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I am submitting herewith a thesis written by Jeffrey J. Agee entitled "Petrogenesis of Opaque Minerals in Kimberlite: Elliott County, Kentucky." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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PETROGENESIS OF OPAQUE MINERALS IN KIMBERLITE:
ELLIOTT COUNTY, KENTUCKY

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ABSTRACT

Two kimberlite pipes in Elliott County, Kentucky contain inclusions of altered crustal rocks, ultramafic xenoliths and a diverse megacryst suite in a groundmass of olivine, picroilmenite, chromite, titaniferous magnetite, pleonaste, perovskite, calcite, and various hydrous silicates. The megacryst assemblage consists of olivine, garnet, picroilmenite, phlogopite, clinopyroxene and orthopyroxene. Rare clinopyroxene-ilmenite and rutile-ilmenite intergrowths also occur.

Ilmenite megacrysts (8.50 to 13.5% MgO) have reversed-zoned rims (13.8 to 16.5% MgO). These rims are surrounded by a perovskite and titaniferous magnetite reaction rim. Ilmenite megacryst cores show correlation of MgO with Fe_2O_3 ; groundmass ilmenites (12.6 to 17.0% MgO) show a similar trend, but have a wider range of Fe_2O_3 . Ilmenite in clinopyroxene-ilmenite intergrowths (13.0 to 13.5% MgO) is at the high MgO end of the megacryst trend. The clinopyroxenes have equilibration temperatures of 1295-1335°C. (Di-En solvus). A rutile-ilmenite intergrowth is surrounded by ilmenite which is compositionally similar to the groundmass ilmenites (14.7% MgO). Ilmenites at Elliott County plot as a portion of a parabolic trend on a Cr_2O_3 versus MgO diagram.

Spinel at Elliott County show the typical kimberlitic trend of Cr→Al-rich spinels, followed by late-stage formation of titaniferous magnetite. Cr and Al-rich spinels are believed to be related to the groundmass stage of crystallization, while the titaniferous magnetites are post magmatic.

Oxide minerals in the Elliott County kimberlite record three periods of formation. The early megacrysts and clinopyroxene-ilmenite intergrowths crystallized from a fractionating liquid at 150km. ($T \sim 1100-1400^{\circ}\text{C}$) as evidenced by MgO trends and association with silicate megacrysts. Subsequently, megacrysts reacted with a more Mg-enriched liquid, resulting in formation of Mg-rich rims. Ground-mass minerals which crystallized from this magma are more magnesian than the earlier more fractionated megacrysts. The final event is the reaction of ilmenite to form perovskite titaniferous magnetite.

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CHAPTER I

INTRODUCTION

The mantle, which comprises over 80% of the earth, is represented at the surface by samples found as inclusions in a variety of volcanic and hypabyssal rocks (e.g. alkalic basalts, minettes and kimberlites). Although these rocks are extremely rare they are our only direct source of mantle material. Kimberlite provides petrologists with most of these mantle samples. Aside from their obvious scientific importance, they are economically vital as the source of natural diamond.

Current theories on the origin of kimberlite involve partial melting of carbonated phlogopite garnet peridotite (Wyllie, 1979; Eggler and Wendlandt, 1979). Two dominant ideas exist concerning the mechanism of partial melting to produce kimberlite: (1) the kimberlitic melts are produced by the ascension of a peridotite diapir which intersects the wet peridotite solidus at depths of 150-200km (Green and Gueguen, 1974); (2) partial melts are produced in the upper mantle due to frictional heating caused by increased spreading rates of overlying crustal plates (Nixon and Boyd, 1973).

From this magma, a distinctive suite of minerals, termed megacrysts, crystallize during the early stages of kimberlite formation (Gurney et al., 1979; Eggler et al., 1979). These large single crystals, up to 20 cm in diameter, consist of olivine, ilmenite, garnet, clinopyroxene, phlogopite and orthopyroxene. They are typically rounded with surface striations indicating they have been

abraded during emplacement. In many cases the megacryst minerals are distinct, both texturally and compositionally, from the corresponding phases which occur in the ultramafic xenoliths (Eggler et al., 1979; Garrison and Taylor, 1980). The ultramafic xenoliths probably represent incorporated wall rocks which have been included accidentally during the movement of the kimberlitic melt through the mantle (Nixon and Boyd, 1973; Eggler et al., 1979). Smaller groundmass minerals form during the late stages of crystallization (Smith et al., 1979). These consist dominantly of olivine, ilmenite, calcite, orthopyroxene, phlogopite and a complex group of spinels set in a matrix of serpentine, phlogopite, chlorite, amphibole, perovskite, calcite, and magnetite.

On the surface, kimberlites are exposed as diatremes or as dikes and sills. The diatremes are usually quite small (hundreds of meters in diameter) and are formed by rapid emplacement of a gas--solid or liquid--solid, fluidized mixture (Clement, 1975). The kimberlite in diatremes typically occurs as a breccia often containing inclusions of local country rocks. The dikes and sills are smaller (0.5-2.0 meters thick) and produce a massive kimberlite which is relatively free of local country rock inclusions (Dawson and Hawthorne, 1973).

An important constituent of kimberlite is the oxide minerals. These phases are the most susceptible to changes in temperature, bulk composition and oxygen fugacity and are present in the megacrysts, as well as the groundmass. They record a large portion of the crystallization history and may provide the most information about the evolution of kimberlite. Ilmenite is the most abundant of the oxide minerals found in kimberlite and is present both as a megacryst and as a

groundmass mineral. A diagnostic feature of kimberlitic ilmenites is their distinctive chemical composition. All are very high in MgO (up to 20 wt.%; Mitchell, 1973).

In addition to widely variable petro-chemical systematics, ilmenites show a large variety of textural relationships. The megacrysts may occur as single crystals or totally recrystallized polycrystalline aggregates. This latter texture may be due to strain acquired by the megacrysts during the emplacement of the kimberlite (Pasteris *et al.*, 1979), or by the movement of the megacrysts within a protokimberlitic diapir (Green and Gueguen, 1974). Perhaps the most unusual occurrence of ilmenite is as lamellar or graphic intergrowths with clinopyroxene and/or orthopyroxene. Various interpretations have been made as to their origin. However, recent experimental work strongly suggests their formation by eutectic or cotectic precipitation (Wyatt, 1977).

Spinel in kimberlite is largely restricted to the groundmass except in the case of spinel peridotite xenoliths or minute chrome-spinel exsolution rods in some ilmenites (Danchin and D'Orey, 1972). The groundmass spinels show complex chemical trends. The early-formed spinels are Cr-to Al-rich; late-stage spinels display increased Ti and Fe^{3+} , with crystallization indicating increasing $f\text{O}_2$ (Haggerty, 1976).

Perovskite (CaTiO_3) is commonly associated with ilmenite and Fe-Mg-Ti spinels, in a selvage formed by a reaction between ilmenite and late-stage kimberlitic fluids (Haggerty, 1973). It is also common as small (0.05-1.0mm) anhedral grains throughout the groundmass and possesses little compositional variation (Mitchell, 1972).

Determining oxide-mineral paragenesis is often difficult for kimberlites. Indefinite crystallization sequences due to incomplete mineral assemblages commonly are all that can be pieced together. This is due to the highly-altered nature of the host rock which obscures primary and secondary features. Therefore, it is always desirable to study these minerals in a relatively unaltered specimen so that details of the textural relations can be used to complement chemical data. The present study concentrates on the chemical and textural relationships of the oxide minerals in two kimberlite pipes in Elliott County, Kentucky. The samples collected are unusual for they are extremely unweathered (by kimberlite standards) which allows for detailed petrographic and chemical analyses. The chemical and petrographic data have permitted a reconstruction of a large portion of the crystallization history of a kimberlite, from megacrysts to groundmass.

Three recent studies have been done on the Elliott County kimberlite. Koenig (1956) published a brief petrographic description. Bolivar (1972) conducted an isotopic study on the carbonates within the kimberlite. Most recently, Garrison and Taylor (1980) investigated the mineral chemistry of silicate megacrysts and xenoliths.

Methods

Samples were collected from two pipes (Figure 1). At pipe 1, collection was restricted to one outcrop. At pipe 2, samples were recovered from two locations, approximately 300 meters apart. Sections of the samples were cut, and polished thin sections were prepared. These sections were studied using transmitted and reflected-light microscopic techniques. Groundmass oxides required high resolution

Figure 1. Map showing the location of the Elliott County kimberlite.

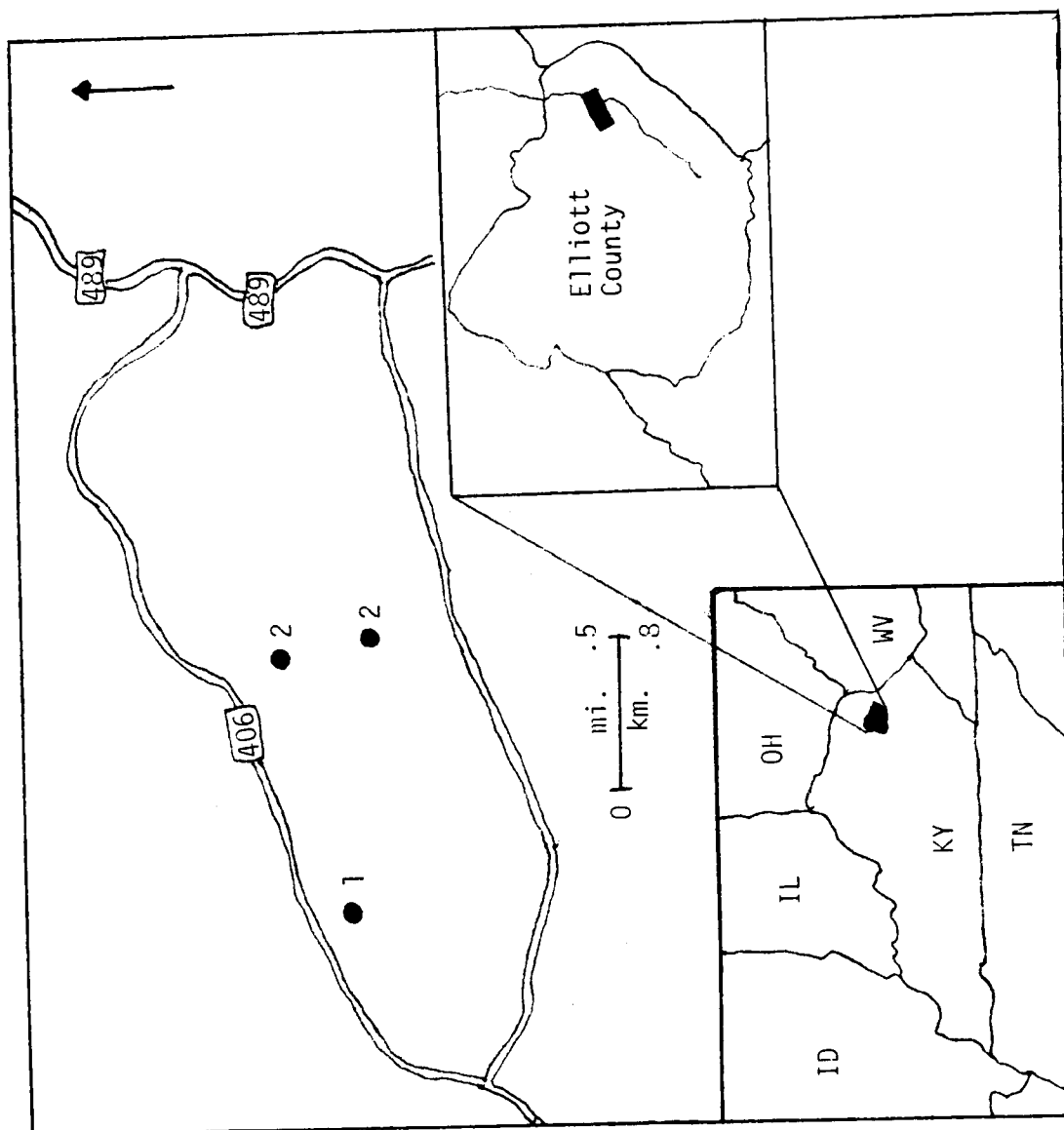


Figure 1

oil-immersion objectives in order to adequately resolve textural features and enhance phase contrasts.

Minerals were analyzed with an automated MAC 400S electron microprobe, using natural and synthetic standards, a beam current of 0.05 micro-amps., a beam diameter of $1\mu\text{m}$, and an accelerating voltage of 15Kv. Correction procedures are those of Bence and Albee (1968) with data by Albee and Ray (1970). Where possible, three to six analyses were performed on each grain, and an average analysis and 1σ standard deviation was computed. Fe^{3+} and Fe^{2+} in ilmenite and spinel were calculated, using a method based on cation charge and site balance.

All microprobe data were stored on computer cards which, in addition to the chemical data, contained a textural code, a designation for the pipe, location of the analysis with respect to the core or rim of the grain, and the thin-section and grain number. Storage of data in this fashion allowed the use of the SAS 79 computer program (Barr et al., 1979) for data manipulation.

CHAPTER II

PETROGRAPHY

The two igneous pipes sampled in Elliott County consist of a kimberlitic breccia (pipe 1) and porphyritic massive kimberlite (pipe 2). The breccia is dark grey to black and consists of abundant (up to 20 modal %), angular to subrounded sedimentary clasts in a fine-grained matrix of serpentine, calcite, chlorite, phlogopite, perovskite and spinel. Crustal xenoliths include clasts of crystalline basement and sedimentary units of shale, limestone and siltstone. Shales and limestones display well-developed rinds of metasomatic alteration indicating the kimberlite was relatively hot when intruded. Dewatering of these sediments has serpentinized the enclosing kimberlite around each clast.

Small phenocrysts of euhedral to subhedral olivine (up to 1mm) are the most abundant groundmass mineral. Approximately 20% of these olivines contain small (25 μ m) sphericle inclusions of ilmenite. Anhedral ilmenite phenocrysts (0.2-1.0mm) are common, and where in contact with the matrix, they are surrounded by perovskite and spinel. The massive kimberlite is similar to the breccia of pipe 1, but does not contain clasts of crustal rocks.

The megacryst suite consists of olivine, ilmenite, garnet, phlogopite, clinopyroxene, and orthopyroxene. Megacrysts average 0.5-1.5cm in diameter. Olivine, phlogopite and ilmenite commonly show evidence for deformation. Phlogopite exhibits kink bands, and some olivine and ilmenite have undulose extinction or show evidence

for recrystallization. Garnet, orthopyroxene, olivine and ilmenite exhibit reaction rims, possibly as a result of disequilibrium between late-stage kimberlitic fluids and the megacrysts. Three graphic clinopyroxene-ilmenite intergrowths and one rutile-ilmenite intergrowth have been recovered from pipe 1. One clinopyroxene-ilmenite intergrowth exceeds 3cm in length.

Ultramafic xenoliths included in the kimberlite are small and usually represent incomplete peridotite assemblages (Garrison and Taylor, 1980). Pipe 1 contains the greatest number and variety of xenoliths, including spinel websterite, garnet peridotite, dunite, and spinel peridotite. Only two ultramafic xenoliths were identified in pipe 2; however, one of these is the largest yet seen, a serpentinized garnet peridotite over 10cm long.

Petrography of Oxide Minerals

Oxide minerals constitute up to 18 modal percent of the Elliott County kimberlite (Bolivar, 1972). Ilmenite is the dominant phase and occurs in six textural settings: (1) as megacrysts (both as single crystals and as monomineralic polycrystalline aggregates 0.5-2.0cm in diameter; Figure 2a); (2) as graphic intergrowths of ilmenite in clinopyroxene (Figure 2b); (3) as thin lamellae of ilmenite in rutile phenocrysts (Figure 2c); (4) as anhedral single crystals ($\leq 10\text{mm}$) which occur throughout the groundmass (Figure 2d); (5) as rounded inclusions (up to $25\mu\text{m}$) within euhedral olivine phenocrysts (Figure 3a); and (6) as small ilmenite grains associated with spinel and perovskite in reaction rims around ilmenite (Figure 3b).

Figure 2. Reflected-light photomicrographs of ilmenite textural types.

- a. Type 1 megacryst ilmenite. Bar = 1mm.
- b. Type 2 clinopyroxene-ilmenite intergrowth. Bar = 2mm.
- c. Type 3 rutile-ilmenite intergrowth. Bar = 100 μ m.
- d. Type 4 groundmass ilmenite. Bar = 75 μ m.

cpx = clinopyroxene

il = ilmenite

pf = perovskite

ru = rutile

mt = magnetite

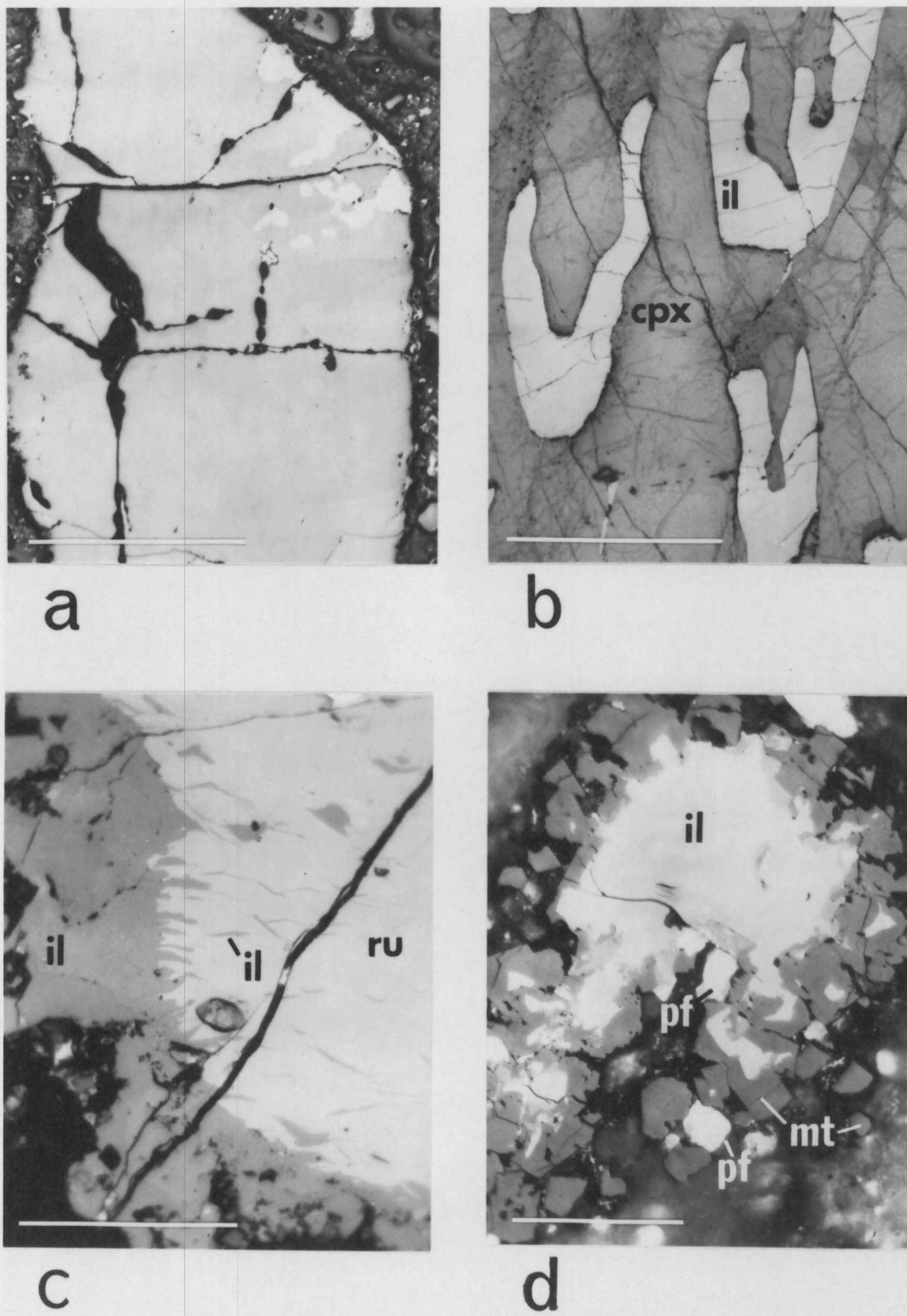


Figure 2

Figure 3. Reflected-light photomicrographs of ilmenite textural types.

a. Type 5 ilmenite inclusion in olivine. Bar = 250 μ m.

b. Type 6 high Mn-ilmenite. Bar = 100 μ m.

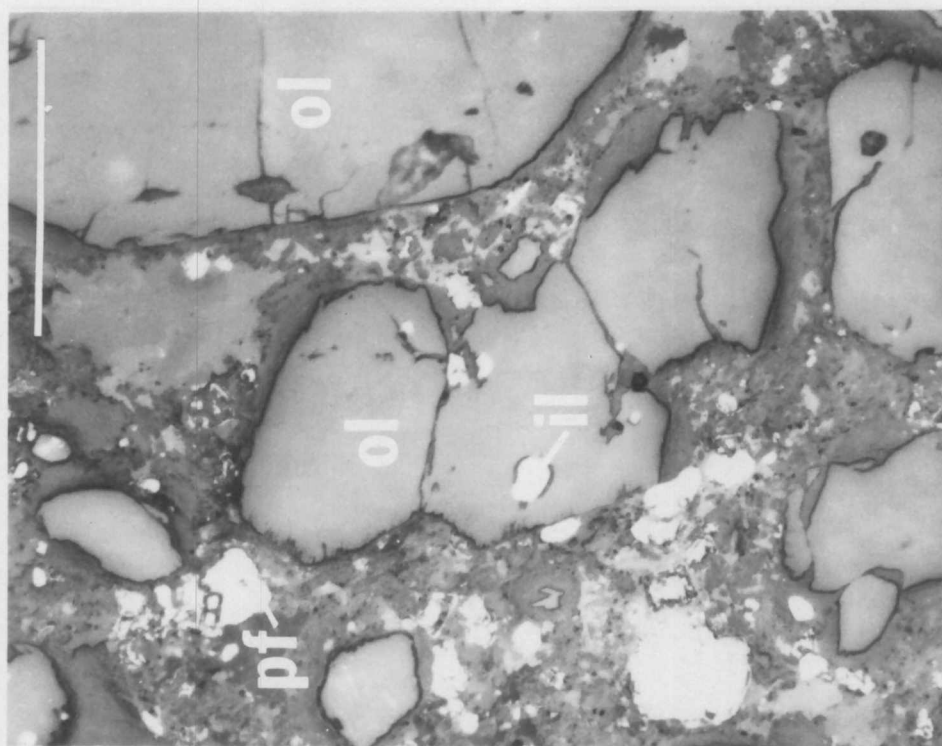
il = ilmenite

mt = magnetite

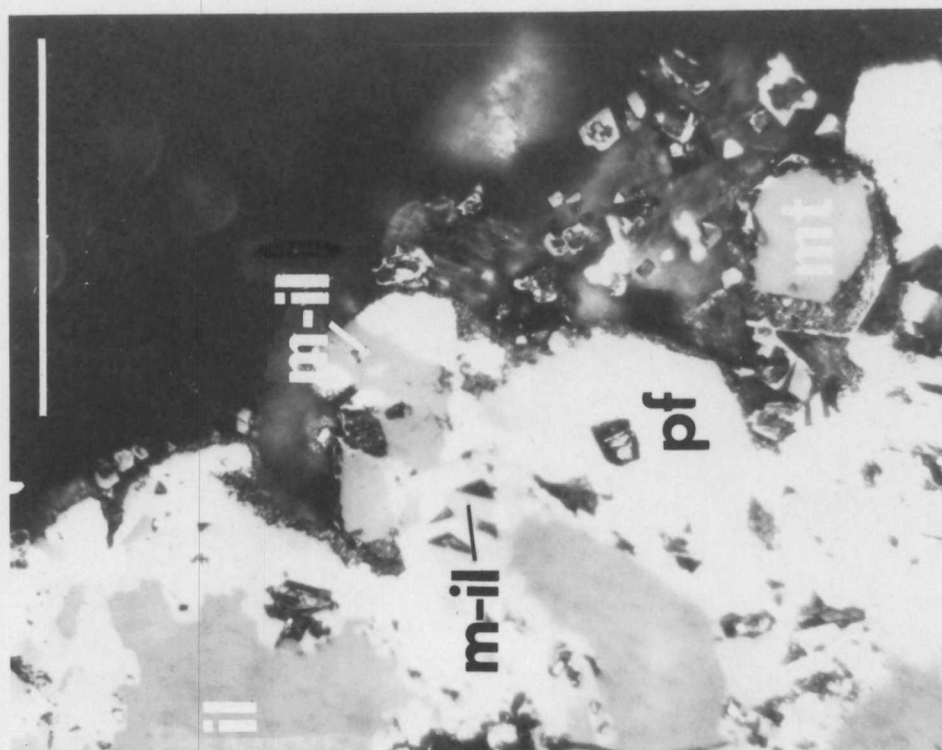
m-il = Mn-ilmenite

ol = olivine

pf = perovskite



a



b

Figure 3

Ilmenite megacrysts have anhedral to subhedral shapes which are attributed to abrasion during emplacement of the kimberlite (Mitchell, 1973). Textures show continuous variation from single crystals with slightly undulose extinction indicating deformation to totally recrystallized polycrystalline mosaics with straight extinction and a high percentage of 120° triple junction boundaries. The following textural features are interpreted as indicative of recrystallization: (a) twin lamellae are occasionally present near edges of megacrysts (Figure 4a); (b) bands of fine mosaic ilmenite are seen traversing coarse grains (Figure 4b); (c) there are long bands or tapering wedges within grains that have slightly different extinction angle from the host (Figure 4c); and (d) some samples show a foliation due to alignment of elongate sutured grains (Figure 4d).

Three graphic intergrowths of clinopyroxene and ilmenite have been recovered from pipe 1. These are very similar to those described from other kimberlite localities in South Africa and North America (Eggler *et al.*, 1979; Gurney *et al.*, 1973). The largest of the three is approximately 3cm long and consists of a single crystal of diopside enclosing saddle-like rods of ilmenite, 2-3 mm in length (Figure 2b). Some ilmenite extends beyond the edge of diopside into the matrix, probably due to differential resistance to alteration between the two phases.

One rutile-ilmenite intergrowth recovered from pipe 2 consists of small ($5 \times 10 \mu\text{m}$) sigmoidal lenses of ilmenite in a rutile host. The rutile is mantled by a polycrystalline rim of ilmenite (Figure 2c). This texture is very similar to that described from South African pipes by Haggerty (1975; 1976) and Mitchell (1973).

Figure 4. Deformation and recrystallization textures in ilmenite megacrysts. Bar = 1mm.

- a. Twin lamellae near edge of megacryst.
- b. Bands of mosaic polycrystalline ilmenite.
- c. Undulose extinction in large single crystal.
- d. Sutured grain boundaries.

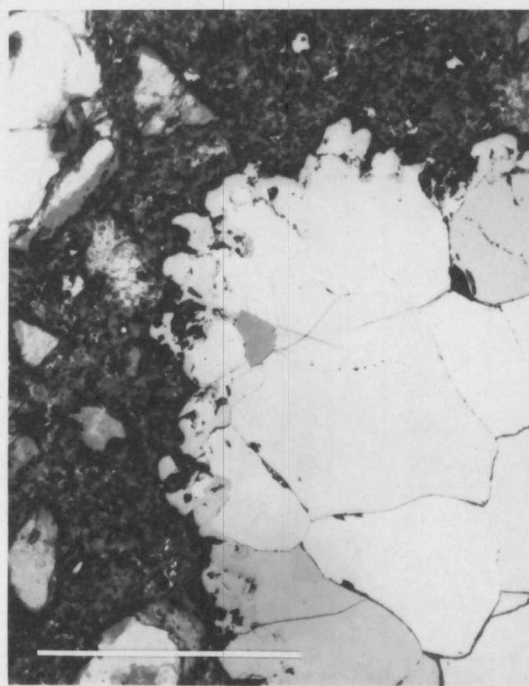
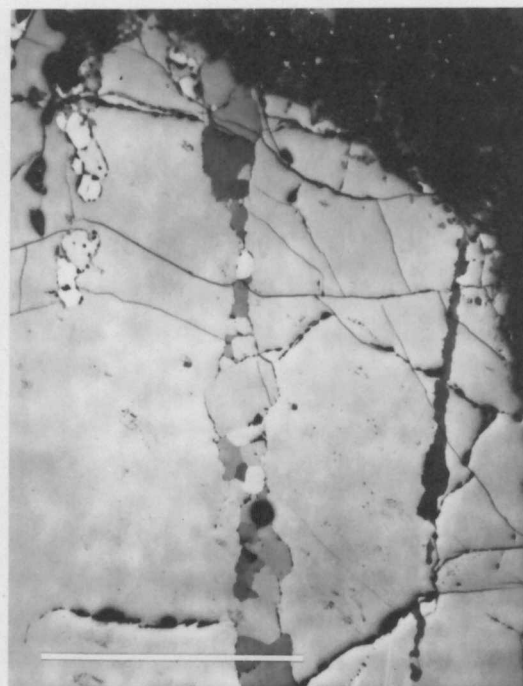
**a****b****c****d**

Figure 4

Haggerty (1975) describes two types of intergrowths: (a) those in which rutile and ilmenite are approximately equal in concentration; (b) those with dominant rutile. The first may be explained by the breakdown of armalcolite (Fe,Mg) Ti_2O_5 (Haggerty, 1975). For those with minor ilmenite, exsolution of ilmenite from a host rutile which contained a few percent FeO in solid solution is considered to be the most likely mechanism.

Anhedral single crystals of ilmenite ranging from a few microns to 1.0mm in diameter occur throughout the groundmass of the kimberlite and in this study are classified as groundmass ilmenites (Figure 2d). These are single crystals and show no evidence of deformation. Haggerty (1973) pointed out the difficulty of distinguishing between disaggregated ilmenite megacrysts and those which crystallized with the other groundmass phases (i.e., are second generation). Petrographic observations alone cannot separate those two ilmenite types. Work on nucleated autoliths (encasements of groundmass kimberlite surrounding an earlier-formed megacryst or xenolith, Danchin et al., 1975), demonstrates that compositional differences exist, and that most of the groundmass ilmenites are not broken megacrysts, but result from a distinctly later stage of crystallization than the ilmenite megacrysts.

Groundmass phenocrysts of olivine are euhedral to subhedral and contain inclusions of ilmenite which are uniformly rounded and reach a maximum of 25 μ m in diameter (Figure 3a).

The final petrographically-distinct ilmenite was formed in reaction rims associated with megacryst and groundmass ilmenite that was in contact with the kimberlite matrix (Figure 3b). This variety

is similar to ilmenites that have been reported from the Monastary Mine (Haggerty et al., 1979) and the Premier Mine, South Africa (Wyatt, 1979).

Spinel

Four different types of spinel are recognized on the basis of color and textural relations: (1) pale blue chromite; (2) grey-blue pleonaste; (3) brown spinel; and (4) brown spinel rods in ilmenite. Types 1, 2 and 3 occur in the matrix of the kimberlite. Type 1 is found either at the core of composite grains which have overgrowths of type 2 (Figure 5a) or as single crystals ($\leq 30\mu\text{m}$). In addition to the overgrowths surrounding chromite type 2 is present as single crystals ($\leq 30\mu\text{m}$) in the matrix. The third spinel is associated with perovskite in reaction rims around ilmenite or as single crystals ($\leq 75\mu\text{m}$) in the matrix (Figure 5b). Type 4 spinel occurs as small ($1 \times 5\mu\text{m}$) rods exsolved from ilmenite (Figure 5c). Texturally, it is similar to those exsolved from ilmenites at the Premier Mine, South Africa (Danchin and D'Orey, 1972). The presence of these exsolution spinels is limited. However, they are found in three of the six types of ilmenite: (1) megacrysts, (4) groundmass, and (5) inclusions in olivine.

Perovskite

Perovskite occurs in two-textural types: (1) as discrete, equant, anhedral blebs approximately $30\mu\text{m}$ across scattered throughout the groundmass and (2) in reaction rims around earlier-formed ilmenites, which were in contact with the kimberlite matrix. This latter type predominates (Figure 5b). It is developed as a zone around ilmenite

Figure 5. Reflected light photomicrographs of spinel and pervoskite.

- a. Composite grain of chromite rimmed by pleonaste spinel. Bar = μm .
- b. Reaction selvage on ilmenite megacryst, note islands of ilmenite within perovskite and magnetite. Bar = $100\mu\text{m}$.
- c. Spinel "exsolution" rods in ilmenite. Bar = $40\mu\text{m}$.

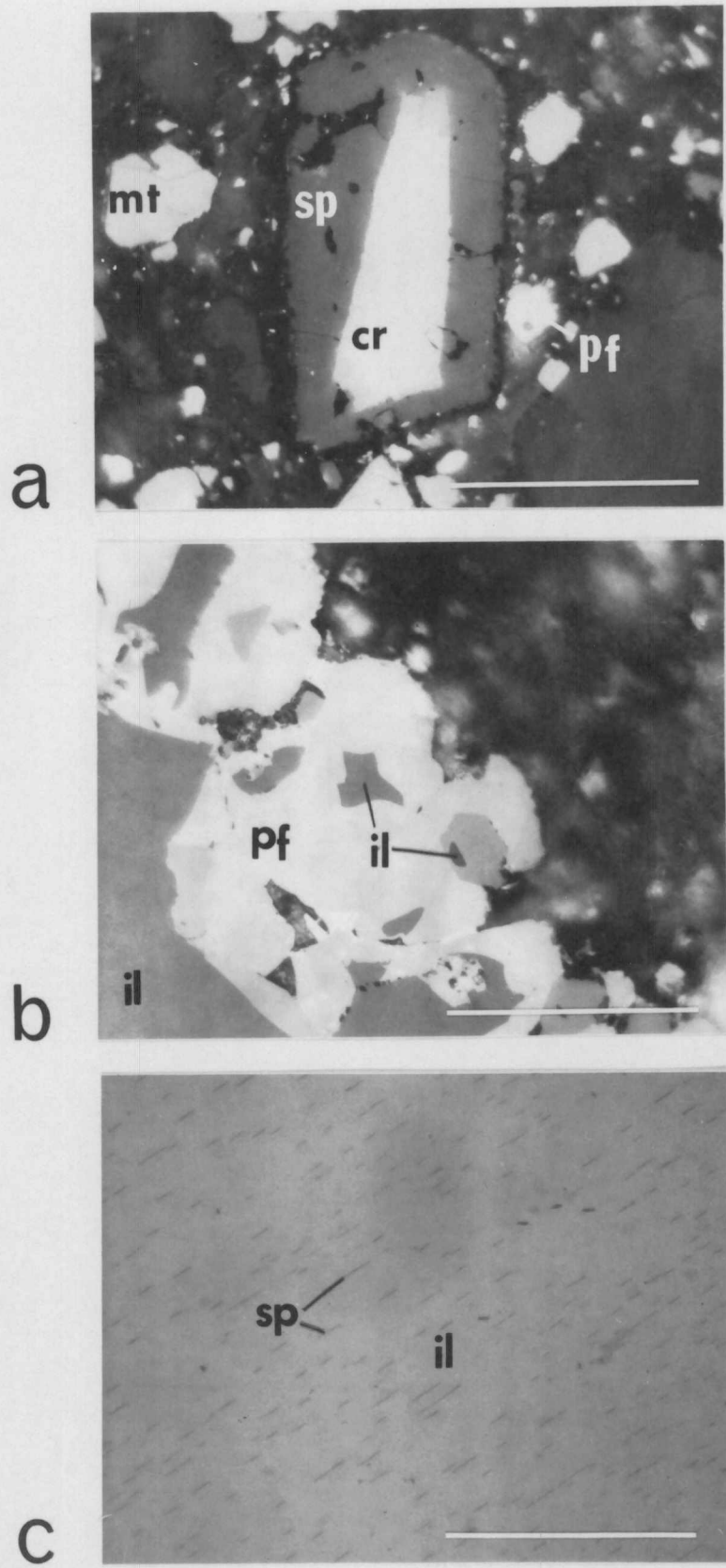


Figure 5

with a fritted, digitate boundary of perovskite projecting into the ilmenite. The width of this zone is variable but is usually 50-75 μ m. Rimming the outer boundaries of the perovskite is a discontinuous zone of subhedral type 3 spinel. These spinels are $\leq 50\mu$ m and some have inclusions of ilmenite in optical continuity with the large ilmenite in the core (Figure 5b). Similar ilmenite inclusions are found in the perovskite (Figure 5b), indicating that the ilmenite has undergone extensive reaction, leaving the remnants of ilmenite as islands. Between the spinel and perovskite are rare occurrences of the type 6 ilmenite (Figure 3b).

CHAPTER III

MINERAL CHEMISTRY

Ilmenite

Kimberlitic ilmenites are characterized by their high MgO and Fe_2O_3 content and can best be represented in the ternary system Fe_2O_3 - MgTiO_3 - FeTiO_3 . Figure 6 shows the range of compositions from a number of kimberlite localities. Many of the published chemical analyses of kimberlitic ilmenites are either heavily weighted toward the megacrysts or textural details are not included with the analyses. As can be seen in Figure 6, the ilmenites from Elliott County occur in two distinct populations: the megacrysts and the more Mg-rich ground-mass ilmenites. Data from this study, as well as from Haggerty *et al.*, (1979), Elthan and Ridley (1979), and Boctor and Meyer (1979), indicate that distinct compositional populations characterize different textural types of kimberlitic ilmenite.

The compositional range of ilmenite megacrysts from Elliott County pipes 1 and 2 are shown in an expanded portion of the hematite-geikelite-ilmenite ternary in Figure 7. Analyses covering a range of compositions are presented in Table 1. Megacryst core compositions produce a well-defined trend from approximately 46 mole % to 32 mole % MgTiO_3 . Accompanying this decrease in MgTiO_3 is an increase in Fe_2O_3 (6.3 to 15 mole %) and FeTiO_3 (from 46 to 54 mole %). Figure 8 is a plot of MgO versus Fe_2O_3 . The megacrysts show a trend of increasing Fe_2O_3 with decreasing MgO. This MgO decrease is expected from normal igneous fractionation.

Figure 6. Ilmenite compositions from Elliott County compared to ilmenites from South Africa (Haggerty, 1975; Mitchell, 1973). All data in Mol. %.

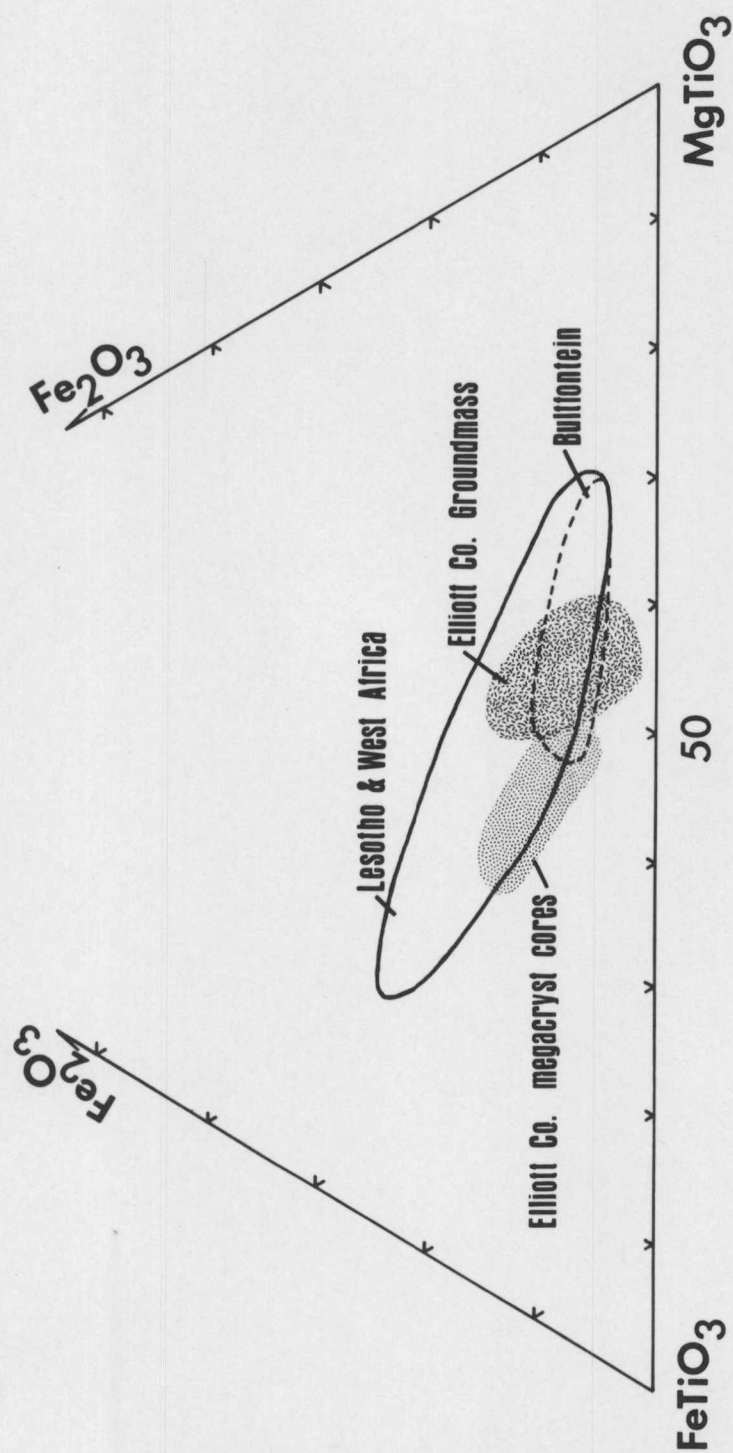


Figure 6

Figure 7. Compositions of different textural types of ilmenite from Elliott County.

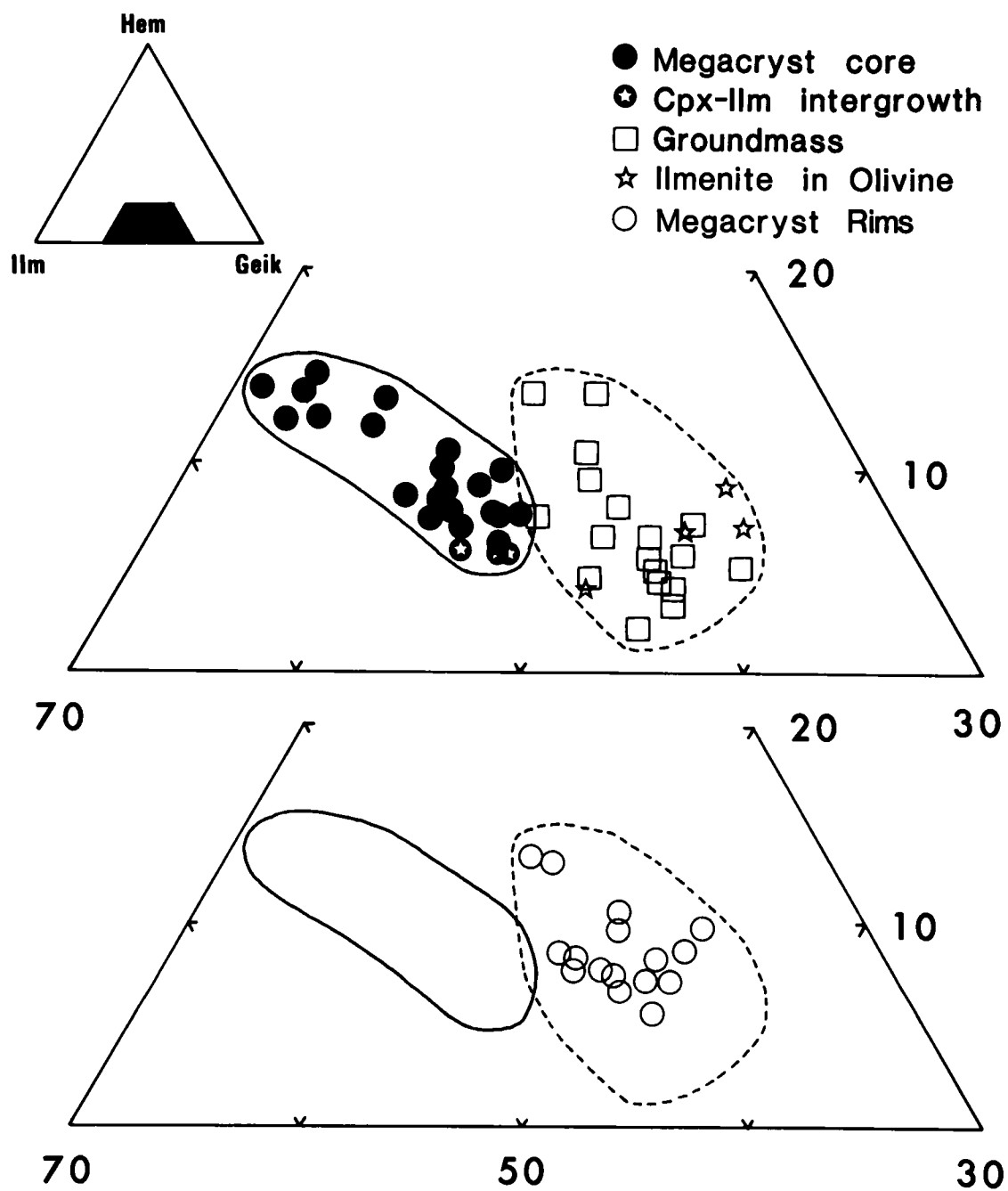


Figure 7

Table 1. Representative average analyses of ilmenite megacrysts.

	Pipe 1				Pipe 2				Cpx-ilm intergrowth
	megacryst		megacryst		megacryst		megacryst		
	core	rim	core	rim	core	rim	core	rim	
TiO ₂	52.3 (4) *	53.4 (2)	48.2 (2)	48.9 (5)	53.0 (4)	53.7 (2)	52.0 (2)	53.5 (5)	54.2 (3)
Al ₂ O ₃	0.63(4)	0.62(2)	0.39(2)	0.52(4)	0.65(3)	0.66(3)	0.61(1)	0.53(1)	0.57(4)
Cr ₂ O ₃	0.07(1)	0.07(4)	0.27(2)	0.30(1)	0.09(2)	0.09(1)	n.d.**	0.35(3)	0.33(2)
Fe ₂ O ₃ ***	9.44	8.95	16.4	15.0	8.86	9.29	9.22	7.58	6.71
FeO	24.6 (6)	23.5 (8)	25.7 (6)	21.5 (9)	25.2 (4)	21.5 (7)	25.9 (8)	21.8 (6)	25.7 (2)
MnO	0.28(3)	0.43(5)	0.31(3)	0.41(1)	0.29(3)	0.39(3)	0.26(2)	0.44(2)	0.24(3)
MgO	12.5 (1)	13.5 (2)	9.33(2)	12.6 (6)	12.6 (1)	15.0 (3)	11.7 (4)	14.6 (1)	13.0 (1)
NiO	n.d.	0.04(3)	n.d.	0.10(1)	n.d.	0.04(2)	n.d.	0.07(6)	0.09(4)
Σ	99.82	100.51	100.60	99.33	100.69	100.67	99.69	98.87	100.84
Cation Basis	3	3	3	3	3	3	3	3	3
Al	0.017	0.017	0.011	0.014	0.018	0.018	0.017	0.014	0.015
Cr	0.001	0.001	0.005	0.006	0.002	0.002	---	0.006	0.005
Ti	0.908	0.913	0.853	0.856	0.910	0.913	0.909	0.923	0.927
Fe ⁺³	0.164	0.153	0.291	0.261	0.152	0.155	0.161	0.131	0.115
Mg	0.430	0.459	0.327	0.437	0.431	0.501	0.404	0.418	0.442
Ni	---	0.001	---	0.001	---	0.001	---	0.001	0.001
Fe ⁺²	0.475	0.448	0.506	0.417	0.480	0.404	0.504	0.418	0.490
Mn	0.005	0.008	0.006	0.008	0.006	0.007	0.005	0.009	0.005
Σ	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000

* units in (1) represent 1 standard deviation of replicate analyses in terms of least units cited.

** n.d. = not detected; less than 0.03%.

*** Fe determined as FeO; oxides based on crystal chemistry.

Figure 8. Electron-microprobe traverse showing compositional variation across the rim of an ilmenite megacryst.

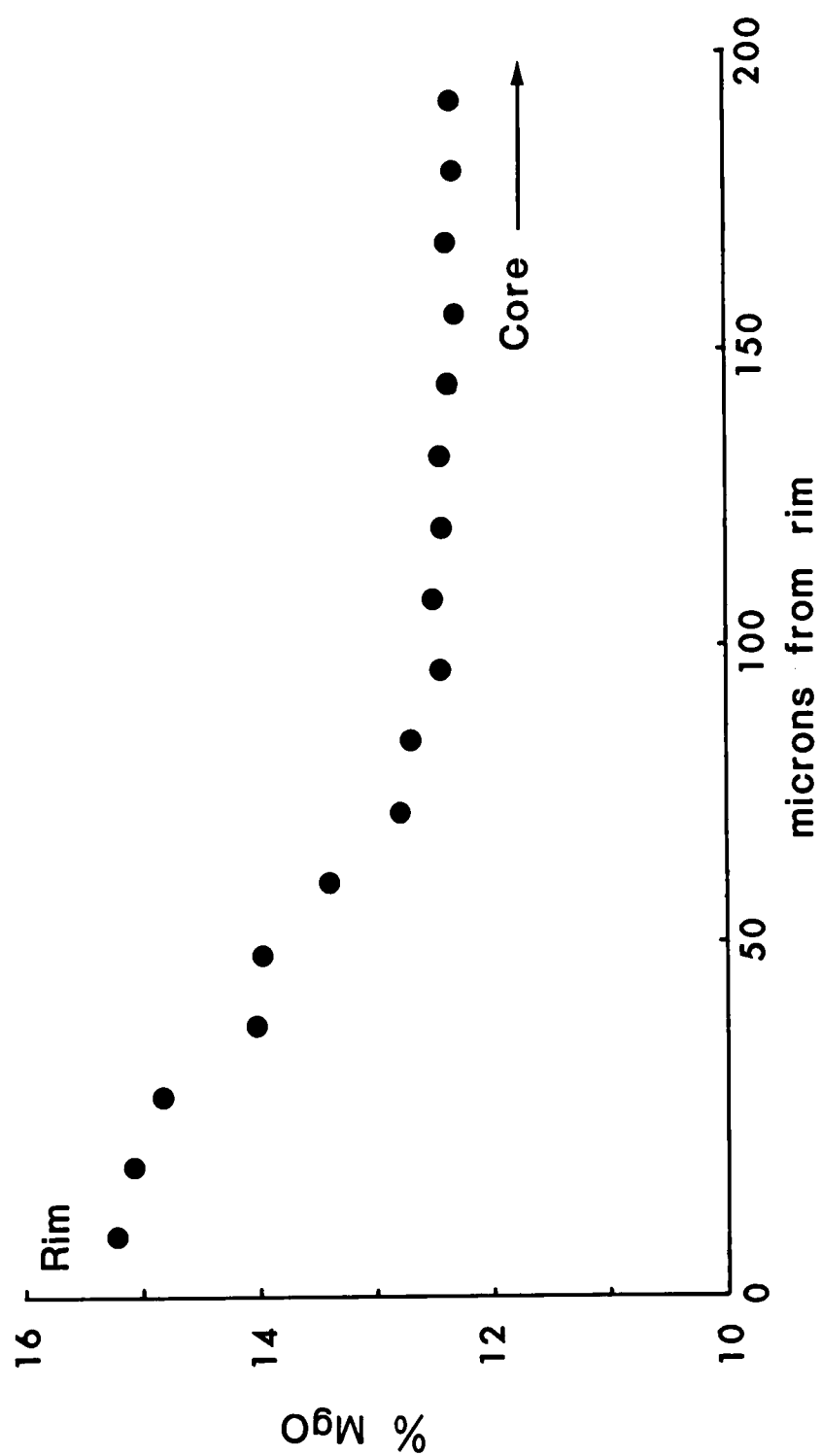


Figure 8

Rims of ilmenite megacrysts show a distinct increase in MgTiO_3 content (46 to 54%) relative to the core composition (32 to 47%, Figure 7, Table 1) and have similar Fe_2O_3 content (4.4 to 10.3 mole % Fe_2O_3) to the megacryst core. There appears to be a well-developed smooth diffusion profile between the megacryst core and the high Mg rim (Figure 9). This profile is developed over a distance of at least 75-100 μm , although the true extent cannot be determined due to the extensive reaction rim of perovskite + titano-magnetite + Mn - ilmenite. Haggerty *et al.* (1979) noted similar compositional zonations in megacryst ilmenites from the Monastary Mine, South Africa and referred to it as the magmatic reaction trend. Elthan and Ridley (1979) also found an increase in MgO near the rims of ilmenites from the Premier Mine.

Ilmenites from the clinopyroxene-ilmenite intergrowths are low in Fe_2O_3 (5.4 to 5.8 mole % Fe_2O_3) but compositionally overlap the more MgO-rich cores of the megacrysts (47 to 53 mole % MgTiO_3 , Figure 7). Although lower in Cr_2O_3 , clinopyroxenes from the clinopyroxene-ilmenite intergrowths (0.06 to 0.38 % Cr_2O_3) have compositions similar to the clinopyroxene megacrysts and have estimates equilibration temperatures (1295-1335 $^{\circ}\text{C}$) which overlap them (1305-1390 $^{\circ}\text{C}$) (Garrison and Taylor, 1980).

The silicate megacrysts at Elliott County also contain well-defined chemical trends (Garrison and Taylor, 1980). Garnet megacrysts display a depletion of Cr_2O_3 (0.21 to 9.07%) with decreasing Mg/Mg+Fe (0.86 to 0.79). Olivine shows a decrease in NiO (from 0.5 to 0.05%) with decreasing Mg/Mg+Fe (0.93 to 0.85), clinopyroxene megacrysts show increasing TiO_2 (0.38 to 0.56%) and decreasing Cr_2O_3 (0.88 to 0.56%)

Figure 9. Compositions of different textural types of ilmenite from Elliott County showing the major variations in kimberlitic ilmenites. All data in wt. %.

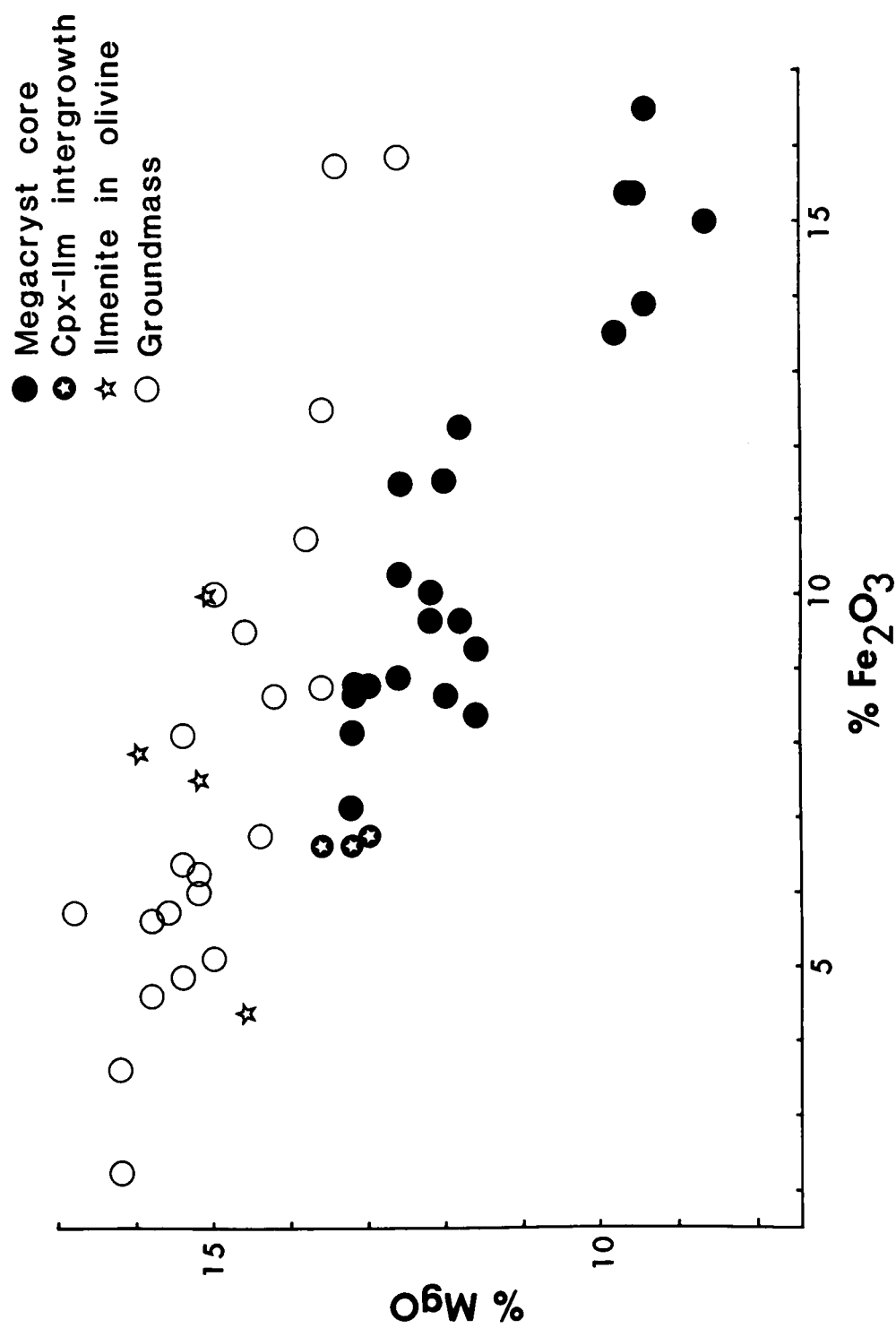


Figure 9

with decreasing $Mg/Mg+Fe$ (0.91 to 0.87). The above trends in megacrysts are attributed to fractional crystallization (Garrison and Taylor, 1980).

The presence of fractionation trends in both the megacryst ilmenites and silicates, the overlap in composition between ilmenite and clinopyroxene megacrysts with those in the clinopyroxene-ilmenite intergrowths and the overlapping temperature ranges of the intergrowths with clinopyroxene megacrysts suggest that the ilmenite and silicate megacrysts were derived from the same magma.

Compositional zonation of megacrysts is not restricted to the ilmenites. Megacryst olivines have cores with Mg that range from 0.93 - 0.85. The rims of these olivines all have Mg between 0.90 - 0.89. In addition the rims are enriched in CaO and depleted in NiO relative to the cores (Garrison and Taylor, 1980).

Groundmass ilmenites, including those as inclusions in euhedral groundmass olivines (Figure 7 and Figure 9, Table 2) are distinctly richer in $MgTiO_3$ than megacryst cores (46 to 57 mole % $MgTiO_3$). They show a wide range of Fe_2O_3 (1.5 to 14 mole % Fe_2O_3) and an enrichment in Fe_2O_3 with decreasing MgO similar to the trends developed by the megacryst cores. The rims of megacrysts (Figure 7) show a compositional overlap with the groundmass ilmenites indicating that the earlier-formed megacrysts were in the process of re-equilibration with the more Mg -rich composition of later-stage groundmass ilmenites.

Previous workers have pointed out the difficulty in distinguishing groundmass ilmenite from disaggregated megacrysts. The ilmenite inclusions in second generation euhedral olivine phenocrysts at Elliott County demonstrates that a more magnesian second stage of ilmenite

Table 2. Representative analyses of Type III, IV, V, and VI ilmenites.

	Pipe 1		Pipe 2		inclusion in olivine	lamellae in rutile	rim of rutile	Type VI
	groundmass	groundmass	groundmass	groundmass				
TiO ₂	55.8	53.3	55.4	51.2	52.3	58.7	57.9	48.3
Al ₂ O ₃	0.29	0.66	0.32	0.96	0.89	n.d.**	0.34	0.41
Cr ₂ O ₃	1.69	0.13	2.71	0.34	4.42	0.06	0.21	0.96
Fe ₂ O ₃ *	5.72	8.72	5.15	12.5	7.86	---	1.86	11.3
FeO	19.8	23.6	20.6	21.5	18.4	28.1	24.4	27.0
MnO	0.54	0.34	0.51	0.45	0.26	0.39	0.60	8.69
MgO	16.8	13.6	16.3	13.6	16.0	13.0	15.4	4.47
NiO	0.07	n.d.	0.14	0.12	0.16	n.d.	n.d.	n.d.
Σ	100.71	100.35	100.13	100.67	100.29	100.25	100.71	101.13
Cation Basis	3	3	3	3	3	3	3	3
Al	0.008	0.018	0.008	0.026	0.024	---	0.009	0.012
Cr	0.030	0.002	0.048	0.006	0.078	0.001	0.004	0.018
Ti	0.932	0.913	0.927	0.874	0.880	1.005	0.975	0.879
Fe ⁺³	0.096	0.150	0.086	0.214	0.133	---	0.031	0.207
Mg	0.556	0.461	0.538	0.462	0.533	0.537	0.513	0.161
Ni	0.001	---	0.002	0.002	0.002	---	---	---
Fe ⁺²	0.367	0.449	0.382	0.408	0.345	0.440	0.456	0.546
Mn	0.010	0.007	0.010	0.009	0.005	0.007	0.011	0.177
Σ	2.000	2.000	2.000	2.000	2.000	1.990	2.000	2.000

* Fe determined as FeO; oxides based on crystal chemistry.
 **n.d. = not detected; less than 0.03%.

crystallization occurs after the megacrysts have formed. The existence of late-stage Mg-rich groundmass ilmenites is also supported by the work on nucleated autoliths (Danchin et al., 1975) from ten separate South African kimberlites; their study revealed that small Mg-rich ilmenites are common within autoliths which surround silicate and less Mg ilmenite megacrysts.

On a plot of Cr_2O_3 versus MgO the relationship between Cr_2O_3 and MgO in kimberlitic ilmenites characteristically shows a "parabolic" configuration (Figure 10; Haggerty, 1975). Haggerty was unable to explain this parabolic distribution. When the compositions of groundmass and megacryst ilmenites from Elliott County are plotted on this diagram, an interesting pattern is revealed (Figure 10). The compositions from the single kimberlite occurrence at Elliott County form the right-hand portion of a parabola, though they are high in MgO and have greater dispersion than the data from Haggerty's compilation. At Elliott County the right-hand portion of a "parabola" is formed as a result of including two populations of ilmenite on the graph. Groundmass ilmenites are restricted to the right (high MgO) side while the less magnesian megacrysts occupy the left.

The earlier megacrysts show little variation in Cr_2O_3 with crystallization; the later-stage groundmass ilmenites have a wide range of Cr_2O_3 . This range from high to low Cr_2O_3 in groundmass ilmenites may be due to the appearance of Cr-spinel as a groundmass phase.

The composition of the rutile-ilmenite intergrowths are given in Tables 2 and 3. The low total of the rutile analysis (Table 3) reflects the presence of Nb which was detected by energy dispersive

Figure 10. Compositions of different textural types of ilmenite from Elliott County. The "parabolic" curve is taken from Haggerty (1975) and is in reference to South African kimberlites.

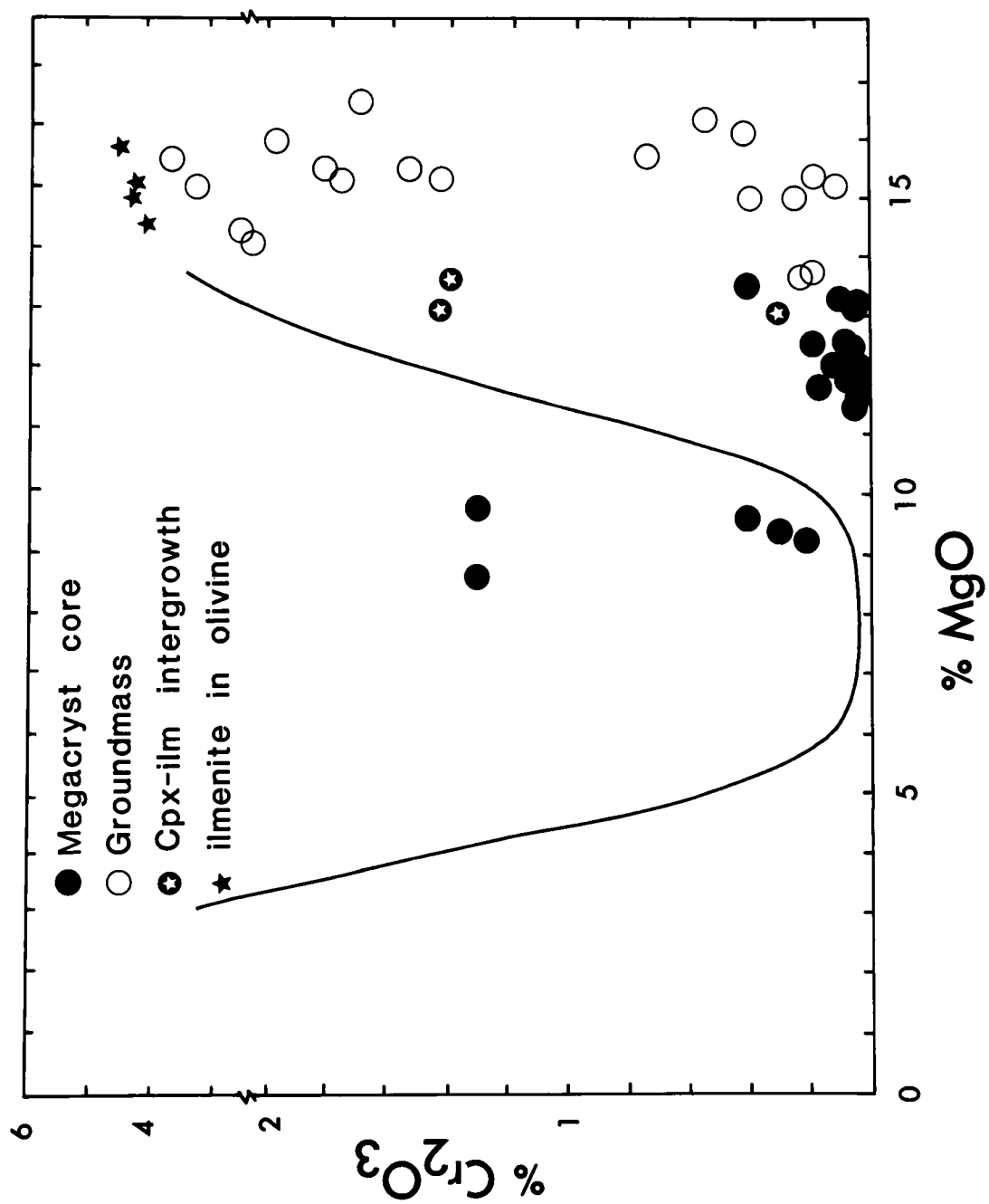


Figure 10

Table 3. Representative analyses of spinels, rutile, and perovskite.

	Type I spinel		Type II spinel		Type III spinel		perovskite	rutile
SiO ₂	n.a.*	n.a.	n.a.	n.a.	n.a.	n.a.	0.09	n.a.
TiO ₂	1.52	3.85	2.05	3.27	21.5	21.0	57.6	97.6
Al ₂ O ₃	8.02	8.70	50.5	46.1	8.48	10.0	0.33	0.11
Cr ₂ O ₃	51.3	49.8	5.78	6.07	2.07	0.46	0.16	n.d.***
Fe ₂ O ₃ **	9.55	8.24	9.78	12.1	27.8	25.5	---	n.d.
FeO	17.0	18.2	11.0	10.1	17.4	22.7	1.40	0.05
MnO	0.52	0.53	0.21	0.11	0.87	0.89	0.13	n.d.
MgO	11.0	12.2	19.8	20.4	22.6	18.4	0.23	n.d.
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CaO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	38.6	n.a.
Σ	98.91	101.52	99.12	98.15	100.72	98.95	98.54	97.76
Cation Basis	4	4	4	4	4	4	3	2
Si	---	---	---	---	---	---	0.001	---
Al	0.317	0.333	1.596	1.488	0.306	0.376	0.008	0.001
Cr	1.363	1.273	0.123	0.131	0.050	0.012	0.002	---
Ti	0.038	0.095	0.041	0.066	0.502	0.498	0.994	0.999
Fe ⁺³	0.241	0.200	0.197	0.249	0.642	0.610	---	---
Mg	0.549	0.590	0.793	0.832	1.034	0.874	0.007	---
Ni	---	---	---	---	---	---	---	---
Fe ⁺²	0.478	0.493	0.245	0.231	0.443	0.605	0.026	---
Mn	0.015	0.015	0.005	0.003	0.023	0.024	0.002	---
Ca	---	---	---	---	---	---	0.951	---
Σ	3.000	3.000	3.000	3.000	3.000	3.000	1.991	1.000

* n.a. = not analyzed. ** Fe determined as FeO; oxides based on crystal chemistry. *** n.d. = not detected.

analysis (EDA). Ilmenite lamellae within the rutile (Table 2) are essentially free of Fe^{3+} . Ilmenite of the rim of the intergrowth has a small amount of Fe_2O_3 and is high in MgO (1.5 mole % Fe_2O_3 , 51.0 mole % MgTiO_3) similar to the groundmass ilmenites. These rim ilmenites display no compositional zoning, suggesting that the ilmenite rim formed at the time of groundmass ilmenite crystallization.

The textural type 6 ilmenite at Elliott County is the high-Mn variety found in the perovskite-spinel reaction rims (18% MnTiO_3 ; 16% MgTiO_3 , Table 2). High-Mn ilmenites have been described in kimberlite by Haggerty (1979), Hsu and Taylor (1972), Boctor and Meyer (1979) and Wyatt (1979). In each case they are associated with late-stage reaction rims or occur in cracks. In the study of Wyatt (1979), the MnTiO_3 content of ilmenites from the Premier Mine was found to increase toward the rim of the grains. These zoned ilmenites are found only in the margins of the kimberlite pipe and in the country rock dikes. Those in the core region of the kimberlite bodies are unzoned and low in MnTiO_3 . Ilmenites found in carbonate-rich portions of the core area show no increase in MnO toward the rim which would seem to contradict the explanation of Haggerty (1979) that accounts for the increased MnO activity as coinciding with the beginning of carbonatitic immiscibility. Wyatt (1979) concluded that high-Mn ilmenites form during post-magmatic interaction of kimberlite with meteoric waters; the Mn^{2+} source being the Transvaal dolomite or country rock felsites into which the kimberlite has intruded. Carbonate wall rock clasts are abundant in the Elliott County kimberlite and offer one possible Mn^{2+} source.

Spinels

The compositional fields for spinels from Elliott County are plotted in a spinel prism (Figure 11) using the method of Irvine (1965). Representative analyses are given in Table 3. Because of the presence of considerable Fe_2TiO_4 the range of ulvospinel component is given on the diagram. The typical kimberlite trend (Haggerty 1976) of early Cr- and Al-rich spinels followed by late-stage crystallization of spinels enriched in Fe^{3+} and Ti is readily seen at Elliott County. This compositional change from Cr- and Al-rich to Fe^{3+} and Ti-rich indicates a late-stage increase in Fe^{3+} in the kimberlite associated with the reaction of ilmenite to form perovskite plus spinel. Haggerty explained this as an increase in the activity of TiO_2 in the melt. However, the association of these magnetites with perovskite plus Mn-ilmenite suggests a secondary origin.

Perovskite

The composition of perovskite shows little variation whether on the rim of an ilmenite or as discrete grains in the matrix (Table 3). They show only minor FeO and MgO in solid solution and are enriched Nb and REE. Boctor and Meyer (1977) considered the abundance of Nb and other REE in perovskite reaction mantles of ilmenites, from the Green Mountain Colorado kimberlite, to be the result of carbonate complexing of the REE's which stabilized them until the late-stage crystallization of the residual kimberlitic fluids. They suggest that the separation of an immiscible carbonate-rich fluid from the kimberlite is responsible for the perovskite compositions. At Green Mountain, REE's were particularly enriched in perovskites in contact

Figure 11. Compositional fields of different spinel types from Elliott County. Range in Mol. % Fe_2TiO_4 is given for each spinel type.

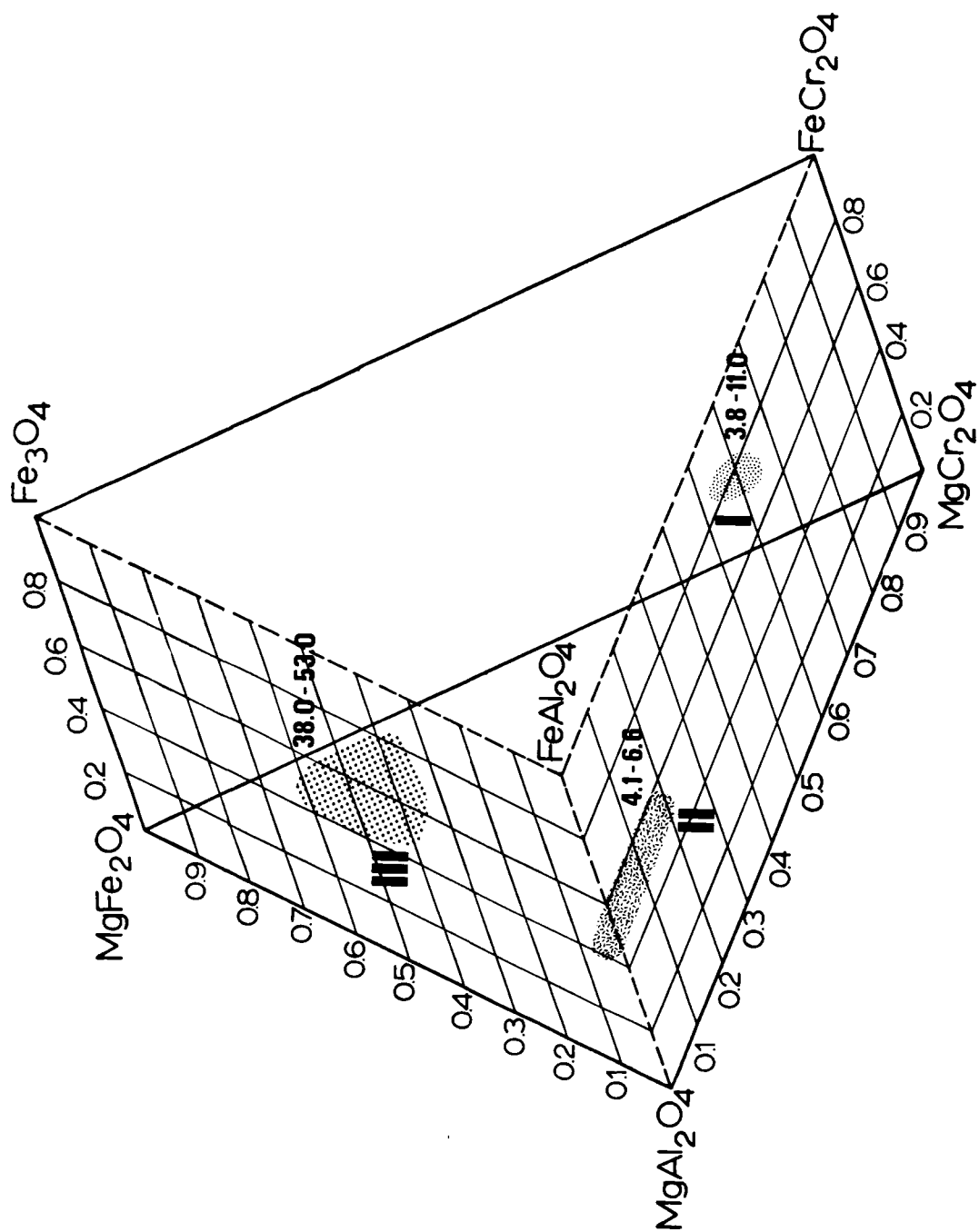


Figure 11

with calcite. Therefore, it would seem that the equilibria between CaO-CO-CO_2 in the kimberlite and the ilmenite, control the perovskite composition. Haggerty (1973) suggested late-stage CO-CO_2 variation and high activity of TiO_2 were responsible for the reaction rim spinels around ilmenites at Liqhobong in Lesotho.

It appears that the late-stage perovskite and spinels may be related to the following reactions:

1. $\text{CaCO}_3 \rightleftharpoons \text{CaO} + \text{CO}_2$ ($\text{CO} \rightleftharpoons \text{CO}_2$ controlling $f\text{O}_2$)
2. $2\text{Ca}_{\text{fluid}}^{+2} \rightleftharpoons \text{O}_{2\text{fluid}} + 3(\text{Fe, Mg}) \text{TiO}_3 + \text{Fe}_2\text{O}_{3\text{ss}} \rightleftharpoons 2\text{CaTiO}_3 + (\text{Fe, Mg})_2\text{TiO}_4 + (\text{Fe, Mg}) \text{Fe}_2\text{O}_{4\text{ss}}$

Obviously these are not the only chemical components involved. Al_2O_3 is also present in the spinel; however, the above mechanism would explain the major element compositions and the late-stage increase in $f\text{O}_2$ as indicated by the spinels.

CHAPTER IV

PETROGENESIS

Previous investigations of oxide minerals in kimberlite (e.g. Haggerty, 1973, 1975, 1979; Danchin et al., 1975) have dealt with the mineralogy of the megacrysts and/or groundmass, as well as with compilations of data from many localities. The Elliott County kimberlite is well-preserved and permits investigation of ilmenite megacrysts and groundmass oxides from a single kimberlite occurrence. The relationship between these different generations of minerals are complex; however, the processes operative in the magma which produced the kimberlite can be separated into three distinct stages of kimberlite evolution: (1) the formation of the megacrysts, (2) the crystallization of the groundmass, with accompanying megacryst back reaction, and (3) late-stage reaction of ilmenite to perovskite and spinel.

The ilmenite, as well as silicate, megacrysts could have originated by two processes: (1) disaggregation of peridotite to form individual mineral grains (Smith et al., 1979) or (2) direct precipitation from a proto-kimberlitic liquid (Eggler et al., 1979; Garrison and Taylor, 1980). The latter origin is preferred for the ilmenite megacrysts at Elliott County because: (1) the ilmenite megacrysts display fractionation trends, (2) the sizes of megacrysts (0.5-2cm) are larger than the grain sizes of peridotites and xenoliths, and (3) ilmenite is extremely rare in peridotite xenoliths.

Inspection of the compositional data from Elliott County megacryst ilmenites reveals two fractionation trends. First, the major

chemical fractionation trend consists of an increase in Fe_2O_3 and FeO with a corresponding decrease in MgO (Figure 7). Mitchell (1979) also noted that Fe_2O_3 was the major species which varied inversely to MgO in megacryst ilmenites from Tunraq (N.W.T., Canada). Secondly, the rims of the ilmenites have increased MgO content, a reversal from the normal fractionation scheme.

Gurney et al. (1979) studied a large number of silicate-ilmenite intergrowths from the Monastary Mine and demonstrated co-variance of MgO between ilmenite and silicates. They suggest that Fe_2O_3 increases in ilmenite may be due to an increase in $f\text{O}_2$ as the kimberlite evolved. Alternatively, increasing Fe_2O_3 in ilmenite may be due to an increase in the $\text{Fe}_2\text{O}_3/\text{FeO}+\text{MgO}$ ratio in the melt as the dominant silicate megacryst phases progressively remove the divalent species. Either mechanism progressively enriches ilmenite in Fe_2O_3 . Therefore, MgO versus Fe_2O_3 in kimberlitic ilmenite is of potential value as a differentiation index.

Pyroxene geothermometry of Elliott County megacrysts (Garrison and Taylor, 1980) shows that pipe 1 clinopyroxenes equilibrated at 1305-1390°C. The clinopyroxene from clinopyroxene-ilmenite intergrowths have equilibration temperatures of 1295-1335°C, suggesting that clinopyroxene was later joined by ilmenite during crystallization of the megacryst suite. The clinopyroxene, garnet, and olivine megacrysts were considered to be derived from a fractionating liquid (Garrison and Taylor, 1980), and the data from the present study indicate that ilmenite megacrysts were derived from the same proto-kimberlitic magma.

Kimberlitic groundmass minerals (e.g. olivine, ilmenite, orthopyroxene) commonly are more magnesian than the more fractionated

members of the megacryst suite (Boctor and Meyer, 1979; Garrison and Taylor, 1980). The groundmass minerals at Elliott County are olivine, ilmenite, orthopyroxene, phlogopite, spinels, rutile and perovskite. The groundmass ilmenite is clearly separated from the megacryst by their high-Mg contents (Figures 7 and 9). The rims of ilmenite megacrysts have equilibrated to compositions which overlap those of the groundmass ilmenite (Figure 7), demonstrating that reverse zoning in megacryst rims is related to the re-equilibration of the earlier megacrysts with the MgO-rich liquid that is crystallizing groundmass minerals.

The presence of rutile in kimberlite has been attributed to the breakdown of armalcolite ($(\text{Fe}, \text{Mg})\text{Ti}_2\text{O}_5$) when it is found in approximately equal amounts as intergrowths of ilmenite and rutile (Haggerty, 1975). The rutile in Elliott County contains less than 2% ilmenite lamellae and cannot be explained by such a mechanism. Haggerty (1976) and Mitchell (1973; 1979) have noted similar forms of rutile from kimberlite in South Africa and Canada. In all three cases, as well as at Elliott County, the rutile is surrounded by ilmenite. Mitchell noted in both studies that the ilmenite surrounding rutile was more magnesian than the megacrysts. At Elliott County, the ilmenite in the rim is also high in MgTiO_3 (52 mole %); it is compositionally similar to the groundmass ilmenites.

Experimental studies (Wyatt, 1979) indicate that the presence of a Cr_2O_3 -rich liquid can stabilize rutile + Cr-spinel and halt the crystallization of ilmenite. If the magma present at the beginning of groundmass crystallization is enriched in Cr_2O_3 , which is evidenced by high- Cr_2O_3 ilmenites up to 4.60% and chromite (51.3%, Cr_2O_3) as the

earliest spinel, then the first Ti-rich phase to crystallize in the groundmass would be rutile, in addition to chrome-spinel. As Cr_2O_3 was progressively depleted in the liquid, ilmenite would again become stable and an early Cr_2O_3 -rich ilmenite would form (i.e., the righthand side of Figure 10). Later ilmenites would become depleted in Cr_2O_3 with crystallization, and the spinels would become more aluminous with crystallization (Figure 11).

The late-stage crystallization of the kimberlite involves the reaction of ilmenite to form perovskite + Ti-magnetite. This reaction suggests a late increase in $f\text{O}_2$ (resulting in magnetite) and an increase in the availability of CaO. The reaction assemblage is also associated with the late-stage formation of high-MnO ilmenite similar to that described by Wyatt (1979) from Premier Mine. He attributed this to deuteric alteration involving the carbonate country rocks. The Elliott County kimberlite contains many xenoliths of carbonate country rocks. If the kimberlite contained residual fluids which interacted with these, thus providing $\text{CaO} + \text{CO}_2$, the reaction of ilmenite to form perovskite and Ti-magnetite would proceed. The very late nature of the reaction is supported by the fact that if the reaction were to occur much earlier in the emplacement history, the delicate fingers of spinel and perovskite surrounding the ilmenite would certainly have been abraded away.

CHAPTER V

SUMMARY

In summary, the oxide minerals at Elliott County are related to three distinct stages in the evolution of the kimberlite. Initial crystallization of ilmenite megacrysts, along with clinopyroxene, orthopyroxene, olivine, garnet and phlogopite (the megacryst assemblage) occurs in a fractionating proto-kimberlitic magma at depths of 150-200km in the upper mantle. The second stage consists of the crystallization of groundmass phases from a liquid that has been enriched in MgO. This Mg enrichment may be due to a decrease in the $\text{FeO}/\text{Fe}_2\text{O}_3$ ratio in the melt (Gurney *et al.*, 1979) or may be caused by the assimilation of carbonated peridotite (Garrison and Taylor, 1980). Rutile and chromite are the earliest oxide minerals to crystallize during this stage, and as the liquid is depleted in Cr_2O_3 , Mg-enriched groundmass ilmenite begins to crystallize. At this point the earlier megacryst ilmenites react to form Mg-rich rims with compositions similar to the groundmass. The last event is the third-stage reaction of ilmenite to form perovskite plus titaniferous magnetite. This may be a consequence of the intrusion of the kimberlite through the carbonate country rocks.

LIST OF REFERENCES

LIST OF REFERENCES

- Albee, A. L. and Ray, L. (1970) Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates. Anal. Chem., 42, p. 1408-1414.
- Barr, A. J., Goodnight, J. H., Sall, J. P., Blair, W. H., and Chilko, D. M. (1979) SAS Users Guide: SAS Institute Inc., 494 p.
- Bence, A. E. and Albee, A. L. (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. J. Geol., 76, p. 382-403.
- Boctor, N. Z. and Meyer, H. O. A. (1979) Oxide and sulphide minerals in kimberlite from Green Mountain, Colorado. In Boyd, F. R. and Meyer, H. O. A., ed., Kimberlites, diatremes, and diamonds: their geology, petrology, and geochemistry, p. 217-228.
- Bolivar, S. L. (1972) Kimberlite of Elliott County, Kentucky (M. S. Thesis), Eastern Kentucky University, 61, p. 8.
- Clement, C. R. (1975) The emplacement of some diatreme facies kimberlites, Phys. Chem. Earth, 9, p. 51-60.
- Danchin, R. V. and D'Orey, F. (1972) Chromian spinel exsolution in ilmenite from the Premier Mine, Transvaal, South Africa. Contrib. Mineral. and Petrol., 35, p. 43-49.
- Danchin, R. V., Ferguson, J., McIver, J. R. and Nixon, P. H. (1976) The composition of late-stage kimberlite liquids as revealed by nucleated autoliths, Phys. Chem. Earth, 9, p. 235-245.
- Dawson, J. B. and Hawthorne, J. B. (1973) Magmatic sedimentation and carbonatitic differentiation in kimberlite sills at Benfontein, South Africa, J. Geol. Soc. Lond., 129, p. 61-85.
- Eggler, D. H. and Wendlandt, R. F. (1979) Experimental studies on the relationship between kimberlite magmas and partial melting of peridotite. In Boyd, F. R. and Meyer, H. O. A., eds., Kimberlites, diatremes, and diamonds: their geology, petrology, and geochemistry, p. 330-338.
- Eggler, D. H., McCallum, M. E. and Smith, C. B. (1979) Megacryst assemblages in kimberlite from northern Colorado and southern Wyoming: petrology, geothermometry-barometry, and areal distribution. In Boyd, F. R. and Meyer, H. O. A., eds., The mantle sample: inclusions in kimberlites and other volcanics, p. 213-226.

- Elthan, D. and Ridley, W. I. (1979) The oxide and silicate mineral chemistry of a kimberlite from the Premier Mine: implications for the evolution of kimberlitic magmas. In Boyd, F. R. and Meyer, H. O. A., eds., Kimberlites, diatremes, and diamonds: their geology, petrology, and geochemistry, p. 206-216.
- Garrison, J. B. and Taylor, L. A. (1980) Megacrysts and xenoliths in kimberlite, Elliott County, Kentucky: a mantle sample from beneath the permian Appalachian plateau. Contrib. Mineral. and Petrol. (in press).
- Green, H. W. II and Gueguen, Y. (1974) Origin of kimberlite pipes by diapiric upwelling in the upper mantle, Nature, 249, p. 617-620.
- Gurney, J. J., Fesq, H. W. and Kable, E. J. D. (1973) Clinopyroxene-ilmenite intergrowths from kimberlite; a re-appraisal. In Nixon, P. H., ed., Lesotho kimberlites, p. 238-253.
- Haggerty, S. E. (1973) Spinel of unique composition associated with ilmenite reaction mantles in the Lihobong kimberlite pipe, Lesotho. In Nixon, P. H., ed., Lesotho kimberlites, p. 149-158.
- Haggerty, S. E. (1975) The chemistry and genesis of opaque minerals in kimberlites, Phys. Chem. Earth, 9, p. 295-307.
- Haggerty, S. E. (1976) Opaque mineral oxides in terrestrial igneous rocks. In Rumble, D., ed., Oxide minerals, Hg 117-Hg 227.
- Haggerty, S. E., Hardie, R. B. III, and McMahon, B. M. (1979) The mineral chemistry of ilmenite nodule associations from the Monastery diatreme. In Boyd, F. A. and Meyer, H. O. A., eds., The mantle sample: inclusions in kimberlites and other volcanics, p. 249-256.
- Hunter, W. C. and Smith, D. (1979) Chemistry and geothermometry of inclusions in pyrope from Garnet Ridge, Az. and Red Mesa, Ut., diatremes, Colorado plateau. Geol. Soc. of Am., Abstracts with Programs, 11, p. 447-448.
- Hsu, J. A. and Taylor, L. A. (1978) An unusual mineralogy in the Norris kimberlite of Tennessee. Geol. Soc. Am., Abstracts with Programs, 10, No. 4, p. 172.
- Irvine, T. N. (1965) Chromian spinel as a petrogenic indicator. Part 1. Theory, Can. J. Earth Sci., 2, p. 648-672.
- Koenig, J. B. (1956) The petrography of certain igneous dikes in Kentucky. Bulletin No. 21, Kentucky Geological Survey, p. 1-56.
- Mitchell, R. H. (1972) Composition of perovskite in kimberlite. Am. Mineral., 57, p. 1748-1753.

- Mitchell, R. H. (1973) Magnesian ilmenite and its role in kimberlite petrogenesis. J. Geol., 81, p. 301-311.
- Mitchell, R. H. (1979) Mineralogy of the Tunraq kimberlite, Somerset Island, N.W.T. Canada. In Boyd, F. R. and Meyer, H. O. A., eds., Kimberlites, diatremes and diamonds: their geology, petrology and geochemistry, p. 161-171.
- Nixon, P. H. and Boyd, F. R. (1973) Petrogenesis of the granular and sheared ultrabasic nodular suite in kimberlites. In Nixon, P. H., ed., Lesotho kimberlites, p. 48-56.
- Pasteris, J. D., Boyd, F. R. and Nixon, P. H. (1979) The ilmenite association at the Frank Smith Mine, R.S.A. In Boyd, F. R. and Meyer, H. O. A., eds., The mantle sample: inclusions in kimberlites and other volcanics, p. 265-278.
- Wyatt, B. A. (1977) The melting and crystallization behavior of a natural clinopyroxene-ilmenite intergrowth. Contrib. Mineral. Petrol., 61, p. 1-9.
- Wyatt, B. A. (1979) Kimberlitic chromian picroilmenites with intergrowths of titanian chromite and rutile. In Boyd, F. R. and Meyer, H. O. A., eds., The mantle sample: inclusions in kimberlites and other volcanics, p. 257-264.
- Wyatt, B. A. (1979) Mangoan ilmenite from the Premier kimberlite. Geol. Soc. S. A., Geokongres, p. 456-460.
- Wyllie, P. J. (1979) Kimberlite magmas from the system Peridotite-CO₂-H₂O. In Boyd, F. R. and Meyer, H. O. A., eds., Kimberlites, diatremes, and diamonds: their geology, petrology and geochemistry, p. 299-316.

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