

A KIMBERLITE, ITS MINERALOGY, AND IMPLICATIONS

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THIE CONVERY

A THESIS SUBMITTED AS PARTIAL FULFILLMENT
FOR THE HONOURS BACHELOR OF
SCIENCE DEGREE

FACULTY OF SCIENCE
MCMASTER UNIVERSITY
HAMILTON, ONTARIO
APRIL, 1990

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ACKNOWLEDGEMENTS

I would like to thank "the company" (which I can not name) and a few of their employees - my friends, R.F.C. and J.P. If not for these people I wouldn't have made it through the summers.

Special thanks to Dr. J.H. Crocket - a fine person and great professor. His help and patience were greatly appreciated. I could not have completed this thesis without him (although he may think that I tried).

Thank you's also to Len Zwicker who prepared some of my slides, and Jack Whorwood and Tom Bryner who helped with the photography.

Finally, love to the one who always fills me with joy, my daughter, Kimberley Jean.

ABSTRACT

Kimberlite diatremes from a single genetic source were examined. Macrocryst and groundmass constituents were identified, as well as their alteration products. It was hypothesized that carbon dioxide and water vapour were present at the time of formation. Limestone inclusions and peridotite xenoliths were examined, as well as fabrics within the xenoliths. It was concluded that water is present in the upper mantle. Ilmenite nodules were determined to be phenocrysts, as opposed to xenocrysts. A paragenetic sequence for the kimberlite was resolved. Ilmenite was classified as the best indicator mineral for exploration purposes.

CHAPTER ONE GENERAL KNOWLEDGE

1.1 Definition of Kimberlite

According to Clement et al (1977), kimberlite is a "volatile-rich, potassic, ultrabasic, igneous rock which has a distinctively inequigranular texture resulting from the presence of macrocrysts set in an essentially microporphyratic matrix".

The matrix contains olivine and several of the following minerals: phlogopite, calcite, serpentine, magnetite, perovskite and ilmenite. Other primary minerals may be present in accessory amounts. The matrix may vary from light yellow to dark green or black, depending upon the type and proportion of phases present.

The macrocrysts belong almost exclusively to a suite of ferromagnesian minerals which include olivine, phlogopite, ilmenite, magnesian garnet, chromian diopside and enstatite. Olivine is extremely abundant relative to the other minerals.

Of course, kimberlite may contain diamond but only as a very rare constituent.

Kimberlite commonly contains rounded inclusions of a variety of ultramafic rocks characterized by mantle-derived peridotites, eclogites and pyroxenites. Variable quantities of crustal xenoliths may also be present.

Kimberlite is often altered mainly as a result of serpentinization and/or carbonatization.

Kimberlite occurs in small diatremes, or in dykes or sills of limited extent.

Following the type locality nomenclature rules of the day, this rock was named, from its occurrence at Kimberley, South Africa, as kimberlite.

1.2 Location Description

Kimberlite samples were obtained from a cluster of diatremes that were intruded into Silurian limestone. The kimberlite-limestone contact was extremely sharp while thermal effects upon the wall-rock were relatively noticeable. Due to erosion, the kimberlite pipes are now exposed at the surface, so sample collection was relatively easy. Approximately six pipes occurred within a 10 km radius of each other. It is assumed that the pipes had a single mantle source, hence are genetically associated, and can be treated as a single sample. The average diameter of the pipes was about 40 metres across, but because the pipes are conical, the initial intrusion diameter would have been larger.

CHAPTER TWO KIMBERLITE CONSTITUENTS

2.1 Minerals

2.1.1 Pyroxene

A common silicate in kimberlite is pyroxene. This kimberlite contained two types - chrome diopside (clinopyroxene) and enstatite (orthopyroxene). The chrome diopside was more common than the enstatite and imparted the characteristic 'green apple' colour to the rock. In thin section, the pyroxenes are generally subhedral and display a short prismatic habit. Crystal sizes up to 0.5 mm can be found and colour varies from yellow to dark green. The pyroxenes occur as high-temperature macrocrysts (probably phenocrysts) and can not be found in the lower-temperature groundmass. Crystals are usually separated from the host kimberlite by a microcrystalline reaction rim, and many are partially replaced along cleavage planes by serpentine and carbonate.

2.1.2 Phlogopite

Phlogopite mica is a typical mineral of kimberlite. Although olivine is generally the most common mineral in kimberlites, some micaceous kimberlites occur where phlogopite is more abundant. The presence of phlogopite in these sections is such that it is either very common or quite rare. The mica occurs as macrocrysts, as well as groundmass component; hence, grain size varies from 1.3 cm to less than 0.1 mm. Crystals are usually euhedral and

tabular in form, with a pale green colour which indicates the phlogopite is rich in ferrous iron. Many grains show buckling and/or kink banding with attendant undulose extinction. This feature can be observed in Plate 1. These signs of strain are likely due to stress within the crystals during their ascent through the crust. Some grains also show alteration and magnetite replacement along cleavage planes.

Although this mica is considered to be a low temperature mineral, phlogopites found in kimberlites have many potential sources. The most obvious and probably most important process producing these abundant phlogopites is direct crystallization from the vapour- and potassium-rich kimberlitic magma. Other potential sources of the phlogopite include the upper mantle, peridotite nodules carried by the kimberlitic magma, and secondary reaction processes occurring in kimberlites.

2.1.3 Pyrope Garnet

Pyrope garnet is another mineral that forms macrocrysts in kimberlite. Although pyrope is generally quite common in kimberlite, these samples contain very few grains. The average grain size is about 1.2 mm with little variation. The crystals are colourless or pink in thin section, but fresh surfaces on larger grains in the hand samples are typically pinkish red. Most crystals have a few euhedral grain boundaries and display the characteristic garnet partings and dodecahedral form.

Pyrope garnet is a high-temperature mineral and must have

crystallized early because no fine-grained garnet occurs in the low-temperature matrix. Accordingly, the macrocrysts show a relationship with the matrix, such that an interaction between garnet and late-stage fluids produces a new low-temperature mineral called "kelyphite". The garnets occur as isolated macrocrysts within the kimberlite matrix from which they are separated by a rind of kelyphite that has developed at the expense of the garnet. The kelyphite - a microcrystalline aggregate of opx, cpx, spinel, phlogopite and serpentine - forms as a consequence of the breakdown and reaction of garnet during transport from regions in which it is a stable phase. A kelyphite rim can be observed on a garnet in Plate 2. In some cases the kelyphite may completely replace the garnet.

2.1.4 Olivine

Olivine and its alteration products represent the most abundant mineral assemblage in kimberlites. In this sample, olivine has two modes of occurrence - as macrocrysts and as groundmass. The macrocrysts are generally rounded in shape and usually occur in the size range 0.5-10 mm though rare crystals up to 3 cm are recorded. Although olivine colours range from very pale green to yellowish-brown with decreasing Mg content, nearly all grains are green which indicates that magnesian olivine (forsterite) dominates. Also, ilmenite inclusions are very common in the olivine grains.

Olivine is very susceptible to hydrothermal alteration and

to weathering and hence, the crystals show relationships with the matrix. For example, the olivine may be partially or wholly replaced by serpentine-group minerals such that nearly all of the crystals are extensively pseudomorphed by a yellow-brown serpentine. The serpentine is usually accompanied by exsolved magnetite that gives the mineral a dark brown or black colour. Even the freshest grains are separated from the matrix by a thin rim of serpentine-group minerals. Antigorite commonly occurs as pseudomorphs after the olivine while chrysotile occurs in veinlets of fine-grained, silky fibres which are usually aligned across the vein. Serpentine alteration is visible in Plate 3.

Following the serpentinization, olivine may be replaced by various combinations of calcite and perovskite (calcium titanium oxide). The perovskite typically forms yellow-brown halos around the earlier-formed pseudomorphed olivines.

2.1.5 Ilmenite

The most common opaque mineral in kimberlite is ilmenite. This titanium oxide can easily be identified in hand samples by its metallic black colour and brownish red streak. Often grains are coated with a greyish-white porcellaneous alteration product called leucoxene, which is merely fine-grained, hydrous titanium dioxide. Plate 4 shows ilmenite with leucoxene alteration. In this kimberlite, ilmenite crystals 16 mm in size have been observed. In polished thin section, the ilmenite may occur as discrete nodules, with an average grain size of 1.0 mm, or as

components of the groundmass. The grains are generally anhedral, but perfectly euhedral, hexagonal crystals (see Plate 5) have been recorded. The most distinctive optical feature of the ilmenite nodules is surface pitting, which can be observed in Plate 6. The pitting often appears to have a distinctive crystallographic orientation which may indicate that the feature is due to alteration. Also, ilmenite displays features such as gross fracturing, recementation by calcite and replacement by serpentine and phlogopite. Ilmenite itself may also occur as inclusions in olivine. These ilmenite grains may be quite large and are usually angular in form. Ilmenite has also been observed enclosing olivine grains that have been replaced by serpentine or calcite, and may also penetrate cracks within the altered olivine grain. Plate 7 shows an ilmenite inclusions in olivine, while Plate 8 shows ilmenite penetrating olivine cracks.

There is abundant evidence that ilmenite nodules are not in equilibrium with their kimberlite host. This is evident by the fact that, in addition to leucoxene, ilmenite also alters to rutile and perovskite (calcium titanium oxide). Rutile has a characteristic deep red-brown colour (see Plates 9 and 10) while perovskite is yellow-brown in thin section. Perovskite and attendant magnetite occur as mantles upon earlier-formed ilmenite and rutile grains. This perovskite mantling relationship reflects the instability of the earlier-formed phases in the kimberlite fluid. Similarly, perovskite is not stable in the residual fluids and the mineral is commonly resorbed and/or mantled by thin rims

of rutile. Since these Ti-bearing oxide minerals are considered to be low-temperature phases, it is believed that they form in response to changes in the magma during ascent.

As noted by Elthon and Ridley (1979), ilmenite mantles associated with perovskite and magnetite on larger ilmenite crystals are not secondary but rather the remnants of the original ilmenite rim. Evidence follows from the fact that both the large ilmenite and the small grains on the rim are pleochroic and simultaneously reach maximum extinction. Also, the replacement of ilmenite by perovskite and magnetite may have been incomplete such that the 'pseudo-secondary' ilmenite rims remain connected to the large ilmenite grain.

Perovskite also occurs as an accessory phase in kimberlite such that crystals are randomly scattered throughout the groundmass.

2.1.6 Carbonate

Common to kimberlite is late-stage carbonatization. While some of the calcite may replace serpentinized olivine, much remains in the primary phase. Carbonates may occur in the matrix with other groundmass minerals, such as olivine, phlogopite, serpentine and ilmenite, and may even occur as calcite veins throughout the kimberlite. These veins may extend for many metres and may also vary in thickness from less than 1 mm up to 15 mm. Commonly the calcite veins produce thermal effects upon the adjacent minerals.

2.1.7 Molybdenite

An opaque accessory mineral that occurs in the kimberlite is molybdenite. This sulphide was found in an altered olivine crystal along grain boundaries and internal cracks and is observable in Plate 11. The molybdenite occurs as fibrous aggregates or as small deformed plates that average 0.5 mm in length. The crystals appear creamy white in thin section and show a prominent cleavage. Many of the crystals also display undulatory extinction and/or possess kink bands. Because molybdenite is such a soft mineral, these deformation features could have been generated by a number of factors.

2.2 Volatiles

Kimberlites are known to travel through the Earth's crust at tremendous velocities and are also known to be explosive if volcanic. This is due in part to the vast amount of volatiles within the magma. Unlike most other silicate magmas, kimberlites originate at high pressures which aids in the initial dissolution of large quantities of both carbon dioxide and water vapour. Accordingly, the crystallization history of kimberlites is closely tied to the dissolution of these two gases during ascent. The fact that the matrix of kimberlites generally contains a carbonate phase strongly supports the view that the melt has been continuously saturated with carbon dioxide during its evolution. Since both carbon dioxide and water vapour solubility decrease dramatically with decreasing pressure, large volumes of these

gases must be expelled from the melt during ascent.

Evidence of this activity is deduced from veins in this kimberlite which are not filled with mineral assemblages. Instead, the veins are vacant, or contain 'frozen' gas bubbles that solidified upon cooling (see Plate 12). If the veins are void, a jigsaw fit of the enclosing rock is noticeable which indicates that the gases actually fractured the kimberlite as they were released. If the veins contain bubbles, the bubbles themselves contain both ilmenite and rutile. These fine-grained opaques usually border the bubble while fluid inclusions occur at the nucleus. These gas veins appear to be similar in size and extend to the calcite veins so it is possible that the gas veins were later intruded by calcite.

Plate 1: Transmitted light; phlogopite grain showing buckling with attendant undulose extinction. Field of view is 1.0 mm.
(XP)

Plate 2: Transmitted light; pyrope garnet with kelyphite alteration rim. Field of view is 2.2 mm.
(PPL)

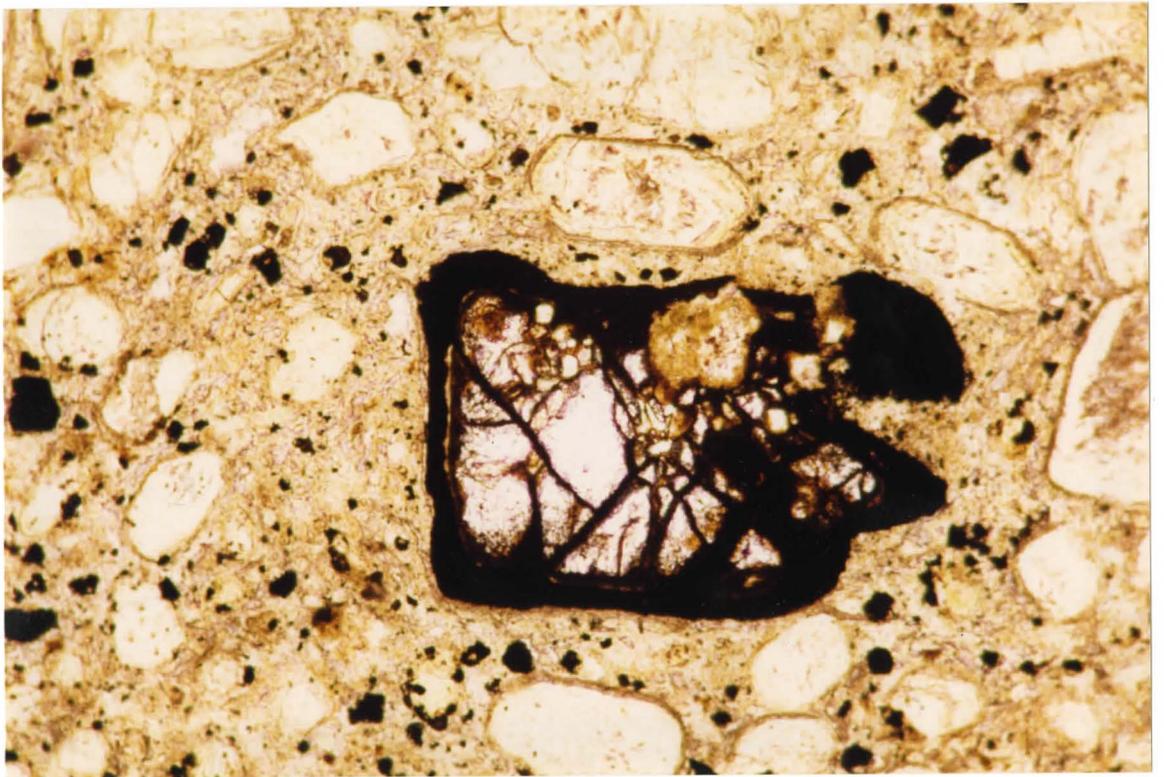
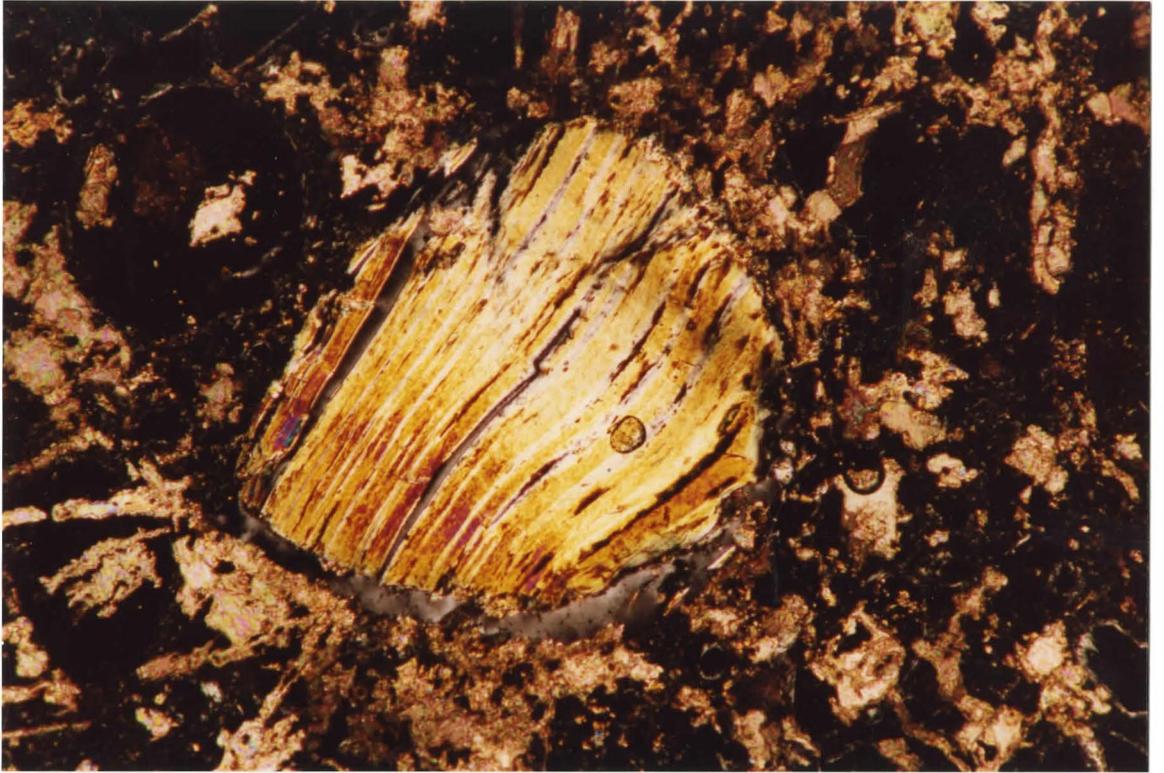


Plate 3: Transmitted light; olivine (pink) altered to
serpentine (yellow veinlets) and magnetite
(black).

Field of view is 5.0 mm.

(PPL)

Plate 4: Transmitted light; ilmenite (black) with leucoxene
alteration (light yellow).

Field of view is 4.5 mm.

(PPL)

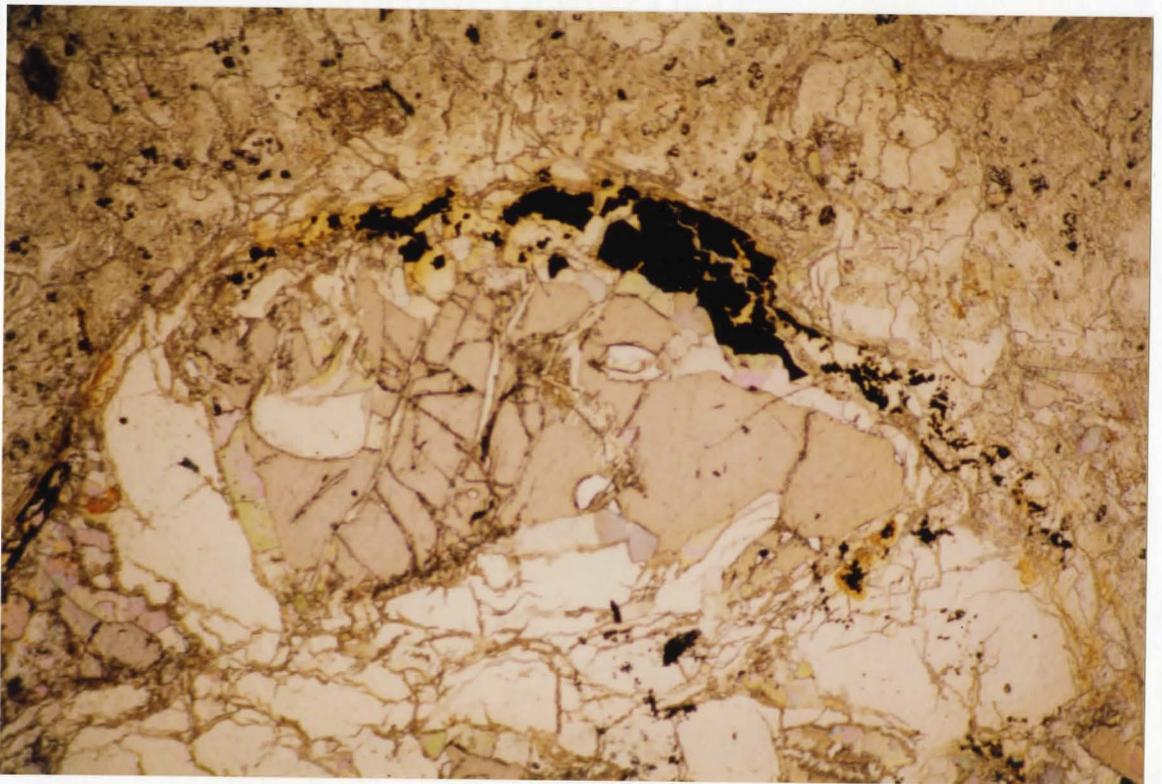
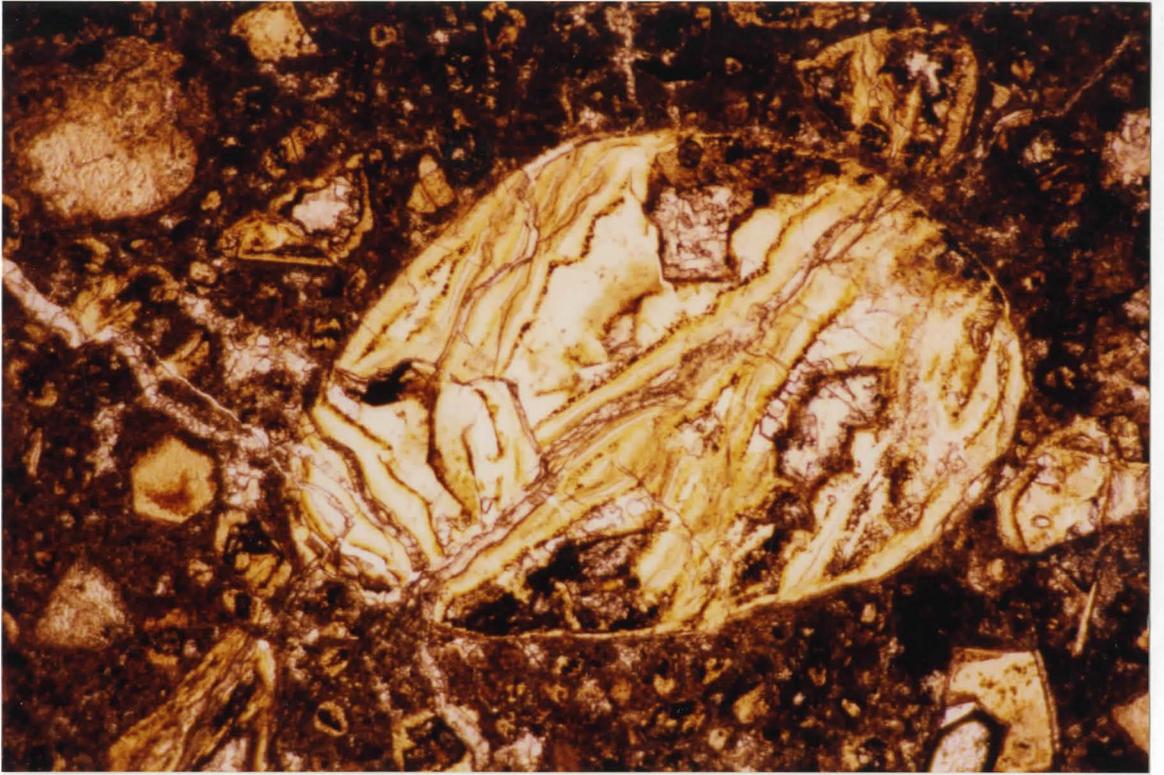


Plate 5: Reflected light; euhedral, hexagonal ilmenite
 grain.
 Field of view is 0.35 mm.
 (PPL)

Plate 6: Reflected light; pitted ilmenite grain.
 Field of view is 2.2 mm.
 (PPL)

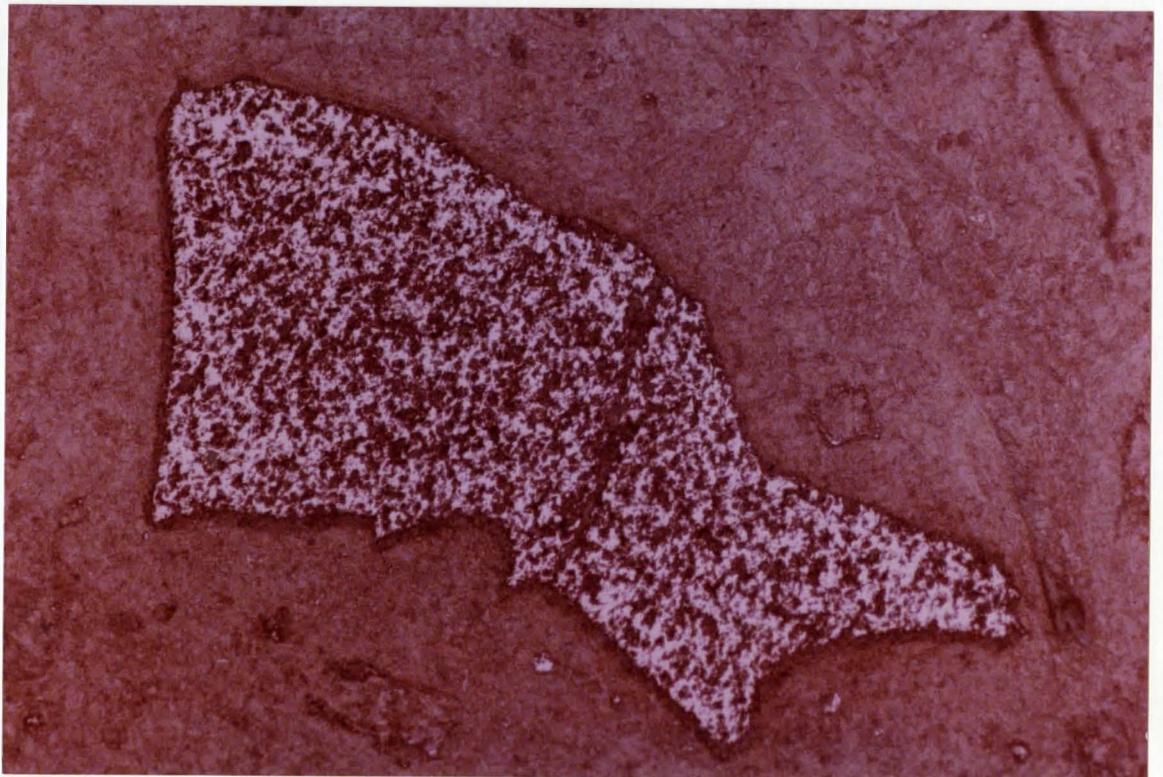
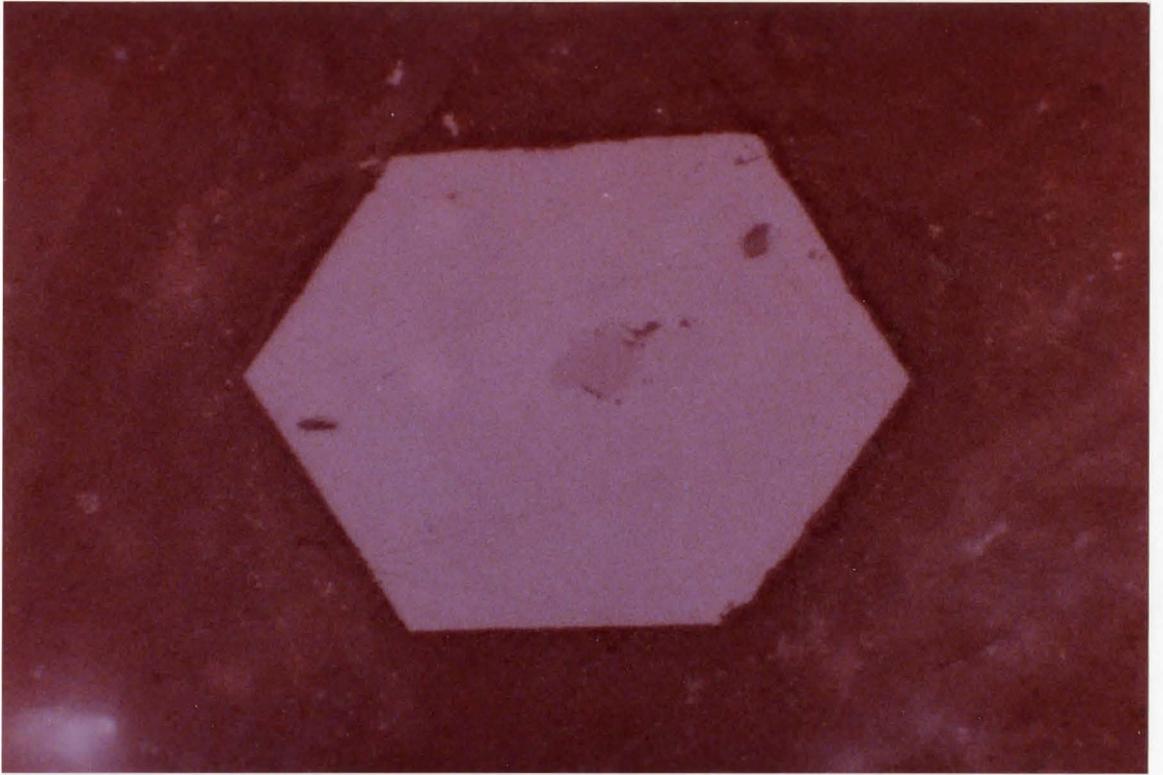


Plate 7: Transmitted light; ilmenite inclusion (black) in
olivine grain (pink).
Field of view is 5.0 mm.
(PPL)

Plate 8: Transmitted light; ilmenite (black) penetrating
olivine grain .
Field of view is 4.0 mm.
(PPL)

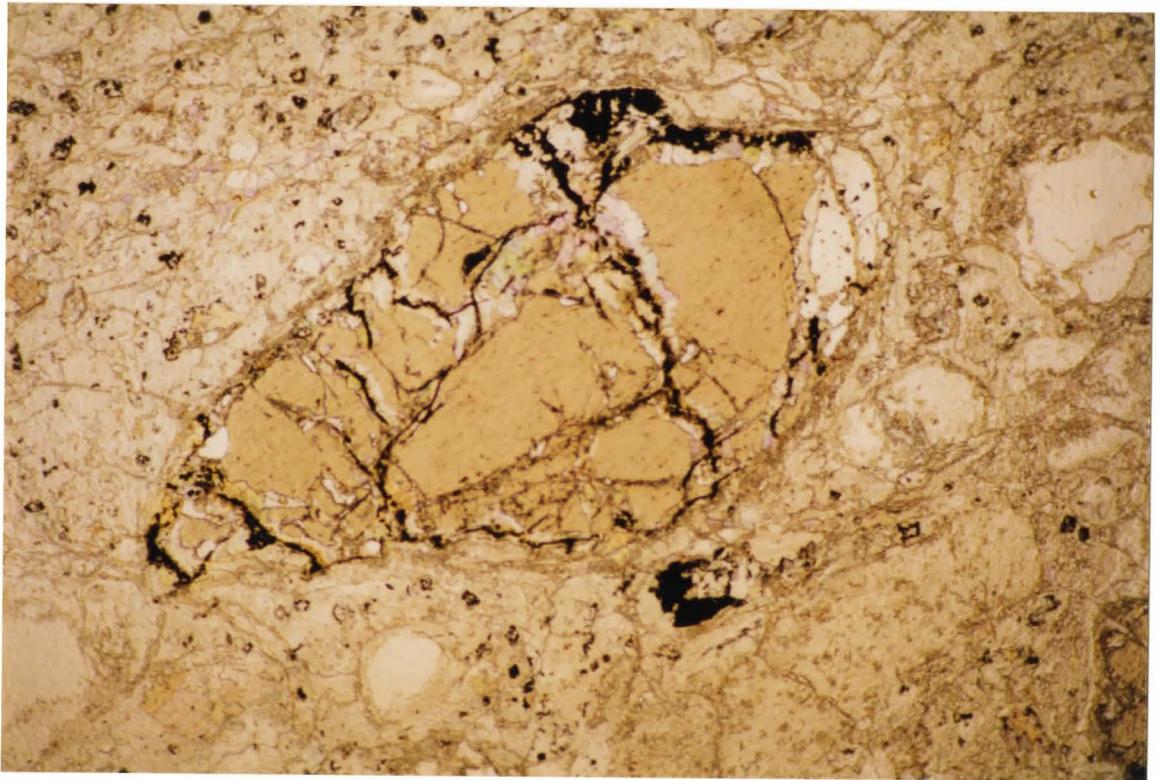
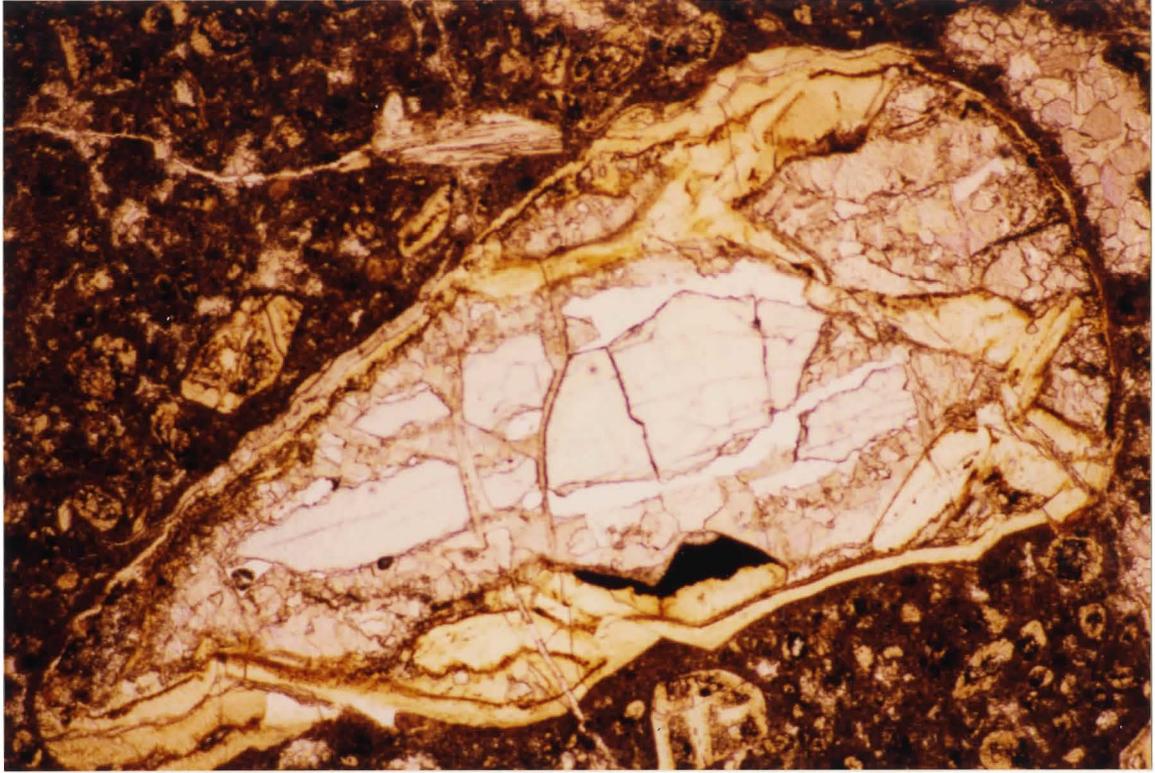


Plate 9: Reflected light; rutile (orange) replacing
 ilmenite (black).
 Field of view is 0.5 mm.
 (PPL)

Plate 10: Reflected light; above in XP.

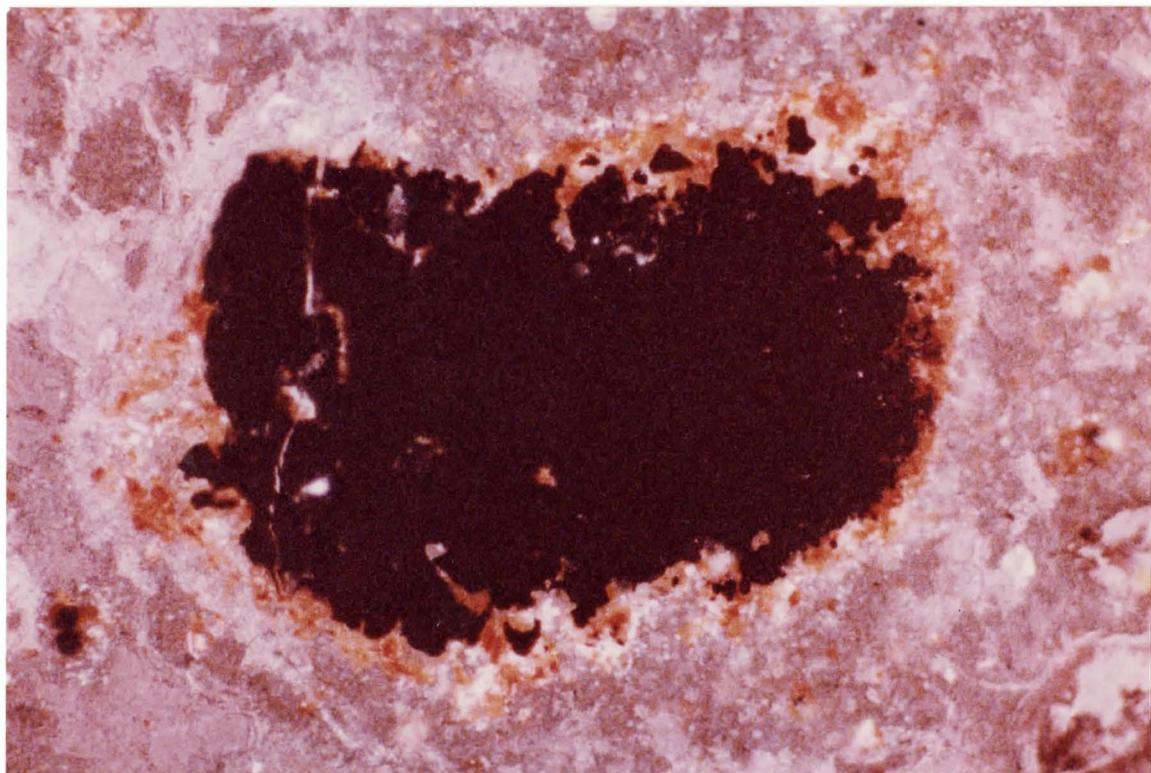
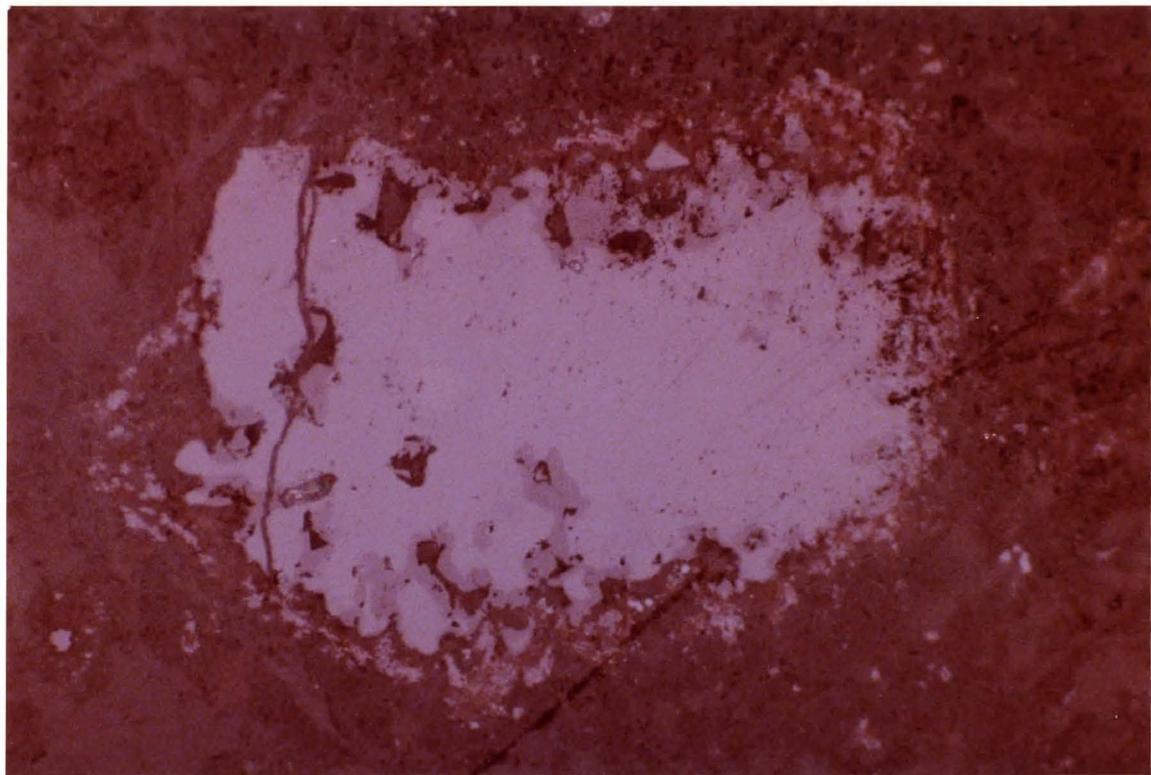
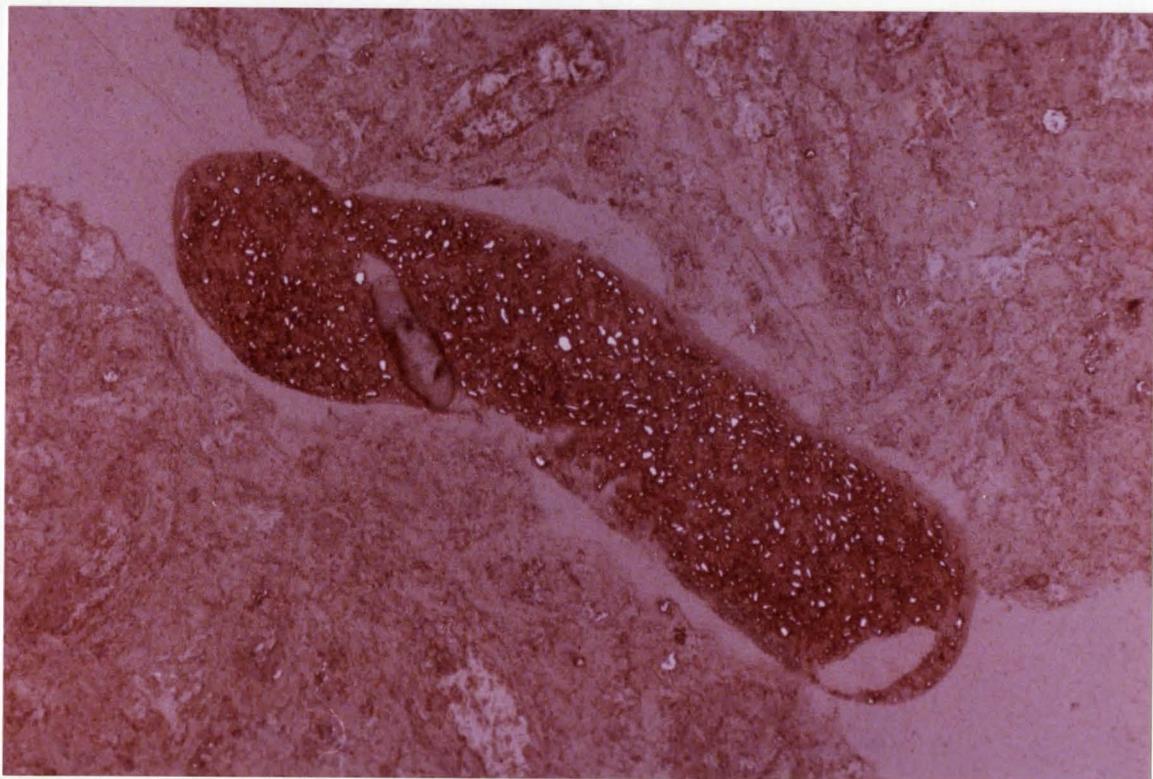
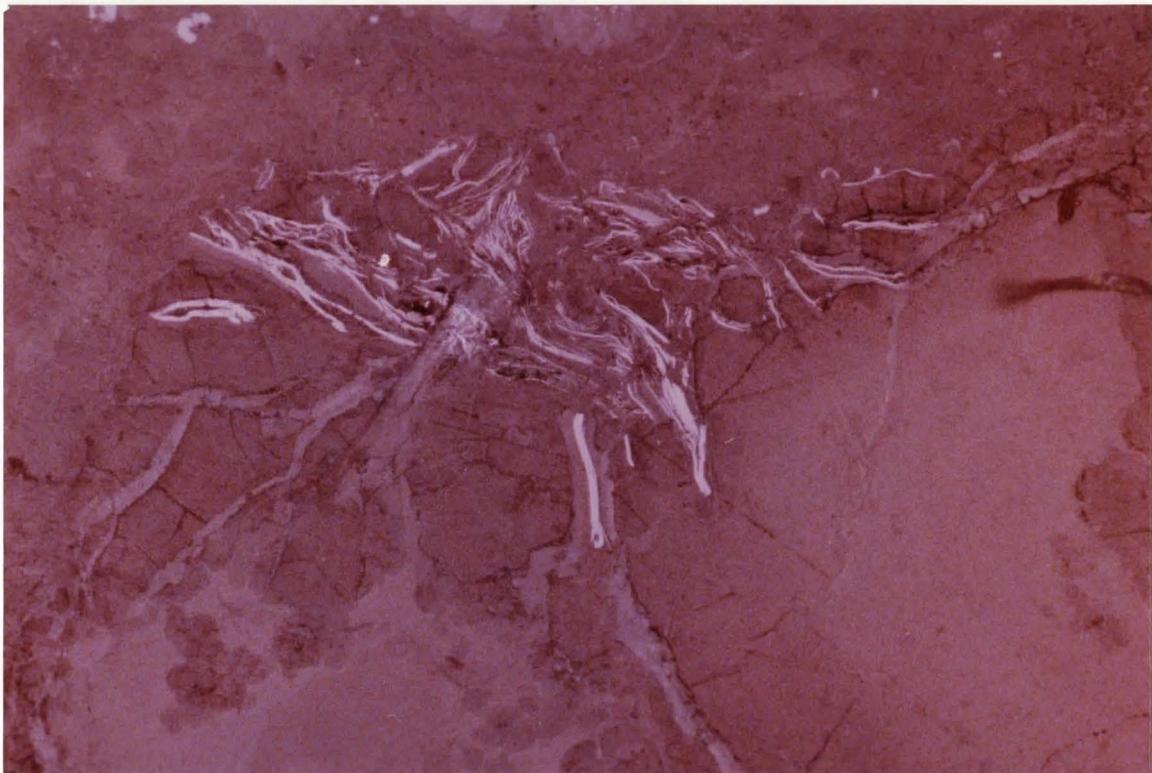


Plate 11: Reflected light; molybdenite (white) along olivine grain boundary. The olivine is to the bottom of the picture.
Field of view is 1.3 mm.
(PPL)

Plate 12: Reflected light; gas bubble in vein with inclusions of rutile (white).
Field of view is 2.0 mm.
(PPL)



CHAPTER THREE XENOLITHS

3.1 Limestone

In addition to the minerals and mineral assemblages already mentioned, xenoliths also occur in kimberlite. These inclusions are of pre-existing rock which are foreign to the kimberlite in which they now occur, and they have been introduced into the melt from some extraneous source. From their derivation in the upper mantle at greater than 200 km to their emplacement in the crust, kimberlites typically will entrain nodules of various origin. They may be fragments of immediate wall-rock, blocks from buried formations, granulites from deep-seated metamorphic terrains or xenoliths of rock-types believed to derive from the Earth's upper mantle. If the inclusions are from the upper mantle, they would be of the peridotite/pyroxenite suite (including lherzolites) or the eclogite suite. In this kimberlite, many angular limestone fragments from the immediate wall are present. They vary in size and shape, with the largest limestone inclusions being greater than 7 cm long. All have some form of alteration border which may be composed of ilmenite, rutile or microcrystalline calcite. The limestone itself may have been recrystallized such that the calcite grain sizes grade from coarse to fine as one moves from the centre of the xenolith to the border.

3.2 Peridotite

In this kimberlite, a xenolith belonging to the peridotite

suite of the upper mantle was also identified. The fragment was 16 mm long, contained euhedral mica (probably phlogopite) and olivine, and had altered to calcite. A fine-grained alteration rim also surrounded the xenolith.

3.2.1 Fabrics

The phlogopites seemed to have a relatively parallel orientation indicating that some stress field in the upper mantle may have aligned the crystals. This alignment is observed in Plates 13 and 14. Dawson (1980) also inferred that there are upper mantle movements from fabrics within xenoliths. He concluded that "the fabrics within the deformed xenoliths are the result of deformation within an anisotropic stress field and have been interpreted as the result of super-plastic flow within the upper mantle" (p. 207). He also concluded that a strong orientation of the olivines and pyroxenes in xenoliths can be seen as evidence for deformation events within the upper mantle.

3.2.2 The Role of Water

Obviously kimberlites represent a valuable source of information on the upper mantle and the study of xenoliths incorporated into kimberlitic magmas during their ascent to the surface has yielded a vast amount of knowledge on the upper mantle.

The undoubted involvement of water in kimberlite magma is indicated by the presence of phlogopite in kimberlites. It seems

likely that these phlogopites formed as a direct result of crystallization from the kimberlitic magma, but the origin of the micas found in xenoliths has much been disputed. It is possible that the phlogopite in the peridotite xenolith is primary, in which case water would be present in the upper mantle. Consequently, as proposed by Sobolev (1977), phlogopite may be regarded as a mineral, typical of the uppermost portion of the upper mantle, where it co-exists with such water-bearing minerals as the amphiboles. Thus, water is probably present in the mantle in the dissolved form in the interstitial melt and in the fluid in equilibrium with the melt, which may significantly affect the solidus temperature of the mantle rocks. The phlogopite may also form as a result of a later phlogopitization, but either theory seems viable at this point.

3.3 Origin of the Ilmenite

The origin of the ilmenite macrocrysts has also been the subject of much dispute over the years. They have been interpreted by Mitchell (1973) to have formed by crystallization under high-pressure in the kimberlitic melt and interpreted to be xenocrystic in origin by Boyd and Nixon (1975).

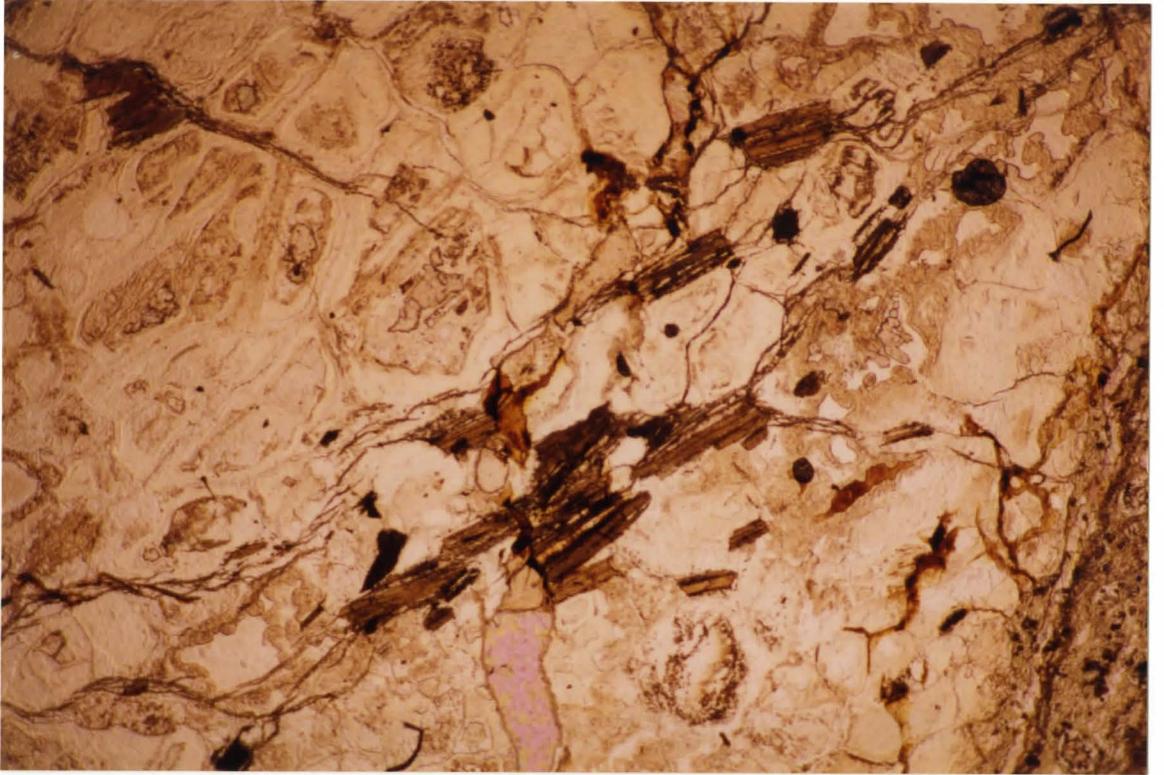
Elthon and Ridley (1979) showed that within peridotite and eclogite nodules collected in kimberlite pipes ilmenite is not a common mineral, but it is abundant within the kimberlite matrix. Therefore, they concluded that scarcity of ilmenite in peridotite and eclogite nodules is evidence that the origin of ilmenite is

by direct crystallization from the kimberlite melt. Also, because each kimberlite pipe possess its own suite of discrete ilmenite nodules, they are likely to be phenocrysts.

Alternatively, the ilmenite grains could be xenocrysts that are only associated with, but unrelated to the kimberlite. As proposed by Shee (1984), the ilmenite inclusions could have formed in a liquid derived from a partial melt of mantle peridotite, lherzolite or eclogite, but ilmenite is rare in these rock suites. Finally, it is also possible that a source region in the mantle that was ilmenite-saturated could have been the origin of the ilmenites. Evidence for the alternative theories lie in the fact that the ilmenite nodules are unstable in the kimberlite magma at time of emplacement - they have reacted with the magma to form perovskite and rutile mantles. Obviously, much has yet to be learned about the origin of the phenocrysts or xenoliths in kimberlites.

Plate 13: Transmitted light; alignment of phlogopites (dark brown) in peridotite xenolith.
Field of view is 4.5 mm.
(PPL)

Plate 14: Transmitted light; above in XP.



CHAPTER FOUR PARAGENESIS

The high-temperature macrocrysts were the first minerals to form in the paragenetic sequence. In the near-surface, low-temperature environment the groundmass minerals formed. The first macrocrysts to crystallize were likely the pyroxenes and pyrope garnets, as they develop at very high temperatures. Also, inclusions of earlier phases do not occur within them. Soon to follow were the ilmenite crystals (if one assumes that ilmenite occurs as a phenocryst). The occurrence of ilmenite inclusions in olivine phenocrysts shows that the ilmenite is a relatively early phase. The last macrocrysts were the phlogopite and olivine grains which occur as relatively lower-temperature phases and which contain inclusions of minerals that were formed prior to their crystallization.

As the kimberlite magma travelled vertically through the crust, the macrocrysts became unstable in the lower pressure. Consequently, the macrocrysts were altered and the groundmass constituents formed. The fine-grained groundmass contained varying degrees of olivine, phlogopite, ilmenite, perovskite and rutile. Simultaneously, kelyphite rims formed on garnets, phlogopite was replaced by magnetite, and ilmenite was altered to rutile and perovskite. Olivine was replaced by ilmenite and rutile, as well as serpentine and magnetite. The pyroxenes and the ilmenite were also serpentinized. In turn, the serpentine was replaced by calcite and perovskite. It seems likely that the molybdenite also formed under these conditions while replacing

olivine. Finally, late-stage calcite veins intruded the kimberlite.

CHAPTER FIVE INDICATOR MINERALS

Kimberlite is a relatively rare rock type. For this reason, exploration involves the use of indicator minerals as these minerals are considerably more widespread than are their source rock. Indicators must be resistant to physical and chemical weathering which allows for their retention in alluvial, glacial, sedimentary and metamorphic records. Easy identification and an absence in most other rock types are other characteristics of indicators that are important. Accordingly, primary kimberlitic phases which are used as indicators are pyrope garnet, ilmenite, chrome-diopside and spinel. Olivine and phlogopite are two diagnostic kimberlite minerals but their ease of alteration excludes them as indicators. In this kimberlite, pyrope, chrome-diopside and spinel (in the kelyphite rims) were all relatively rare. Of course, this is another disadvantage for indicator minerals. The only indicator mineral of any potential in this kimberlite is ilmenite. It is one of the most characteristic minerals of kimberlite and plays a key role in kimberlite exploration. Its ease of concentration, resistance to alteration and characteristic bright metallic lustre classify it as the most important indicator mineral.

CHAPTER SIX CONCLUSIONS, RECOMMENDATIONS FOR FURTHER WORK

6.1 Conclusions

Kimberlites have unusual mineralogy. It is because of this that geologists find them so intriguing. Their petrography and petrographic relationships give a detailed history of kimberlites from the time of their initial formations to the time of their alterations. Inclusions in kimberlites also provide information as to the composition of the upper mantle, the role of water in the upper mantle, as well as movements in the upper mantle. Microscopic examination of ilmenite nodules persuades one to believe that ilmenite occurs in kimberlites as phenocrysts.

6.2 Recommendations for Further Research

Further studies of kimberlites should be made, especially with regard to the nature of co-existing phases, the minor element geochemistry, and possible occurrence in other rocks derived from great depth in the mantle. Stability fields of minerals, such as ilmenite and phlogopite, should be determined so their optimum pressure, temperature, and oxygen fugacity parameters can be resolved. Also, the role that volatiles, such as carbon dioxide, play in kimberlite formation should be examined. Finally, exploration techniques should be expanded so as to increase recovery potentials.

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