	1.37	1.37	0.84	
L.O.I	9.97	12.72	8.76	11.25	11.82	8.82	7.73	11.81	11.44	10.98	6.75	8.60	7.10	
H ₂ O	0.48	0.45	-	-	-	-	-	0.61	3.11	-	-	-	-	
TOTAL	99.89	99.30	100.47	98.75	99.83	99.92	99.38	98.51	99.02	99.39	99.54	100.82	98.91	

Continued .

TABLE 3:1 (Continued)

	TRACE ELEMENTS												
	DB/P1	DB/P2	DB/P3	DB/P4	DB/P5	DB/P6	DB/P7	DB/P8	DB/C1	DB/C3	DB/C4	DB/C5	DB/C6
SR	1287	1107	991	1154	1403	1196	1445	2239	888	1069	680	864	1356
RB	69	56	41	40	28	65	99	96	95	75	113	115	102
Y	14	16	15	13	24	14	16	13	13	13	12	13	12
ZR	255	287	274	262	390	257	274	260	223	236	202	205	173
NB	121	117	119	109	152	113	128	117	92	99	86	89	69
ZN	55	50	57	61	61	62	67	57	61	60	67	64	68
CU	54	48	52	64	90	53	83	70	33	42	45	34	33
CO	86	84	89	88	72	89	89	81	75	83	78	81	80
NI	1272	1190	1384	1395	954	1490	1334	1151	1073	1270	1269	1244	1249
V	179	80	89	94	126	110	154	142	80	58	116	89	124
CR	1514	1489	1521	1506	1894	1501	1427	1398	1179	1315	1113	1199	1053
TH	7	6	-	7	10	7	-	5	5	-	-	-	-
CE	107	107	106	91	174	113	101	103	84	82	73	78	76
ND	51	56	65	38	75	52	45	46	35	36	31	34	33
LA	61	64	49	65	114	69	68	55	43	58	45	51	53

TABLE 3:2

RANGES AND ENRICHMENT TRENDS IN THE CORE AND PERIPHERAL KIMBERLITE

<u>MAJOR ELEMENTS (%)</u>					
	DB/P5	PERIPHERAL	P	C	CORE
SiO ₂	29.81	32.50 - 36.00		+	37.50 - 41.50
TiO ₂	2.66	1.70 - 2.09	+		1.20 - 1.80
Al ₂ O ₃	3.21	2.00 - 3.00		+	4.00 - 6.00
Fe ₂ O ₃	9.84	10.00 - 10.50	+		8.50 - 9.50
MgO	31.14	34.00 - 37.00	+		30.00 - 33.00
CaO	19.04	8.00 - 13.70	+		7.00 - 10.00
Na ₂ O	0.42	0.35 - 0.75		+	0.85 - 1.30
K ₂ O	0.20	0.59 - 1.40		+	1.60 - 3.50
P ₂ O ₅	3.47	1.70 - 2.40	+		1.00 - 1.60
<u>TRACE ELEMENTS (PPM)</u>					
SR	1403	800 - 2200	+		700 - 1400
RB	28	27 - 100		+	75 - 115
Y	24	12 - 18	+		11 - 13
ZR	390	250 - 290	+		170 - 240
NB	152	110 - 130	+		70 - 100
ZN	61	50 - 67			60 - 68
CU	90	44 - 90	+		33 - 43
NI	954	1150 - 1500			1000 - 1300
CO	72	87 - 89			73 - 87
V	126	80 - 180			55 - 125
CR	1894	1300 - 1500	+		1000 - 1300
TH	10	5 - 7	+		- - 5
CE	174	90 - 115	+		75 - 85

Peripheral Kimberlite

MgO and CaO are enriched in the Peripheral Kimberlite relative to the Core variety (Fig. 3:5 and Table 3:2). This is reflected in the presence of significant amounts of calcite and serpentine in the matrix of this kimberlite. Fe_2O_3 is enriched in this kimberlite type by a relatively small but consistent amount (1%), which is reflected in the greater quantity of opaques (magnetite, ilmenite and chromite) seen in thin section. This supposition is also supported by a greater abundance of TiO_2 and Cr in this kimberlite.

K_2O (up to 1.4%) and Al_2O_3 (up to 3%) in the Peripheral kimberlite has resulted in the crystallization of some phlogopite in the groundmass of this type. A plot of K_2O vs. Al_2O_3 for both the Peripheral and Core Kimberlites shows the strong positive correlation of these oxides as is expected as phlogopite is the host for both these elements (Fig. 3:6). The plot also clearly differentiates between the Core and Peripheral Kimberlites.

P_2O_5 , fixed in apatite, is enriched in both kimberlites but the Peripheral Kimberlite has up to twice as much as the Core variety, (Table 3:2).

One sample of the Peripheral Kimberlite (DB/P5) has a somewhat different major element chemistry to the others. Petrographically the specimen is also slightly different, being deficient in large olivine inclusions and having more abundant matrix minerals. As illustrated in Table 3:2 the rock is low in SiO_2 compared to the other specimens from the Peripheral Kimberlite. The groundmass is calcite-rich and this is reflected by the higher CaO concentration. MgO is lower due to the smaller amount of olivine present. There is very little phlogopite in the matrix and this is reflected in the low K_2O content (0.20%). Other components enriched relative to the other Peripheral specimens are TiO_2 and P_2O_5 . This may be a simple relative enrichment due to the lesser amounts of MgO and SiO_2 (in olivine) present. Olivine inclusions make up about 20% of the specimen whereas the normal Peripheral Kimberlite has about 40% (visual estimate).

Trace and Minor Elements

The distinct difference between the two types of kimberlite is also reflected in the trace element chemistry. Only four elements, Ni, Co, Zn and V, show no systematic differences between the two kimberlites or trends within individual kimberlites.

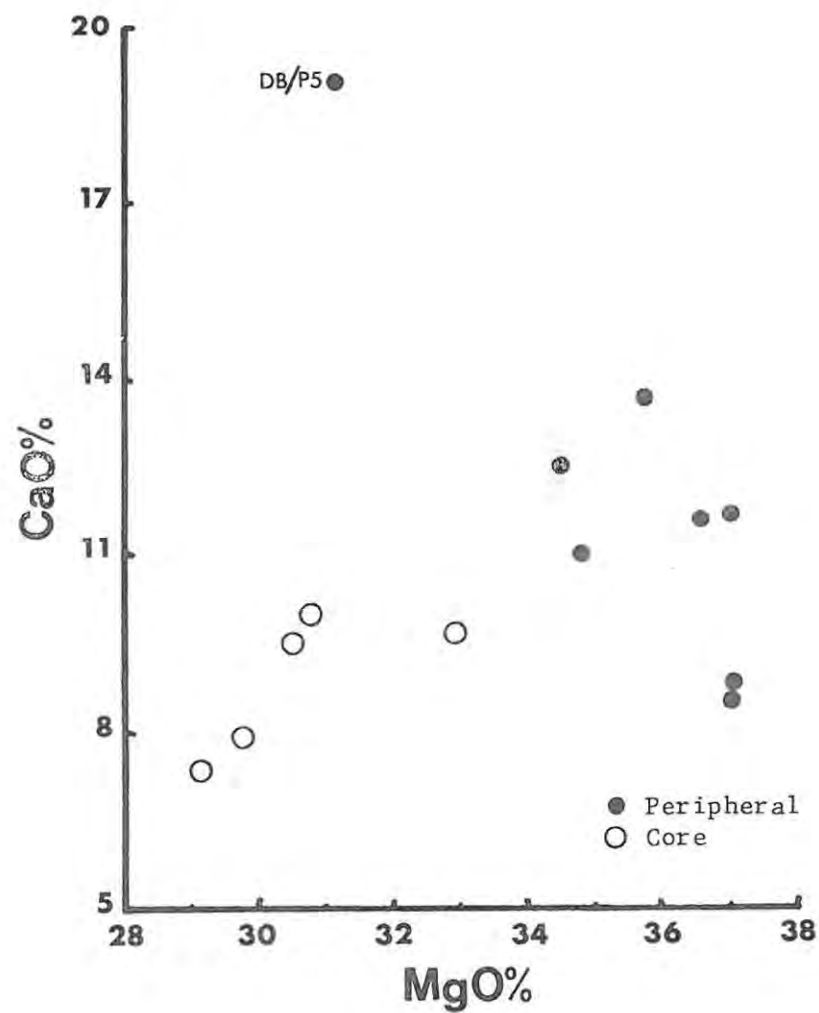


Fig. 3:5 CaO vs. MgO.

A positive correlation between CaO and MgO is illustrated by this diagram.

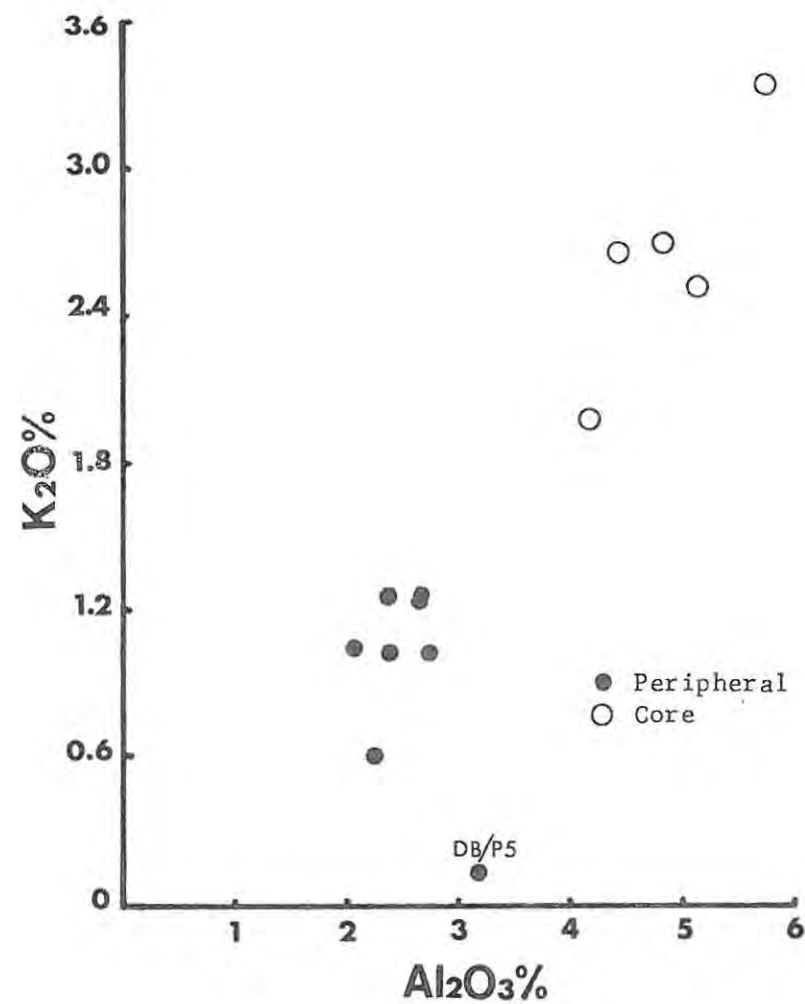


Fig. 3:6 K₂O vs. Al₂O₃.

There is a strong positive correlation between these components. The Core is more enriched in both.

As shown in Table 2:2 the Core Kimberlite is enriched in Rb relative to the Peripheral type, while the latter is enriched in Sr, Zr, Nb, Cu, Th, REE and Cr. These differences are discussed in the following sections.

Nickel and Cobalt

These elements are strongly fractionated into residual olivine on partial melting, e.g. (D_{ol}^{Ni} 13-23.5, Leeman & Scheidegger (1977); D_{ol}^{Co} 3.6-6.0, Duke (1976)). The concentrations of Ni and Co are therefore linked to the amount of xenocrystic olivine present in the rock. This is illustrated by DB/P5 which is depleted in olivine inclusions and consequently in both Ni and Co.

Zinc and Vanadium

There does not appear to be any systematic relationship of these elements to any of the major elements including TiO_2 and Fe_2O_3 . V is however probably concentrated in the Ti bearing minerals and Fe oxides (Duncan & Taylor, 1968), and not in olivine as Duke (1976) has found D_{ol}^V to be .02-.09. The distribution of Zn between different phases is not well known, but it may be concentrated in a minor sulphide phase if it is present, but may also be included in ilmenite, and other Ti bearing phases, which may contain significant quantities of Zn (Mitchell, 1977). Ilmenite alone cannot account for all the Zn present in the rock as it is a minor phase.

Rubidium

Rb is enriched in the Core Kimberlite which has a higher K_2O content than the Peripheral type, and more phlogopite as a phenocrystic and matrix phase. The K/Rb ratio of the Peripheral Kimberlite is however lower than that of the Core type by a substantial amount (Fig.3:7). DB/P5 has the lowest K/Rb of all the samples as well as the lowest concentrations of K_2O and Rb (Fig.3:7).

Strontium

Sr is enriched in the Peripheral Kimberlite which also has a higher calcite content. Sr is probably incorporated in the calcite as this element is preferentially concentrated in the carbonate as opposed to the silicate phase (Koster van Groos, 1975). Although DB/P5 is enriched in CaO and calcite, Sr is not enriched to the same extent (Table 3:2). This is shown by the $^{Ca}/Sr$ ratio of 98 which is much higher than the average of 62 for the other Peripheral specimens. This suggests that DB/P5 is a portion of the Peripheral Kimberlite which crystallized early as Sr is preferentially concentrated in

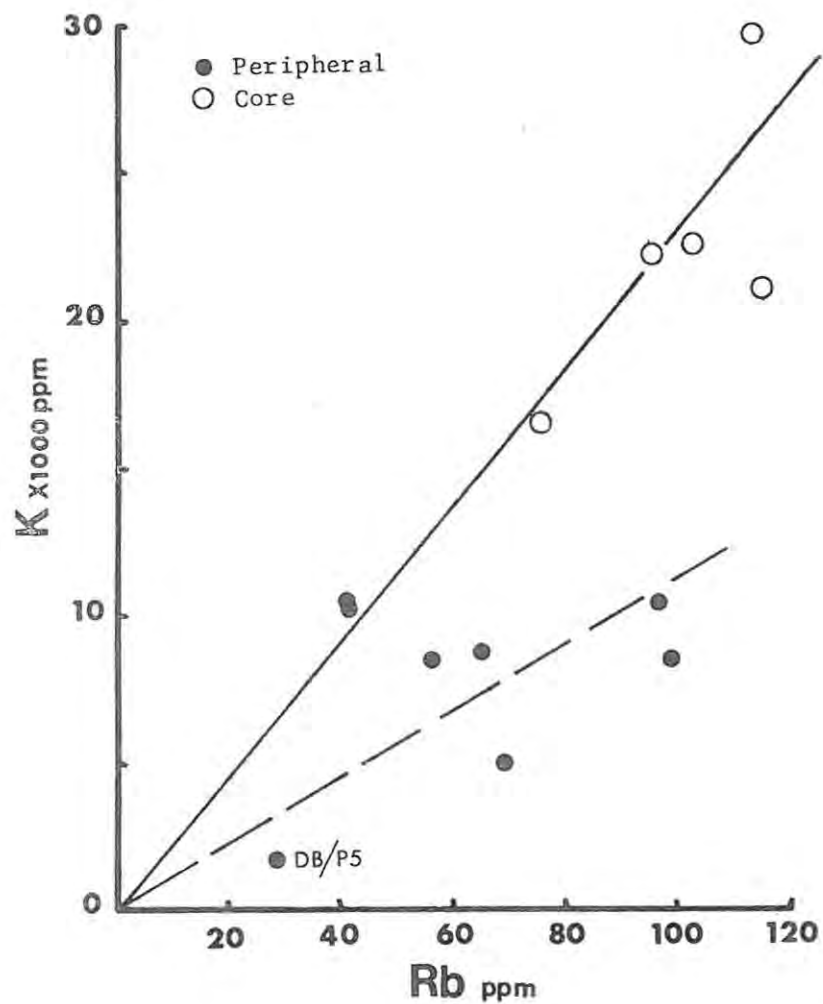


Fig. 3:7 K vs. Rb.

The Peripheral Kimberlite has a lower abundance of both K and Rb and a lower K/Rb than the Core type. Core K/Rb (solid line) $\pm$ 220 and the Peripheral (dashed) K/Rb $\pm$ 110.

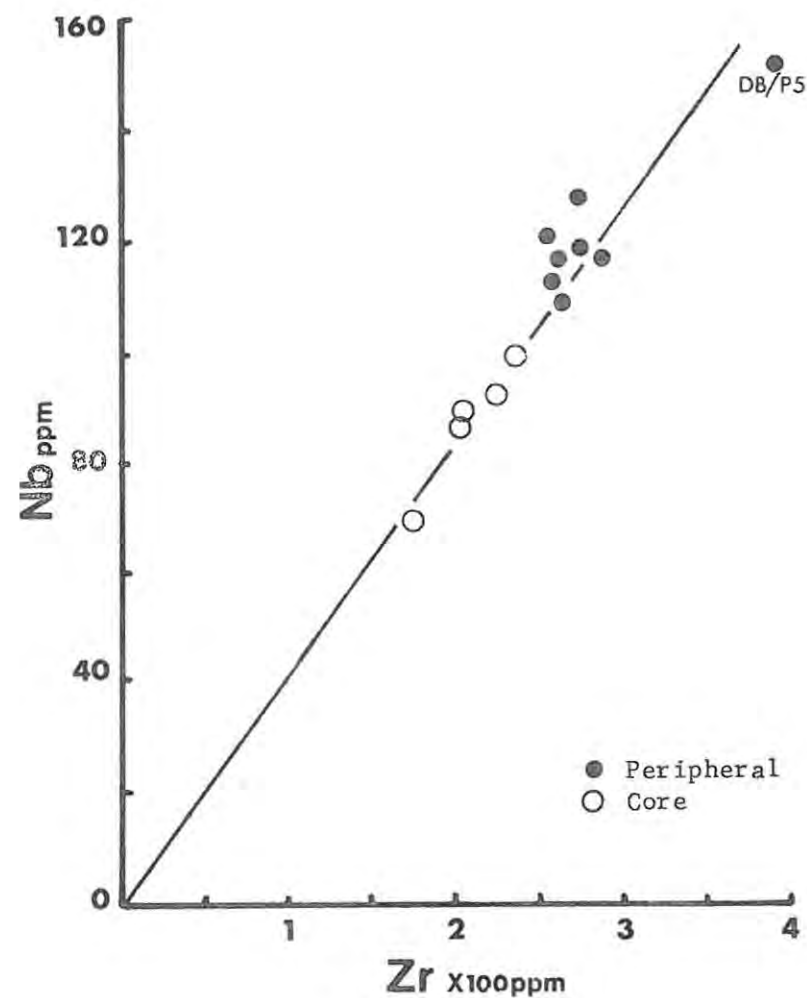


Fig. 3:8 Zr vs. Nb.

The Zr/Nb ratio of both kimberlites is about 2. The Peripheral has a higher concentration of Zr and Nb.

the liquid, on crystallization of carbonate melts (Koster van Groos, 1975).

Yttrium

The Peripheral Kimberlite is slightly enriched in Y relative to the Core variety, and the matrix rich Peripheral sample DB/P5 is considerably enriched. This suggests that the matrix minerals are the host for this element. Carbonates reject Y (Lambert & Holland 1974) and it is therefore probably not concentrated in calcite. It is therefore probably fixed in matrix apatite and perovskite.

Y has a similar charge and ionic radius to a heavy rare earth element and its behaviour is also discussed in the section on rare earth elements (REE).

Zirconium and Niobium

These elements show a strong positive correlation and the Zr/Nb ratio is similar for both the Peripheral and Core Kimberlites. Both elements are concentrated in the groundmass phases as DB/P5 is significantly enriched in both elements, (Fig. 3:8). Nb is probably concentrated in ilmenite, titanomagnetite and perovskite. Zr is probably also present in perovskite but minor zircon may also be present although it has not been observed in thin section.

Light Rare Earth Elements (LREE)

There is a strong positive correlation between the LREE (La, Ce, Nd) and elements such as Zr, Nb and Th. Enrichment in the LREE of the Peripheral compared to the Core Kimberlite, is illustrated by Ce, the most abundant REE. The latter averages about 100 ppm in the Peripheral Kimberlite and 75-85 ppm in the Core variety. DB/P5 is even more enriched with 175 ppm Ce, (Table 3:2).

Thorium

This element is enriched in the Peripheral Kimberlite and is present up to 10 ppm in the DB/P5 specimen. The Core variety has Th abundances that are at or below the detection limit of 3 ppm, only one specimen having 5 ppm. The average concentration is probably about 3 ppm which is half that of the Peripheral variety.

Chromium

The concentration of Cr in the Peripheral Kimberlite averages about 1400 ppm which is higher than the Core variety. The DB/P5 specimen of the Peripheral

Kimberlite has a considerably higher concentration (1900 ppm) than the average, despite a decreased amount of olivine which has a D_{ol}^{Cr} of about 1-5 (Duke, 1976), and therefore probably contains a significant amount of Cr. This suggests that Cr is concentrated in the groundmass opaques (magnetite, ilmenite and chromite) and possibly serpentine. Mitchell (1977) has found that picro-ilmenite has a high Cr content (124-5632 ppm) as have Nixon & Kresten (1973), (25-30,000 ppm).

Copper

Cu is enriched in the Peripheral Kimberlite, (Table 3:2). The distribution of Cu among the different matrix minerals is unknown. There however appears to be an even distribution among the matrix material and inset olivine, as the DB/P5 specimen which is depleted in the latter and enriched in the former has an average Cu concentration. Cu may also be included in ilmenite (Mitchell, 1977) and possibly in disseminated sulphides, although the latter were not observed.

Rare Earth Elements and Yttrium (REE)

La, Ce and Nd are light REE, while Y has very similar geochemical characteristics to a heavy rare earth (HREE) (Frey et al., 1968). These elements behave as a coherent geochemical group (Haskin et al., 1967).

A plot of the chondrite normalized abundance versus atomic number has been used by many workers to interpret REE data (Frey et al., 1968; Haskin & Schmitt, 1967; Philpotts et al., 1972; and others). Paul et al. (1975), Mitchell & Brunfeldt (1975) and others, have shown that kimberlite is strongly enriched in the LREE relative to the HREE. A plot of chondrite normalized abundances for the De Beers Mine kimberlites also show strongly fractionated REE patterns, (Fig. 3:9).

There is however a small but definite relative enrichment in the LREE in the Peripheral Kimberlite as opposed to the Core variety, illustrated by the higher average Ca/Y ratio of the Peripheral (7.3) as opposed to the Core (6.3). There is also an absolute enrichment in all rare earths in the Peripheral Kimberlite. The strong enrichment in LREE relative to the HREE indicates that minerals concentrating HREE and Y such as clinopyroxene (Lambert & Holland, 1974) and garnet (Kay & Gast, 1973), were residual phases in the mantle. Other minor residual phases concentrating Y may also have been residual.

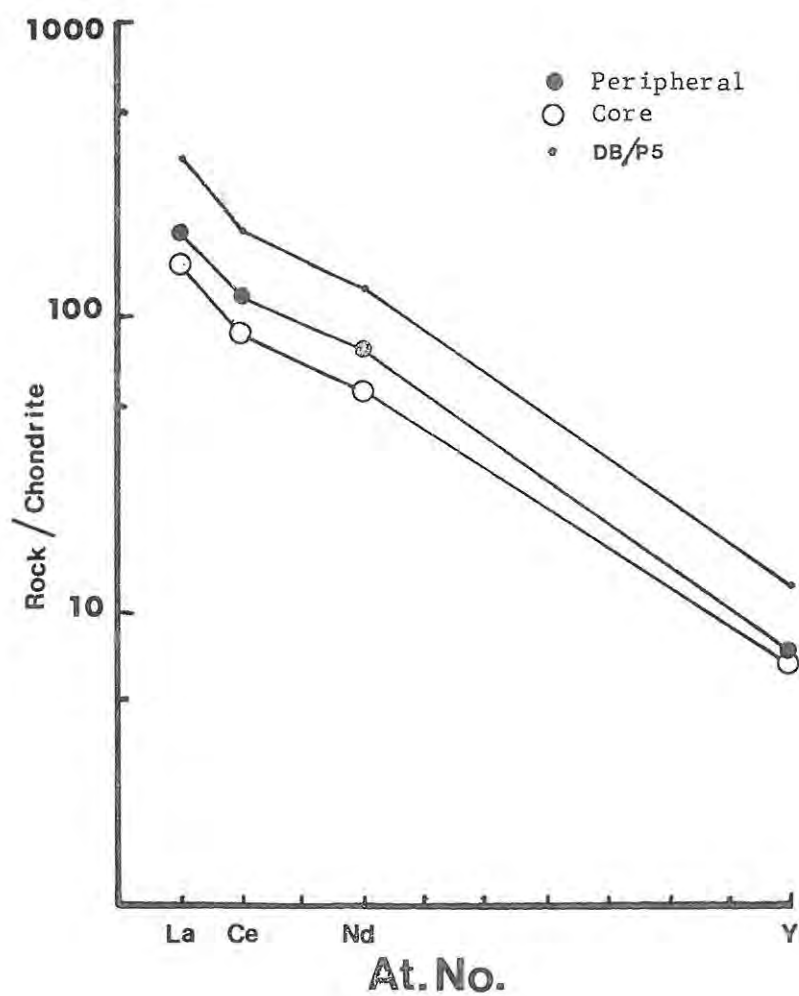


Fig. 3:9 REE plot.

This plot illustrates the slightly more fractionated nature of the Peripheral Kimberlite (closed circles) as opposed to the Core type (open circles). DB/P5 has a very similar pattern to the average for the Peripheral Kimberlite, but does have a higher abundance of Light and Heavy REE.

Discussion of the Results

Introduction

Three models relating the Peripheral and Core Kimberlites are examined in the light of the chemical and petrographic data, and the field relationships. The models comprise a melting model involving two melting episodes in the same part of the mantle, and two models involving differentiation of a single initial magma to produce the two kimberlites intruding the same pipe.

Physical models are set up first and tested using the chemical data and known crystal/liquid partition data. The problems associated with the use of published distribution coefficients have been discussed in Chapter 1, and the data used is the best under the circumstances. Furthermore no distribution data is available for some phases, e.g. picro-ilmenite.

It has been suggested that primary mantle consists of four phase garnet hercynite (O'Hara, 1968; O'Hara et al., 1975 and others). Accessory minerals important to the genesis of kimberlite are phlogopite (Beswick, 1976; Yoder & Kushiro, 1969; Dawson & Davidson, 1965; Modreski & Boettcher, 1973; Carswell, 1975), ilmenite (Mitchell, 1977; Mitchell, 1973a; Mitchell & Clarke, 1976; Mitchell et al., 1973; Nixon & Boyd, 1973; Gurney et al., 1973 and others) and recently carbonate minerals such as magnesite and dolomite have been recognized as being possible phases in the mantle (Wyllie & Huang, 1975; Wyllie, 1977; Eggler, 1975 and others). Apatite may also be present in some cases, and titanoclinohumite and potassic richterite have also been suggested as possible important sources of K, Ti and water in the mantle (Aoki, 1974; Erlank & Rickard, 1977; McGetchin et al., 1970).

The models proposed are similar to those described in Chapter 2 for the Letseng-la-terai kimberlites. (Fig. 2:12; 2:13).

The Melting Model

It is possible that two melting episodes occurred in the same part of the mantle and that the first kimberlite (the Peripheral) is therefore related to the second (the Core Kimberlite).

Beswick (1976) has shown that residual phlogopite in any melting episode is enriched in Rb relative to K as the distribution of K and Rb favours the

incorporation of K in the melt ($D_{\text{phlog.}}^{\text{Rb/K}}$ approx. 3). This leads to an increase in the $^{\text{K}}/\text{Rb}$ of the melt, relative to the initial source rock $^{\text{K}}/\text{Rb}$, and strongly decreases this ratio in the residual phlogopite. Therefore magmas derived by successive melting episodes involving residual phlogopite will have lower and lower $^{\text{K}}/\text{Rb}$ ratios.

A plot of K vs. Rb (Fig.3:7) shows the fields of K and Rb for the two varieties of kimberlite from De Beers Mine. The Core type is richer in K and Rb, and has a higher $^{\text{K}}/\text{Rb}$ than the Peripheral Kimberlite. It is however the younger kimberlite, and the reverse relationship would be expected if the two kimberlites were from the same source regions, and phlogopite was residual after the first melting episode.

Phlogopite which is residual after partial melting is depleted in excess Al_2O_3 and SiO_2 , and approaches stoichiometry (Robert, 1976 a). Subsequent melting episodes would be expected to produce less of these two components in the magma. In the case of De Beers Mine the first kimberlite (Peripheral) is depleted in these components, while the Core (the second intrusion) is enriched to the extent where an Al_2O_3 and SiO_2 containing phase, cecollite, crystallizes in addition to phlogopite. This is the reverse situation to what would have been expected if the two kimberlites were from the same source area.

The De Beers Mine kimberlites contain appreciable quantities of P_2O_5 , the Peripheral variety being more enriched. Apatite is not an established phase in the mantle at the relevant P.T. conditions and the phase relationships of apatite are not known to high pressure. Thompson (1975) has suggested that mantle phosphorus and Na_2O are contained in sodic garnet. This garnet only contains small amounts of P_2O_5 (.3% max.), and the distribution on partial melting is unknown. However assuming a mantle with 10% garnet with a small distribution coefficient for phosphorus ($D_{\text{Gt}}^{\text{P}} = .001$) then a 1% modal partial melt (kimberlite) will contain 3% P_2O_5 and with incorporated mantle material which is usually about 50% the whole rock kimberlite would contain a maximum of approx. 1.5% P_2O_5 . It is also unlikely that successive melting of the same source would produce a similarly high P_2O_5 content in the magma. This suggests that the Core Kimberlite has not been derived from the same area as the Peripheral variety.

The enrichment of Na_2O in the Core Kimberlite relative to the Peripheral Kimberlite is also inconsistent with derivation from the same source area assuming that Na is contained in Garnet or omphacitic pyroxene and that $D_{\text{Gt}}^{\text{Na}} < 1$ and $D_{\text{Cpx}}^{\text{Na}} < 1$, as melting of these phases should increase the Na_2O content

of the first melt the second melt being depleted in this component. However the reverse is true in the case of the two De Beers Mine kimberlites suggesting that they are not related by this model.

Chromium is enriched in the Peripheral Kimberlite. Since the $D_{\text{Cpx}}^{\text{Cr}} = 8-36$ (Duke, 1976), the first melt should be depleted in Cr as residual clinopyroxene preferentially holds the Cr and a second melt would then top a relatively enriched source and therefore be richer in that component. This therefore suggests that the two kimberlites did not top the same source.

It therefore appears that the kimberlites are not related by this melting model, and did not tap the same source.

The 'Cumulate' Core and 'Residual' Peripheral Kimberlite Model

An initial melt is generated, and while moving upwards differentiates into two fractions, the top of the magma column being the Peripheral, and the bottom the Core Kimberlite, as this is the order of intrusion in the diatreme. The Core Kimberlite could thus be crudely considered a cumulate and the Peripheral Kimberlite a residual of an initially homogeneous magma derived in a single melting episode.

This model is unlikely on physical grounds as the Core Kimberlite appears to have been richer in volatile constituents. It explosively penetrated through to the surface and is more fragmental with more evidence of volatile activity such as autoliths. Fractionation downward of such a volatile rich magma is unlikely. It may however have generated the gaseous fraction by differentiation at a later stage after the separation of the two magmas.

Possible fractionating phases (megacrysts) are ilmenite (Mitchell, 1973), phlogopite (Dawson & Smith, 1975), carbonate (Wyllie & Huang, 1975), garnet (Gurney & Switzer, 1973), clinopyroxene, orthopyroxene and olivine.

Fractionation and downward movement of phlogopite megacrysts could explain the higher K and Rb content for the Core kimberlite, and also the higher Al_2O_3 concentration. However the higher K/Rb ratio of the Core Kimberlite is not explained as fractionating phlogopite has a lower K/Rb than the magma from which it crystallizes as this phase preferentially concentrates Rb at the expense of K by a factor of 3 (Beswick, 1976). The Core Kimberlite should then have a lower K/Rb than the Peripheral variety.

Garnet fractionation would explain the REE patterns as the Core Kimberlite would be enriched in HREE and Y, and the Peripheral variety depleted. The periphery would also be depleted in Al_2O_3 by the fractionation process. To explain the chemistry it would however have to fractionate with phlogopite as

garnet does not remove K and Rb from the residual melt.

Ilmenite fractionation would increase the TiO_2 and Fe_2O_3 contents of the Core Kimberlite as well as the Zr, Nb, Cr, V and Co relative to the Peripheral type as ilmenite concentrates these elements (Mitchell, 1977; Nixon & Kresten, 1973). It would also depress the Zr/Nb ratio of the Core Kimberlite as the Zr/Nb of megacrystic ilmenite is about 0.5 and that of kimberlites about 2. Furthermore the Peripheral Kimberlite is enriched relative to the Core variety in all the elements that would be depleted by ilmenite fractionation. It is therefore clear that fractionation of this phase could not have played any part in the model proposed.

Olivine fractionation is also untenable as it would increase the MgO and Ni concentration of the cumulate (Core Kimberlite fraction). The Peripheral Kimberlite is richer in MgO, and the Ni contents are approximately the same. Similarly clinopyroxene fractionation would increase the Cr content of the cumulate, and what would have been the cumulate is in fact depleted in Cr.

Carbonate (dolomite or magnesite) can exist on the liquidus of kimberlites (Wyllie, 1977) but fractionation of this phase does however not solve the problem as this should produce a difference in the Ca/Sr ratio in the two kimberlites. Sr is preferentially incorporated in the melt (Koster van Groos, 1975) and the cumulate (Core kimberlite) should have a higher Ca/Sr ratio than the residual (Peripheral kimberlite) besides the core having an absolute increase in $CaCO_3$. There is no observable fractionation of the Ca/Cr ratio and the Peripheral Kimberlite is enriched in CaO and Sr compared to the Core type. Fractionation of carbonate is therefore not feasible.

Apatite could also have been a fractionating phase. However no apatite megacrysts have ever been reported in kimberlite, and fractionation of this phase would have depleted the Peripheral Kimberlite in P_2O_5 and the REE. The Peripheral Kimberlite is enriched in these elements relative to the Core Variety.

This model is therefore implausible on chemical as well as physical grounds.

The Parental Magma Model

A second crystal fractionation model in which the Peripheral Kimberlite is parental, and the Core type is thus a residual liquid after some fractionation also fails to explain the chemical differences between the kimberlites. It is however more plausible on physical grounds, as this model easily accounts for the higher volatile component of the Core Kimberlite.

The enrichment in SiO_2 , Al_2O_3 , K_2O , Rb and Na_2O is explained by fractionation of phases poor in these components such as olivine. This would however not change the K/Rb ratio.

Fractionation of apatite would go a long way to explain the chemistry of the kimberlites as P_2O_5 , REE, Y, and Th would be removed. However it would have to be coupled with the removal of ilmenite which would to some extent explain the depletion in Cr, Zr, Nb, Fe_2O_3 and TiO_2 of the Core Kimberlite. As shown before, however, ilmenite fractionation should change the Zr/Nb ratio to higher values for the residual liquid and this has not occurred. Furthermore the Core variety should also be depleted in V which is preferentially incorporated into ilmenite (Duncan & Taylor, 1968). Fractionation of heavy phases such as ilmenite would probably have been linked to the movement of diamond which should have been depleted in the Core Kimberlite. The reverse is true, the Core Kimberlite being enriched in diamond relative to the Peripheral type.

The model, though physically plausible, fails on chemical criteria.

Conclusion

The two kimberlites intruded into the De Beers Mine diatreme appear to be unrelated by consecutive melting episodes of the same source area or by the differentiation models proposed. It seems that they were therefore derived from different mantle sources. This implies considerable mantle inhomogeneity laterally or vertically, depending on the position of the two source areas.

CHAPTER 4

THE ORIGIN AND IMPLACEMENT OF KIMBERLITESIntroduction

In the previous sections of this work the primary object was to examine the relationships between different kimberlites in a composite diatreme; whereas here the chemical, physical and field data as a whole are considered to evolve a cohesive hypothesis for the origin, differentiation and intrusion of kimberlite magmas.

Several hypotheses for the origin of kimberlite have been proposed, the Residual liquid and Insipient Melting hypotheses being most commonly invoked. The Residual model proposed by O'Hara and others (O'Hara & Yoder, 1967; O'Hara et al., 1975 and Gupta & Yagi, 1977) envisages fractionation of a biminerallitic eclogite from a picritic melt at high pressure, the residual alkaline liquid being kimberlitic. Insipient melting of garnet lherzolite (<1%) involving hydrous phases such as phlogopite, to produce a kimberlitic liquid, is the second major hypothesis (Dawson, ~~1970~~; 1971).

There is however no simple division between the two hypotheses, and various intermediate opinions such as partial melting followed by some differentiation have been expressed by some researchers (Mitchell, 1933a; MacGregor, 1970). Diverse suggestions as to the phases fractionating from the liquid have been made, Mitchell (1973a; 1977) considering ilmenite important in the initial stages of kimberlite genesis, but he believes olivine fractionation favoured by Mc Gregor (1970) to be unimportant on the basis of microprobe determination of inset and matrix olivine in kimberlites (Mitchell, 1973b).

The upward movement of the kimberlite magma is a subject of some conjecture. Some believe in a diapiric uprise of magma due to a density contrast (Eggler & Wentland, 1977; Green & Gueguen, 1974), which is of necessity a slow process, and if it leaves the PT region where diamond is stable, resorption of the diamond may occur. Other proposals are that the magma is very rapidly transported and emplaced (O.L. Anderson, 1977).

Formation of the kimberlite diatremes is also controversial. The first ideas of explosive boring (Wagner, 1914; Crookes (1897) quoted by Williams (1932)) have more recently been questioned by Dawson (1962) who proposed a fluidization process for the intrusion of kimberlite. This suggestion has been supported by Mc Getchin (1968) and by experimental work of Woolsey et al. (1975) and Mc Cullum (1976). On the other hand Lorenz (1975) proposes that kimberlite diatremes are possibly partly pheartomagmatic in nature.

Clearly there is considerable controversy about most aspects of kimberlite formation and a synthesis of ideas is therefore a difficult task.

Depths from which Kimberlite and Diamonds are Derived

There are several lines of evidence suggesting that kimberlites are derived from very deep in the mantle, probably well below the Low Velocity Zone (L.V.Z.) the base of which is at approximately 150 km corresponding to a pressure of 50 kb (Johnson, 1967).

Using mineral barometers and thermometers Boyd & Nixon (1975), Mc Gregor (1975) and others have determined the equilibration pressures and temperatures of suites of peridotite nodules. The highest pressures are logically the minimum depths from which the kimberlite magma could have been derived. For the Kimberley and Lesotho nodules maximum pressures of 65 kb (200 km) and 60 kb (180 km) respectively, were recorded (MacGregor, 1975; Boyd & Nixon, 1975).

Pyroxene-ilmenite lamellar intergrowths provide ambiguous evidence for their depth of origin. Boyd & Nixon (1973) favour an eutectoid intergrowth origin for the nodules in the L.V.Z., which were then incorporated by the kimberlite magma as xenoliths. Ringwood & Lovering (1970) believe that intergrowths could be due to exsolution, and the homogeneous phase must have crystallized at about 350 km depth ($\pm$ 120 kb), thus extending the possible depth from which kimberlite is derived to that part of the mantle.

Mineral barometric evidence from inclusions of olivine, clinopyroxene, orthopyroxene and garnet in diamond indicates that the diamonds enclosing them crystallized at pressures of 40 to 65 kb ($\pm$ 110 km to 200 km) (Meyer & Tsai, 1976) (Fig. 4:1).

Bravo & O'Hara (1975) deduce from experimental results that a kimberlitic partial melt can only be derived at pressures considerably higher than 30 kb.

All this evidence indicates that kimberlites are generated at pressures greater than 45 kb which is equivalent to about 140 km depth (Fig. 4:1).

Composition and Chemical Development of the Mantle, and the Genesis of Diamond

Studies of ultra mafic nodules in kimberlites have lead to the suggestion that the mantle is composed principally of garnet lherzolite (O'Hara et al., 1975 and others). This is however only an approximation of the actual mantle composition, as a variety of other more depleted ultramafic nodules such as dunites and harzburgites, as well as eclogites and other problematic discrete nodules are present in kimberlite. Furthermore the simple four phase lherzolite does not contain phases that are suitable hosts for the volatiles and many of the

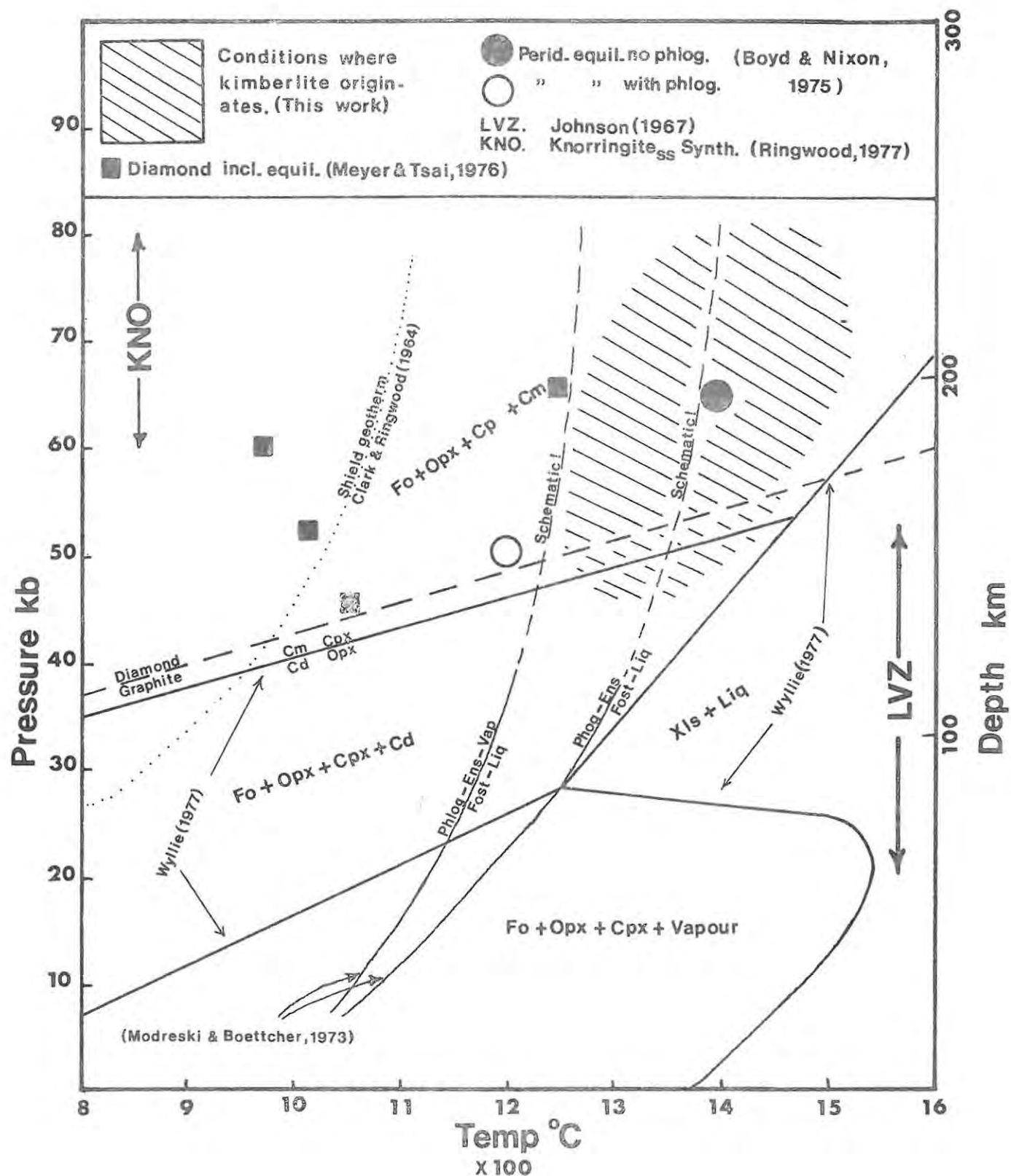


Fig. 4:1 Pressure Temperature grid for the mantle with phlogopite and carbonates. Data taken from Wyllie (1977) for the system $\text{CaO-MgO-SiO}_2\text{-CO}_2$ with 0.2% CO_2 . Melting of phlogopite from Modreski & Boettcher (1973) with the dashed extrapolation by the Author (Schematic!). Shaded area is the P.T. region where Kimberlite originates (This work).

elements (Ti, Nb, K, etc.) that are concentrated in kimberlite.

For this reason the existence of phlogopite has been postulated as a phase containing many of the 'kimberlitic' elements in the mantle (Dawson & Davidson, 1965). Another possible hydrous phase is titanoclinohumite (McGetchin et al., 1970). Wyllie & Huang (1975), Wyllie (1977) and Eggler & Wentland (1977) have emphasized the importance of CO_2 where kimberlite is generated in the mantle. Additional possible phases are therefore dolomite and magnesite (Wyllie, 1977) (Fig. 4:1).

Alternatively Boettcher et al. (1977), Erlank & Rickard (1977), Lloyd & Bailey (1975) have suggested metasomatism of the mantle peridotite occurs introducing H_2O , CO_2 , K, Ti etc., before or contemporaneously with the partial melting that produces the kimberlite magma. This mechanism overcomes the problem of the 'barren' four phase garnet lherzolite as a source for kimberlite magmas. The metasomatism may also explain features such as the low Zr/Nb ratio of kimberlite noted in this study and others.

Another proposal that can possibly account for the unusual chemistry of kimberlite is the postulate that there are static chemical plumes in the mantle below the L.V.Z. (D.L. Anderson, 1975), that may contain many of the refractory 'kimberlitic' elements e.g. Zr, Nb, Th, Ca, Al and V.

The mantle where (and when) kimberlites are generated by small amounts of partial melting therefore may contain olivine, clinopyroxene, orthopyroxene, garnet, phlogopite, carbonate and other phases. It is also enriched in elements such as Fe, Ti, Nb, REE and P.

The environment indicated by mineral inclusions and trace elements in diamond, is different from the present mantle lherzolite (Ringwood, 1977; Bibby et al., 1975). Inclusions in diamond of olivine, orthopyroxene, Cr-diopside and garnet have unusual features summarized by Meyer & Tsai (1976), Ringwood (1977) and Ringwood & Kesson (1977). The most striking features are high Cr, high Mg, low Ca and low Ti. Ringwood & Kesson suggest that this is due to diamond having crystallized in a cumulate from a picritic magma and not from kimberlite. This implies a xenocrystic origin for diamond in kimberlite and not a phenocrystic origin as suggested by Mitchell & Crockett (1971a) and others.

As diamonds cannot move about independantly in the mantle if the latter is solid there must have been an early metasomatic episode when an introduction of Ca, Fe and possibly Al and Si occurred at some stage in the Precambrian after the formation of diamond. This metasomatized protomantle subsequently equilibrated to form the 'normal' mantle lherzolite. The introduction of Ca

probably lead to the formation of more clinopyroxene and garnet which in turn lead to the redistribution of Cr and the garnet changed character to become more Ca rich while the Cr entered the structure of the extra diopside. The eclogitic parts of the mantle would also be subject to the same metasomatism. The inclusions in the diamond are armoured by the latter phase, and represent portions of the Mg rich, Ca poor protomantle.

Subsequent to the metasomatic episode just described the pervasive metasomatism introducing K, Ti, Zr, Nb, etc., suggested by Boettcher et al. (1977) and others, and discussed previously, occurred.

Later partial melting would liberate some of the diamonds from their host rocks and these would be included in the kimberlite magmas. These magmas may possibly form in areas of high diamond concentration, such as eclogitic parts of the mantle, due to mineralogical control; thus liberating more diamond in some cases.

The mantle has thus probably been modified by several metasomatic and other events over time, and the inclusions in diamond represent the earliest mantle which was partially picritic (Ringwood, 1977; Bibby et al., 1975). This obviously implies an Archean age for the inclusions and the diamond host.

Generation and Intrusion of Kimberlite

Any hypothesis to account for kimberlite magmatism has to take into account the following factors:

- a) The chemistry of kimberlites.
- b) The need for a heat source that will raise the temperature of the mantle peridotite above its solidus.

The second consideration immediately introduces problems for the Residual hypothesis, which requires temperatures well above the solidus of garnet herzolite, before cooling and eclogite fractionation takes place. This of necessity takes the herzolite through the incipient melting stage which occurs at considerably lower temperatures indicated by the breakdown of phlogopite (Modreski & Boettcher, 1973) (Fig. 4:1).

D.L. Anderson (1975) has suggested that chemical plumes exist in the mantle containing refractory elements that include Ca, Ti, Fe, Th, O, REE and Al. Plumes such as these provide a ready static source of energy from the fission of U and Th. The material in the plume may heat up the surrounding mantle which may start to melt as it is less refractory. At higher temperatures incipient melting of the more refractory mantle material in the plume may occur. The

first phase to break down would be phlogopite (Fig. 4:1) and melting will continue isobarically until enough liquid is present for mobility to be increased and the melt may then accumulate, or the whole mass may start to move diapirically.

Only after the liquid from the partial melting episode has accumulated can processes involving crystal fractionation occur. At this stage the accumulated liquid may start to crystallize minerals that occur as megacrysts such as ilmenite, olivine and phlogopite. Fractionation of these phases can at this stage change the composition of the liquid as suggested by Mitchell (1973a).

The liquid, megacrysts and refractory nodules may then start to move upward into the L.V.Z. and addition of partial melt and solid material (xenocrysts and xenoliths) from that source could occur (Nixon & Boyd, 1973). Movement of the magma must be quite rapid as diamonds could be resorbed once the magma moves out of the PT field where diamond is stable (Fig. 4:1).

At this stage the main gas phase is water while CO_2 is still included in carbonates. At a certain pressure carbonates become unstable and CO_2 is rapidly evolved (Wyllie, 1977) (Fig. 4:1). Very rapid upward movement now takes place, possibly as proposed by O.L. Anderson (1977).

Once the kimberlite magma enters the crustal environment the emplacement is largely controlled by structural features and it may intrude as dykes or sills. However the kimberlite magma evolves a considerable quantity of gas which must escape upwards to the surface. Structurally weak zones in the earth's crust such as the intersection of faults or other weak spots may provide an avenue for the gas to escape.

Escaping gas may attain very high velocities and with material picked up in the conduit would rapidly start to erode the vent which would assume the shape of a kimberlite pipe (Hawthorne, 1975). The process of erosion by the gas may be similar to that shown by Woolsey et al. (1975) and would probably not be an explosive process, due to heated groundwater, such as the phreatomagmatic maar diatreme mechanism proposed by Lorenz (1975). A large proportion of the country rock dislodges and entrained by the gas may be ejected at high velocity from the diatreme, only a certain proportion of the randomly mixed material remaining.

The kimberlite liquid which may split into an immiscible carbonate and silicate fractions (Clement, 1975), would then enter the diatreme and be displaced by a gas-liquid-solid fluidization process, as described by Lewis (1969), in the vent forming autoliths and the Kimberlite breccia. During this process

further material may be dislodged from the vent walls and subside into the fluid giving the crudely stratified appearance of the crustal inclusions in many pipes.

The model proposed here differs from that of Clement (1975) in that the diatremes are not considered to be due to explosive breaching of the rocks, but to the escape (over a longer period) of gas under high pressure eroding the pipes. An explosive mechanism is unlikely to produce well rounded crustal xenoliths, or a vent with very steeply dipping sides as indicated by Hawthorne (1975).

CHAPTER 5METASOMATISM OF CRUSTAL XENOLITHSIntroduction

Diatreme facies kimberlite (Dawson, 1971) is often contaminated by a variety of wall rock xenoliths which vary in size and composition, and come from different stratigraphic positions in the crust and upper mantle. These inclusions which range from pinhead size to over 150m in diameter, also vary greatly in degree of rounding due to mechanical abrasion in the active diatreme. Fragile inclusions of shale or coal are often not extensively abraded (Williams, 1932), while much harder rocks may be well rounded. The xenoliths of crustal origin comprise a wide variety of rocks such as granites and regional metamorphics from the Basement. Sedimentary and volcanic material from the overlying formations are also included if the diatreme penetrates through the cover rocks.

Thermal metamorphism and metasomatism of the included material and country rock by the diatreme facies kimberlite is generally not very extensive (Williams, 1932; Dawson, 1971) even though the xenoliths are not in chemical equilibrium with the kimberlite magma which is of extreme composition. This is in direct contrast to the effects of the hyperbyssal facies kimberlite (Dawson, 1971), which is similar in composition to the diatreme facies variety, but has a very much more marked metamorphic and metasomatic effect on the country rock (Dawson & Hawthorne, 1970; Ferguson et al., 1973). Dawson (1971) attributes this lack of thermal or chemical effects in the diatremes to strong adiabatic cooling of the fluidized kimberlite magma (Dawson, 1962) which is believed by him and others to be very rapidly intruded, a figure of 400 ms^{-1} at the surface having been estimated by McGetchin (1968).

Although limited, metasomatism of the included fragments in the diatreme facies kimberlite does occur and certain features have been documented by Ferguson et al. (1973) and others who found that metasomatic alteration is generally confined to carbonation and hydration. Reaction is rarely complete and the original textures and minerals are often well preserved, except in cases of extreme metasomatic hydration. According to Ferguson et al. (1973), the altering agent was probably a hydrous, carbon dioxide and alkali complex rich deuteric fluid, derived from the crystallizing kimberlite.

The Letseng-la-terai kimberlite pipe in North Eastern Lesotho has intruded through, and sampled Precambrian basement, and the comparatively undisturbed overlying Mesozoic Karoo sequence. The basement material incorporated by this kimberlite includes gneisses and amphibolites containing plagioclase, garnet, biotite, amphiboles and pyroxene, and also rocks containing alkali feldspars such as perthite, and quartz. Xenoliths of the overlying Karoo sequence include sandstones, shales and abundant basaltic fragments.

Metasomatized xenoliths of the basement rocks and Karoo volcanics were collected, and form the basis of this petrographic and chemical investigation of their alteration by the kimberlite magma.

Petrography

In general the alteration of the included crustal material in the Letseng-la-terai kimberlite takes the form of low temperature hydrothermal conversion of the minerals to more hydrous species, and the formation of late stage calcite veins, similar to that reported by Ferguson et al. (1973) and Bloomer & Nixon (1973).

Coarse grained basement rocks of high grade metamorphic and igneous origin, consisting of assemblages which include plagioclase, alkali feldspar, quartz, biotite, amphibole and pyroxene, show fairly extensive alteration by the hydrothermal phase of the kimberlite magma. New minerals formed include natrolite, cebolite, diopside, chlorite, woodfordite and calcite. The basaltic inclusions from the Karoo sequence have not been affected as much as the more coarse grained basement varieties. For the basalts the alteration is more cryptic, and only the finest selvages of natrolite and cebolite are present around plagioclase grains and in cracks. There may also have been some leaching of the plagioclase (Busenberg & Clemency, 1976), however this is not apparent in thin section. Late stage calcite veins are also fairly common but not ubiquitous. The metasomatic effects are also partly masked by pre-metasomatic deuteric alteration of the lava on consolidation, resulting in the presence of pre-existing zeolites and calcite, before incorporation in the kimberlite. The mineralogy of the basement and basaltic xenoliths is summarized by Table 5:1.

In the basement xenoliths transformation of primary minerals proceeds inwards from the grain boundaries, eventually converting the whole grain to the new phases. The original texture of the rock is well preserved in the

TABLE 5:1 MINERALOGY OF XENOLITHS

ORIGINAL	LCN 1	LCN 2	LCN 5	LCN 6	LCN 7	LCN 8	LCN 10	LCN 11	L19 RIM	L 19 CENT	L2 RIM	L2 CENT	L21 RIM	L21 CENT
1.Quartz			?	?			?							
2.K-Feldspar			+	+										
3.Plag.	+	+	+	+	+	+	?	?	+	+	+	+	+	+
4.Pyrox.					+				-	-	+	+	+	+
5.Amphi					+				+	+				
6.Garnet		+		-		+								
7.Biotite	+		+			+	-	-						
8.Calcite											-	-	+	+
9.Other											-	-	+	+
REPLACEMENT														
Natrolite	+	+	+	+	+	+	+	+	+	-	-		-	
Cebollite	-	+	+	-	-	?				-	-		-	
Talc?				+										
Chlorite	-		-		-	-	-							
Diopside			-	+			+							
Serpent.											-		-	
Calcite			-			+	-	+					+	-
Original present	3,7	6	7	2	3,4,5	3,6,7	7	7	3,4,5	3,4,5	3,4,8,9	3,4,8,9	3,4,8,9	3,4,8,9

+ MAJOR
 - MINOR
 ? UNCERTAIN

initial stages when mafic minerals are unaffected and large plagioclase remnants remain. In the more advanced stages the pre-existing fabric is largely lost due to replacement by new phases. At this stage only very small remnants of plagioclase may remain and mafic minerals, especially biotite, are also affected. New mafic minerals such as diopside start to form at this stage.

Minerals such as garnet may however persist even when all the other original minerals are completely altered to the new phases and garnet remnants often assist in the identification of the original nature of the rock.

Metasomatic alteration generally proceeds in the following way:-

- a) Plagioclase is the first mineral to exhibit alteration. It is partially converted to natrolite which forms fine selvages along the grain boundaries (Fig.1).
- b) With more advanced alteration the natrolite extends into the core of the grain and a fine rim of brown felted cebolite forms at the original plagioclase grain boundary. The plagioclase is thus, ideally, mantled by natrolite with an outer rim of cebolite (See Fig.2).
- c) An even more advanced stage is reached when the plagioclase is almost all converted to natrolite and cebolite, the latter mineral being clear and forming large areas enclosing patches of natrolite. At this stage biotite starts exhibiting alteration to peninite and some small slightly elongate, subhedral, prismatic grains of diopside also appear. (Fig.3).
- d) The final stage is attained when all the plagioclase is altered to natrolite and cebolite, and these minerals occur as well formed, the former as non fibrous crystals with distinct twinning and the latter as clear, well-aligned fibrous crystals giving it a somewhat micaceous appearance, with only a trace of the brown felted variety at the edges. Biotite is largely converted to peninite and well developed prisms of metasomatic diopside are often present. (Fig.4).

Calcite often appears at stage C. It occurs as subhedral to anhedral grains forming at the junctions between the other phases. (Fig.3).

Late stage veinlets of calcite are also quite common but bear no reaction relationships to the host, and may be due to late meteoric effects.

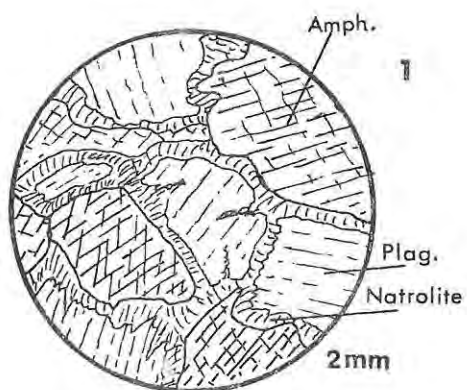


Fig.1 Stage a : Fine selvages of natrolite surround plagioclase.

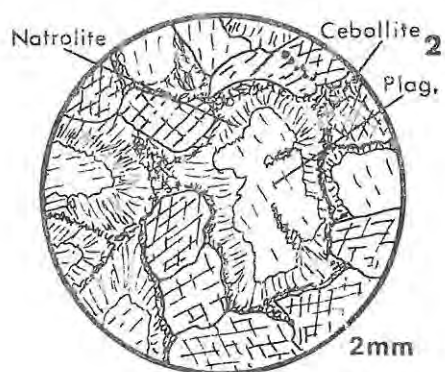


Fig.2 Stage b : More extensive natrolite development and cebolite occurs on the original grain boundaries. Plagioclase is more eroded.

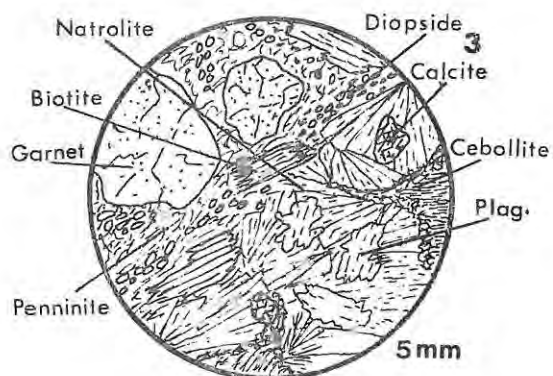
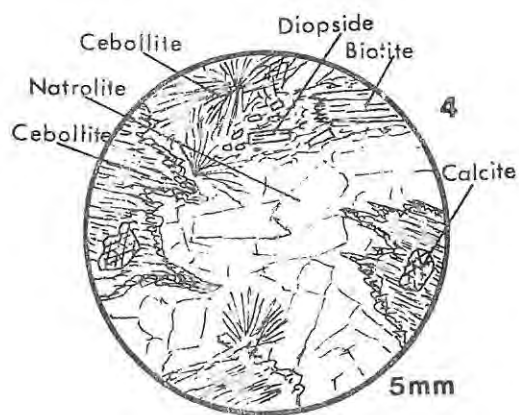


Fig.3 & 4 Stage c : Very little if any plagioclase is left. Introduced diopsides are present, biotite is altered to penninite. Natrolite occurs as a fibrous variety (Fig.3) and a twinned lathlike type (Fig.4). Extensive areas of cebolite are present in the two forms discussed in the text. Calcite is a common phase.



Xenoliths initially containing an assemblage of albite and K-feldspar exhibit natrolite develop from the sodic phase but only very small amounts of cebollite are present. Talcose(?)woodfordite is in this case a relatively major product that appears to have been formed from components introduced by the hydrothermal fluids. K-feldspar remains as remnants in the rock and appears to be quite resistant to alteration.

In general the mafic minerals are well preserved with the amphiboles, pyroxenes and garnet being particularly resistant to alteration. Olivine is usually serpenititized while biotite is progressively converted to peninite. Opaques have suffered no visible alteration at the edges, and reflected light microscopy revealed no alteration.

Metasomatic changes in the crustal xenoliths and the various stages are summarized by the following diagram, the horizontal bars representing the time in which the relevant mineral crystallized.

Stages	a	b	c	d	Late Meteoric
Natrolite	—————	—————	—————		
Cebollite	—————	—————	—————		
Woodfordite	- - - - -	- - - - -	? - - - -		
Diopside			—————		
Serp/Chlor.		.. ———			
Calcite			... ———		—————

Intergrowths between the metasomatic phases are common, while the boundaries between the pre-existing and introduced phases are sharp.

Petrography of the Analysed Xenoliths

Three xenoliths 10-15 cm in diameter were selected for further chemical study. These are; L-19 an amphibolite from the Basement, L-2 a fine grained, massive basalt and L-21 a coarser grained amygdaloidal basalt.

The L-19 amphibolite xenolith is well rounded and about 15 cm in diameter. In thin section it shows a well developed polygonal, equilibrium metamorphic texture, and consists of andesine, hornblende and diopside, the amphibole being dominant. Some apatite is also present as an additional primary phase. A

foliation is developed, but it is not marked and did not appear to have influenced the metasomatism. Towards the edge of the specimen, the alteration is marked, up to half of the individual plagioclase grains being converted to natrolite. At the very edge there is no cebollite developed but calcite is quite common. This calcite + natrolite assemblage only persists for about 5-10 mm into the xenolith where calcite disappears and finely fibrous brown cebollite takes its place. The alteration also diminishes rapidly towards the interior of the xenolith where the plagioclase grains are mantled by a thin rim of natrolite and cebollite. The mafic minerals, hornblende and pyroxene, display no alteration and apatite is also not affected. These relationships are illustrated by figures 5 and 6.

Xenoliths of basalt are very common in the kimberlite and range from 0,5 mm to several meters in diameter. The very small xenoliths up to about 10 mm in diameter are strongly altered to a cloudy mixture of clays and related minerals. The larger basaltic xenoliths, two of which (L-2 and L-21) have been selected for further work, have been altered by hydrothermal and possibly meteoric processes, evidence for which is the development of some natrolite, cebollite and late stage calcite veins.

L-2 is a very fine grained glomeroporphyritic rock with isolated aggregates of plagioclase set in a very fine grained intergranular matrix consisting of plagioclase laths and granular pyroxene. Some serpentinized olivine and patches of intersertal green glassy material that has devitrified, are also present. Large patches of an opaque oxide poikilitically enclose the other minerals and is thus the last phase to form besides the glass and the later metasomatic phases. Deuteric auto-alteration has lead to the formation of calcite as quite a common phase replacing the plagioclase phenocrysts. This auto-metasomatism is not very extensive, and is relatively uniform over the whole specimen.

Alteration by the kimberlite magma is slightly more marked towards the edge of the xenolith. A small amount of natrolite is visible on the edges of some plagioclase grains. The mafic minerals are in this case also slightly altered to serpentine and possibly chlorite. Thin cracks traversing the xenolith have natrolite and cebollite developed in them. The natrolite is fibrous and oriented perpendicular to the sides of the fracture sandwiching a thin line of brown, fibrous cebollite situated on the original line of the crack. (See Fig.5). Late stage calcite veins were not observed.

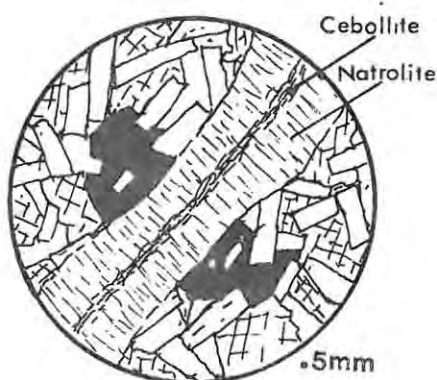


Fig.5 (The L2 xenolith)

Small crack in basalt (Plagioclase, pyroxene, magnetite) lined with natrolite. Cebollite is present in the center of the crack.

The L-21 inclusion is a rather coarse grained amygdaloidal basalt that has suffered a considerable amount of deuteritic auto-metasomatism not connected with the hydrothermal effects of the kimberlite magma. These are devitrification of the glass present and extensive carbonation of the plagioclase.

Towards the edge of this xenolith some natrolite and cebollite is developed on the edges of the amygdales. Late stage calcite veins, with no reaction relationship to the host, traverse the rock and occasionally surround grains as well as amygdales.

In summary it is apparent that mineralogical changes are generally more marked and clearer in the more deep seated Basement xenoliths, and in all cases the edges are more altered than the centres of the xenoliths.

A summary of the properties and mode of occurrence of the metasomatic minerals follows.

The Metasomatic Minerals

Natrolite

This mineral occurs as fibrous, radiating material and non-fibrous, twinned crystals. It is developed after plagioclase with the concomitant formation of cebollite, woodfordite or calcite. It is ubiquitous as an alteration product due to the hydrothermal effects of the crystallizing kimberlite, and has been described by Du Toit (1908) and Williams (1932) from other kimberlites, and Bloomer & Nixon (1973) from Letseng-la-terai.

The optical and x-ray diffraction data for natrolite are summarized in Table 1 and match closely those of Deer et al. (1963) and Meixner et al. (1956) respectively.

Table 5:2

Natrolite - $\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$		Diffract. Data (Diffractometer)				
		I/I ₀	dÅ			
Colour :	colourless	100	6.55	27	3.195	8 2.256
Relief :	moderate + ve	60	5.88	36	3.151	9 2.195
Biref :	moderate to low	30	4.66	17	3.101	15 2.176
Extinction:	parallel	25	4.57	25	2.941	
Orientation:	length slow	35	4.39	65	2.865	
Biaxial	-ve, 2V mod.	35	4.35	12	2.571	
Habit :	Fibrous radiating material	45	4.15	12	2.445	
	+ Twinned anhedral elongate	33	4.11	15	2.409	
	grains.	3	3.633	7	2.330	
		5	3.262	8	2.320	

Cebollite

It is a very rare mineral first described by Larsen & Shaller (1914) as a low temperature alteration product of melilite, and all subsequent descriptions (Krank, 1928; Larsen & Goranson, 1932; Tilley & Harwood, 1931; Larsen, 1942 and Rodygina, 1971) have also reported this paragenesis. In this case, however, the mineral is associated with the alteration of plagioclase. (Patches of clear, fibrous, parallel to radiating needles, grading outward into a fine-fibrous, felted material intergrown with natrolite, characterize this mineral. It always co-exists with natrolite although the reverse is not necessarily true. Initially it forms at the original grain boundaries of the plagioclase and progressively becomes more extensive as the latter phase is converted to the natrolite + cebollite assemblage. Very fine selvages of cebollite on the original line of cracks through the xenoliths where there has been development of natrolite from plagioclase are also found.

The optical and x-ray diffraction data which match closely those of Larsen & Goranson (1932), and Neuman & Bergstol (JCPDS card No. 16-695) are summarised by Table 5:3.

Cebollite - $\text{Ca}_5\text{Al}_2(\text{OH})_4\text{Si}_3\text{O}_{12}$		Debye-Scherrer camera 5.73 cm				
	I/I_0	$d\text{\AA}$	I/I_0 visual			
Habit : Fibrous radiating	10	3.67	10	2.33	50	1.712
Relief : medium positive	30	3.49	60	2.28	15	1.653
Colour : colourless to red-brownish	80	3.29	40	2.14	15	1.601
Biref : moderate $\delta = 0.031$	90	3.08	10	2.09	30	1.548
Orient : parallel extinction and length slow	100	2.90	20	1.995	50	1.485
Other : Habit is variable and brownish type is felted	50	2.73	20	1.876	60	1.464
	50	2.58	20	1.825		
	30	2.47	70	1.753		

?Woodfordite (ettringite)

This is a very rare mineral first described by Murdoch & Chalmers (1958) from Crestmore, California. It is an extremely hydrated Ca mineral containing $\text{CO}_3^{=}$, $\text{SO}_4^{=}$ and OH^- radicals.

It was found in only one xenolith investigated, occurring as a talcose mass of moderate to low negative relief and low birefringence. The optical properties and x-ray diffraction data determined (Table 3) match those of Murdoch & Chalmers, (op.cit.) and JCPDS card No. 13-350.

Table 5:4

Woodfordite (ettringite) ; $\text{Ca}_6\text{Al}_2(\text{SiO}_4, \text{SO}_4, \text{CO}_3)(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$					
	I/I_0	$d\text{\AA}$			
			15	3.06	
Colour : colourless	100	9.5	80	2.69	
Habit : Knotted talcose mass	80	5.56	35	2.54	
Relief : Mod. to low negative	20	4.95	80	2.103	
Biref : low	30	4.64	20	2.055	
Extinct : parallel	80	3.83	10	1.970	
Orientation : length fast	10	3.57	20	1.848	
Uniaxial : -ve.	30	3.40	10	1.616	
	20	3.17	10	1.591	

The presence of this mineral which is extremely hydrated and contains carbonate and sulphate ions suggests a hydrous metasomatizing solution with carbonate and sulphate ions present.

Calcite

Two generations of calcite occur. An early phase associated with the initial metasomatism occurring as sub- to anhedral grains in close association to natrolite where extreme metasomatism has taken place. Later meteoric solutions have deposited calcite as veins and stringers traversing the rock with no reaction relationship to the host.

Extreme birefringence, variable relief on rotation of the stage and a uniaxial -ve character characterize the mineral in thin section. As reaction takes place with dilute HCl and the XRD data determined, summarized in Table 5:5, matches that of a pure calcite internal standard other carbonates, such as dolomite, appear to be absent.

Table 5:5

Calcite - diffractometer

I/I ₀	5	100	7	6	27
dÅ	3.855	3.038	2.846	2.498	2.286

Diopside

Diopside occurs as small euhedral prisms in the strongly metasomatized xenoliths and may have formed from introduced magnesium, and or as a result of the chloritization of biotite, a process which releases Mg (Kresten, 1973).

The properties are similar to those described by Larsen & Goranson (1932), and Larsen (1941) for similar introduced diopside in association with low temperature minerals. Marsh (1975) also describes diopside as an introduced metasomatic mineral from Granitberg S.W.A.

In thin section it is a prismatic greenish mineral with high relief, high birefringence and a large extinction angle of approximately 40°. The grains were too small for a 2V determination.

Penninite

In the more advanced stages of alteration biotite is commonly altered to pleochroic green peninite with low anomalous 'berlin blue' interference colours. Kresten (1973) and Ferguson et al. (1973) describe chlorite from kimberlite and metasomites respectively, but do not identify the variety.

Chemical Variations due to Metasomatic and Meteoric Effects

Very little chemical work on the metasomatism of crustal xenoliths has been done, besides that of Ferguson et al. (1973). Fenitization specifically has however received more attention (Martin et al., 1975) but in general probably occurred at higher temperatures than the metasomatism of the crustal xenoliths from Letseng-la-terai, as the latter has a mineralogy consistent with low temperatures.

An approach similar to that of Ferguson et al. (1973) has been adopted for this investigation.

Concentric rings approximately equal in width, analogous to onion rings, from the outer to the inner portion of each of the three xenoliths were analysed by XRF technique (Appendix A) for the major elements and Rb, Sr, Y, Zr and Nb. The abundance data are listed in Table 5:6.

The major elements, Rb and Sr proved to be the most useful for showing the metasomatic and meteoric effects on the xenoliths, and these have been used in plots of element vs. distance from the edge of the xenolith for the rocks analysed.

Chayes (1962, 1967) has pointed out the dangers of plotting oxides vs. oxides of a closed array, i.e. a weight percent major element analysis. To guard against distortions introduced by the closed array, the various oxides, on a water and L.O.I. free basis, have been converted to element moles, and a ratio between the element in question and an element that is not participating in the metasomatism was plotted against depth into the xenoliths (Pearce, 1968). A constant reference element that does not react or move during the metasomatic event is selected and any variations in its percentage concentration are only due to it being part of the closed array (Pearce, 1968).

Titanium was chosen as the constant denominator for the L-21 and L-19 xenoliths as this element is present in the minerals not affected by the metasomatism such as amphiboles and pyroxenes, and does not move during zeolite facies metamorphism (Pearce & Cann, 1973; Cann, 1970). Manganese was chosen

TABLE 5:6

Major and trace element abundances from the Rim (OR) to the center of each xenolith analysed

	<u>L2</u>						<u>L21</u>			
	OR	II	III	IV	V	VI	OR	II	III	IV
SiO2	47.79	48.91	49.23	49.13	49.23	49.92	41.02	44.18	45.36	45.16
TiO2	1.57	1.61	1.60	1.61	1.62	1.62	1.08	1.05	1.06	1.07
Al2O3	12.49	13.43	13.62	13.51	13.59	13.84	13.04	14.01	14.31	14.09
Fe2O3	14.87	14.87	14.80	14.68	14.82	15.22	12.57	11.81	11.84	11.93
MnO	0.23	0.23	0.24	0.22	0.22	0.23	0.20	0.19	0.18	0.18
MgO	8.19	6.95	6.77	6.59	6.65	6.66	9.02	9.01	8.97	8.85
CaO	8.95	9.39	9.38	9.33	9.30	9.49	10.69	9.16	8.83	8.83
Na2O	2.79	2.78	2.70	2.61	2.57	2.39	3.07	3.48	3.56	3.75
K2O	1.12	1.50	1.57	1.60	1.61	1.61	1.12	0.47	0.26	0.25
P2O5	0.25	0.17	0.17	0.16	0.17	0.17	0.20	0.13	0.13	0.13
LOI	1.95	1.29	1.38	1.09	1.14	0.88	7.92	5.57	5.12	4.94
TOTAL	100.20	101.13	101.46	100.53	100.92	102.03	99.93	99.06	99.62	99.18
SR	254	312	329	322	313	323	311	268	244	227
RB	11	12	11	12	11	11	45	17	10	8
Y	34	31	31	31	32	31	27	26	26	26
NB	3	3	3	4	3	3	3	3	3	3
ZR	123	124	125	129	127	127	95	95	96	96

Continued.

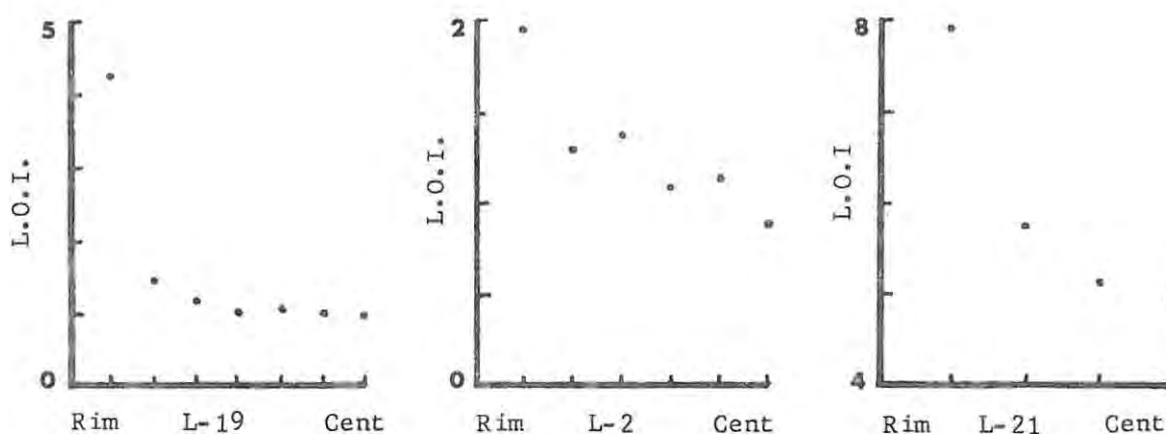
TABLE 5:6 (Continued)

	<u>L19</u>						
	OR	II	III	IV	V	VI	VII
SIO2	42.73	46.48	46.77	47.41	45.81	46.91	47.93
TIO2	1.66	1.73	1.73	1.72	1.70	1.73	1.72
AL2O3	12.38	14.66	14.47	14.58	14.01	14.50	14.51
FE2O3	13.92	14.49	14.31	14.09	13.86	14.02	14.19
MNO	0.19	0.17	0.17	0.18	0.17	0.17	0.17
MGO	7.29	6.12	6.15	6.05	6.03	6.02	6.05
CAO	12.63	10.53	10.64	10.61	10.40	10.54	10.73
NA2O	4.24	4.68	4.51	4.44	4.32	4.22	4.20
K2O	0.82	1.00	1.01	1.04	1.07	1.11	1.14
P2O5	0.32	0.23	0.22	0.22	0.22	0.23	0.23
LOI	4.24	1.44	1.14	0.97	1.05	0.96	0.95
TOTAL	100.42	101.53	101.12	101.31	98.64	100.41	101.82
SR	191	125	125	132	136	137	146
RB	8	9	9	9	10	9	10
Y	38	39	37	37	36	38	38
NB	6	6	5	4	5	5	6
ZR	143	147	148	142	141	141	144

for the L-2 xenolith as this had large patches of opaque oxide that lead to sample inhomogeneity between zones with respect to Ti. Mn is also not a participant in the reactions and is therefore immobile, as it is also present only in the relatively unaltered, mafic minerals of the L-2 xenolith.

In each case ratios have been plotted against depth into the xenoliths as the abscissa. Loss on ignition and the trace elements have been plotted directly.

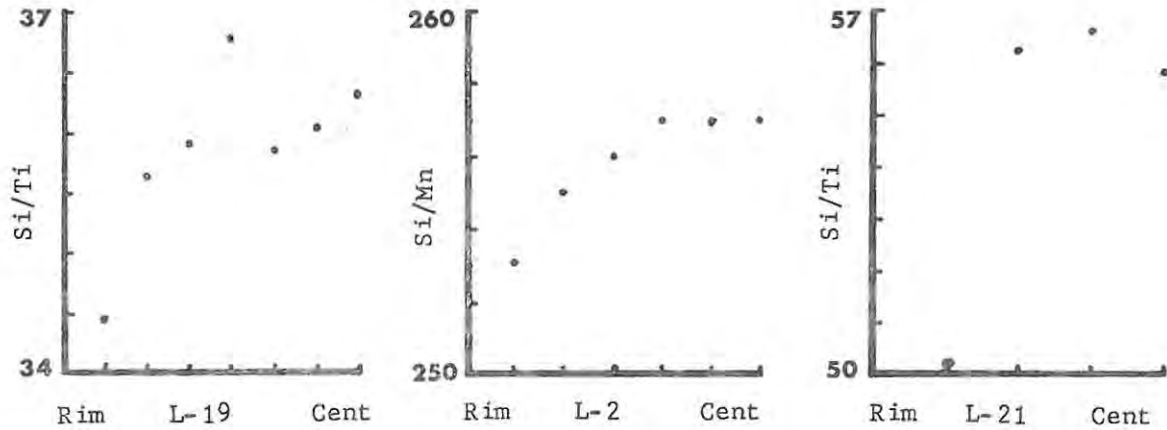
Loss on Ignition



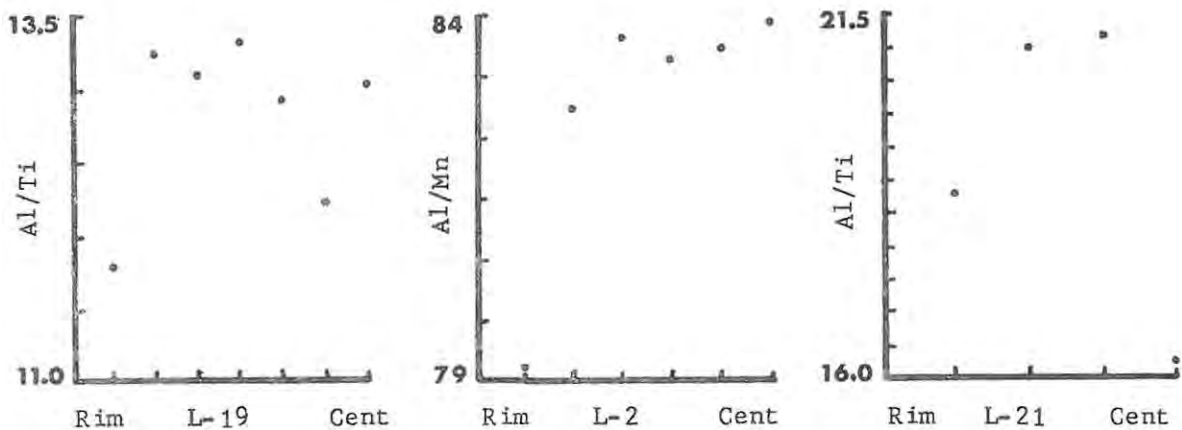
Loss on Ignition is a combination of the abundance of CO_2 , H_2O^+ and the addition of oxygen to FeO converted to Fe_2O_3 . It serves very well to indicate the relative alteration from the edge to the centre of the xenoliths, which clearly decreases towards the centre in all cases. There is no discrimination of hydrous and carbonate minerals by the curves.

The curves also clearly illustrate that the gross alteration is not linear with depth but roughly hyperbolic, as expected. The effect is due to the greater abundance of hydrous minerals, such as natrolite, and the introduction of calcite as a primary metasomatic phase, and as late stage veinlets towards the edges of the xenoliths.

L-19 has more abundant natrolite towards the edge and some primary calcite is present. L-2 has no calcite developed, but natrolite is present while L-21 has small amounts of natrolite present, and a significant number of calcite veins.

Silicon

As can be seen Si decreases towards the edge of all the xenoliths. Clearly there is a direct relationship between loss of Si and alteration as shown by the L.O.I. plot. This due to the removal of Si in solution as a consequence of the metasomatic formation of natrolite and/or leaching. The concomitant formation of cebollite is not enough to retain all the Si released, and the excess is removed by diffusion in the metasomatic fluid.

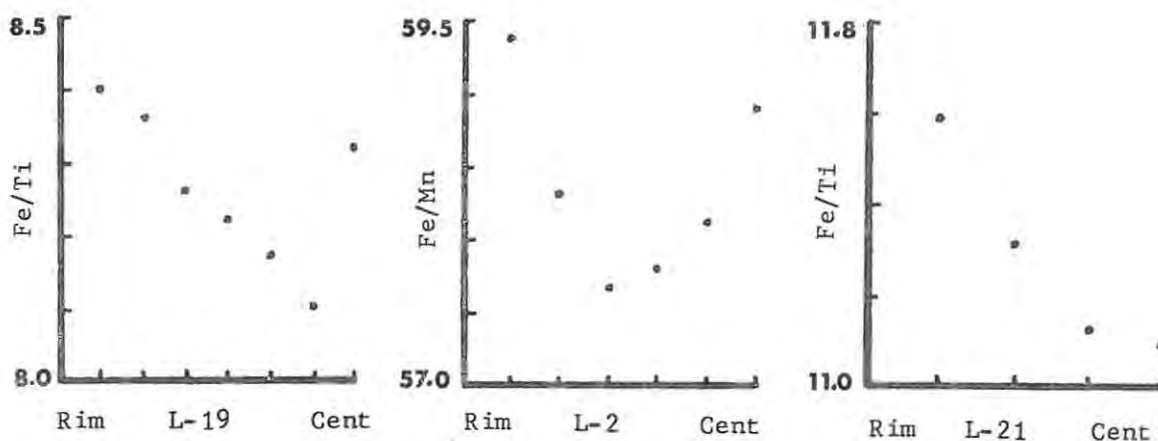
Aluminium

Al/ follows a fairly consistant pattern for all the xenoliths except L-21

which has one anomalous analysis, which may be due to sample inhomogeneity, as the inner sample is quite small and fairly large zeolitic amygdales occur in this rock.

The trends are flat to the outer rim where there is an abrupt decrease of Al in each case. This implies that there has been significant removal of Al only at the edges of the xenoliths. The reason for this trend is apparent in the L-19 xenolith, which has no cebolite developed at the edge and the Al produced by the reaction of plagioclase to form natrolite has therefore been removed. A similar situation is probably responsible for the trends in L-2 and L-21. Removal of Al as well as Si has therefore taken place at the rims of these inclusions.

Iron

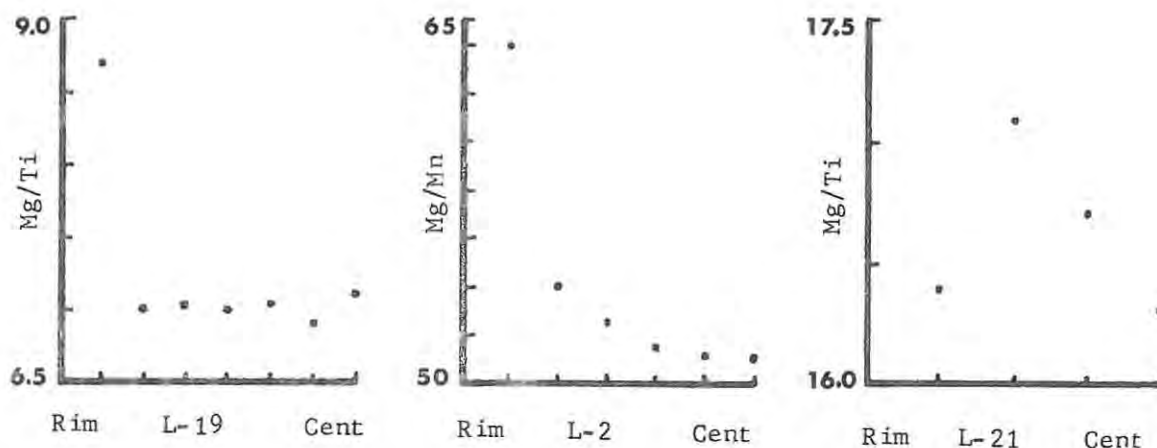


In all cases there is an increase in Fe towards the edge of the xenoliths. The variation in Fe is not very great and the two anomalous central analyses in L-19 and L-21 may be due to some sample inhomogeneity with respect to the mafic minerals, hornblende in the case of L-19 and possibly magnetite or ilmenite in the case of L-2.

The increase of Fe towards the edge of the xenoliths is not well understood. There do not seem to be any minerals containing introduced Fe and as kimberlite is low in Fe, introduction from that source should be limited. Serpentinization of the kimberlite may however produce some excess Fe as well as Mg, which could be incorporated in other minerals such as cebolite. Ferguson et al. (1973)

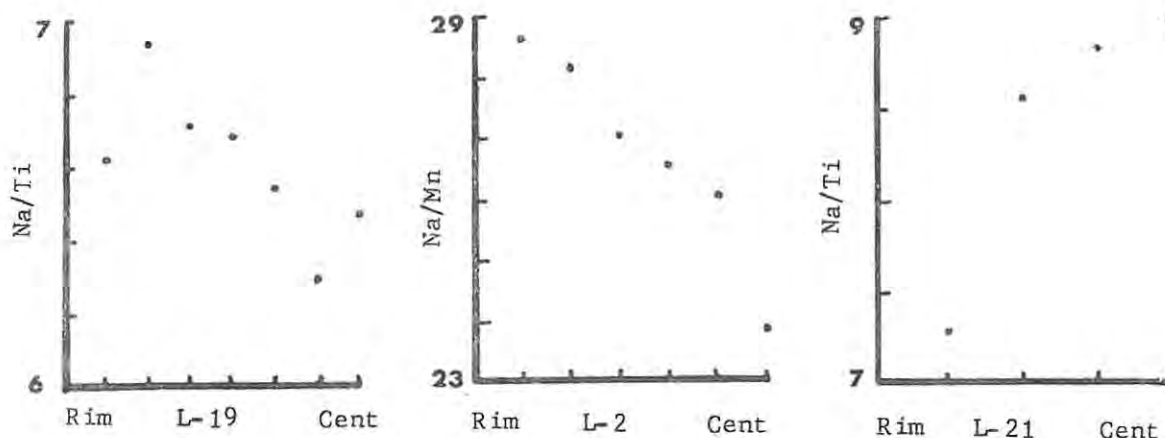
found that on fenitization of salic rocks Fe was introduced, and in the mafic rocks removed. In this case only the salic minerals are taking part in the reaction and Fe may therefore be introduced in all cases.

Magnesium



The fairly abrupt increase in the amounts of Mg towards the edge of L-19 suggests that some Mg has infused, possibly as a component in the calcite metasomatically introduced towards the rim. The steady increase, and then abrupt fall of Mg in the L-21 xenolith is possibly due to serpentinization at the edge of the xenolith, leading to a nett outflow of this component (Cerný, 1968). L-2 on the other hand has an increase of Mg not attributable to introduction as a component of calcite as the latter mineral is not introduced at the rim. A small infusion of Mg, fixed as brucite, due to the serpentinization of the kimberlite (Cerný, 1968) may be the cause but this cannot be verified optically. Kresten, (1973) has shown that considerable amounts of Mg are released from kimberlites, including that of Letseng-la-terai, on hydration.

Sodium

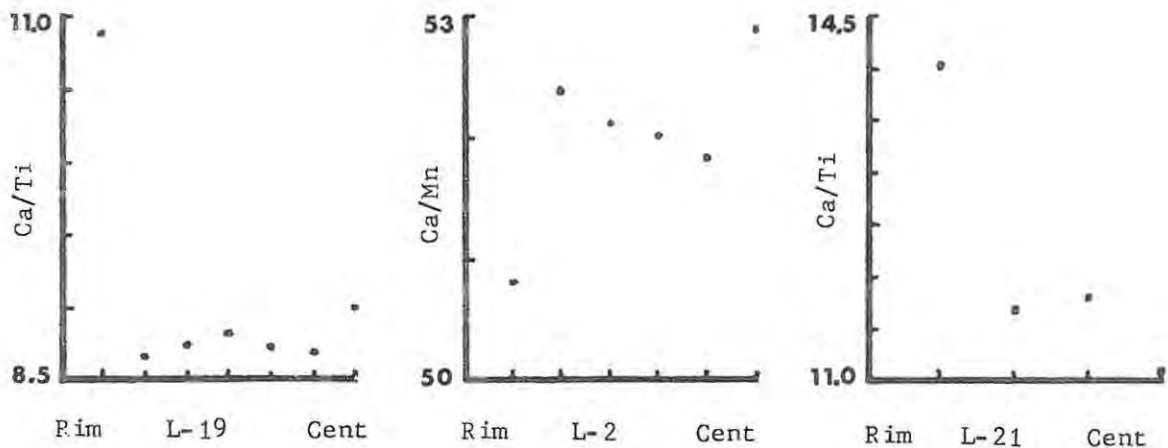


The increase of Na towards the rim of the L-19 xenolith is consistent with the alteration of plagioclase to natrolite, as this mineral is extremely sodic and the element is fixed in this phase.

A similar distribution occurs in the L-2 xenolith for the same reason, as natrolite is developed in this xenolith as well. In the case of L-21 there is a definite decrease of sodium towards the margin of the xenolith.

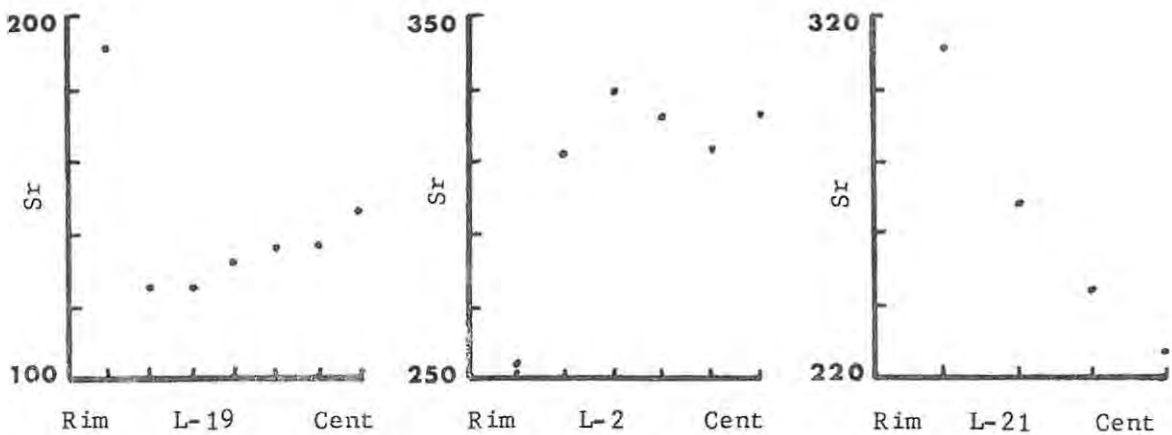
Leaching of Na appears to have taken place here and is possibly related to a different leaching effect at lower temperature. Busenberg & Clemency (1976) have experimentally shown that Na, Si and Ca can be leached from plagioclase at low temperature (25°C) and under a $P\text{CO}_2$ of 1 atm.

Calcium



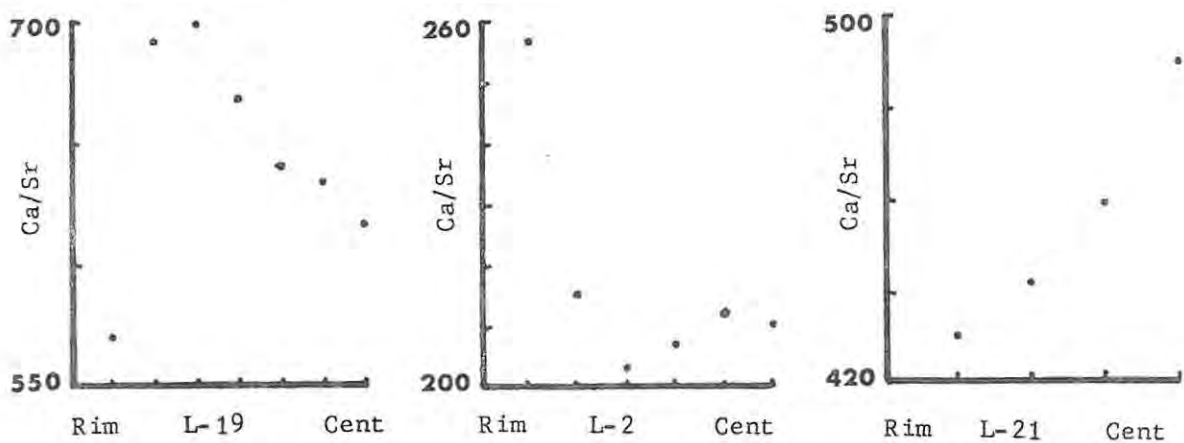
The three inclusions have completely different curves for the distribution of Ca with depth. L-19 shows an abrupt increase in Ca at the margin which is due to introduced calcite only at the edge of this xenolith. L-2 has the opposite trend, an abrupt decrease at the edge due to the excess products of the reaction of plagioclase to form natrolite; Ca, Al and Si all being removed and no late stage calcite being formed. The Ca increase towards the edge of L-21 is due to some late stage secondary calcite, introduced as veins and fillings around grains, that has no apparent reaction relationships to the host xenolith. This is probably a very late phenomenon and may be due to deposition of calcite by much cooler meteoric water, as opposed to the earlier metasomatic introduction of calcite in L-19 which is concomitant with natrolite.

Strontium



The behaviour of Sr mimics that of Ca in the xenoliths. L-19 has a steady decrease of Sr towards the margin, and then a sharp increase. This shows that natrolite and cebollite do not accept Sr readily into their structures. The abrupt increase in Sr at the edge of the xenolith is due to the introduced kimberlitic calcite having a fairly high Sr concentration. L-2 on the other hand shows a steady decrease towards the edge of the xenolith, and as there has been no introduction of calcite towards the margin, the Sr does not show the same pattern as the L-19 xenolith. L-21 has late stage introduced calcite and this introduction overshadows any loss of Sr due to the formation of natrolite and cebollite.

The Calcium/Strontium Ratio



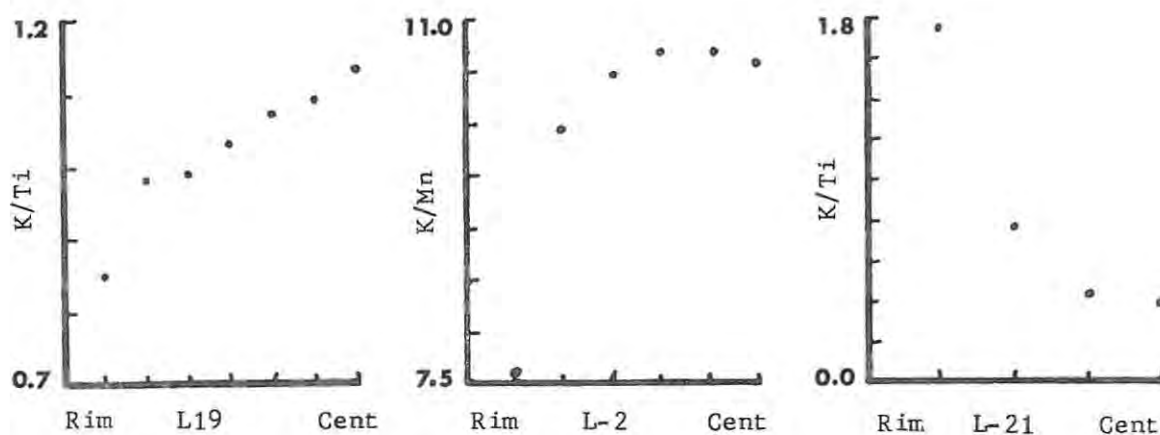
This ratio illustrates clearly that strontium is probably contained in the introduced calcite, and that the other minerals such as natrolite and cebolite reject strontium, which then moves outward towards the margin in the case of L-19 and L-2.

L-19 has Calcite only at the rim and this has a low Ca/Sr ratio, similar to the kimberlite, and this is imposed on the outer part of the xenolith. Deeper into the inclusion where cebolite is developed and no calcite is present the Ca is much greater relative to the Sr, as the new minerals reject the latter. However there is a steady decrease in the ratio with depth, as there is less formation of natrolite and cebolite and the plagioclase has not lost any of the strontium present in its structure.

L-2 has very little if any introduced calcite and shows a similar pattern to the interior part of the L-19 xenolith, due to the formation of natrolite.

L-21 shows the reverse trend to the others which is due to the late stage introduction of calcite in the form of veinlets and stringers visible in thin section. As these are more abundant towards the edge of the xenolith, a lower ratio results as this introduced phase is high in Sr relative to Ca.

Potassium

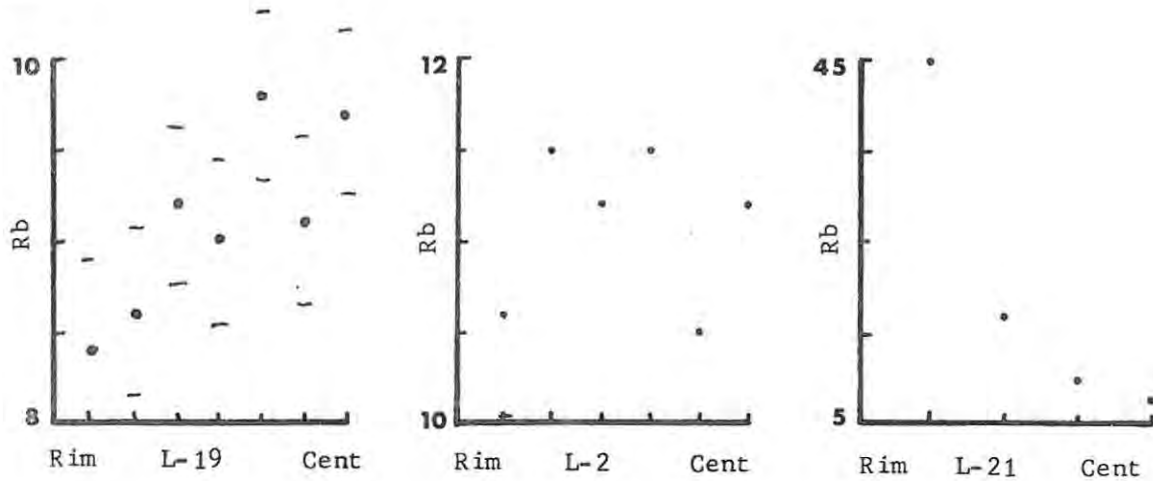


All the plots have different trends, but there is a definite tendency towards equilibration with the kimberlites enclosing the xenoliths. In all cases the K concentrations in the outer rims are very similar and approximately equal, to that of the enclosing Kimberlite.

	Kimberlite K6	L19-OR	L-2 OR	L21-OR
K_2O	0.99	0.86	1.13	1.22

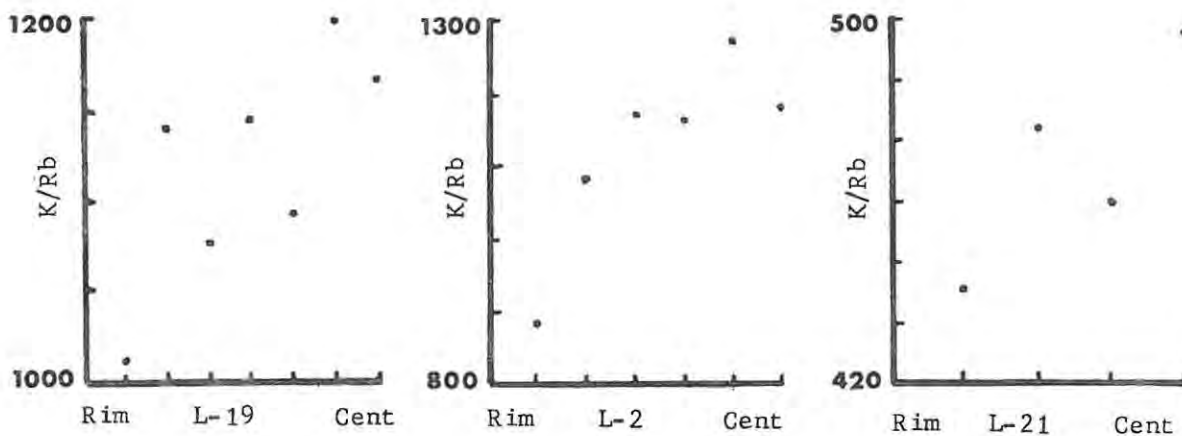
There are no obvious K bearing phases in any of the xenoliths except the devitrified glass in L-2 and L-21. It therefore appears that the K is concentrated along grain boundaries as suggested by Erlank, (1969), and possibly in the plagioclase and zeolites. A nett removal of K occurred in the case of L-19 and L-2, while L-21 had an addition of the element.

Rubidium



The trends exhibited by L-19 and L-2 are similar, that of L-21 is different. L-19 has a slight positive correlation with depth, although this is not well established as the precision of the determination, indicated at 1σ by the small bars, is not sufficient. L-2 has a flat trend and rubidium appears to have been immobile in this rock. L-21 does however show significant enrichment towards the margin. This is probably due to the more porous nature of L-21 which has cracks and a significant amount of zeolitic amygdaloids.

The Potassium/Rubidium Ratio



In all cases there is a positive slope with depth. This illustrates the tendency of the xenoliths to equilibration with the enclosing kimberlite which has a lower K/Rb ratio compared to that of all the xenoliths.

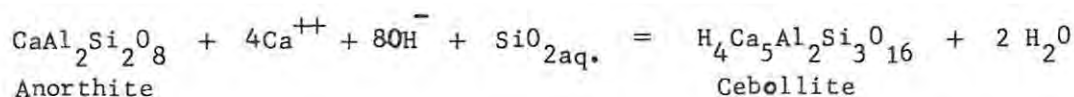
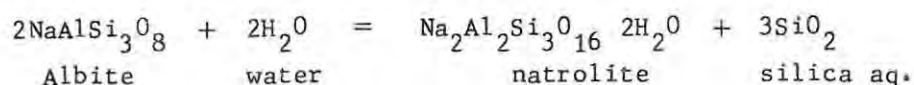
Formation of the Metasomatic Phases

The metasomatism of the crustal xenoliths appears to have occurred under specific conditions defined by the introduced phases. There are two stages of metasomatism. An early high temperature and a later low temperature stage. Initially on intrusion of the kimberlite and the inclusion of the crustal material, the first metasomatic alteration occurred. This stage continued until the kimberlite was fully consolidated and primary magmatic fluids were no longer active. The second stage is due to low temperature fluids, possibly partly meteoric in origin, re-distributing minerals soluble under the relevant conditions.

Movement of fluid within the pore space of the crustal xenoliths was probably very limited, and involved the initial infusion of the metasomatic fluid on incorporation of the xenoliths. Introduction and removal of ions such as Ca^{++} , K^+ , Rb^+ , OH^- , CO_3^{--} etc. probably occurred by diffusion in the static interstitial fluid. Active flow of fluids may however have occurred at the outer rim of the xenoliths. Garrels et al. (1949) have shown that diffusion in fluids is an important mechanism for the transport of ions over relatively restricted distances and the formation of new minerals.

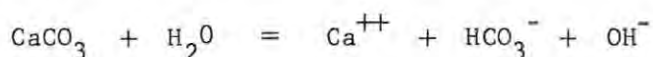
The Natrolite-Cebollite Paragenesis

The formation of natrolite and cebollite in the crustal xenoliths requires the removal of some Si in solution and the addition of Ca for the latter mineral to be able to form. Natrolite is undersaturated with respect to silica compared to the plagioclase it is derived from. As natrolite is a sodic mineral it must form from the albite component of the plagioclase while cebollite forms from the anorthite component with some additional Ca and Si. The following tentative reactions illustrate the relationship between plagioclase and its metasomatic alteration products:



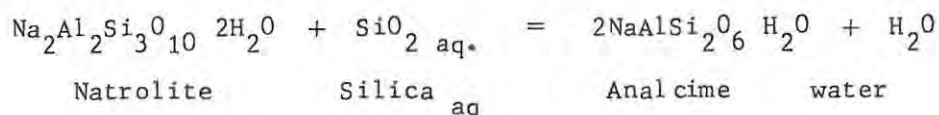
A sodic plagioclase will produce more natrolite and less cebolite, with more Si going into solution. The amount of cebolite formed is also dependant on the Al released by the reaction as this is not an introduced component as is revealed by the abundances in the crustal xenoliths analysed. At the edges of the xenoliths ~~of the xenoliths~~ there has been some removal of Al, and cebolite is much more restricted there.

Experimental work by Senderov (1974) has shown that natrolite forms under high pH conditions at temperatures of up to 250°C. Under all other conditions a more calcic or more silica-rich zeolites form. As extra Ca has to be added to form cebolite it follows that the fluid had Ca^{++} in solution. The most plausible source for extra Ca^{++} is CaCO_3 in solution, the reaction for its dissolution in aqueous fluids is given by Garrels & Christ (1965):



This reaction leads to an alkaline environment and provides a convenient source for the relevant ions. Larsen & Goranson (1932), Tilley & Harwood (1931) and Larsen (1941) report both natrolite and cebolite as alteration products of melilite in an environment where abundant CaCO_3 was available to go into solution in the fluids responsible for the alteration, while Nashar & Davis (1960) report natrolite forming with calcite from solution.

The formation of zeolites could possibly define the activity of aqueous silica (Senderov, 1965), as well as the pH of the solution. As analcime may form under similar conditions to natrolite (Coombs et al, 1959; Miyashiro & Shido, 1970) the upper limit for the activity of $\text{SiO}_{2\text{aq}}$ in the fluid can be defined by the reaction:



It therefore appears that the crustal xenoliths were metasomatized under conditions of high pH and a $\text{SiO}_{2\text{aq}}$ activity lower than that defined by the reaction given above. A fluid with Ca^{++} , HCO_3^- and OH^- in solution and a low PCO_2 appears to be the most plausible metasomatizing agent.

The Natrolite-Calcite Assemblage

Towards the edge of the L-19 amphibolite xenolith, and many of the smaller xenoliths, considerable amounts of calcite are developed with natrolite, often with much less cebolite present. It seems that in this case Al as well as Si was leached by the metasomatic fluid as shown by the plot for Al in L-19. Peterson (1971) points out that Al is soluble at low and at high

pH values while it is relatively insoluble at intermediate values. As calcite is stable it appears that the fluid had a high pH. Deeper into the L-19 xenolith where no calcite formed, the Al appears to have been immobile. This may be due to a slow diffusion rate for this element under the prevailing conditions, while active flow of the fluid through the pore space towards the edge of the xenolith may have aided leaching.

The Mg value towards the edge of the L-19 xenolith rises in sympathy with Ca. This may be due to this early calcite phase being Mg-rich in all the xenoliths. Calcite can take up to 9 mol.percent MgCO_3 into its structure (Deer et al., 1968).

Alteration of the Mafic Phases

In general the mafic phases except biotite and olivine, are fairly resistant to metasomatic alteration, and these are progressively altered to new phases. Alteration of both phases to serpentine and chlorite leads to a release of Mg into the solution (Kresten, 1973).

With progressive metasomatism biotite is converted to penninite in the chlorite group. This is essentially a hydration reaction due to the hydrothermal conditions. Olivine is always largely serpentized where it does occur, again due to the availability of hot aqueous fluids. Johannes (1968) shows that the reaction of olivine to serpentine and brucite occurs below about 350°C at the relevant low pressure conditions (less than .5 kb) in the pipe.

In the kimberlite the serpentization of olivine leads to Mg being removed in solution (Kresten, 1973) while Cerný (1968) has suggested that removal of Mg due to serpentization of ultra mafic bodies may lead to Mg metasomatism. This process may lead to the introduction of Mg into the xenoliths. Similarly serpentization of mafic minerals in the inclusions could lead to a new outflow of Mg from the xenoliths in some cases, as in the L-21.

Introduction of Diopside

Diopside occurs as clusters of very small euhedral to subhedral grains and as larger prismatic crystals. The formation of this phase was probably due to some introduced Mg from the kimberlite (Cerný, 1968) and possibly as a result of the excess Mg present when chloritization of the biotite in the xenoliths occurs (Kresten, 1973).

The Ca has also been introduced into the xenoliths. Enrichment of both Ca and Mg towards the rims of the L-19 and L-2 xenoliths suggests that this

happened. The Si would be derived from the excess produced when plagioclase is converted to natrolite and cebolite. Larsen (1941) and others report diopside from an environment where cebolite and natrolite were forming.

The Natrolite + Woodfordite Assemblage

Talcoose masses of woodfordite, a very hydrous mineral with the composition $\text{Ca}_6 \text{Al}_2 (\text{SO}_4, \text{SiO}_4, \text{CO}_3) (\text{OH})_{12} \cdot 26\text{H}_2\text{O}$ occur in one xenolith. It is very undersaturated and the presence of SO_4 , as CO_3 and OH^- radicals strongly suggests that these radicals were significant components of the metasomatic fluid. These components including Ca were not derived from the host xenolith, which in this case appears to have been 'granitic' in composition as there are considerable amounts of perthitic alkali feldspar preserved. The natrolite in this case appears to have been derived from a fairly sodic plagioclase, possibly oligoclase.

Late Stage Calcite Veins and Late Meteoric Alteration

Calcite veins showing no reaction relationship to the host xenoliths are probably very late stage and due to re-distribution of the carbonate by fluids with a component of meteoric water. These veins are common in the L-21 xenolith which exhibits strong enrichment of Ca towards the edge. Mg is not similarly enriched and it seems that the late stage calcite is not rich in this component, as is probably the case with L-19. It therefore seems that Mg was not re-distributed and was introduced earlier in the metasomatic process.

The swamp on the surface at Letseng-la-terai (Bloomer & Nixon, 1973), a literal translation of the name being "The Swamp at the Corner", may have caused the groundwater seeping down to be slightly acid, aiding dissolution and movement of the Calcite. This late stage fluid also probably altered the smaller xenoliths and kimberlite to assemblages containing clay and saponite, both of which are fairly abundant in the Letseng-la-terai kimberlite (Kresten, 1973). He describes this alteration of the kimberlite, as an in situ effect and not a result of weathering, as it occurs under all climatic conditions.

Nature of the Metasomatizing Fluids

The fluid responsible for the metasomatism of the crustal xenoliths appears to have had specific properties, and these changed with falling temperature. Greenwood (1967) has shown that there is limited miscibility

between $\text{H}_2\text{O} + \text{CO}_2$ below 350°C at and below 2kb, therefore the metasomatic fluid was probably essentially water with only a small component of CO_2 . However it may have been saturated in CO_2 for the conditions prevailing (Ferguson et al., 1973).

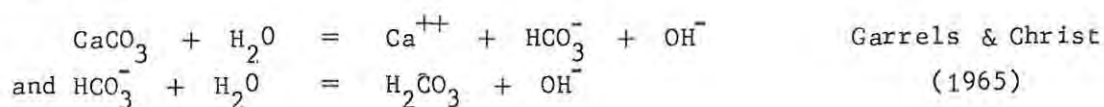
Carbon dioxide tends to decrease the pH of a solution due to the following reaction (Garrels & Christ, 1965):



A low activity of SiO_2 aq. in the fluid is indicated by the formation of natrolite (Senderov, 1965; 1974; Miyashiro & Shido, 1970) in the crustal xenoliths. This is due to the kimberlite magma being silica undersaturated, furthermore hydration of the mafic phases does not release SiO_2 aq. into solution. Mitchell (1973b), believes the activity of Silica rises rapidly in late deuteric fluids, however this appears not to have been the case at Letseng-la-terai.

Both Ca- and Mg-bearing metasomatic phases occur in the crustal xenoliths. The progressive hydration of kimberlite releases considerable amounts of brucite which is removed in solution at Mg^{++} and OH^- (Kresten, 1973), this Mg^{++} would raise the concentration in the fluid and it could be introduced into the xenoliths where it would be incorporated as a component of calcite and diopside. Ca is also available in the solution as calcite is a common late stage mineral in the kimberlite and would be dissolved by the fluid. This component of the fluid is reflected in the crustal xenoliths by the introduction of calcite and other minerals such as woodfordite, cebollite and diopside, with considerable amounts of Ca in their formulae. The late stage calcite veins, such as those of L-21, show that Ca was present in the fluids over the whole temperature range, and long after the consolidation of the kimberlite.

The pH of the metasomatic fluid was probably high initially as natrolite could only be synthesized under high pH conditions (Senderov, 1974), and the solution of Si and Al is also accelerated (Peterson, 1971; Senderov, 1974 and others). Solution of calcite and brucite would probably lead to the high pH postulated for the fluid:



The metasomatic minerals cebollite + woodfordite contain OH^- radicals and their formation would probably be favoured by a high pH.

Woodfordite contains $\text{CO}_3^{=}$ as does calcite, which suggests that the activity of this ion was also high. Other anions in solution included $\text{SO}_4^{=}$, as woodfordite also contains this species. No mineralogical evidence for any others was found but the enrichment of P towards the edge of all three analysed xenoliths suggests that it may be fixed with Cl^- and or F^- and these anions may have been important in the fluid.

Ferguson et al. (1973) have suggested that complexes of NaCl and K_2CO_3 may be carriers for heavy metals. However the Letseng-la-terai K6 Kimberlite is anomalously low in K, and in some cases K moves out of the xenoliths, as in the case of L-19 and L-2. Brines containing NaCl are also unlikely as metasomatizing solutions, Tomasson & Kristmansdottir (1971) have found that thermal brines, up to 200°C , preferentially attack mafic minerals, while plagioclase is altered to a lesser extent. Furthermore no natrolite was described by them, only calcic zeolites.

The temperature range over which the metasomatism here described took place is fairly difficult to estimate (Ferguson et al., 1973). It has however taken place below approximately 250°C as natrolite is not stable above this temperature (Senderov, 1974). As intrusion and cooling was probably rapid (Dawson, 1971), the formation of the new phases must therefore have been rapid, and a temperature of over 100°C was probably maintained for the bulk of the alteration to natrolite and cebollite, and the introduction of the early calcite.

As the temperature fell below this value the reaction rate must have decreased and eventually when cooling was complete only cold solutions circulated, in this case probably partly meteoric in nature, and caused redistribution of calcite which has a high solubility at low temperatures and higher partial pressures of CO_2 (Clark, 1966). A drop in the CO_2 content of the water as it percolated down would have resulted in the deposition of calcite in veins such as those of the L-21 xenolith and others. This late stage water may also have been slightly more acid from the swampy conditions on surface described before.

Conclusions

In summary there appears to have been two stages in the metasomatism of the crustal xenoliths. The early stage occurred during the intrusion, by a

fluidization process, of the kimberlite magma (Dawson, 1962) and the assemblages containing natrolite were formed at temperatures of up to 250°. At temperatures below 340°C (Bowen & Tuttle, 1949; Johannes, 1968) the serpentinization of olivine within the kimberlite allowed Mg to become mobile (Kresten, 1973), and this element was introduced into the xenoliths and diopside and Mg rich calcite, or dolomite (Ferguson et al., 1973), formed. The alteration process also resulted in the removal of silica due to the formation of silica poor minerals such as natrolite at less than 250°C (Senderov, 1974) which being hydrous made the assemblage water rich.

At a later stage after the consolidation of the kimberlite and at lower temperatures residual solutions, possibly with a component of slightly acid meteoric water, deposited some calcite as small veins and stringers evident in many of the xenoliths. This process probably also altered the very small xenoliths included in the kimberlite to an assemblage containing clays and related minerals in addition to the phases described here.

The low temperature metasomatic effects in the Letseng-la-terai and possibly other kimberlites documented by this and other studies appear to be fairly complex and require more detailed study with analysis of the phases, such as the two generations of calcite, for better understanding.

APPENDIX AX-Ray Fluorescence Spectrometry

All major and trace element analysis were obtained using x-ray fluorescence spectrometry. The instrument used is a semi automatic Phillips PW 1410 spectrometer fitted with a Teletype and paper tape punch. Data reduction was done by computer.

Major Elements

All the major elements except Sodium were determined in duplicate on fused glass discs using the method of Norrish & Hutton (1969). Sodium was determined separately on a pressed powder briquette.

A glass reference disc (FSL-11) was calibrated using international reference standards, and the concentration values for the latter were taken from Flanagan (1973).

Full corrections were made for dead time, background and instrumental drift.

The instrumental conditions were as follows:

Voltage	-	55 kV
Amperage	-	40 mA
Tube	-	Chromium
Counter	-	Flow
Crystals	-	LiF 200 (Ti, Fe, K, Ca and Mn)
		TLAP (Mg and Na)
		PET (Si and Al)
		Germanium (P)

Pulse height discrimination was also used.

Trace Elements

All the trace elements were determined on pressed powder briquettes.

Full corrections for background, mass absorption and spectral line interferences were made. Corrections were also applied for deadtime and instrumental drift.

Calibration was done using International rock standards and the values used are listed in Table A:1.

The instrumental conditions were as follows:

Voltage	-	55 kV
Amperage	-	40 mA

TABLE A:1

Standard values used for trace elements

	AGV.	GSP	BCR	G-2	KL-11*	M-38*	OK-272*	DTS	PCC	NIM-D	JB-1	NIM-N	NIM-G
RB	65.0	255	46.5	170	15.3	212	88.0	-	-	-	-	-	-
SR	670	238	340	492	199.5	80.0	113	-	-	-	-	-	-
Y	20.3	25.0	34.5	10.7	24.0	40.5	29.0	-	-	-	-	-	-
ZR	237	535	195	324	98.8	199.5	164	-	-	-	-	-	-
NB	11.0	24.5	10.5	9.0	6.5	18.5	74.5	-	-	-	-	-	-
CO	-	-	38.0	-	50.8	25.0	-	133	112	206	-	-	-
CR	-	-	14.0	-	271	96.0	-	3150	2500	2900	-	-	-
V	-	-	380	-	233	125	-	10.0	30.0	45.0	-	-	-
ZR	83.0	-	122	-	78.5	118	80.0	-	-	-	84.0	60.0	-
CU	52.0	-	15.0	-	86.0	37.0	1.5	-	-	-	56.0	14.0	-
NI	14.0	-	9.0	-	67.4	46.0	860	-	-	-	135	120	-
LA	35.0	-	25.0	96.0	-	-	-	-	-	-	-	-	-
CE	65.0	-	54.0	165	-	-	-	-	-	-	-	-	-
ND	39.0	-	29.0	55.0	-	-	-	-	-	-	-	-	-
TH	7.0	108	-	25.0	-	-	-	-	-	-	-	-	50.0
PB	35.0	55.0	-	29.0	-	-	-	-	-	-	-	-	48.0

* University of Cape Town (Geochemistry Department. In House Standards)

- Not used

Tube - Tungsten
 Counter - Flow and Scintillation for Zu, Cu and Ni
 Scintillation all other trace elements.
 Crystal - LiF 220.

Precision Run (L10)

A single sample (L10) was prepared in the following way. Initially the sample was broken into pieces slightly larger than a matchbox, cleaned in de-ionized water and dried. The sample was then reduced in a jaw crusher, (previously cleaned and pre-contaminated) to thumbnail size chips. Eleven aliquots were then split from the sample and individually prepared for analysis.

Each aliquot was reduced in a swingmill with an Mn steel vessel, and then in an agate mortar and pestle to less than 300 mesh. 5gm was then compressed into a briquette with a mixture of boric acid and Bakelite as a backing.

H_2O^- and LOI were determined at $110^{\circ}C$ and $1000^{\circ}C$ respectively on 2-4 gm portions of each of the eleven aliquots. The ashed powder was then used to make duplicate fused glass discs (Norrish & Hutton, 1969).

The analytical data for major and trace elements are listed in Table A:2 and a statistical analysis of the results in Table A:3. A further two columns (counting precision and the Lower Limit of Detection) indicate the approximate average counting precision and Lower Limits of Detection for single samples.

The statistical analysis puts limits on the precision and accuracy that can be assumed from a single determination, on a coarse grained, heterogeneous rock such as a kimberlite.

TABLE A: 2

ALIQUOTS OF L10 ANALYSED TO TEST PRECISION

	L10/A	L10/B	L10/C	L10/D	L10/E	L10/F	L10/G	L10/H	L10/I	L10/J	L10/K
SiO ₂	37.53	37.20	37.32	37.30	37.32	37.20	38.15	37.59	37.06	37.23	37.34
TiO ₂	1.61	1.59	1.59	1.60	1.62	1.60	1.64	1.62	1.58	1.59	1.61
Al ₂ O ₃	5.18	5.19	5.17	5.15	5.26	5.19	5.27	5.30	5.18	5.16	5.16
Fe ₂ O ₃	9.92	9.80	9.84	9.87	9.80	9.74	10.16	9.86	9.72	9.86	9.88
MnO	0.15	0.14	0.15	0.15	0.16	0.14	0.15	0.15	0.14	0.14	0.14
MgO	24.69	24.66	24.86	24.62	24.80	24.78	25.28	25.04	24.87	24.71	24.58
CaO	7.16	7.09	7.08	7.14	7.16	7.05	7.31	7.21	7.22	7.10	7.24
Na ₂ O	0.40	0.39	0.41	0.40	0.39	0.39	0.41	0.39	0.40	0.42	0.41
K ₂ O	1.97	2.00	1.99	1.95	2.02	1.98	2.07	2.04	2.00	2.00	1.96
P ₂ O ₅	0.52	0.51	0.52	0.52	0.52	0.52	0.53	0.52	0.51	0.53	0.52
L.O.I.	8.12	8.04	8.02	8.19	8.11	8.15	7.86	8.00	8.36	7.75	7.91
H ₂ O ⁺	2.72	2.76	2.84	2.64	2.87	2.55	2.71	2.71	2.57	2.63	2.77
TOTAL	99.97	99.36	99.79	98.60	100.00	99.29	101.36	100.43	99.60	99.12	99.52

continued

Table A:2 continued

	L10/A	L10/B	L10/C	L10/D	L10/E	L10/F	L10/G	L10/H	L10/I	L10/J	L10/K
SR	614	592	572	579	601	578	594	592	603	576	582
RB	70	70	68	70	69	67	72	69	69	68	69
Y	14	14	14	14	14	14	15	13	14	14	14
ZR	164	162	159	160	162	156	166	157	159	158	160
NB	90	90	89	90	90	88	92	91	91	90	91
ZN	67	68	68	68	67	67	70	68	67	69	70
CU	51	51	54	60	52	48	53	54	51	55	53
NI	1171	1170	1178	1148	1188	1179	1230	1177	1146	1151	1157
LA	45	46	44	45	46	44	45	45	43	46	45
CE	76	76	77	73	80	77	77	81	83	80	84
ND	33	31	35	32	36	31	33	33	35	35	34

TABLE A:3
STATISTICS OF THE L10 PRECISION RUN

MAJOR ELEMENTS				TRACE ELEMENTS					
	$\bar{X}$	s	$s/\bar{X} \%$		$\bar{X}$	s	$s/\bar{X} \%$	COUNTING PRECISION 1s PPM	L.L.D. PPM
SiO2	37.39	0.29	1.00	SR	589	13	2.22	0.9	1.4
TiO2	1.60	0.02	1.09	RB	69	1.2	0.03	0.5	1.3
Al2O3	5.20	0.05	0.98	Y	14	0.36	2.61	0.4	1.3
Fe2O3	9.86	0.12	1.18	ZR	160	3	1.87	0.6	1.4
MNO	0.15	0.01	4.61	NB	90	1.1	1.22	0.5	1.4
MGO	24.81	0.20	0.82	ZN	68	1.1	1.64	0.6	1.4
CAO	7.16	0.08	1.10	CU	53	3.0	5.76	2.1	6.0
NA2O	0.40	0.01	2.61	CO	83	-	-	0.8	3.0
K2O	2.00	0.04	1.76	NI	1172	24	2.03	1.7	1.4
P2O5	0.52	0.01	1.22	V	139	-	-	1.1	3.9
L.O.I.	8.05	0.17	2.09	CR	904	-	-	1.8	2.6
H2O	2.71	0.10	3.79	LA	45	0.9	2.10	1.5	5.0
TOTAL	99.85			CE	79	3.3	4.24	3.2	12.0
				ND	33	1.7	5.07	1.7	6.0
				TH	7	-	-	1.1	3.1

APPENDIX BX-Ray Diffraction

A Phillips Cobalt x-ray tube with a Fe filter was used for all diffraction work. The conditions were as follows:

Voltage - 40 kV

Amperage - 25 mA

Wavelength - Co $K\alpha_{1,2}$ = 1.79 Å

Diffractometry

If enough sample was available diffraction traces were run on -300 mesh powder using the Phillips PW 1050/25 goniometer with a sealed xenon counter and chart recorder. The diffractometer was set up to move at $1^\circ 2\theta$ per minute, and the chart recorder at 1cm per minute.

After measurement of the chart obtained, the d spacings were calculated using the Bragg equation:

$$n\lambda = 2d \sin \theta.$$

Powder Photographs

Limited quantities of the mineral extracted from uncovered thin sections under the microscope necessitated the use of a Debye-Scherrer camera (5.73 cm diameter). The sample obtained was rolled into a thin rod with Gum Tragacanth and mounted on a thin fibre.

Exposure time for the photographs varied between $\frac{1}{2}$ and 2 hrs. Measurement of the film was done with the aid of a Norelco film reader. Each line was measured twice and corrections were made for film shrinkage using available back reflections. The d spacings were calculated using the Bragg equation.

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