THE SURFACE TEXTURES ON PYROPE, PICROILMENITE AND CHROME DIOPSIDE FROM KIMBERLITE

by

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ABSTRACT

The examination and interpretation of surface features on pyrope, picroilmenite and chrome diopside from kimberlite gives valuable information on the history of these minerals both during and after kimberlite emplacement. Descriptions and scanning electron photomicrographs of surface features observed on these mantle-derived minerals from thirty-four kimberlites having a global distribution are presented. Careful observations established the age relationships between the different surface features on each of the minerals studied, and enabled the compilation of a classification scheme of these surface features. This proposed classification scheme is based on the chronological sequence of formation of the surface morphological characteristics observed on these mantle-derived minerals and separates those which are formed during kimberlite emplacement (primary features), from those resulting from in-situ weathering and diagenetic etch processes (secondary features).

The mineralogy, structure and mode of formation of kelyphite are discussed in relation to kimberlite emplacement. Pyrope encrusted by kelyphite is commonly found in most garnet peridotites, some eclogite xenoliths from kimberlite, as well as a few garnet-bearing serpentinites. Although the relative abundance of kelyphite-encrusted garnet varies from one kimberlite to another, kelyphite shells are most commonly developed on mauve garnets which are most probably derived from peridotite and are least commonly found on orange varieties from eclogites. Evidence obtained in this study support the interpretations made by Wagner,(1914);

and Reid and Dawson, (1972), who maintain that kelyphite borders around garnets from peridotite have formed by reaction between garnet and surrounding olivine and in some cases orthopyroxene to produce a spinel-two pyroxene assemblage. In contrast, the kelyphitic material rimming garnets in eclogite nodules from kimberlite consists predominantly of phlogopite with accessory amounts of twinned feldspar microlites, amphibole, spinel and glassy material.

During the ascent of kimberlite magma garnet lherzolite nodules are moved from depths of approximately 150 km to less than 50 km within the upper mantle. The movement of garnet out of it's stability field (ie. from the garnet lherzolite stability field into the spinel lherzolite stability field), would trigger the process of kelyphitization of pyrope within the peridotite nodules. The proposed zone of kelyphitization of pyrope lies within the spinel lherzolite stability field and is most likely to occur at temperatures of 900°C to 1300°C and pressures of 10 kb to 25 kb within the upper mantle. The phlogopite-rich 'kelyphitic' material formed around garnets in eclogite xenoliths from kimberlite is considered to have formed in the region of the lower crust by the action of alkalies and volatiles associated with the hydrous phase of kimberlite emplacement.

The underlying sub-kelyphitic surfaces formed on pyrope as a result of kelyphitization are described. There is a direct relationship between the different types of surface features found on the sub-kelyphitic surfaces and the structure and mineralogy of the kelyphite shells surrounding garnet and filling cracks within garnet.

An extensive literature survey on the sculpturing of garnet indicates there is much debate on the causes, time of occurrence and significance of sculptured surfaces on garnet. The formation of sculptured features on garnet has been attributed to the mechanism of crystal growth, breakage or mechanical weathering, corrosion and regeneration and chemical etching.

Intricately sculptured surfaces on garnet, ilmenite and chrome diopside from kimberlite indicate that these minerals are not in equilibrium with their kimberlite host. These sculptured surfaces form on those minerals by resorption (chemical etching) processes during kimberlite emplacement, and are not the result of crystal growth. The morphology and mechanism of formation of these sculptured features are discussed in relation to the information obtained from the artificial reproduction of etch features similar to natural occurring sculptures on these mineral grains. Sculptured surfaces produced on pyrope and chrome diopside are most likely to occur in the temperature range 500°C to 900°C by resorption processes during kimberlite emplacement.

Reaction between ilmenite and kimberlite groundmass fluids result in the development of mineralogically complex mantles, composed of perovskite, spinel and ferro-magnesian silicates surrounding ilmenite from kimberlite. The reaction rims on ilmenite form during the build up of CO_2 - rich residual fluids and crystallisation of the rapidly quenched kimberlite liquid at about 600°C in the final stages of kimberlite emplacement. Textural evidence indicates that these reaction mantles clearly form at the expense of ilmenite and their development leads to the rough blocky sculptured surfaces commonly found on ilmenite from kimberlite.

A detailed study of surface modifications by in-situ weathering on mantle-derived minerals from the upper weathered portion of the Jwaneng kimberlite pipe, in south eastern Botswana, indicate that the relative stability of the mantle-derived minerals during the decomposition of kimberlite is as follows :- Ilmenite is extremely stable, garnet shows slight surface modifications, while chrome diopside is almost completely eliminated by in-situ weathering of kimberlite, with the result that very few chrome diopside grains are liberated from the kimberlite. Kelyphite shells surrounding garnet are progressively decomposed by in-situ weathering of kimberlite, paralleling the decompositional trend shown by chrome diopside.

Intrastratal solution in lateritic (ferricrete) soils overlying kimberlites results in the corrosion of garnet and chrome diopside, while ilmenite is relatively unaffected by diagenetic etching in high energy chemical environments. The development of honeycomb surfaces on the extensively corroded garnets causes them to become milky in appearance and display large embayments and irregularly-shaped outlines as a result of removal of garnet by solvent attack. Rapid decomposition and complete elimination of chrome diopside occur in lateritic environments by intrastratal solution. Continued solvent attack leads to widespread surface disintegration, resulting in a colour change of the chrome diopside grains from deep emerald green to pale whitish green.

CONTENTS

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1.0 INTRODUCTION

In order to define the aims and objectives of this research study it is necessary to outline some aspects of the mineralogy and petrology of kimberlite, which is the original host rock to the pyrope, picroilmenite and chrome diopside grains, the surface features of which are described in detail in this thesis.

The discovery of the first kimberlite diatreme on the farm Jagersfontein in the Northern Cape in 1870 heralded the great diamond rush to the Kimberley area. It was however, only in 1887 that the name "kimberlite" was first proposed by Carvill Lewis for what he regarded as "a serpentinised diamondiferous mica peridotite". Since then numerous contributions to many aspects of the geology, petrology and mineralogy of kimberlite have appeared in the literature Wagner (1914), Williams (1932), Dawson (1967), and Meyer (1979), have presented excellent reviews of the available data on kimberlite. Yet little is known of the surface features of these characteristic minerals from kimberlite. The results of this research study are presented to make a contribution to a certain aspect of kimberlite geology which has been almost ignored.

Kimberlite intrusions occur as relatively small diatremes (commonly known as pipes), and as dykes (or fissures) and sill-like bodies. They are generally found on stable shield or cratonic areas, but there are examples of kimberlite occurring in orogenic zones. Although concentrated in southern and east Africa, Brazil and U.S.S.R., they are found worldwide. The dating of kimberlites by use of Rb/Sr methods, (Allsopp and Barrett, 1975), zircon ages (Davis, 1977) as well as fission track ages (Naesner and McCullum, 1977), has shown that kimberlite activity has occurred sporadically throughout geological time, from Precambrian to late Cretaceous.

Petrographically kimberlite is an ultrabasic inequigranular rock which contains macrocrysts (phenocrysts or xenocrysts) of olivine, phlogopite, picroilmenite,magnesian garnet, chromian diopside and enstatite, set in a fine grained matrix. The matrix contains, as prominent primary phenocrystal and/or groundmass constituents, olivine together with several of the following minerals; phlogopite, calcite, serpentine, diopside, monticellite, apatite, spinels, perovskite and ilmenite (Clement et al., 1977). One or more of the above minerals may be absent or rare in any given kimberlite, which also may or may not contain diamond. Skinner and Clement (1979), have devised a classification scheme of kimberlite based on the relative abundance of the groundmass constituents.

Kimberlite has long been known to contain a variety of ultramafic xenoliths characterised by mantle-derived peridotites, eclogites and pyroxenites. Textural studies of these ultramafic xenoliths by Boyd (1973), Harte (1977), allows them to be divided into four principal textural types ie. coarse, porphyroclastic, mosaic-porphyroclastic, and granuloblastic. Chemical and mineralogical studies have shown that much of the textural variety must originate within the upper mantle and have been derived from depths greater than 150 km within the mantle. Kimberlite intruding the crust has transported mantle and lower crustal fragments to the earth's surface.

The characteristic suite of heavy minerals (S.G greater than 2.90) from kimberlite, invariably includes vivid red, mauve and orange pyrope-rich garnets, picroilmenite, and bright green chrome diopside, together with enstatite and olivine in greater or lesser amounts. These crystals, from 0,1 to 5,0 mm in size, are referred to as phenocrysts or xenocrysts (or both) and pose a problem with regard to genesis. Some workers (Mitchell, 1973 ; and Gurney et al., 1979) would consider these crystals as phenocrysts and maintain they are true kimberlitic minerals crystallised from and associated with the kimberlite magma at depth. In contrast, others doubt this origin and consider these crystals as xenocrysts derived from the fragmentation of peridotites, pyroxenites and eclogites. A term megacryst has been suggested by Dawson (1980), to avoid any genetic connotation since detailed mineralogical studies of kimberlite have shown that these crystals (0,5 to 5,0 mm in size) consist of both xenocrysts and high-pressure phenocrysts.

Large monomineralllic crystals, varying in size from 2 - 20 cm, referred to as megacrysts, are common to many kimberlites in southern Africa (Nixon and Boyd, 1973). These large crystals may consist of olivine, ortho- and clinopyroxene, garnet, ilmenite, phlogopite and rare zircon. (Gurney et al. 1979). In other instances these megacrysts are single phase, sometimes polycrystalline xenoliths which have been termed 'discrete nodules' by Boyd (1973). These large crystals are usually of greater size than minerals derived by fragmentation of ultramafic xenoliths. Although studies have been undertaken by many scientists the genesis of these megacrysts and discrete nodules is still subjective. Valid arguments have been provided for both xenocrystic and phenocrystic origins.

This study is only concerned with garnet, ilmenite and chrome diopside in the size range (0,5 mm to 4,0 mm) which approximates to the minerals found in ultramafic nodules ($>$1cm). Although olivine, orthopyroxene and clinopyroxene form the basis of the mineralogy of the ultramafic xenoliths in kimberlite, pyrope, picroilmenite and chrome diopside are common accessories. These mineral grains constitute between 1 and 2% by weight of kimberlite and are, for the most part, regarded as xenocrysts, derived from the mechanical disaggregation of pre-existing upper mantle rocks, the same or similar rocks that provide the ultramafic nodules in kimberlite. The majority of garnet, picroilmenite and chrome diopside crystals from kimberlite are generally rounded in shape and show reaction relationships with the kimberlite matrix (eg. garnet is surrounded by rinds of 'kelyphite' while picroilmenite is rimmed by perovskite). There is also abundant evidence that these minerals are not in equilibruim with their kimberlite host as indicated by the finely pitted and intricately sculptured surfaces on garnet, ilmenite and chrome diopside crystals from kimberlite. The purpose of this research study is the examination of surface features formed on these'mantle-derived minerals' during kimberlite emplacement,with the aid of a scanning electron microscope. In addition, the surface modifications caused by weathering effects on the mineral grains were also investigated.

1.1 Aims and objectives of this research study.

The project was undertaken at the Anglo American Research Laboratories and forms part of a much broader investigation into the nature and origin of kimberlite and associated rock types. The study was implemented with the following objectives in mind :-

1) Describe and interpret the different surface textures found on pyrope, picroilmenite and chrome diopside from kimberlites having a global distribution.

2) Classify these surface textures into a logical sequence of formation, separating those which have formed during kimberlite emplacement from those which are produced on these mantle derived minerals after the intrusion of kimberlite by in-situ and diagenetic etch processes.

3) Establish whether or not different surface textures are formed on these minerals by different modes of kimberlite emplacement ie. pipes, dykes and sills.

4) Study the structure and mode of formation of kelyphite in relation to kimberlite emplacement. Examine the underlying sub-kelyphitic surfaces formed on pyrope as a result of kelyphitization, and relate the variety of surface features found on the sub-kelyphitic surface to the structure of the kelyphite shells around garnet and filling cracks within garnet.

5) Reproduce the surface features formed on pyrope, picroilmenite and chrome diopside by artificial etching experiments and attempt to explain the mechanism of chemical etching (dissolution or resorption) of these minerals during kimberlite emplacement.

6) Examine the distribution of pyrope, picroilmenite and chrome diopside in the weathered profile of a kimberlite pipe, prior to their liberation and subsequent transportation.

7) Study the effect of in-situ weathering processes on pyrope, picroilmenite and chrome diopside during the weathering of kimberlite.

8) Determine the order of relative stability for garnet, ilmenite and chrome diopside during the decomposition of kimberlite.

9) Determine which colour/types of garnet are most susceptible to diagenetic etching (intrastratal solution).

10) Compare sculptured surfaces on pyrope extracted from the upper weathered portion, with those recovered from relatively fresh kimberlite (blue ground), in order to, either substantiate, or repudiate, the theory proposed by some Russian workers (Afanasyev et al, 1976) that sculptured surfaces on kimberlitic garnets can be ascribed to the process of weathering.

11) Investigate whether or not these mantle derived minerals are trapped in ferricrete or lateritic soils overlying kimberlites, or whether they are progressively destroyed by intrastratal solution.

1.2 Analytical methods and preparation of samples studied.

The surface features were studied on approximately 10,000 pyropes; 17,000 picroilmenites and 6,000 chrome diopside grains from 34 different kimberlite localities. These mineral grains were hand-picked from heavy mineral concentrates (S.G. $>$ 2,85) from samples which were chosen from kimberlite pipes, dykes and sills in order to establish whether or not different surface features are formed by different modes of kimberlite emplacement. Although most of the samples investigated are from southern African kimberlite localities, some of them originate from the U.S.S.R., the U.S.A., Australia and Brazil. It was hoped that a study of the micromorphology of these minerals, particularly garnet, would provide valuable information on their history both before, during and after the emplacement of kimberlites.

For convenience the present study was restricted to mineral grains of a particular size. Wherever possible, a representative number of grains ranging in size from minus 4 mm down to plus 0,5mm in diameter were chosen for detailed surface textural studies. Grains within this size range are large enough for examination under the binocular microscope and not too large to be examined in a scanning electron microscope. In order to obtain an unbiased selection of mineral grains from each sample concentrate, the following procedure was used. The minus 4 mm plus 0,5 mm fraction of each concentrate was divided into four equal portions using the cone and quartering method. Grains of pyrope, picroilmenite and chrome diopside were then hand-picked, from one quartered portion of each concentrate, until a maximum of approximately 100 grains of each mineral were extracted. The garnet grains from each concentrate were then colour-coded under the binocular microscope into four colour groups. i.e. mauve, red, orange and pink. (Colour Plates A, B to F).

Individual mineral grains were examined under a binocular microscope at magnifications of up to 50 times. A selection of mineral grains representing all the shapes and surface characteristics encountered, were selected for detailed examination in a JEOL JSM - 35 scanning electron microscope. Considerable depth of focus can be obtained with this instrument and, this together with the high magnification capability (up to 100,000 times) and the high resolving power (10 µm), allows a wide range of photographic illustrations. (See illustrations in Volume 2).

All the mineral grains examined in the scanning electron microscope were ultrasonically cleaned in a solution of "Decon 75" surfactant. They were then mounted on brass specimen stubs, using colloidal silver solution as adhesive. The mineral grains were coated with 10-20 µm thick coatings of carbon and then gold in a JEOL JEE - 4B vacuum coating unit fitted with a tilt rotation stage.

In addition, use was made of the Kevex Energy Dispersive Micro-X 7000 analytical spectrometer attached to the scanning electron microscope. This instrument allows rapid, non destructive identification and semi-quantitative chemical analysis of mineral grains and their coatings during detailed surface textural examination either on a multi-coloured display screen or by use of a computer print out system.

1.3 Classification of surface textures

Before describing the surface textures found on pyrope, picroilmenite and chrome diopside from kimberlite it will be constructive to consider a general classification of these surface features and how they relate to kimberlite emplacement. This proposed classification presented in Table I (See Volume 2) is based on the chronlogical sequence of formation of surface morphological characteristics observed on these mantle-derived minerals during this study. In this respect the interpretation of observations adopted was where surface features are superimposed on other textures, the underlying textures pre-date those which are superimposed on them. In this way age relationships between the different surface features on each mineral studied were established by observations using a scanning electron microscope.

These surface features which are considered to form on the different minerals studied under the same geological environment have been grouped together in the classification scheme. The classification is broadly divided into two groups as follows.

1) Primary surface features.
2) Secondary surface features.

1) Primary surface features

Primary surface features are those surface morphological characteristics which have formed as a result of reaction between kimberlite liquid and the mantle-derived minerals during magma ascent and kimberlite emplacement. Such surface features are the kelyphitization of pyrope and the formation of sub-kelyphitic surfaces, sculpturing or chemical etching of mantle-derived minerals by the kimberlite liquid during upward transport and emplacement, and the formation of reaction mantles surrounding ilmenites during the crystallisation of the kimberlite groundmass.

2) Secondary surface features

Secondary surface features are those surface features which form on mantle-derived minerals after kimberlite emplacement. These features are clearly younger than the primary surface features and, in most cases, modify or form at the expense of the primary surface features, by in-situ weathering and diagenetic etch processes. For example, the replacement of sculptured features (hillocks and etch pits) on pyrope, by enlarged solution cavities, give rise to the formation of honeycomb textures and the partial destruction of pyrope in lateritic soils. Ilmenite shows very little surface modification and is extremely stable to diagenetic etching, whereas garnet and particularly chrome diopside are markedly affected by intrastratal solution in lateritic environments.

The thesis is structured in relationship to the proposed surface texture classification scheme presented in Table I. For convenience, the secondary surface features are discussed first, followed by a detailed examination of the primary surface features and their relationship to kimberlite emplacement.

2.0 THE EFFECTS OF IN-SITU WEATHERING PROCESSES ON THE SURFACE TEXTURES ON PYROPE, PICROILMENITE AND CHROME DIOPSIDE FROM THE DEEPLY WEATHERED PROFILE OF THE JWANENG KIMBERLITE PIPE

A detailed study was undertaken of the microsurface textures of 17,869 mineral grains (7,689 pyrope, 7,006 picroilmenite and 3,174 chrome diopside grains) from the upper weathered portion of the Jwaneng kimberlite pipe, situated approximately 100 km west of Gaborone in the Ngmaketse district of south eastern Botawana.

2.1 Sampling procedures

Heavy mineral concentrates from six selected 15 inch jumper drillholes (BH 15/4, 15/5, 15/11, 15/13, 15/15 and 15/25), were chosen for detailed investigation. These concentrates were collected where possible at 10 metre intervals, from surface to a depth of 150 metres from a series of drillholes, arranged in grid fashion, over the kimberlite pipe. These six jumper drillholes are located as close as possible to a line running from SW to NE forming a cross-section (A-B) across the trilobate-shaped kimberlite pipe as indicated in Figure 1.

Because each concentrate was recovered from the same volume of sample material, they were able to be statistically compared in spite of the variation in weight of concentrate recovered from each 10 metre zone.

In order to compare the surface textures of the kimberlitic minerals and their relationship to the different zones of weathering within the pipe it is necessary to first outline the geology of the pipe.

2.2 Geology and depth of weathering of the Jwaneng kimberlite pipe.

The Jwaneng kimberlite pipe is trilobate in shape, trending SW-NE, consisting of south, central and north east lobes, and having a surface area of 50 hectares (Figure 1). The pipe intrudes shales of the Timeball Hill Formation of the Pretoria Group and is overlain by Kalahari sediments, averaging 40 metres in thickness (Figure 2).

Information gathered from borehole core logging, of drillholes numbered 186, 235, 213, 200 and 216D and from mapping of Shafts 1 and 2, situated roughly along the cross-section A-B as shown in Figure 1, enabled a detailed geological cross-section to be drawn across the kimberlite pipe. (Figure 3).

2.2.1 Sedimentary cover

The Kalahari sedimentary cover overlying the pipe consists of an upper fine-grained, structureless, yellow aeolian sand approximately 10-15 metres thick, which grades into semi-consolidated sandstone layers at the base. The lower portion of the Kalahari cover is comprised of nodular grey silcrete, grading into pink, green and ochre-coloured calcrete, over interbedded clay horizons and conglomeratic gravels (pebbles 5-20 mm in size) which rest directly on the kimberlite and country rocks. Sedimentological studies by Minter and Brewer (1979) indicate that the kimberlite was topographically 15 metres higher than the host rocks at the onset of gravel deposition. All three lobes of the kimberlite body display distinct dome shapes (see Figure 3), where they drop away sharply at both the necks and country rock boundary, resulting in thickening of the gravels along the margins of the pipe and over the two necks. The gravels are thought by Minter and Brewer (op cit), to be mass flows originally derived from Dwyka tillite.

2.2.2 Weathered profile of kimberlite

The weathered profile of the Jwaneng kimberlite extends to a depth of approximately 110 metres and may be divided into four distinct zones, as follows:-

Upper red carbonated kimberlite tuff breccia;pale green kimberlite tuff breccia; brown oxidised tuffisitic kimberlite and massive hard blue serpentinised brecciated tuffisitic kimberlite.

2.2.2.1 Red carbonated kimberlite

The top portion of the kimberlite is extremely decomposed, consisting mainly of calcite, clay and hydrated iron oxides. It varies in colour from light pink to red due to concentrations of goethite and clay material. Xenoliths are more or less totally carbonated and sedimentary features are poorly preserved. There is a gradual change from pink to green kimberlite between 60 to 70 metres from surface.

2.2.2.2 Pale green kimberlite

This kimberlite is generally friable, varying from structureless to a well bedded epiclastic rock. Preserved sedimentary layering is comprised of roughly bedded xenoliths in a soft highly chloritised clastic matrix. Recognisable country rock fragments consist mainly of sandstone and, shale and comprise 50-60 per cent of the rock. Alteration products are mainly chlorite and serpentine, with extensively developed sub-horizontal networks of calcite veins.

2.2.2.3 Brown oxidized kimberlite

Brecciated tuffisitic kimberlite becomes more competent and changes to a brown or buff colour with serpentinisation more noticeable due to decrease in weathering, while oxidation is only well developed along minor fracture zones. This brown, slightly altered kimberlite, is generally present at a depth of 90-100 metres from the surface as a thin zone between the pale green kimberlite and the hard blue kimberlite. It was also intersected in borehole log 206 as a layer within the red carbonated kimberlite, as shown in the geological cross-section (Figure 3). The zone occupied by the brown oxidized kimberlite is considered to represent the zone of water table fluctuations above which the kimberlite exhibits progressive stages of alteration/decomposition by weathering processes.

2.2.2.4 Blue serpentinised kimberlite

A gradual change from brown to dark blue kimberlite occurs at a depth of 100 to 110 metres from the surface as shown in the cross-section A-B (Figure 3). However, in shaft No. 1 (see attached log by P.J. Bartlett, Figure 4), there is an irregular undulating interface between the oxidized brown kimberlite and the unaltered blue ground. The dark blue kimberlite exhibits a segregationary texture, becoming harder with depth, and shows less oxidation than the kimberlite above the water table. Abundant shale breccia inclusions, some of which are highly carbonaceous with significant amounts of iron pyrites, occur below the water table.

Petrographic examination by Clement and Skinner (1978), has shown the upper part of the Jwaneng pipe to represent the poorly stratified basal remnants of a sedimentary kimberlite (crater facies), possibly with associated tuff deposits, overlying tuffisitic breccias within the diatreme proper. The presence of bedded sequences within the pipe has been confirmed by exposures in Shaft No. 1 (Figure 4). These do not necessarily indicate the presence of water-laid sediments. However, conglomeratic layers are present in the stratified zone between 70-90 metres in Shaft No. 1, indicating that at least some of the bedded material at Jwaneng is of sedimentary origin.

The larger size of the composite pipe, the absence of apparent flaring of the three lobes, and the lack of 'typical' crater facies rocks over much of the pipe testifies to considerable (but not complete) erosion of the crater zones. According to the kimberlite pipe model proposed by Hawthorne (1975), the probable position of the present day surface of the Jwaneng pipe is situated on the join between the crater zone and the diatreme zone, suggesting a removal of approximately 150 to 300 metres of sedimentary kimberlite by erosion before deposition of the Kalahari sedimentary cover.

3.0 RELATIVE ABUNDANCE OF PYROPE, PICROILMENITE AND CHROME DIOPSIDE FROM THE WEATHERED PROFILE

Detailed statistics on the number of mineral grains examined from eighty concentrates obtained from the six jumper drillholes, as well as shape, and different surface textures displayed by the mineral grains are recorded in Tables II to VII.

The number of garnet, ilmenite and chrome diopside grains from each drillhole, together with the important surface textural changes displayed by the indicator minerals are graphically illustrated against the detailed geological cross-section of the weathered profile of the Jwaneng kimberlite pipe in Figure 5.

From results presented in Figure 5 the following deductions can be made.

3.1 Chrome diopside

a) With the exception of jumper drillholes 15/15 and 15/25 in the NE lobe, chrome diopside is abundant (more than 100 grains) in all the concentrates recovered from the dark blue kimberlite at depths of 110 to 150 metres from the surface. The scarcity of chrome diopside at this depth in the kimberlite in the NE lobe, might suggest that it is mineralogically different to the other kimberlites at Jwaneng, and that the relative proportion of chrome diopside is low. The sudden increase in the amount of chrome diopside recovered from concentrates at 130 metres in 15/15 and at 110 metres in 15/25 may be caused by the large number of pyroxene-bearing xenoliths in this part of the pipe.

b.) There is a substantial decrease in the number of chrome diopside grains in passing upwards from the hard blue kimberlite into the soft pale green kimberlite and the mineral is virtually absent at the base of the red carbonated kimberlite. This drastic reduction and eventual elimination of chrome diopside in the upper weathered portion of the kimberlite by in-situ weathering processes, implies that only a very small proportion of the chrome diopside would be liberated from the kimberlite at the surface. (see Figure 5 drillholes15/5 and 15/13).

3.2 Garnet and ilmenite

a) By comparison with chrome diopside, pyrope garnet and ilmenite are plentiful in all the concentrates examined from the six drillholes which penetrate the weathered profile of the pipe. In most cases, these minerals show only a slight decrease in numbers at the top of the weathered kimberlite. They, thus appear to be more resistant to in-situ weathering processes than chrome diopside. Garnet and ilmenite are also common in the conglomeratic gravels and calcrete overlying the pipe, but very few grains were recovered from the wind blown Kalahari sand at the surface. Slight abrasional rounding was noted on forty two ilmenite grains (6,0 per cent), from the aeolian sand cover, while garnet, on the other hand, shows no sign of attrition, probably because of its greater degree of resistance to abrasion.

b) As shown in Figure 5, there is a progressive decrease in the number of garnets with kelyphite coatings towards the upper part of the weathered profile at Jwaneng. Observations made by Berner et al (1979), on weathered pyroxene grains from soil samples and on artificially etched pyroxene grains, indicate that augite and diopside weathered or dissolved more rapidly than hypersthene and enstatite. Similar decompositional trends are shown by chrome diopside and kelyphite at Jwaneng (Figure 5), with kelyphite being slightly more resistant to weathering than chrome diopside. It is, therefore, evident that the kelyphite shells surrounding garnet are progressively decomposed by in-situ weathering, with the result that, only a small number of kelyphite encrusted garnets are likely to be liberated from the kimberlite (see Figure 5; drillhole 15/13 was the only drillhole containing a few kelyphite encrusted garnets in sediments overlying the pipe).

c) The number of garnet grains displaying diagenetic etch features, mainly in the form of trichitic cavities (Plate 1), increases from near the contact between the pale green kimberlite and the blue kimberlite (water table); these become more common towards the top of the weathered profile in the red carbonate kimberlite.

d) 291 composite ilmenite grains (4 per cent), (Plate II7), were found exclusively within the concentrates from the kimberlite, and were absent from the sediments overlying the pipe. It is to be expected that these polycrystalline grains, having less mechanical strength than discrete ilmenite grains, would disaggregate relatively soon after liberation from the kimberlite. The presence of these grains could, be used as an indication of the proximity of a kimberlite host.

4.0 INTERPRETATION OF SURFACE TEXTURES ON CHROME DIOPSIDE, ILMENITE, AND DIFFERENT COLOURED GARNETS FROM THE WEATHERED PROFILE AT JWANENG

Six graphs summarising the information recorded in Tables II to VII are presented in Figure 6. This diagram shows the proportions of various types of surface textures displayed by chrome diopside, ilmenite and the different coloured groups of garnet, plotted in relation to the weathering of the pipe. These proportions, expressed as percentages, were calculated using the number of mineral grains displaying each type of surface texture, relative to the total number of grains in each mineral population, or colour group, for the total borehole sample. This method of data presentation was chosen in preference to one based on the percentage of grains in each 10 metre sample. Although both methods show identical trends within the kimberlite, the percentage of each 10 metre sample projects false trends in the sedimentary cover, as a result of the low mineral content of these samples.

4.1 Colour coding of garnet population

The garnet grains from each concentrate were colour-coded under the binocular microscope into four colour groups, i.e. mauve, red, orange and pink. This was done to investigate whether or not different coloured pyrope grains exhibit different surface textures, which might be related to differences in origin or garnet composition.

The colour of garnet from kimberlite (e g. Jagersfontein, Dokolowayo and Premier Mine) appear to be mainly a function of TiO_2 and Cr_2O_3 (Wyatt, Unpublished data - Anglo American internal report, 1978). Microprobe analyses of garnet from kimberlites have shown that the mauve varieties are rich in Cr_2O_3 and appear to be genetically related to peridotites, while the orange garnets are high in TiO_2 and low in Cr_2O_3 and tend to be derived from eclogites and/or megcrysts. The pink and red garnet groups fall between these two extremes. However, it must be borne in mind that garnets having the same colour do not necessarily belong to the same paragenetic group. For example, some red garnets appear to be chemically allied to some mauve garnets, while other red garnets have compositions more closely related to orange garnets.

From the data illustrated in Figure 6 the following interpretations are made.

A large proportion (39 per cent) of the garnet grains extracted from the Jwaneng concentrates are mauve in colour (Table VIII). The remainder of the garnet population could be divided into red (25 per cent), orange (25 per cent) and pink (11 per cent). The numbers of different coloured garnets are reasonably constant throughout the weathered kimberlite, but decrease rapidly within the sedimentary cover as depicted in Graph 1, Figure 6. This is presumably due to the movement of sand and transport of grains away from the pipe by wind action. The numbers of ilmenite and chrome diopside grains (Table IX) have also been included on this graph for comparative purposes.

4.2 Kelyphite and sub-kelyphitic surfaces on different coloured garnets

Detailed microscopic examination of almost 8000 garnet grains from the Jwaneng kimberlite indicates that remnants of kelyphite shells, although present on garnets from all four colour groups (plotted in Figure 6 Graph 2), are more commonly developed on mauve garnets (Table VIII). As many as 21 per cent of the mauve garnets display kelyphite coatings, while the percentage of kelyphite encrusted garnets from the other colour groups is less than 8 per cent. Because the formation of kelyphite is considered to be the result of an isochemical reaction between olivine and garnet (Reid and Dawson, 1972), it follows that peridotitic garnet (mauve), are more likely to have been kelyphitized than the other colour varieties. Kelyphite crusts preserved on garnet become progressively less common towards the top of the soft green kimberlite at a depth of 70 metres as a result of in-situ weathering. Above this point, only a few mauve garnets encrusted with portions of kelyphite, were recovered at the top of the weathered kimberlite and in the sedimentary cover.

Exposed sub-kelyphitic surfaces (see TableVIII)were found predominantly on mauve garnet (44 per cent), when compared with the other three colour varieties. As shown in Figure 6, Graph 3 this type of surface tends to be least common on orange (eclogitic) garnet (11 per cent). The progressive decomposition and removal of kelyphite from garnet by in-situ weathering processes, results in a complimentary increase in the proportion of garnet grains which display exposed sub-kelyphitic surface towards the top of the weathered kimberlite.

Only a small number of detrital garnets in the sedimentary cover still retain their sub-kelyphitic surfaces.

4.3 Proportion of sculptured surfaces on kimberlite minerals

4.3.1 Garnet

Sculptured surfaces consisting of combinations of rounded hillocks and etch pits, are present on garnet from all four colour groups as illustrated in Figure 6 Graph 4. This type of surface (see Table VIII), tends to be more commonly developed on red and orange garnet (80 per cent), than on pink (68 per cent) and mauve garnet (37 per cent).

As a result of the preferential development of kelyphite on mauve (peridotitic) garnet, sculptured features are less common on these garnets than on the other colour groups.

The combined percentages of sculptured garnet from all four colour groups, are plotted in Figure 7.

This distribution is surprisingly constant from a depth of 150 metres (72 per cent sculptured garnet) to 50 metres (75 per cent sculptured garnet). From the top of the kimberlite, however, the proportion of sculptured garnet decreases markedly within the Kalahari sediments overlying the pipe. The sculptured surfaces on garnet from the unweathered blue ground (110 to 150 metres), and on those in the topmost weathered part (50 to 60 metres) of the Jwaneng kimberlite were found to be identical. This similarity, together with the consistency in the percentage of garnet exhibiting sculptured surfaces throughout the weathered profile at Jwaneng, indicates that these etched surfaces show no relationship to weathering, but rather form, by dissolution or (resorption of garnet) during kimberlite emplacement. This result is in complete contrast to the results reported by some Russian workers (Afanansyev et al, 1976) who claim that sculptured garnets only typify the upper weathered horizons of kimberlite pipes and form by weathering processes.

4.3.2 Ilmenite

Although many of the 7000 ilmenite grains examined from Jwaneng, were fragmental in appearance, rough blocky sculptured surfaces were observed on 40 per cent of the grains (Table IX). The proportion of sculptured grains is reasonably constant (similar to garnet) throughout the weathered profile depicted in Figure 6 Graph 5. Similarly, sculptured surfaces become progressively scarcer on ilmenite recovered from the top of the red carbonated kimberlite and are rare on detrital grains extracted from the overburden which exhibit slightly abraded surfaces.

4.3.3 Chrome diopside

Grains of chrome diopside with sculptured surfaces are abundant (71 per cent) in the concentrates from the hard unweathered blue kimberlite at 150 metres from surface (Table IX).

The proportion of sculptured grains decreases progressively through the weathered profile to a point (70 metres from surface), at which chrome diopside is generally absent, apparently due to corrosion and decomposition by in-situ weathering (Figure 6 Graph 5).

5.0 SURFACE MODIFICATIONS BY IN-SITU WEATHERING IN THE JWANENG KIMBERLITE PIPE

5.1 Garnet

Three types of diagenetic etch modifications are commonly found on pyrope from the upper weathered portions of kimberlite pipes, namely :-

1) Trichitic cavities
2) Chattermark trails
3) Oriented v-shaped solution pits.

These diagenetic etch features are superimposed on the sculptured surfaces formed by exposure to the kimberlite magma during emplacement (resorption) and therefore clearly younger than the sculptured features and form by other processes which post-date the crystallisation of kimberlite.

5.1.1 Trichitic cavities

Trichitic cavities, first described by Bauer and Hrichova (1966), are tiny square to rounded voids, pits or etch tunnels which may penetrate deeply in towards the centre of pyrope grains (Plate 1). Where present, they appear to be randomly developed on all garnet surfaces.

Quantitative scanning electron microscope investigations show that trichitic cavities are the main diagenetic etch features present on garnet grains from the weathered kimberlite at Jwaneng. The first appearance and development of trichitic cavities occurs on garnet recovered from within the blue serpentinized kimberlite just below the water table and reaches a maximum within the upper red carbonated kimberlite (Figure 6 Graph 6). The proportion of diagenetically etched garnet then decreases towards the surface within the Kalahari cover.

In the*SEM only their surface expression, is apparent with square openings (Plate 2), varying in size from 0.1 mm to approximately 0.004 micrometre in diameter. However, under transmitted light, trichitic cavities appear as thin curved, branching, somewhat irregular features (Plate 3), having rounded cross-sections which taper inwards within the pyrope. Their distribution is also irregular, from single microscopic voids (Plate 4), to a dense network of microscopic cavities (Plate 5). Usually the peripheral zones contain a high concentration of trichitic cavities and there is a gradual transition to a central kernel devoid of cavities (Plate 6). The cavities generally occur in groups or layers and are apparently developed along dislocation planes which intersect the surface of garnet grains, as well as other zones of structural weakness (cracks, etc.), within garnet (Plate 7).

*Scanning Electron Microscope

These concentrations of trichitic voids, situated along dislocation structures and forming tangled arrangements as seen in transmitted light, outline well defined sub-grain boundaries within the pyrope (Plate 8). These boundaries perhaps formed by creep within the mantle (Carstens 1969). Irradiation of pyrope with thermal neutrons followed by laboratory etching experiments (Hrichova, 1966), indicate that trichitic cavities in pyrope are due to corrosion (etching out) of fission tracks caused by spontaneous fission of traces of radiogenic Pb within pyrope. Trichitic cavities are seen on garnets extracted from the upper weathered portions of kimberlites, and are commonly developed on corroded detrital pyrope grains recovered from sediments in the vicinity of kimberlite occurrences.

5.1.2 Chattermark trails

Chattermark trails on pyrope are composed of crescentic marks forming patterns of parallel oriented, uniformly spaced fractures (Plate 9), occurring as trails which may differ from each other in width, length and orientation. These trails or arcuate grooves are randomly developed (Plate 10) on garnet surfaces and may cut across one another. They vary in width from 3 μm to 20 μm, and average 0.06 mm in length. The number of chattermark per trail varies from 5 to more than 20. Arcuate grooves resembling chattermark trails appear to be extremely rare on kimberlitic garnets. They have been observed on conchoidal breakage surfaces on a few garnets from Jwaneng (Plate IO), and were seen to be superimposed on sculptured surfaces on a garnet from Montrose No.3 kimberlite pipe (Plate 9). These trails are generally associated with other well known chemically formed features, such as oriented v-shaped solution pits (Plate IO) (Margolis, 1968; Bull, 1977).

Glacial chattermarks on scoured rock surfaces have long been recognised to result from glacier movement over fixed bedrock (Chamberlain, 1888). Folk (1975), suggested that such features on the surfaces of garnets recovered from sediments indicated glacial transport of the sediment. From tertiary sediments examined by Folk, between 5 and 35% of the garnets exhibited chattermark trails. Bull (1977) described chattermark trails on euhedral crystal faces on quartz grains from a cave in South Wales and suggested that these were chemically formed features.

Gravenor and others (1978), extended the technique to infer a relationship between the percentage of chattermark grains and the distance of transport of the material by the glacier. Later work (Gravenor, 1979) further extended this hypothesis to identify the distance of glacial transportation and also to identify those garnet grains that had been recycled in successive glaciations.

These chattermark textures have been described by various authors (see Bull et al, 1980) as being formed by glacial grinding, diagenesis, mechanical (sub-aqueous) action, and chemical etching.

The development of chattermark trails on pyrope from weathered portions of kimberlites is envisaged to have formed by a combination of both mechanical modification and chemical action. Mechanically induced zones of strain may develop on garnet by buffeting, particularly between the hardest minerals, i.e. diamond, zircon and garnet, during kimberlite emplacement. Preferential solution of garnet along these zones of weakness by diagenetic etching results in the formation of chattermark trails, which at first glance, resemble mechanically produced percussion scars, but are in fact, etched out (exposed) strain dislocations on garnets.

Therefore, chattermark trails may not be solely the product of glacial action, but in fact, also result by diagenetic (in-situ) etching in the upper weathered portions of kimberlites. Chattermark trails have not been observed on ilmenite and chrome diopside from kimberlite.

5.1.3 Oriented v-shaped solution pits

Pyropes from weathered kimberlite also exhibit small shallow oriented v-shaped solution pits (Plate II), developed mainly on conchoidal fracture surfaces, but in some cases superimposed on sculptured features. These diagenetically produced features form a fine stippled pattern and result from chemical solution of garnet by percolating groundwaters (Plate I2).

Crystallographically oriented etch pits, similar to those found on pyrope from kimberlite have been observed on quartz sand grains by Biederman (1962); Krinsley and Newman , (1965). Krinsley and Funnell, (1965), have demonstrated by laboratory experiments, using low concentrations of hydrofluoric acid and sodium hydroxide, that these oriented v-shaped pits found on quartz sand grains are of chemical origin. Similar etch features have been produced experimentally by Nickel (1973) on almandine garnet. It is therefore, logical to assume that pyrope garnet is susceptible to similar surface modifications during diagenesis. The degree of this diagenetic pattern (modification) is

grains have been exposed to circulating groundwaters.

5.2 Proportions of diagenetic etch features

5.2.1 Garnet

Diagenetic etch features are superimposed on sculptured surfaces and breakage surfaces alike, and clearly post-date these features. They are more commonly seen on mauve and pink garnets, whilst orange and red colour varieties appear to be more resistant to diagenetic modifications (Figure 6 Graph 6). Trichitic cavities are the most common form of surface modification resulting from diagenetic etching, but some garnets also exhibit chattermark chattermark trails and v-shaped oriented solution pits. These features, collectively grouped as diagenetic etch features, were observed on no more than 4 per cent of the garnets examined from Jwaneng (Table X).

5.2.2 Ilmenite

Ilmenite, unlike chrome diopside and to a lesser extent, garnet, is extremely stable and appears to be unaffected by weathering processes in kimberlite (Table X). Slight tarnishing of conchoidal fractures and incipient development of fine stippling (Plate 13) are the only alteration features seen on a few detrital ilmenites recovered from the base of the calcrete overlying the pipe. Similar diagenetic etch features were also found on ilmenites from calcrete, overlying the Sikereti Kimberlites in the Panneveld region of Bushmanland, Northern Namibia/SWA.

5.2.3 Chrome diopside

The alteration of chrome diopside by weathering is accompanied by a change in colour from bright emerald green to dull pale whitish-green. This change was detected on approximately 19 per cent of the chrome diopsides examined from Jwaneng (see Table X). Small irregular shaped solution cavities (Plate 14), commonly developed on freshly broken surfaces, signify the beginning of diagenetic etching. Alteration proceeds along cracks (Plate 15), and cleavage planes (Plate 16) parallel to (100) and (010), which become milky white in colour. The proportion of chrome diopside grains displaying alteration/ decompositional features reaches a maximum within the brown oxidized kimberlite (i.e. in the zone of water table fluctuations), as illustrated in Figure 6 Graph 6.

Intense diagenetic etching leads to widespread surface disintergration (Plate 17), obliterating cockscomb terminations and forming fluted surfaces (Plate 18). Dissolution also proceeds inwards from the periphery of extensively altered grains, resulting in the development of a mesh-like structure (Plate I9), which consist of a maze of small solution cavities and hollows, resembling a whitish-green sponge (Plate 20).

Pervasively etched grains are extremely friable and either break up or are progressively altered to serpentine, calcite and clay, resulting in their almost complete removal in the upper weathered profile of the kimberlite.

5.3 Conclusions

The following conclusions can be made with respect to in-situ weathering processes on pyrope, picroilmenite and chrome diopside from the weathered profile of the Jwaneng kimberlite pipe.

1. The distribution of pyrope and ilmenite is relatively constant compared with chrome diopside. The latter mineral shows a progressive decrease in abundance upwards and is eventually eliminated by in-situ weathering processes towards the top of the weathered kimberlite

pipe. On the other hand garnet and ilmenite only decrease slightly in numbers towards the top of the weathered pipe, and they are also common in the conglomeratic gravels and calcrete overlying the pipe. Garnets do, however, decline rapidly in numbers within the surface aeolian sand probably as a result of transportation away from the pipe by wind action.

2. The order of relative stability of the mantle derived minerals during the decomposition of kimberlite is as follows:- Ilmenite is extremely stable, garnet shows slight surface modifications, while chrome diopside is almost completely eliminated by in-situ weathering of kimberlite, with the result that very few chrome diopside grains are liberated from the kimberlite.

3. Kelyphite shells surrounding garnet are progressively decomposed by in-situ weathering of kimberlite, paralleling the decompositional trend shown by chrome diopside. Thus only a small number of kelyphite encrusted garnets are liberated from the top of the weathered kimberlite profile. Kelyphite, although found on garnet from all four colour groups is more commonly developed on mauve garnets which are most probably derived from peridotite.

4. Sub-kelyphitic surfaces are more common on mauve garnet than on the other colour groups. Progressive decomposition and removal of kelyphite from garnet results in a complementary

increase in the proportion of garnets grains which display exposed sub-kelyphitic surfaces, towards the top of the weathered kimberlite pipe.

5. Sculptured surfaces are more commonly developed on red and orange garnet (eclogites-megacrysts) and appear to be least common on mauve garnets. Preferential formation of kelyphite on mauve garnet (peridotites), evidently protects their surfaces (from resorption by kimberlite liquid) during emplacement and therefore, restricts the development of sculptured features on these garnets. Sculpturing of garnet, ilmenite and chrome diopside is caused by dissolution or resorption (chemical etching) during kimberlite emplacement, and is not the result of in-situ weathering processes as reported by some Russian workers (Afanasyev, et al, 1976).

6. Development of diagenetic etch features, in the form of trichitic cavities, chattermark trails and oriented v-shaped solution pits, superimposed on sculptured features and breakage surfaces alike, are the only surface modifications present on pyrope as a result of in-situ weathering. These features form along structural weaknesses within garnet and begin to appear on garnet recovered from the blue serpentinized kimberlite just below the water table, becoming increasingly common through the weathered profile, and reaching a maximum in the upper red carbonated kimberlite which is rich in hydrated iron oxides. Mauve and pink coloured garnet are more susceptible to diagenetic etching than the other colour varieties. Ilmenite, by comparison with garnet and chrome

diopside, is apprently stable and is unaffected by weathering processes in kimberlite.

6.0 CORROSION OF MANTLE DERIVED MINERALS IN LATERITIC SOILS OVERLYING KIMBERLITE

Lateritic (ferricrete) soils overlying kimberlites have been found to mask surface heavy mineral anomalies. A study was therefore directed towards establishing whether the mantle derived minerals are trapped in the ferricrete or whether they are progressively destroyed by solution.

Samples were collected during pitting operations over the Montrose No.3 kimberlite pipe in the Cullinan district near Pretoria, and at the Dullstroom kimberlite fissure in the eastern Transvaal. The pits penetrated ferricrete, overlying both kimberlites close to where drill cores had shown that the underlying fresh kimberlite contains abundant mantle derived minerals. Two sites were sampled at Montrose and are referred to as the East and West cuts, while only one pit was dug into the Dullstroom kimberlite. Soil samples, weighing approximately 50 kg each, were taken through the soil cover, and into the weathered kimberlite at both localities (Figures 8 and 9).

Approximately 3000 mineral grains (206 garnets, 2700 ilmenites and 27 chrome diopsides), from the Montrose kimberlite and 1000 garnet grains collected from the Dullstroom kimberlite fissure were examined. Details regarding the shape, surface characteristics and degree of diagenetic etching displayed by the mineral grains in each sample from

Montrose and Dullstroom are given in TablesXI andXII respectively.

Four distinct types of surface texture were recognised, namely:-

(1) Kelyphite encrustations
(2) Exposed sub-kelyphitic surfaces
(3) Sculptured surfaces
(4) Diagenetic etch features

Descriptions of these textures as developed on each mineral type are as follows:-

6.1 Garnet

Remanants of kelyphite and exposed sub-kelyphitic surfaces were found on 12 per cent of the garnet grains from Montrose. These surfaces are present only on grains in samples from immediately above and immediately below the ferricrete horizon in both cuts.

Sculptured surfaces on garnet were observed on 37 per cent of grains from Montrose and 86 per cent of grains from Dullstroom. These surfaces, are considered to have formed by reaction between xenocrystal garnet and kimberlite magma by dissolution processes during kimberlite emplacement.

Some garnets with sculptured features preserved over their entire surfaces, were seen to occcur in nearly all the samples, with the exception of samples from the top of the nodular ferricrete horizon. Many of these garnet grains which appear to be unaffected by in-situ diagenetic etching are cuboid in shape (Plate 21). Afanasyev et al.,(1976), established that cuboid-shaped garnets change very little during laboratory etching experiments and they consider that this crystal form is in equilibrium with the process of dissolution.

6.1.1 Honeycomb surfaces

Honeycomb or coarse sugary surfaces (Plate 22) consist of combinations of oriented solution pits, anastomosing grooves, enlarged trichitic cavities (i.e. solution cavities) and irregular hollows. These features are generally initiated along zones of weakness in the garnet crystals, and were observed on 44 per cent of the garnets from Montrose and 26 per cent of garnets from Dullstroom. They clearly post-date 'original' surfaces i.e. sub-kelyphitic and sculptured surfaces (Plates 23 and 24), in that they are superimposed on the sculptured surfaces, and result from diagenetic etching.

6.1.2 Progressive stages in the modification of garnet surfaces

Relatively unaltered, often broken and angular garnet fragments with areas of sculptured surfaces (Plate 25), liberated by weathering from the host kimberlite are acted upon by intrastratal solution. Artificial etching in the laboratory has shown that etching proceeds more intensely on freshly broken surfaces. Oriented v-shaped solution pits, superimposed on the large smooth conchoidal fractures, herald the beginning of diagenetic etching (Plate 25).

A few garnets exhibit hillocks which are apparently being replaced by a series of smaller hillocks (Plate 26). The development of small hillocks on larger ones has also commonly been found on garnets extracted from many kimberlite concentrates and, therefore, probably represents a continuous process in the development of hillocks, rather than two distinct cycles of etching.

Etch features, similar to those ascribed to dissolution processes in kimberlites, have been reported in the literature on detrital non-kimberlitic garnets. These features are thought to have been produced by diagenetic etching (Boswell, 1924; Bramlette, 1929; Beveridge, 1960). Sobolev and others (1951) consider these sculptured features on detrital almandine to be growth phenomena originating in metamorphic rocks, while Afanasyev (1976) regards sculptured surfaces (i.e. original surfaces) on kimberlitic garnet grains to be formed by weathering in kimberlite. Should the formation of fine textured etch hillocks occurs by solution of detrital garnet in sediments (Koen, 1955), it appears that their development could, only result in the early stages of diagenesis. Clear evidence gathered from the present investigation indicates that, as diagenetic etching proceeds, there is a continuous removal of sculptured features and replacement by honeycomb textures.

The enlargement and coalescing of etch pits and trichitic cavities (Plate 27) gives rise to the formation of anastomosing grooves and interconnecting hollows (Plate 28). Trichitic cavities, superimposed on sculptured surfaces (i.e. primary features) on grains from kimberlite are generally rare, and vary from 0.004 mm to 0.1 mm in diameter. Continued diagenetic etching increases the size and density of trichitic cavities (Plate 29), forming solution cavities and gives the garnet surfaces a milky appearance (Plate 30). SEM examinations show that prolonged diagenetic etching leads to widespread surface disintegration, with the formation of coarse, sugary etched surfaces (Plate 31) consisting of a maze of hollows, grooves and pits. A multitude of square to rounded solution pits and cavities develop at the expense of the original or sculptured surfaces (Plate 32). These pits have a strong, preferred orientation (Plate 33) and penetrate deeply into corroded garnet grains, ultimately giving rise to a honeycomb texture (Plate 34). After the almost complete obliteration of the original surfaces only small, perched remnants of original surfaces remain, surrounded by widespread solution pits and hollows (Plate 35). Large embayments and irregularly shaped outlines of the extensively corroded garnet grains (Plate 36) testify to considerable removal of garnet by intrastratal solution.

Diagenetic etching, which may finally result in the destruction of garnet grains, is highest in the ferricrete horizon. Extensively dissolved garnet grains from this horizon display extremely coarse solution pits, generally 0,1 mm in size, penetrating deep into the centre of the grains (Plate 37). These extremely large etch pits were only found on garnets from the ferricrete horizon. Concentration of ground waters or lateral movements or changes in the chemical composition of interstitial water may account for the increased removal of garnet by solvent attack.

Pale yellowish-brown coatings or 'skins' of clay material are encrusted around some of the grains examined. These clay coatings are probably due to post-depositional infiltration of clay particles, carried by percolating ground waters, into interstitial voids and hollows within the corroded garnet grains (Plate 38). The contacts between clay and garnet are sharp. This is evidence, according to Walker et al.,(1978), of in-situ replacement of silicate minerals by clays. This process would have assisted in the removal of garnet from the soil cover overlying the kimberlites. Alternatively, infiltrating clay particles may have accumulated in voids and hollows within the corroded garnet grains, thereby protecting them from further dissolution.

Coarse sugary surfaces (i.e. honeycomb textures), have also been observed on garnets from a laterite crust overlying a kimberlite from Viuva Nunes, Coromandel area, Minas Gerais, Brazil (D. du Toit - personal communication, 1978), where the surface anomaly is deficient in garnet although the laterite itself is studded with ilmenites.

6.2 Ilmenite

Large quantities of ilmenite were recovered from both samples from Montrose (468.8 gms and 26.2 gms respectively). Ilmenite is not present in the Dullstroom kimberlite. A total of 300 ilmenites of various size were selected at random from each sample and these grains are considered to be representative of the ilmenite concentrate from each sample. Rough blocky sculptured surfaces, often associated with whitish or brownish reaction mantles of perovskite, were noted on 55 per cent of the ilmenite grains examined. Composite grains which consist of aggregates of ilmenite crystals, are a common feature of the Montrose kimberlite.

Incipient modifications thought to have been caused by diagenetic etch processes were observed on only 4 per cent of ilmenite grains at Montrose. These modifications consist of small etch pits, generally rounded in shape, with a preferred orientation (Plate 39). Also developed are sub-parallel, sinuous grooves (Plate 40), or oriented striations. These etch features appear to have formed by preferential etching, possibly, along zones of weakness, or as a result of variations in chemical composition (i.e. exsolution lamellae) within the ilmenite grains (Plate 41 and 42). These two types of etch features tend to form on separate surfaces with different crystallographic orientations (Plate 43), which further suggest that they originate by chemical etching. Polished section examination of these grains revealed the presence of exsolution lamellae which were analysed in the SEMQ microprobe and found to be hematite in composition. Similar diagenetic etch features have been found by the author on ilmenite grains from the Zarnitsa pipe in U.S.S.R., the Orroroo kimberlite dykes in Australia, and the Lusu kimberlite in south western Zambia.

6.3 Chrome diopside

Chrome diopside grains were found only in samples AHP005 and AHP010 from Montrose, taken from the weathered kimberlite at a depth of 4 metres. Sculptured surfaces (Plate 44), were seen on 75 per cent of these grains. These surfaces consist of pointed, hacksaw-like terminations, thought to have formed as a result of resorption during kimberlite emplacement.

Diagenetic etching or weathering has also effected a large proportion (42 per cent) of the chrome diopside grains examined. Small rectangular shaped solution pits and deep cavernous hollows, superimposed on the original surfaces (Plate 44), testify to corrosion by intrastratal solution. Continued solvent attack leads to widespread surface disintegration, resulting in a colour change of the chrome diopside grains from deep emerald green to pale green, almost white (Plate 45).

6.4 Relationship between ferricrete and removal of kimberlitic minerals

The optimum conditions for the formation of laterites (ferricrete), appear to be high rainfall, high temperatures, intense leaching, strongly oxidizing environment, subdued topography, long duration of weathering and a chemically unstable parent rock (Levinson, 1974). These conditions are met within the tropics, particularly where the drainage is good. Under these conditions intense leaching of alkalies, alkaline earths, silica and other mobile elements, gives rise to an enrichment of iron, aluminium and titanium. Nodular zones in laterites occur midway between the upper and lower limit of the fluctuating water table (Bayliss, 1972). Lateritization, therefore, most readily, takes place in the zone of water table fluctuation. Rainwater, the major source of near surface ground waters, on contact with soil or exposed rock surfaces is both acid and oxidizing, both conditions favouring chemical attack. Lateritic soils generally have a pH of 5 - 7 (Ross and Kerr, 1931). Under these slightly acidic conditions garnet (almandine) is more unstable than in strongly acidic or alkaline solutions are shown by results obtained in laboratory etching experiments on the chemical stability of minerals (Nickel, 1973).

The intensity of diagenetic etching and the percentage of extensively corroded garnets (i.e. with honeycomb textures) is highest in the nodular ferricrete horizon overlying the Montrose No. 3 kimberlite pipe (Table XI and Figure10). A similar trend was also found at Dullstroom (Table XII and Figure 11).

Ilmenite is generally more resistant to diagenetic alteration than garnet and is considered to be a stable mineral (Hartman, 1955), which can sometimes be shown to increase upwards in the laterite profile, indicating its residual nature (du Bois and Jeffrey, 1955).

Scrutiny of the results presented in Table XIII shows an upward decrease in the quantity of ilmenite from samples collected in the East cut, while ilmenite from the West cut has an erratic distribution in the soil profile. The difference in the quantity of ilmenite obtained from the two sample sites may be due to local variations in ilmenite content in the Montrose No. 3 kimberlite pipe.

The ilmenite grains displaying minor diagenetic etch features were recovered mainly from the nodular ferricrete horizon and to a lesser extent from the surface red-brown soil (See Figure 10).

The apparent low resistance of chrome diopside to chemical weathering is illustrated in Figure 10. Rapid decomposition of chrome diopside by percolating groundwaters within the weathered kimberlite results in the progressive upward elimination of this unstable mineral, which was found to be absent from the upper three metres of the soil profile. This evidence may further explain why chrome diopside is not often encountered in prospecting samples, but is seen only in scatter aureoles in the immediate vicinity of kimberlite occurrences.

6.5 Conclusions

The following conclusions can be made with respect to the behavior of kimberlite mineral grains in lateritic environments.

(a) Honeycomb textures formed on garnets from the ferricrete soil profile overlying the Montrose No. 3 kimberlite, are identical to those found on garnets from Dullstroom. These surfaces post-date sculptured surfaces (which are formed by resorption during kimberlite emplacement), and therefore, must have formed by diagenetic etching.

There is a progressive decrease in the garnet content of samples taken from the weathered kimberlite to the surface.

The distribution of garnets displaying honeycomb or coarse sugary surfaces shows a complementary increase, from 10 to 20 per cent in the weathered kimberlite samples, to approximately 55 to 65 per cent in the soil samples at the surface. These trends reach peaks of 80 to 100 per cent in the samples taken at the top of the ferricrete horizon.

The ferricrete horizon, where water table fluctations favour chemical weathering, contain extensively corroded garnets. Progressive stages in the development of honeycomb textures eventually cause almost complete obliteration of sculptured surfaces particularly in the nodular ferricrete horizon. These garnets reflect intense solvent attack by intrastratal solutions. The result is considerable destruction of garnet in the lateritic soils covering both the Dullstroom and Montrose No. 3 kimberlite.

(b) Ilmenite is considerably more resistant to diagenetic alteration than garnet. Minor diagenetic etch features were however, observed on a few ilmenite grains. Ilmenite is abundant in the surface soil over the Montrose No.3 pipe but does not occur in the Dullstroom kimberlite.

The foregoing etch features were superimposed on conchoidal fracture surfaces and on crystal faces of subhedral crystals forming composite ilmenite grains. In comparison with garnet the sculptured surfaces (i.e. formed during kimberlite emplacement) on ilmenites are only mildly modified by solution. Nevertheless, as with garnet, the solution features on ilmenite are highest in the nodular ferricrete horizon. The incipient development of diagenetic etch features and the erratic distribution of ilmenite, unfortunately precludes the establishment of any destructive or residual trend in the laterite profile.

(c) Chrome diopside is rapidly decomposed by in-situ chemical weathering within the weathered kimberlite, and is absent from the upper portion of the soil profile.

(d) No evidence of abrasion or coating of iron oxide was found on any of the mineral grains examined and it appears that the kimberlitic minerals are not preferentially trapped in the ferricrete horizon or removed from the soil cover by erosion. The decrease in the number of indicator mineral grains towards the surface is primarily due to solution.

7.0 KELYPHITE AND SURFACE TEXTURES DEVELOPED ON KELYPHITE-ENCRUSTED GARNETS FROM KIMBERLITE

Kelyphite is a term derived from the Greek word "Kelyphos" meaning a rind or shell. A definition by Holmes (1920) states that kelyphite is "composed of microcrystalline aggregates of pyroxene or amphibole, which sometimes appear around garnet where it would otherwise be in contact with olivine or other magnesium-rich minerals". In this chapter the literature is reviewed and observations made on 858 kelyphite-encrusted garnet grains are discussed. These kelyphite-encrusted garnets were selected from heavy mineral concentrates from thirty kimberlite occurrences situated throughout the world (Table XIV). All selected kelyphite-encrusted garnets were examined under the binocular microscope and in the scanning electron icroscope. Petrological examinations of thin sections of kelyphite rims enclosing garnet from ultrabasic nodules and kimberlites were also carried out. A study of this kind was undertaken in order to document the structure and mode of formation of kelyphite rims surrounding garnet from kimberlite. An attempt has been made to explain the associated surface features formed on garnet during kelyphitization and their relationship to kimberlite emplacement.

7.1 Early studies on kelyphite

Reaction coronas or kelyphite rinds formed around garnets in peridotitic and eclogitic xenoliths in kimberlite and in other basic and metamorphic rocks have evoked comment from many investigators.

Muller (1846) was the first to describe these peculiar shells, in this case composed of a green mineral surrounding garnet, from a serpentinite at Greifendorf in Saxony. Schrauf in 1882 was the first to coin the term "kelyphite" for "rims" or "borders" surrounding garnet. Schrauf (1884) assumed the kelyphite to be a mineral, despite the fact that Lasaulx (1883) had shown that kelyphite consists of a mineral mixture. Later Mrha (1900) proved that the kelyphite, present in certain peridotites, was a mixture of rhombic and monoclinic pyroxene, spinel and amphibole.

Becke, in 1882 and 1886, described kelyphite structures consisting of an inner mantle of radially arranged light brown birefringent mineral, together with brown biotite and an outer mantle of hornblende, bronzite and diallage. He also showed that spinel was present in the kelyphite shell and considered that these kelyphite borders were of secondary origin. He suggested that the reaction producing the kelyphite might be as follows:-

$$\underset{\text{pyrope}}{Mg_3Al_2Si_3O_{12}} + \underset{\text{olivine}}{Mg_2SiO_4} \longrightarrow \underset{\text{spinel}}{Al_2MgO_4} + \underset{\text{amphibole}}{Mg_4Si_4O_{12}}$$

Holland (1896), suggested that the reaction borders around garnets represent a stage in the growth of garnet from the disintergration of original ferromagnesian silicates and, consequently, they do not always indicate destruction of garnet. Bonney (1899) suggested that the kelyphite be restricted to occurrences of secondary origin, applying the term "corona" to those that are primary.

7.2 The proportion of kelyphitized garnet in kimberlite

The relative abundance of kelyphite - encrusted garnets varies considerably from one kimberlite to another. In some cases, for example the Newlands Mine and Clarkton pipes, the majority of garnets recovered from heavy mineral concentrates are coated by kelyphite. However, concentrates from other kimberlites, such as the Orapa pipe in Botswana and Massif V in Zaire, contain very few garnets which display kelyphite shells. (See Table XIV). Possible explanations which may account for this are as follows :-

1) Either garnet grains might not have been in contact with olivine for long enough periods at pressures suitable for the formation of kelyphite
2) Or, majority of garnet population in some kimberlite pipes are derived from eclogites and/or websterite xenolithic material, as is possibly the case at Orapa.
3) Or perhaps the degree and depth of weathering in different kimberlite pipes, may have some effect on the decomposition of kelyphite particularly in the upper weathered zones of kimberlite occurrences.
4) Alternatively, fragmentation of ultramafic xenoliths during the vapour - solid fluidized intrusion of kimberlite, kelyphite may be removed from garnet by breakage and/or scouring. Those kimberlites which contain only a few kelyphite-encrusted garnet probably contain few ultramafic xenoliths and the degree of resorption of diamond and garnet should be proportionally higher than in kimberlites having an abundance of kelyphitized garnet.

5) On the other hand, garnets collected at Orapa and Massif V have almost certainly been obtained from crater fill sediments (sedimentary kimberlite) where abrasion could have occurred and weathering is likely to have been extreme.

7.3 Structure and mineralogy of kelyphite

Many observations have been made on kelyphite shells surrounding garnets in kimberlite and in peridotitic and eclogitic xenoliths from kimberlites. Wagner (1914, p. 64), was the first to draw attention to the structure of kelyphite borders. He noted (op cit), that they are made up of three to four rudely concentric shells and that each shell possesses a crypto-fibrous structure. Fiala (1966) described a garnet lherzolite from Sklenne in the Bohemian massif in which he noted that the inner part of the reaction rim consisted of a fine grained 'symplectite'. This zone consisted of ortho-pyroxene and chrome-spinel with diopside, surrounded by a coarser layer of enstatite. The monoclinic pyroxene was later identified as en-diopside (Klein and Padera, 1972). Wagner (1914) recorded that a reaction takes place between olivine and garnet (in peridotite nodules) but is absent where the garnet is in contact with clinopyroxene. For this reason 'kelyphitic' rinds may or may not be developed in eclogite xenoliths. The kelyphitic material, formed by the alteration of garnet in eclogites contains, in addition to an abundance of mica, minor twinned feldspar microlites, pale secondary amphibole, green spinel and glassy material (Wagner, 1914; Whitfield 1971).

Phlogopite, concentrated nearby or adjacent to garnet in both eclogite and peridotite xenoliths from kimberlite pipes (Plate46), has been reported by Williams (1932); Dawson (1962); Whitfield (1971) and Nixon (1973). Phlogopite forms the main constituent of some kelyphitic borders surrounding garnets (Plate 47).

The clinopyroxenes in many of the garnet lherzolite xenoliths examined by Carswell (1975) from South African kimberlite pipes commonly have marginal 'porous' zones which are significantly depleted in the jadeite molecule compared with the primary (unaltered) cores. As no feldspar or other Na_2O and Al_2O_3 rich phase could be detected, associated with the marginal zones Carswell concluded that the jadeite released has probably been taken up in secondary phlogopite and amphibole, which frequently occur adjacent to garnet and appear to be secondary. Work done by Delaney, et al (1980), on the chemistry of micas from kimberlites and mantle derived xenoliths, has shown that micas from kelyphite rims around garnets from peridotite xenoliths tend to be Cr-rich and have higher FeO and TiO_2 than the primary textured micas. These secondary micas in kelyphitic rims around garnet can be interpreted either as a product of metasomatism by fluids rich in mobile elements including H_2O and K within the mantle (Gurney-personal communications - 1979) or as a redistribution of K (and Ti) in undepleted garnet lherzolites (Danchin, 1979). The phlogopite rimming garnet may also form by the action of alkalies and volatiles, associated with the hydrous phase of kimberlite emplacement on garnets. The K-Rb-Cs relationship of this phlogopite is comparable to that of the host kimberlite (Berg, 1968).

Reid and Dawson (1972) found that in the reaction coronas around garnets in peridotitic inclusions in carbonatitic tuffs the common hydrous phase, i.e. the phlogopite of kimberlitic kelyphitic rims is absent. The structure of the reaction rims around the garnets in xenoliths from the Lashaine carbonatite, is regarded as the 'dry phase' of kelyphite formation, could be divided into three major zones as follows:-

1. Immediately adjacent to the garnet is a dark microcrystalline aggregate, averaging 0,1 mm wide, in which individual phases cannot be readily distinguished (Zone 1).

2. A zone of fine grained acicular crystallites (0.1 to 0.4 mm wide) in a feathery aggregate, orientated approximately normal to the garnet margin, consisting of small grains of spinel with pyroxene aggregates (Zone 2).

3. An outer zone (0.4 to 0.8 mm wide) which is coarser grained with euhedral crystals of spinel and clinopyroxene, largely enclosed by orthopyroxene (Zone 3).

The width of individual zones varies from garnet to garnet and even in different portions of the corona around a single garnet.

A typical example of a kelyphitised garnet in a sheared garnet peridotite from the Premier Mine (Plate 48) is described below.

Three zones can be recognised in the kelyphite shell. Moving outwards from the garnet these are as follows :-

1) A thin selvage comprised of radially structured orthopyroxene aggregates, with interstitial bundles of very thin crystals up to 0,15 mm long.

2) A zone of orthopyroxene crystallites up to 0,5 mm long, arranged in radial fashion, with occasional spinel occurring as interstitial sinuous patches.

3) A coarser, outer zone of orthopyroxene crystals, approximately 1 mm long, with chromite and clinopyroxene concentrated in the outermost part, averaging 0,3 mm in size. Isolated flakes of phlogopite and accessory carbonate, occurring only in the outermost zone of the kelyphite shell were probably formed by induced metasomatism during the intrusion of the volitile-rich kimberlite.

In some cases the alteration of garnet is so extreme that the original presence of garnet is indicated only by a tiny residual core or kernel of garnet (Plate 49).

Williams (1932), has made reference to some kimberlites having no garnet whatsoever. These cases can probably be explained by total kelyphitization of garnet, leaving only fibrous kelyphitic knots. In these cases all of the garnets in the incorporating nodules must have been entirely kelyphitized prior to disaggregation of the nodules and incorporation of kelyphitized garnet into the kimberlite. Evidence of several garnet/olivine reactions which had gone to completion were found by Lock and Dawson (1980), in peridotite xenoliths in the Letseng-La-Terae kimberlite in Lesotho.

Measurements made by Troneva et al (1979), on the thickness of kelyphite coatings on differently coloured garnets from Yakutian kimberlites in U.S.S.R., has shown that as a rule the coatings on violet pyropes are thicker (0.31 mm to 0.56 mm) than on orange varieties (0.15 mm to 0.27 mm) in one and the same kimberlite.

The results of the present study indicate that pyrope encrusted by kelyphite is found in all garnet peridotites, in some eclogite xenoliths from kimberlite, as well as, in a few garnet bearing serpentinites. Such kelyphite, which may be as much as 2 mm thick, forms radially oriented fibrous rims around the pyrope grains which become rounded during kelyphitisation. The kelyphite frequently displays at least two distinct zones as shown in Figure 12.

The inner zone, (usually 1.0 - 1.5 mm thick) consists of radially oriented aggregates, composed of rhombic pyroxene and spinel with minor clinopyroxene. The outer zone has a more granular appearance, averages 0.5 mm in thickness and consists of a combination of the following minerals,(which have been identified by x-ray diffraction technique);-rhombic and monoclinic pyroxene, spinel, amphibole, phlogopite and carbonate. Phlogopite, although commonly present, is not an essential constituent (Reid and Dawson, 1972). Phlogopite, together with other constituents such as amphibole and carbonate, has probably been introduced, by percolating potassium and water-rich fluids from the host kimberlite. These fluids cause the formation of secondary hydrous phases, particularly towards the outermost part of the kelyphite shell (Plate 48).

In some cases three, four or more zones may be identified within a kelyphite crust (eg. Plates 48 and 49). The contact between the zones is gradational. The grain dimensions increase towards the outermost zone but rarely exceed 0.1 mm in size. The boundary between the olivine-rich peridotite groundmass and the kelyphite shell is commonly sharp.

Thin cracks and veinlets,approximately 0,3 mm wide, filled with fibrous kelyphitic material often penetrate into garnet grains. The kelyphite in these cracks is composed of acicular orthopyroxene crystals, arranged either parallel, or at right angles to the walls of the cracks (Plate 80 and 82). Spinel occurs interstitially to the orthopyroxene. Homogeneous and oscillatory zoned, skeletal and subhedral spinels are present in garnet kelyphite shells.

Complex zoning has been reported by Haggerty (1975), as a characteristic feature of these secondary spinels from kelyphite surrounding garnets. Compositional trends as exhibited by spinel core-mantle relationships in zoned spinels from the groundmass of kimberlites vary from $MgCr_2O_4$ - $FeCr_2O_4$ to $MgAl_2O_4$ - $FeAl_2O_4$ (spinel prism), whereas secondary spinels from kelyphite define an inverse trend. The significance of compositional trends for spinels in kelyphite shells formed around garnet, the inter-relationship of these kelyphitic spinels with spinels in the groundmass and the unusual textural occurrences of skeletal (quench?) spinel crystals in these kelyphite coatings are as yet not fully understood.

7.4 Textural characteristics of sub-kelyphitic surfaces on garnet

Removal of kelyphite shells surrounding garnets from kimberlites and ultrabasic nodules exposes the underlying sub-kelyphitic surfaces formed on garnets during the process of kelyphitization.

The removal of portions of the kelyphitic shell from garnet surfaces proved difficult in those cases where the kelyphite was relatively fresh or contained appreciable amounts of phlogopite. When exposed the sub-kelyphitic surfaces underlying these phlogopite-rich kelyphite shells exhibit contorted flake-like impressions on the garnet surfaces (Plate 50). On the other hand, where the kelyphite is partly decomposed and does not contain mica, the latter could easily be removed, using a pair of tweezers and a sharp needle (Plate 51). Under the kelyphite coating garnets exhibit a smooth, waxy surface called the sub-kelyphitic surface. This surface, when viewed under the binocular microscope, has a matte appearance and is covered by fine stippling (Plate 53). At high magnification in the SEM, the sub-kelyphitic surfaces on garnets are seen to be composed of masses of minute square to triangular-shaped hollows, exhibiting a preferred orientation (Plates 52, 54, 55 and 56). These hollows are considered to be the root impressions of acicular pyroxene crystals (Plate 57). The latter constitute the bulk of kelyphitic shells, and are arranged, in most cases, approximately normal to garnet surfaces (Plate 58 and 59). A close examination in the SEM, of the underside of a portion of kelyphite removed from a garnet (Plate 60), revealed the presence of a multitude of tiny crystals, like "bristles in a brush", (Plate 61), which can easily be matched with the finely pitted nature of the sub-kelyphitic surfaces exposed on the garnet grains depicted in Plate 54, 55 and 56. In view of the foregoing association it is apparent that pitted sub-kelyphitic surfaces are clearly related to the process of kelyphitisation, rather than to resorption of garnet, and there can be little doubt that kelyphitic alteration is partly responsible for the rounding of garnets in kimberlites. In rare instances kelyphitized garnets do not have rounded sub-kelyphitic surfaces. For example, the author has examined a single octahedral-shaped garnet from Premier Mine, which was partly encrusted by kelyphite (Plate 62) and also a pyritohedral-shaped garnet (Plate 63), from a kimberlite in the Van Zyl's Rust area of the northern Cape Province, exhibiting sub-kelyphitic surfaces (Plate 64).

To explain the preservation of their euhedral morphology and disclose additional information about their origin, these euhedral garnets were analysed in an ARL SEMQ electron microprobe. Results obtained show that these garnets, contain moderate Cr_2O_3 (2.86 wt %), moderate to low CaO (5.29 wt %) and low TiO_2 (0.06 wt %). Using the statistically based chemical classification of garnets from kimberlites and their xenoliths by Dawson and Stevens, 1975; and Danchin and Wyatt, 1979 these garnets could be classified in the group dominated by garnets derived from four phase garnet lherzolites (peridotite), which are common inclusions in many kimberlites. Both garnets are mauve in colour which also suggests a peridotitic paragenesis. However, almost every garnet examined from peridotite xenoliths is rounded due to kelyphite alteration. Such alteration occurs by reaction between garnet and olivine, and to a lesser extent with clinopyroxene (Reid and Dawson,

1972) as a result of upward movement of peridotite nodules in the rising kimberlite magma. On the other hand, some garnets from eclogite xenoliths have also been grouped in this category in the statistical cluster analysis mentioned earlier. Shee (1978), has found chrome-bearing garnets in eclogites containing chromite from the Orapa pipe in Botswana. These garnets are similar in composition and colour to the garnets under discussion. These euhedral garnets with their well preserved large smooth crystal faces, could therefore have been derived from eclogite containing chromite, or other pyroxene bearing xenoliths in which garnets are only slightly kelyphitized. These nodules probably were disaggregated only in the final stages of kimberlite emplacement where the euhedral garnets would not be reacted upon (resorbed) by the cool kimberlite liquid.

In a few cases (10 per cent), the development of kelyphite fibres is tangential to the surfaces of garnet (Plate 65). In these cases, the underlying sub-kelyphitic surfaces have a rough, uneven appearance (Plate 66) consisting of randomly oriented and intersecting, rod-like impressions of the acicular pyroxene crystals (Plate 67 and 68).

In some instances the underlying garnet surfaces have a wrinkled appearance, consisting of cirque-like, meandering ridges (Plate 69 and 70). Occasional rounded protrusions or blocky humps (Plate 7I) are also present on sub-kelyphitic surfaces and these structures exhibit smooth or finely pitted surfaces. These features are most commonly developed on the mauve garnets and to a lesser extent on red garnets, but were not observed on orange or pink varieties.

A peculiar lumpy type of sub-kelyphitic surface (Plate 72), previously seen only on a few garnets from the Sloan 2 kimberlite in Colorado and from the Clarkton pipe in South Africa, also appears to be commonly developed on garnets from Jwaneng. This lumpy surface has a rolling or domed appearance, which is finely pitted (Plate 73), due to kelyphite formation normal to the garnet surface (Plate 74). In some cases, however, the domed areas are outlined by an irregular network of interconnecting furrows (Plate 75), resembling a pattern of mud cracks. This pattern is mirrored in the form of ridges, on the underside of the kelyphite crust removed from the garnet surface (Plate 76). The furrows may represent subgrain boundaries or an irregular pattern of dislocations within the garnet. Occasionally these domed areas exhibit radiating fan-shaped impressions (Plate 77). These occur on garnets whose inner kelyphite shells, are made up of rosette-like aggregates tangential to the garnet surface (Plate 78), instead of being composed of masses of acicular pyroxene crystals normal to the garnet surfaces. The outer kelyphite shell is granular in appearance. These abnormal fan-shaped patterns on the sub-kelyphitic surfaces, therefore, represent an imprint of the extraordinary structure of the inner kelyphite shells surrounding some garnets.

Very thin cracks and fractures filled with kelyphitic material (Plate 79), are a common feature of many of the grains examined. Breakage along these fractures generally exposes a criss-cross or mesh-like, platy development of kelyphite when viewed in the SEM (Plates 80 and 81). The differences in the structure of kelyphite developed around and within garnet grains is possibly caused by variations in confining pressure and availability of space along grain boundaries and within crystals. An exception to this rule was found in the development of asbestiform-structured kelyphite observed filling cracks in a garnet from one of the Bellsbank dykes (Plate 82).

7.5 Age relationship between sub-kelyphitic surfaces and sculptured features on pyrope

Sculptured features are commonly found on garnets from kimberlite as discussed earlier in the thesis and are occasionally observed adjacent to kelyphitic rinds on some garnet grains (Plate 83). These etch features, which might be considered as "etched remnants of original surfaces", occur as conical to rounded hillocks, and imbricate wedge markings (Plate 84). They are thought to form as a result of resorption of garnet, by reaction between the garnet surface and kimberlite magma, during kimberlite emplacement.

Abrupt changes between sub-kelyphitic surfaces and sculptured surfaces have been observed (Plate 85). In support of the aforementioned, it has been established by Afanasyev (et al 1976), that artificial etching of kimberlitic garnet has shown that, the sub-kelyphitic surfaces are least affected during laboratory etching. Only narrow sinuous grooves appear (see Plate 85 and 89). However, freshly broken garnet surfaces are readily attacked, giving rise to the formation of sculptured surfaces. Evidence revealed during detailed studies of the close association of sculptured features and sub-kelyphitic surfaces on individual garnet grains (Plate 86), has shown that sculptured features, which clearly post-date the sub-kelyphitic surfaces (Plate 87), form at the expense of the exposed sub-kelyphitic surfaces (Plate 88), as a result of chemical etching by the kimberlite liquid. These two unique surface textures are thought to be unrelated and have formed by different processes during the emplacement of kimberlites.

The development of sub-kelyphitic surfaces and sculptured surface textures on the same garnet grains, can be explained as follows:- Fragmentation of ultramafic xenoliths, liberates kelyphite -encrusted garnet into the kimberlite magma. Portions of the protective kelyphite shells are broken or scoured off, exposing parts of the garnet surfaces to attack by the kimberlite fluid (Plate 89). This results in the formation of sculptured features mainly on the conchoidal breakage surfaces which are younger than the kelyphite and exposed sub-kelyphitic surfaces on garnets from kimberlite.

8.0 SCULPTURED SURFACES ON PYROPE

After extensive examinations of the surface textures of garnets from many kimberlite localities it has become apparent that sculptured features are commonly found on pyrope from kimberlite. These sculptured features are represented by combinations of hillocks and etch pits (Plate 90). Artificial etching of pyrope crystals show that these sculptured features are crystallographically controlled, with a tendency for hillocks to be exhibited by surfaces which approximate to cube faces and pits to be preferentially developed on dodecahedral and octahedral surfaces (Mendelssohn, 1971).

Etching can be defined as the process whereby chemical reaction between a solid and an etchant results in the formation of sculptured features on the surface of the solid. It is generally thought that different etch features result from variations in the surface reaction or dissolution rates brought about by crystallographic orientation effects, lattice imperfections and variations in chemical composition (Gatos, 1975).

8.1 Hillocks

Hillocks occur as hummocky or mammillary surfaces and are commonly observed only on surfaces which approximate to cube faces (100) on garnet grains. Individual hillocks vary in shape. Varieties include flat topped polygonal (Plate 91), pyramidal (Plate 92), conical (Plate 93) and drop-like (Plate 94) types and they also occur as spherical mounds

(Plate 95). This series of shapes probably characterises the degree of solution of garnet, increasing from drop-like to pyramidal. Hillocks are frequently massed together (Plate 96) such that the shapes of adjacent individuals are distorted. They may be stepped or terraced (Plate 97), possibly due to pronounced zoning or other variations in garnet composition. Hillocks may be so delicate as to be detected with difficulty even under high magnification in the SEM, or may be so prominent (Plate 99), that the external shape of the grain is visibly modified (Plate 100). They range in diameter from 100 microns to as small as 1 micron. Variation in hillock summits may be caused by preferential etching and rate of dissolution (resorption) on different areas of the garnet surfaces.

When developed on surfaces removed from the cubic orientation, eg. parallel to the dodecahedral crystal boundaries, these features are flattened like "pointed roofing slates" arranged row upon row and are identical to "imbricate wedge markings" (Plate 98) as described by Rahmani (1973) which impart a "micro-scaly" appearance to the garnet. These imbricate wedge markings have equilateral outlines with apical angles that range between 70° and 75°.

8.2 Pits

These are small depressions, varying from rectangular to rhombohedral and from hexagonal to triangular in shape. Individual pits are very small and relatively deep. Apparently, as etching proceeds these pits become larger in areal extent and coalesce. Rhombic-shaped to rectangular etch pits tend to form on dodecahedral faces (Plate IOI and IO2), whilst those on the octahedral orientations are triangular to hexagonal in shape (Plate IO3).

On intensely etched garnet grains it is usually possible to find nearly all the above-mentioned types of sculptured features with predominance of one or two, determined by the micro-morphology of the grain itself.

8.3 Shape of garnet.

Whereas crystal faces on non-kimberlitic garnets may be well developed (Plate IO4), pyrope in kimberlites occurs mainly as irregularly-shaped grains, generally rounded without crystal form (eg. Plate IO5). Occasionally, however, octahedroid and cuboid-shaped crystals of chrome pyrope are found in kimberlite (eg. Plate IO6 and IO7).

8.3.1 Rounded garnets

Most garnet grains extracted from kimberlite concentrates are rounded, almost spherical in shape (Plate IO8) as exemplified by the rounded pyrope from kimberlite No. 13, Premier satellite province but rounded crystal coigns and edges can sometimes just be distinguished. The surfaces of the grains generally exhibit fine etch features. These vary from nearly circular hillocks to boat-shaped and rhombic pits and trigonal pits. By utilizing the relationship between surface features and garnet crystallography (Mendelssohn 1971), the crystal forms of the grain can be determined. It is a combined octahedron-dodecahedron - cube with the lattermost form slightly predominant. Curvature of individual crystal surfaces is marked, however, and they grade into one another across very subdued edges.

On the other side of the grain an unusual raised, relatively coarsely sculptured cubic surface of square outline occurs (PlateI09). The relatively coarse nature of this surface suggests that it reflects a relatively advanced stage of etching, which is difficult to reconcile with its relative elevation. It is possible that advanced etching initially reduced the grain to a size indicated by the raised surface; then renewed etching affected the entire grain excepting for the local, raised area which was protected from further attack.

8.3.2. Euhedral garnets

Euhedral garnets from kimberlite are rare, but have occasionally been found in concentrates from the Newlands and Premier Mines, the Rietfontein pipe, Benfontein Sill and the Sekretariskop occurrence in South Africa, the Sloan kimberlite in Colorado USA, Massif V in Zaire and from some Yakutian kimberlites in the USSR (Afanasyev et al, 1976). Such garnets have also been found in the Lusu kimberlite from Zambia and in sediments in South West Africa (Figure 13 locality map). These euhedral garnets are cuboid, octahedroid or rhombo-dodecahedroid in shape and vary in size from 0,5 mm to 5,0 mm in diameter. Cuboids are cubes with curved faces and commonly occur as single distorted crystals or as combined forms. Their surfaces are covered almost entirely by rounded hillocks, with minute etch pits restricted to the intersection of cube faces (Plate 107).

Surface textural examination of a few euhedral garnets from a kimberlite in the Van Zyl's Rust area of the Northern Cape Province revealed some interesting facts. Optical microscope examinations showed that the mauve garnet crystals are made up of combined dodecahedron-octahedron-cube forms (Plate 110). Individual crystal faces are smooth, with sharp edges. Viewed in the SEM, at high magnification scanty development of extremely fine textured sculptured surfaces (Plate 111), can be seen. The rounded hillocks are preferentially developed on cubic surfaces, whilst rhombic and triangular-shaped etch pits form on dodecahedral and octahedral surfaces, respectively.

The preservation of large smooth crystal faces, together with the finess of sculptured surfaces which are only poorly developed on some crystallographic surfaces, suggest that these euhedral garnets have escaped most of the resorption which kimberlitic garnets usually experience. It seems likely, therefore, that these garnets derive from zenoliths that were not disaggregated till the later stages of kimberlite emplacement.

8.3.3 Irregularly-shaped garnets

Three unusually shaped garnets (two mauve and one pink) having rounded nodular outlines (Plate 112), resembling crystal aggregates were examined from the kimberlite at Muza in the U.S.S.R. The presence of finely textured sculptured surfaces (PlateII3), over the entire surfaces of these lumpy-shaped garnets, show that they have been subjected to resorption processes. Detailed microprobe analyses across each grain are presented in Table XV The mean values of each globular grain indicate that these garnets can be classified as Ti-poor peridotitic garnets (Danchin and Wyatt, 1979) having variable amounts of Cr_2O_3. Scrutiny of the data in Table XV suggests that the chemical compositions of the centres of each grain are different to the edges, particularly in Cr_2O_3 CaO and FeO contents. Apart from a slight zoning in chromium no major chemical differences are present in the garnet grains. This rules out the possibility of chemically different regions existing in each grain which, etched at different rates, gave rise to globular shapes. It is, therefore, suggested that these globular-shaped garnet grains were probably combined crystal forms or crystal aggregates, which were subsequently rounded by extensive resorption during kimberlite emplacement, thereby resulting in their unusual nodular shape.

Rare, exceptionally coarse etch features have been found on garnets from kimberlite in Angola (Mussumuige), Colorado U.S.A. (Sloan 2) and South Africa (Premier Mine) and Clarkton pipe (Plates II4 and II5).

8.4 Proportion of sculptured garnets in kimberlite

Statistical examinations of 9136 garnets from five different kimberlite occurrences as detailed in Table XVI indicates that on average, 62 per cent of garnets from kimberlite exhibit sculptured features.

Scrutiny of the results presented in Table XVI, shows that although sculptured surfaces are present on pyrope, the proportion of sculptured grains varies considerably from one kimberlite to another, eg. sculptured surfaces are present on 85 per cent of pyrope from the Dullstroom kimberlite fissure, as compared with only 3 per cent from the Redondao kimberlite in Brazil. Sculptured surfaces occur on garnets from all four colour groups, but tend to be more commonly developed on red and orange garnet (80 per cent), than on pink (76 per cent) and mauve garnet (40 per cent). As a result of the preferential development of kelyphite on mauve (peridotitic) garnets, sculptured features are less common on these garnets than on the other colour groups. The kelyphite crusts presumably protected the surfaces of the mauve garnets which were therefore least acted upon by the kimberlite magma.

Sculpturing of pyrope, is caused by either dissolution or resorption (chemical etching) during kimberlite emplacement. Variations in size, shape and orientation of sculptured features on pyrope, is directly related to the intensity of resorption and reaction processes active during kimberlite emplacement, as well as the control exercised by the different etching rates of crystallographic surfaces on garnet. The degree of sculpturing is also influenced to some extent by the accidental protection of the surfaces of garnet which have been partly surrounded by kelyphite shells.

9.0 SCULPTURED SURFACES ON PICROILMENITE

9.1 Shape of ilmenite from kimberlite

Magnesian ilmenite is found in kimberlite in accessary amounts and commonly occurs as single rounded crystals (Plate II6) or polycrystalline aggregates (Plate II7) from 100 μm - 10 cm in size which rarely display euhedral morphology. Ilmenite less commonly occurs as large ovoid nodules (10 - 50 mm) and as eutectic-like intergrowths with diopside or enstatite. Compared with ilmenites from other igneous rocks, kimberlitic ilmenites although having a wide compositional range within the ilmenite - geikeilite series, are distinguished by their high MgO, high Cr_2O_3 and intermediate Fe_2O_3 contents. (Carmichael, 1967; Lovering and Widdowson, 1968; Haggerty, 1975; Mitchell, 1977).

9.2 Leucoxene - perovskite reaction rims on ilmenite

Crystals of ilmenite imbedded in kimberlite in some cases are surrounded by fringes of brown perovskite crystals (Plate II8) and/or peculiar borders of whitish, brownish or yellowish crusts of powdery material (Plate II9). This material, which has a fine granular appearance (Plate I20), was described by Wagner (1914), as earthy leucoxene. Energy dispersive micro-analysis of this ultra-fine granular material in the scanning electron microscope has shown it to be composed essentially of Ca and Ti and an x-ray powder diffraction pattern confirmed it to be perovskite. These powdery coatings which form a thin film of variable thickness (0,1 to 3,0 mm) around the periphery of ilmenite grains are always associated with etched (sculptured surfaces) on ilmenite (PlateI2I). These perovskite-rich coatings (reaction rims) are particularly common on ilmenite from the De Beers and Monastery Mines, and clearly indicate that these ilmenite grains are not in equilibrium with the kimberlite magma. Reaction rims of perovskite surrounding ilmenite could be explained as follows (Frick, 1973).

$$(MgFe)\ TiO_3 + CaCO_3 \longrightarrow CaTiO_3 + CO_2 + (Mg,Fe)O$$

The presence of small euhedral grains of Mg-rich magnetite in association with the perovskite grains around ilmenite suggests that magnetite is a possible product of this reaction. Alternatively the (Mg,Fe)O may be taken up in other minerals eg. ferromagnesian silicates.

Mitchell (1972) has shown the reaction rims surrounding ilmenite from the Bultfontein pipe, South Africa, to be composed of a complex inner zone consisting of intergrowths of perovskite, ilmenite and ferromagnesian silicates (probably serpentine and chlorite), and an outer zone of euhedral perovskite crystals (PlateI22). In the present study acicular, randomly oriented crystals of ferromagnesian silicates (confirmed by energy dispersive analysis) forming a mesh-like aggregate (PlateI23), were observed only on ilmenite grains from the Redondao kimberlite in Brazil. These acicular crystals,presumably of serpentine, were developed on small pyramid-like crystals of ilmenite

(Plate I24), which may represent either small ilmenite overgrowths on large rounded xenocrystic grains (Plate I25), or initial development of euhedral protuberances comprising blocky sculptured surfaces. Powdery perovskite forms the outer zone of the reaction mantles (Plate I26). These reaction products imply that the ilmenite breaks down, releasing Mg and Fe which combine with silica in the groundmass fluids, to form the ferromagnesian silicates. This is followed by the formation of perovskite which prevents further reaction of the ilmenite with the kimberlite residuum.

Euhedral-shaped crystals of perovskite, in some cases, corroded by groundmass material, (Plates 127 and 128), are often moulded upon the etched surfaces of ilmenite grains. Similar wreaths of perovskite also occur around olivine phenocrysts and have clearly aggregated around the margins of ilmenite and olivine. These earlier crystals have probably acted as nucleation sites for the crystallisation of perovskite followed by interstitial consolidation of the groundmass and carbonate phases.

In support of the above explanation there appears to be no significant difference in composition between the perovskite in the groundmass of the kimberlite and those from the reaction rims surrounding ilmenites, (Mitchell, 1972).

The presence of rhythmically mantled zones of alternating ilmenite and spinel with perovskite occurring in the outermost border zones on xenocrystic picroilmenite (Plate I29), has led Haggerty (1975), to suggest that widespread post-spinel crystallisation of perovskite is clear evidence for the development (existence) of late stage Ti-rich liquids. According to Wagner (1914), because of the very low silica content of the kimberlite magma, these Ti-rich fluids acted as a strong acid which presumably etched the surfaces of xenocrystic ilmenite grains.

Polished section examination of ilmenite reaction mantles (Plate I30) indicates that perovskite crystals may merge into, or penetrate, the ilmenite which implies that they have developed at the expense of the mineral. These perovskite borders may, therefore, originate by interaction between originally homogeneous ilmenite grains and the Ca-rich residuum of the kimberlite magma, which finally solidified to form the carbonate matrix of the rock.

9.3 Rough blocky sculptured surfaces on ilmenite

According to Mitchell (1973) ilmenites from kimberlite generally show the effects of fluidisation abrasion in that they are roughly ovoid in shape. However, detailed examinations on magnesian ilmenite from many kimberlite occurrences demonstrate that their surfaces are etched and the rounding of ilmenites are the result of chemical resorption rather than fluidisation. At low magnifications (up to 100 times) under the binocular microscope these sculptured surfaces give the ilmenite a pimpled appearance (Plate I3I). However, at higher magnifications in the SEM these etched surfaces consist of rough (Plate I32), or blocky features (Plate I33). Unlike garnet these sculptured features on ilmenite show no crystallographic control and display identical features on all crystal surfaces (Plate I34).

The development of perovskite crusts around ilmenite result in irregular, embayed or sutured features (Plate I35), and removal of these powdery crusts exposes the underlying rough, irregularly sculptured, surfaces on ilmenite (Plate I36). At high magnification these resorbed surfaces clearly reveal their formation by corrosive agencies (Plate I37).

Some ilmenite grains from loam samples overlying kimberlite in the Molubezi area in Zambia are partly or completely coated by soft greenish-brown clay material and brown euhedral crystals of iron oxide (Plate I38). X-ray diffraction and energy dispersive analysis of this coating, indicated that it is comprised of a mixture of montmorillonite clay, rutile and hydrated iron oxides and may represent decomposed kimberlite (?). Rough blocky surfaces were noted on the partly coated ilmenite grains, implying that sculpturing of the ilmenite occurred before or contemporaneously with the crystallisation of the kimberlite groundmass.

9.4 Proportion of sculptured ilmenite from kimberlite

Computation of detailed observations made on 16167 ilmenites from seven different kimberlite are represented in Table XVII. Perusal of the data recorded in Table XVII suggests that on average 28 per cent of ilmenites from kimberlite exhibit sculptured surfaces.

However, the percentage of ilmenites displaying rough blocky sculptured surfaces varies considerably from one kimberlite to another. For example, 73 percent of the ilmenites obtained from the Redondao kimberlite in Brazil were sculptured while only a few (3 per cent) of those from the Green and Grey kimberlite types at Premier Mine in South Africa exhibit the same surface features. The formation of rough blocky sculptured surfaces on ilmenite is directly related to the reaction of ilmenite with carbonate-rich fluids in the final stages of kimberlite emplacement producing reaction mantles around ilmenite. (see section 9.2 and 9.3). It follows, therefore, that kimberlites which contained appreciable quantities of CO_2-rich fluids should have an abundance of ilmenites partly or completed rimmed with perovskite-spinel reaction mantles and displaying sculptured surfaces.

10.0 SCULPTURED SURFACES ON CHROME DIOPSIDE

10.1 Shape of chrome diopside from kimberlite

Chromiferous diopside, (greater than 3.0% Cr_2O_3) is a very conspicuous accessory constituent of kimberlite because of its bright emerald green colour. It occurs as angular (Plate I39) to well rounded (Plate I40) xenocrystic grains, varying from 0,1 mm to 5,0 mm in size. Occasionally it forms large megacrysts up to 10 cm in diameter, and is also found intergrown with pyrope and ilmenite. Euhedral crystals of chrome diopside (Plate I4I), of prismatic habit are extremely rare in kimberlite concentrates. Detailed examination of the surfaces of chrome diopside grains from many kimberlite occurrences indicate that they, like garnet and ilmenite, are characterised by sculptured features. They could only have resulted by resorption processes (chemical etching by the kimberlite magma) which acted upon the mineral grains during kimberlite emplacement. Sculptured surfaces on chrome diopside consist of pointed hacksaw or cockscomb terminations, lens-like etch pits and hummocky surfaces.

10.2 Pointed hacksaw or cockscomb terminations on chrome diopside

Inspection in the SEM, of sculptured features on chrome diopside from kimberlite (blue ground), show they characteristically consist of sharp pointed hacksaw or cockscomb terminations

(Plate I42). These reflect preferential dissolution (chemical etching) along lattice planes (cleavage) transverse to the c axis. These cockscomb or hacksaw terminations are commonly developed on the pyramidal surfaces (110), with a strong preferred orientation paralled to the c axis.

10.3 Lens-like pits

In contrast, the prismatic surfaces (111) exhibit finely pitted appearances (Plate I43), with the development of lens-like etch pits (Plate I44), preferentially orientated with their long axes parallel to the c axis of the mineral grains. Selective etching on prism surfaces, presumably at the outcrops of dislocations, gives rise to a mesh-like texture. Knowledge of the crystallographic control of these distinctive features on chrome diopside provides a method for determining the orientation of surfaces of otherwise anhedral grains.

Similar features, described by Rahmani (1973), on augite and hornblende from Upper Cretaceous - Paleocene sandstones in Alberta, have been attributed to diagenetic etching by intrastratal solution. This has already been discussed in detail in Section 5.2.3 on the effects of in-situ weathering processes on chrome diopside from the weathered profile of the Jwaneng kimberlite pipe.

10.4 Hummocky surfaces

In rare instances hummocky surfaces (Plate I45), have been noted on chrome diopside grains from the Benfontein Kimberlite Sill. These features resemble etch hillocks commonly developed on cube surfaces on pyrope from kimberlite. A chrome diopside grain from the Jwaneng kimberlite pipe was seen to be covered by terraced surfaces (Plate I46),which are similar to the flat topped polygonal etch features found on pyrope. (For comparison see Plates 9I and 94).

10.5 Proportion of sculptured chrome diopside from kimberlite

Result obtained from meticulous observations on 5142 chrome diopside grains from seven different kimberlite occurrences suggest that on average 64 per cent of chrome diopside grains from kimberlite exhibit sculptured features. This figure is very similar to the average percentage of sculptured garnet from kimberlite (62 percent) as discussed in section 8.4. The close similarity of the proportions of sculptured garnet and chrome diopside suggest that the sculpturing of these two minerals is related and that resorption of these mantle-derived minerals probably occurs within similar temperature and pressure conditions during kimberlite emplacement.

11.0 MECHANISM OF SCULPTURING

11.1 History of hypotheses

An extensive survey of the literature on the sculpturing of garnet has shown that there is still much debate on the causes, time of occurrence and significance of sculptured features on garnet surfaces. The formation of sculptured surfaces on garnet grains has been attributed to the mechanisms described below.

11.1.1 Crystal growth

Some investigators treat such surfaces as a growth phenomenon. Sauer (1900) was the first to examine garnet surface textures. He noted the sculptured appearance of some grains and attributed these features to secondary growth. Other investigators (eg. Honess 1927, Bobrovin, 1951, Koen 1955, and Simpson, 1976), have interpreted these sculptured features as growth phenomena. Vernadsky and Kurbatov (1937), have stated that only uvarovite and andradite can crystallise from aqueous solutions at near surface temperatures and pressures, whereas other garnet types originate under different thermodynamic conditions. Skocet and Cadek (1960), on the other hand, claim that almandine crystals in sandstones of the Ostravia-Karvina basin have an authigenic origin. Sobolev et al. (1951), discount the regeneration of garnet in sediments and consider the sculptured surface textures of detrital almandine to be growth phenomena originating by metamorphic processes. These sculptured surfaces appear to be composed of growth plates which are very similar to "imbricate wedge markings" described by Rahmani (1973), on garnets from the Upper Cretaceous-Paleocene sandstones of Alberta and ascribed to diagenetic etching. Rumble and Finnerty (1974) have described grossularite-spessartine overgrowths poikiloblastically rimming almandine garnet in metavolcanic rocks formed in biotite-grade regional metamorphism in Eastern Vermont, U.S.A. Sculpturing of pyrope from kimberlite is sometimes developed on convex surfaces (probably crystal faces), and on recognisable breakage surfaces. The sculptured features developed on the conchoidal fracture surfaces are generally much finer textured than those developed on convex areas. Fragmentation of pyrope grains during kimberlite emplacement also exposed these broken surfaces to the corrosive medium, which then acted upon these surfaces. Therefore, for these cases, a growth origin is highly unlikely.

The possibility that sculptured features such as those illustrated by Simpson (1976) result from growth can be discredited in the following way. If the external pattern on garnet grains is the result of overgrowth it should be possible, at least in some specimens, to identify the core which formed the nucleus of the growing grain in much the same way as cores can be identified in some quartz overgrowths.

A study of many garnet grains from kimberlite both under transmitted light and in the electron microprobe has failed to show any evidence of such cores. Slight chemical zoning in kimberlite garnet is apparent in some instances, but the vast majority of sculptured garnets show no chemical variations.

11.1.2 Breakage or mechanical weathering

Some workers have assumed that sculpturing is due to breakage along cleavage planes (Rastall and Hemmingway, 1940), possibly developed during initial breakage of grains at the source area (Hubert, 1971). However, garnet exhibits only rare fracturing along (100) and much more commonly displays a brittle uneven conchoidal fracture (Deer, Howie and Zussman, 1962). Sculpturing is, therefore, definitely not related to cleavage.

11.1.3 Weathering

Afanasyev et al.,(1976) pointed out that sculptured garnets are found in sediments of different ages which have been derived from a variety of rock types. They also maintain that sculptured grains only occur in the upper (weathered) horizons of some Yakutian kimberlite pipes, and in scatter aueoles formed from the detritus derived from the outcrops of kimberlite bodies. They suggest that pyrope is relatively unresistant to weathering and that the quantity of sculptured garnets is related to the intensity of weathering. Afanasyev (op cit), observations appear to be erroneous because sculptured garnets also occur in concentrates recovered from unweathered parts of kimberlite bodies, as discussed in detail in Section 4.3.1 (See also Chapter 8.0).

11.1.4 Corrosion and regeneration

Other workers (Laury, 1968; Simpson, 1976; and Sobolev, 1976) have provided evidence of overgrowths on and the solution of, detrital garnet. The positive features (hillocks) they claim can only have been formed by crystal growth,(indicated by their symmetry), while the pits (negative features), are undoubtedly due to solution. It is difficult to accept that these sculptured features form by two quite different processes, the one resulting in corrosion and the other in regeneration, thereby implying stages of diagenesis and regressive epigenesis of detrital garnet in sediments.

11.1.5 Etching

1) In sediments

Between 1900 and 1930, a number of workers, including Gilligan (1920), Mackie (1923) and Boswell (1924), noted what they called "etch patterns" on the surfaces of detrital garnets and they regarded these as evidence for solution of the mineral, sometimes along cleavage planes (Smithson 1942). Buckley (1951) considered the mechanics of etching, and discussed the problem of "etch hillocks" in detail. He described them as being "raised islands of the original surface" which have been produced by corrosion of material around them. He concluded that, because they did not necessarily possess a symmetry related to that of a crystal face, they could not have formed by crystal growth. Another feature that has generally been attributed to chemical etching is pitting (McMullen, 1959; Pettijohn, 1957; Beveridge, 1960). Etch pitting takes the form of numerous square, rhombic, hexagonal to triangular shaped pits that cover parts of the grain surfaces and impart a matte appearance to the garnet surface. According to Hrichova (1966), these surface sculptures have never been observed on garnets in primary rocks, eg. in pyrope peridotites, granulites,gneisses,etc. He and many others therefore, assume a secondary origin for the sculptured surfaces on detrital garnet in sediments. In sharp contrast to Hrichova's observations sculptured garnets are abundant in every kimberlite examined in the course of this study.

Sculptured features are not unique to kimberlitic garnets but have also been found on non-kimberlitic garnets which have been derived from sediments of Karroo age (Permian-Triassic) and older. Other researches (Koen, 1955; Rahmani, 1973; and Simpson, 1976) have considered that these sculptured features could only have formed by post-depositional diagenetic etching. Given sufficient time diagenetic etch processes could conceivably remove all or some evidence of transportational abrasion, thereby producing etch features identical to those related to resorption in the kimberlite. Alternatively, the assimilation of garnet-bearing crustal material during emplacement may result in sculpturing of both 'non-kimberlitic' and 'kimberlitic' garnets by the kimberlite magma.

2) In kimberlite

Sobolev (1959) mentions rounded etch features consisting of conical hillocks found "not infrequently" on garnets in the Mir kimberlite pipe in U.S.S.R. In 1964 Frantzesson described prominent cone-like, drop-like, pyramidal and imbricate sculptured features on pyrope from other Yakutian kimberlite bodies. Most workers agree, that the sculptured features, now observed under much higher powers of magnification using the scanning electron microscope, are the result of chemical etching and not crystal growth. Furthermore, etch features identical to those found in nature have been artifically produced on pyrope in the laboratory by chemical etching (Hrichova, 1966; Mendelssohn 1971).

11.2 Experimental studies on the artificial etching of garnet

Muller (1877) noted the effect of carbonic acid on the surfaces of various minerals, but it appears that Bramlette (1929), referred to by Sauer,(1900) was the first to claim to have reproduced sculptured textures on garnet, by subjecting garnet to the action of hydrofluoric acid. Artificial etching of almandine was carried out by Rinne and Kulaszewski (1925) and by Koen (1955). Sculptured surfaces obtained by etching with hydrofluoric acid were similar to those observed on naturally etched almandine, and include imbricate wedge markings and pyramidal shaped sculptured features.

Pyrope has been also artificially etched in the laboratory by Bauer and Hrichova (1966) and by Mendelssohn (1971). Various corrosive solutions have been used, such as hydrofluoric acid (H.F. 48%) and caustic soda (NaOH B.P. 165°C), but according to Mendelssohn (1971), phosphoric acid (H_3PO_4 98%) at 150°C appears to constitute a low temperature analogue for the poly-acidic solutions likely to be encountered in the kimberlite.

In general the etching experiments using all the above-mentioned etchants showed that all of the characteristic sculptured features (described previously) are visible after about three days of etching. Although the etch features (hillocks and pits) tend to become larger with time (Bauer and Hrichova, 1966), the general pattern of etching does not change. As mentioned previously cuboid-shaped garnets change very little during laboratory etching, but the large hillocks previously present on their surfaces are replaced by a series of smaller ones (Plate I47).

Laboratory etching proceeds considerably more rapidly on freshly broken surfaces, indicating that a relationship exists between the corrosion rate and the degree of surface perfection. Chemical etching is the only process involved in the formation of artificially produced sculptured features on pyrope. It is concluded, that the artificial reproduction of etch features (similar to natural occurring sculptures on garnet), by acid treatment, definitely indicates that they originate in nature by resorption or dissolution (chemical etching), and not by crystal growth.

A conspicuous result of the experiments discussed is that etch hillocks, rather than pits, are developed on surfaces approximating cube faces, whereas etch pits of different shapes form on the dodecahedral and octahedral surfaces. The same crystallographic control governs the formation of sculptured features on pyrope from kimberlites. This is further evidence that natural hillocks and etch pits on pyrope from kimberlite can be ascribed,in every case,to etching.

Artificial etching of garnet in the laboratory has shown that the mechanisms of chemical etching control the shape and formation of sculptured features. Distinctive features are related to different rates of dissolution along crystal faces with different crystallographic orientations. The relative dispositions of the various, experimentally produced features are shown in Plate I48), together with their accompanying stereographic projections (after Mendelssohn 1971) (Figure 14).

11.2.1 Factors affecting the dissolution process

Dissolution is affected by a number of factors, such as crystallographic orientation, crystal perfection, purity of the solid and concentration and composition of the etchant. Influence of orientation is pronounced in relatively slow reactions, (Plates II4 and II5), whilst in fast reactions the removal of surface atoms may be so rapid (Stranski and Suhrmann, 1947), that chemical polishing results (Plate I49). The effect of an etchant on garnet is anisotropic, that is to say it's physical properties vary according to different crystallographic direction.

Orientation effects on the etching of garnet are responsible for the frequently observed concave (pits) which form preferentially on surfaces with slower etching rates and convex features (hillocks) occurring only on surfaces with the fastest etching rates.

11.2.2 Formation of etch pits

The initiation of etch pits is considered by Batterman (1957), as a nucleation process. Active nucleation sites correspond to dislocation intersections with the surface of crystals, point defect clusters, sites of surface damage and foreign particles on the surface. Such nucleation sites would be attacked by the etchant giving rise to the formation of etch pits. The formation of etch pits is determined by the reactivity of the surface which is orientation dependent. It was found (Mendelssohn, 1971), that the rates of dissolution for different crystal faces on garnet decrease in the order cube (100) > dodecahedron (110) > octahedron (111), using HF as an etchant.

The development of an etch pit occurs only on the slow etching crystal surfaces on garnet, when the etching rate along a dislocation is greater than the etching rate along the crystal surface (Figure 15).

Conversely, the greater the reactivity (dissolution rate) of the surface, the less likely is the formation of etch pits. (Figure 16).

Therefore, etch pits form less readily on the (110) than the (111) surfaces and even less readily on the (100) surfaces. Etch pits are most readily formed on the surfaces which have the slowest dissolution rate. (octahedral and dodecahedral surfaces respectively).

11.2.3 Morphology of etch pits

The shape and depth of etch pits is dependent upon the relative etching rates at points of weakness or other irregularities along the different crystallographic surfaces on garnet as shown schematically in Figure 17.

Thus, on the octahedral surfaces triangular to hexagonal shaped pits (Plate 103) are formed, as shown in Case I, while etch pits on dodecahedral surfaces are rectangular to rhombohedral in shape, sometimes exhibiting a step-like structure as shown in Case II (Plate 150), probably as a result of coalescence of etch pits and slight variations in the rate of etching.

11.2.4 Origin of etch hillocks

The same laws which govern the formation of etch pits also apply to the formation of etch hillocks. The appearance of hillocks on the faster etching surfaces, but not on the slower ones, can be illustrated in the two sequences shown in Figures 18 and 19. The effect of an inhibitor, such as a surface contaminant, kelyphite coatings, or variation in chemical composition could account for variations in size and shape of the hillocks.

The instability of a hillock due to an adhering contaminant on a slow-etching crystal surface is first considered (Figure 18).

Initially, the adherant or coating will protect the surface it covers and will be left raised above the surrounding surface as the latter is dissolved(t1). However, as soon as this raised portion is accentuated (t2), other crystal orientations are introduced at the sides of the hillock. Since, in the case under consideration, the surface is the slowest to dissolve, the sides will recede faster, and the etch-resistant portion will be undercut (t3), and eventually severed (t4).

The stability of a hillock on a fast etching crystal surface is now discussed and schematically illustrated in Figure 19.

In this case, for an impurity attached to a fast-etching crystal surface, the sides formed will not be as heavily attacked (t3) and will approximate to the most slowly-dissolving surface, with the rate of etching decreasing up the sides of the hillock (Plate I5I). Once the protective capping is removed (t4) conical hillocks are formed. These hillocks will be preserved as the surface on which they form will continue to etch at a faster rate (Rd) than the other surface.

11.3 Artificial etching of ilmenite in carbonate melts

In spite of an extensive literature search no information was obtained on the artificial etching of ilmenite. Therefore, a considerable amount of time was spent in developing various techniques for the dissolution of ilmenite in carbonate melts, in order to simulate natural conditions during the final stages of the crystallisation of kimberlite. Powder mixtures, consisting of varying amounts of $Na_2 CO_3$, CaO, K_2CO_3, CaCl and SiO_2 were prepared and heated in nickel crucibles in a electric furnace. Ilmenite grains, approximately 1,0 mm in size, bounded by freshly broken fracture surfaces, were handpicked from heavy mineral concentrates from Wesselton Mine for the experiments.

The experiments were performed at atmospheric pressure at temperatures ranging from $300^{o}C$ to $1000^{o}C$. Once melting of the different mixtures was achieved the ilmenite grains were allowed to react with the carbonate melts over periods of from half an hour up to 20 hours duration. On completion of each run the ilmenites were recovered from the carbonate melts and examined in the SEM.

On inspection the treated ilmenite grains were partly or completely rimmed by whitish-brown coatings and isolated rounded brown crystals, (Plate I52). The brown crystals are composed essentially of Ca and Ti as indicated by energy dispersive analysis and are probably perovskite. However, they were too small for confirmation using x-ray diffraction techniques. Removal of the coating material revealed the presence of rough undulating reaction surfaces (Plate I53), resembling those found on picroilmenite from kimberlite.

Artificially produced sculpturing on ilmenite, similar to those formed on kimberlitic ilmenites, were developed on grains reacted in a carbonate melt produced from a mixture of Na_2CO_3/K_2CO_3 (8 gms), CaO (1 gram) and SiO_2 (1 gram) at a temperature of ± 750°C for 5 hours. The reaction producing the sculptured features on ilmenite might be as follows :-

$$Na_2CO_3/K_2CO_3 + CaO + SiO_2 + \underset{\text{(ilmenite)}}{FeTiO_3} \rightarrow CaCO_3 + (Na,K)SiO_2 + \underset{\text{(perovskite)}}{CaTiO_3}$$

Attempts were also made to etch ilmenite grains chemically for periods of from 5 hours to 20 hours, first using concentrated hydrochloric acid (30% pure-commercial grade) and then hydrofluoric acid (70% pure-technical grade). No evidence of dissolution of ilmenite could be detected on any of the grains treated in hydrochloric acid, whilst those treated with hydrofluoric acid displayed coarsely etched surface (Plate I54). These etched surfaces did not, in any way, resemble naturally sculptured surfaces on kimberlitic ilmenite. They were seen to consist of stepped or terraced surfaces, exhibiting strong crystallographic control in two directions, parallel to $\{0001\}$ and $\{10\bar{1}1\}$. They give the impression of having formed by chemical stripping of ilmenite, layer by layer (Plate I55). Furthermore, peculiar crevasse-like etch grooves were developed by the etchant probably along weaknesses (cracks) within the ilmenite grains. Such features have not been observed on any naturally sculptured ilmenite from kimberlites but are commonly found on pyrope and chrome diopside.

The results obtained from these etching experiments indicate that sculpturing of ilmenite probably takes place during kimberlite emplacement, by interaction between ilmenite crystals and the kimberlite groundmass fluids (carbonate residuum), rather than by resorption (chemical etching) of ilmenite by the kimberlite magma.

11.4 Experimental sculpturing of chrome diopside

Angular, freshly broken chrome diopside grains, extracted from kimberlite samples from the Wesselton Mine were chemically etching using concentrated hydrochloric acid. After acid treatment for approximately 17 hours the chrome diopside grains had changed from angular to sub-rounded in shape (Plate I56), and were covered by etch features, identical to those found on grains derived from kimberlite.

Stepped or terraced surfaces, grading into sharp pointed hacksaw terminations (Plate I57), were developed on the outer convex edges of the grains, while finely pitted surfaces were formed on flat (prismatic) surfaces. Close inspection of the finely pitted surfaces (Plate I58), show them to consist of masses of oriented lens-like pits, parallel to the c axis. They are identical to those occurring on prism surfaces of chrome diopside grains from kimberlite. Similar artificially produced etch features have been produced on pyroxenes and amphiboles by Berner et al (1979).

The close similarity between sculptured features exhibited by chrome diopside from kimberlite and those produced on grains treated in the laboratory, strongly suggest that their formation is the result of chemical etching (resorption) during kimberlite emplacement.

12.0 GENESIS OF KELYPHITE AND SCULPTURING OF PYROPE, PICROILMENITE AND CHROME DIOPSIDE DURING KIMBERLITE EMPLACEMENT

The relative ages and chronological classification of the different surfaces textures formed on pyrope, picroilmenite and chrome diopside during kimberlite emplacement is the theme of this thesis. Evidence is presented that indicate that the formation of kelyphite and its associated sub-kelyphitic surfaces on pyrope clearly predate the sculpturing of pyrope, picroilmenite and chrome diopside. In terms of these surface textural criteria it is possible to outline a sequence of events affecting these mineral grains during kimberlite emplacement.

12.1 Emplacement of kimberlite

There have been many theories of kimberlite petrogenesis. The liquid is generally thought to be derived either by partial melting of peridotite (Dawson, 1971, Mysen and Boettcher, 1975), or by fractional crystallisation (O'Hara and Yoder, 1967; MacGregor, 1970). Others have argued that anatexis (Boettcher et al,1979) and metasomatism of mantle peridotites (Erlank and Rickard, 1977) are the mechanisms of kimberlite derivation. Recent experiments by Eggler and Wendlandt (1979), and Wyllie (1979), have shown that the partial melting of a phlogopite-carbonate-garnet lherzolite is the favoured parental material for the formation of liquids of kimberlitic composition at pressures of 40 - 60 k bars in the temperature range 1250°C to 1500°C. The carbonate, probably in the form of magnesite or calcite, must be present for kimberlite liquid to be generated. Gurney and Harte (1980), have suggested that relatively localised melting occurs at depths of between 200 to 300 km within the upper mantle at temperatures of 1400°C - 1500°C. These liquids would rise, producing local concentrations, or intrusions into the lithosphere. Eruptive processes sampling mantle and melts at different levels could produce hybrid magmas approaching kimberlite in composition as proposed by Boyd and Nixon (1973).

Coarse textured, porphyroclastic and granuloblastic ultramafic xenoliths incorporated into the kimberlite liquid during emplacement, exhibit shearing, plastic deformation and annealing textures, (Boyd and Nixon, 1975; Harte, 1977), indicating complex multiphase deformation events within the mantle. Some of these deformation textures within ultramafic nodules probably would not have survived long under the temperatures pertaining within the upper mantle and hence their preservation is viewed as being due to deformation associated with the kimberlite event just before incorporation of the xenoliths into kimberlite and rapid transport to the surface (Bouiller and Nicolas, 1975).

The kimberlite is a gas charged, hydrous magma which ascends through the mantle and the crust sampling wallrocks along parts of its journey to the surface. It is intruded rapdily up a system of deep-seated fractures, breaking through to the surface forming as a pipe or dyke or sill-like body (Hawthorne, 1975). Dawson (1962) concluded that kimberlites are emplaced by the process of fluidization, a process in which fragmental material is transported in a fast-moving gas stream with solids suspended in gas (CO_2 and H_2O). Clement (1975), has put forward strong evidence that at least some of the fluid is calcite-rich liquid that separated as an immiscible fluid from the ascending kimberlite, forming a highly volatile zone at the top of the ascending kimberlite, this is a source of highly concentrated explosive fluid. Adiabatic expansion associated with break through of the magma at the surface resulted in a notable decrease in temperature such that thermal metamorphic effects even on sedimentary xenoliths are negligible, and subsequent quenching possibly aided in the preservation of diamond in kimberlite. The initial explosion vent would then be enlarged by fluidized fragmental material drilling upwards and slumping of wall-rock fragments into the vent (Clement, in preparation). This fluidization creates a circular or ellipsoidal diatreme or pipe, resembling a funnel, being wider at the surface than further down (Hawthorne, 1975). Later surges of upwelling kimberlite magma may form tuffisitic dykes or plugs of hypabyssal facies kimberlite and kimberlite breccia within cavities and fractures in the vent kimberlite. After the intrusive activity further slumping into the diatreme occurs with wash and back fill of material from the surrounding kimberlite tuff cone accumulating in the central depression or crater-lake. This simplified overall picture may be complicated by several pulses of kimberlite intrusion within the same vent (Donaldson and Reid, 1977).

12.2 Formation of kelyphite

Four possible origins for kelyphite have been forwarded :-

1) Serpentinization

Williams (1932) proposed that the formation of kelyphite is related to the process of serpentinization and agrees with Sederholm's (1916) suggestion of a deuteric formation during late stage crystallisation, rather than one of secondary origin.

2) Water vapour from kimberlite magma

Nixon (1963), draws attention to the lower specific gravity of kelyphite (3.204), compared with that of the garnet (3.692) and infers that the kelyphitization took place after deformation in some sheared nodules, as a late mineral aggregate, formed by the sudden release of pressure during kimberlite intrusion. The lower density and increase in volume is reflected by the appearance of radiating cracks in the adjacent minerals surrounding the kelyphitized garnet.

Nixon et al (1963), have shown that garnet, relative to its alteration product kelyphite, is richer in SiO_2, Al_2O_3 and CaO, and poorer in Cr_2O_3, MgO, OH and alkali and alkaline earth trace metals, and suggest that water vapour is the only essential chemical ingredient involved in the change. In this respect kimberlite liquids would provide sufficient water vapour to generate the kelyphitization of garnet, suggesting that kelyphitization occurs by reaction with kimberlite fluids rather than by reaction between garnet and olivine in ultramafic nodules.

3) Primary crystallisation

Because of the lower Al_2O_3 and CaO content of the kelyphite when compared with the garnet analyses, Klein and Padĕra (1972), submit that the Al and Ca-rich components in the form of (garnet) crystallised from a peridotitic magma, resulting in the decrease in Al and Ca and relative increase in Mg of the original melt. An excess of Si and Mg in the melt then gave rise to the symplectic intergrowth of enstatite, diopside and spinel, forming the kelyphite shells surrounding pyrope. This sequence is explained by them, as part of a rythmic crystallisation trend also giving rise to the repetitive occurrence of garnet-rich and spinel-rich peridotites at Hamry in Bohemia. The formation of kelyphite by Klein and Padĕra (op cit) is therefore considered to be a primary crystallisation phenomenon and not a reaction phenomenon.

4) Reaction process due to instability of garnet

Rost and Grigel (1969), showed that the chemical composition of the kelyphite and garnet present in the garnet lherzolites Central Europe are practically the same (ie. concerning the elements Al, Ca, Cr, Fe, and Ti). Reid and Dawson (1972) indicate that the reaction between garnet and olivine, to produce kelyphite, is apparently isochemical with garnet and olivine contributing to the bulk chemistry of the reaction. Minor amounts of Na, U and P may however, be introduced (Kleeman 1969). For this reason certain authors consider that pyrope is replaced by the kelyphite.

This may also apply to the so called "younger" generation of kelyphite consisting of orthopyroxene and spinel, described by Klein and Padèra (1972) which occurs only in veinlets within the pyrope. The kelyphite filling cracks within the garnet, is considered by Klein and Padèra (1972), to represent a younger kelyphite generation because it does not contain clinopyroxene, and presumably forms after the kelyphite shells which commonly surround pyrope grains, having no contact with olivine or orthopyroxene. They interpret this kelyphite as forming at the expense of pyrope, in some cases replacing the entire rounded pyrope grain within the older kelyphite shell under conditions where the older kelyphite generation is stable, as shown in Figure 20. This explanation seems unlikely in view of the fact that retrograde changes affecting pyrope may cause its breakdown to a mixture of fibrous hornblende, plagioclase, green biotite and iron ore (Alderman, 1936). At an advanced stage of alteration the garnet may be replaced by epidote and chlorite (Deer, Howie and Zussman, Vol. I, 1965 p. 98). Detailed examination of the contact between the outer radially structured kelyphite and the randomly oriented kelyphite filling the cracks in garnets from kimberlite failed to establish any age differences. The two types of kelyphite are therefore considered to be part of the same generation having formed contemporaneously (Plate I59).

Evidence obtained in this study support the interpretations made by Wagner (1914); Reid and Dawson (1972); and to some extent Lensch and Rost (1972), who maintain that the kelyphite borders or reaction coronas around garnets from peridotite have formed by reaction between garnet and surrounding olivine and occasional orthopyroxene to produce a spinel-two pyroxene assemblage.

The two-pyroxene-spinel coronas formed around garnets in garnet lherzolites result from the movement of garnet from the garnet lherzolite stability field into the aluminous spinel lherzolite stability field. This reaction is taken as an indication of a decrease in pressure as a result of the upward movement of peridotitic material, by the ascent of kimberlite magma, from a depth of approximately 150 km to less than 50 km within the upper mantle, provided the temperature was maintained at around 1000°C (Reid and Dawson, 1972). This prediction is based on results of a series of high temperature and pressure experiments on 'pyrolite' compositions by Green and Ringwood, (1967) and MacGregor, (1970).

The boundary between the spinel and garnet peridotite stability fields has been investigated for the ternary system MgO - Al_2O_3 - SiO_2 by MacGregor (1964 and 1965); for the quaternary system CaO - Mgo - Al_2O_3 - SiO_2 (MacGregor, 1965; Kushiro and Yoder, 1966; O'Hara, Richardson and Wilson, 1971; and Dixon and Presnall, 1977); and for multi-component systems (Green and Ringwood, 1967 and 1970; MacGregor, 1970). Apparent temperatures of equilibration for five western alpine lherzolite complexes (Alpe Arami, Finero, Balmuccia, Baldissero and Lanso) were computed by Ernst (1977), which allowed him to outline the plagioclase, spinel and garnet peridotite stability fields.

Using the data available in the published literature on phase equilibria from both experimental and natural systems and the information obtained from this research study an attempt was made to estimate the upper and lower temperatures and pressures of formation of kelyphite during kimberlite emplacement (Figure 21).

In view of the considerable debate as to whether or not the methods used to establish these temperature/pressure estimates are valid, and because of the experimental uncertainty of the garnet-spinel transition the following deductions are somewhat speculative.

The ascent of kimberlite magma along a theoretical cooling path (see Figure 21), would move garnet lherzolite nodules into the spinel lherzolite stability field at temperatures of between 1000°C to 1100°C. The movement of garnet out of its stability field would trigger the process of kelyphitization of pyrope within the peridotite nodules. In the system MgO - Al_2O_3 - SiO_2 the reaction :

Orthopyroxene + spinel = garnet + olivine was established by Wood (1977) to lie between 23.5 kb and 24 kb at 1100°C and 22 kb and 23.2 kb at 1000°C. Agreement of these results with the experiments of MacGregor (1974) is reasonably good (Figure 21). The exact position of the spinel - to-garnet lherzolite transition curve is uncertain, but it is encouraging that the results obtained by Wood (1977) lie within the limits of published determinations. In particular, coarser crystals were obtained by MacGregor (1974) in the temperature range from 1100°C to 1300°C, but the grain size decreased at both higher and lower temperatures, suggesting that the garnet - spinel transition (kelyphitization of pyrope) reactions, takes place most readily over the abovementioned temperature range. Should the formation of kelyphite result as a product of an isochemical reaction between garnet and olivine (Reid and Dawson, 1972) it is therefore a subsolidus reaction. The proposed zone of kelyphitization of pyrope lies within the spinel lherzolite stability field between the anhydrous solidus and the continental (shield) geothermal gradient (Figure 21). Kelyphitization is most likely to occur at temperatures of 900°C to 1300°C and pressures of 10 kb to 25 kb. This zone corresponds to a depth of between 30 to 80 km within the upper mantle. In the unlikely event of kimberlite intruding along a cooling path close to the continental geothermal gradient, the minimum temperature and pressure conditions at which kelyphitization of garnet could possibly occur appears to be in the region of 600°C and 15 kb.

In view of the absence of plagioclase in kelyphite shells surrounding garnet in peridotite xenoliths from kimberlite it appears that kelyphitization of pyrope does not continue beyond the boundary between the spinel lherzolite and plagioclase lherzolite fields. However, the 'kelyphitic' material formed around garnets in eclogite nodules consists predominantly of phlogopite with accessory amounts of twinned feldspar microlites, amphibole, spinel and glassy material (Whitfield, 1971). He considers that slight melting of the clinopyroxene and, possibly, even of the garnet, accentuated by traces of water on the garnet-clinopyroxene interface, produces these reaction rims during the intrusion of kimberlite. The phlogopite-rich kelyphitic material rimming garnets in eclogites is considered to have formed at high levels within the lower crust by the action of alkalies and volatiles associated with the hydrous phase of kimberlite emplacement.

Possible evidence of high level deformation of peridotites have been suggested by Lock and Dawson (1980), from evidence of disruption of pyroxene - spinel coronas around garnet in lherzolites from the Letseng satellite pipe, Lesotho; the inference is that the deformation took place after the lherzolite had moved out of the garnet stability field. This high level deformation of ultramafic xenoliths could cause disruption of some kelyphite coronas surrounding garnet and result in the liberation of some kelyphite-encrusted garnet into the kimberlite magma by the disaggregation of ultramafic xenoliths.

Kelyphitization of garnet, predates sculpturing of xenocrystal garnet, ilmenite and chrome diopside by resorption processes active during kimberlite emplacement.

12.3 Resorption of pyrope and chrome diopside

Disaggregation of ultramafic xenoliths incorporated into kimberlite liberates pyrope, picroilmenite and chrome diopside into the kimberlite magma. Breakage or plucking of portions of the protective kelyphite shells exposes the surfaces of garnet to attack by the kimberlite fluid and gas. The reason for the rounded shape of garnet with kelyphitised, sub-kelyphitic and/or sculptured surfaces is apparently due to high temperature (700°C to 900°C) etching ie. chemical reaction, dissolution or fusion (Yuskin and Fishman, 1971). The same also applies to subrounded chrome diopside grains commonly found in kimberlite.

Interesting results were reported by Scarfe, Takahasi and Yoder Jr. (1979) from experimental dissolution studies of mantle minerals (olivine, orthopyroxene, clinopyroxene, spinel and garnet). These experiments were performed in an alkali basalt melt at pressures of 12.5 kb to 14 kb and temperatures ranging from 1325°C to 1400°C. At 14 kb, dissolution of clinopyroxene is faster than olivine, orthopyroxene, and spinel. The time taken to completely dissolve 0,05 cm - diameter spheres of clinopyroxene is 60 - 100 min.at 1325°C and 14 kb. Garnet dissolves rapidly at 12,5 kb but the rate of dissolution of garnet decreases with increase in pressure as the stability field of garnet is approached. Over this pressure range these investigators maintain that olivine is the most resistant of the common mantle minerals to dissolution that affect mantle minerals in xenoliths during transport to the surface in alkali basalt magma.

It is known that dissolution of crystals frequently reduces the strength of their near-surface layers due to the widening of micro-cracks, whereas thermal influences enhance annealing. Considerable strengthening of the outer zone of fused pyrope crystals (by 1,3 times) has been recorded by Hrichova, (1966). Yushkin and Fishman (1971), also investigated the change in hardness (strength) along the cross-section of sculptured pyrope crystals. The results obtained showed significant variations in hardness, from 1191 kg/mm^2 in the inner portions, increasing to 1627 kg/mm^2 in the peripheral zone. According to Yushkin and Fishman (op cit) sculptured surfaces of rounded pyrope grains can therefore, be regarded as surfaces of etching at temperatures high enough for fusion to have occurred. This implies mantle conditions. On the other hand, as discussed previously, artificial etching of kimberlitic garnet, has also been successfully demonstrated at relatively low temperatures (150°C) in the laboratory. However, as yet, hardening of the surface has not been investigated in garnet etched at low temperatures. It may be that sculpturing of pyrope and chrome diopside possibly commences during the initial stages of sequential melting associated with kimberlite magma formation, and that garnet and chrome diopside grains incorporated into the kimberlite liquid in the mantle, are continuously reacted upon (etched), during the process of kimberlite emplacement, terminating only on solidification at the surface. However, it is proposed that sculptured textures produced on pyrope and chrome diopside are most likely to occur in the temperature range 500°C to 900°C by resorption processes during or before kimberlite emplacement. In support of this prediction fine-textured sculptured features were artificially produced on garnet and chrome diopside in carbonate melts at temperatures of ± 750°C.

Many researchers (Kennedy and Nordlie, 1968; McFadden, 1977) have drawn attention to the virtual lack of thermal metamorphic effects shown by kimberlite on the adjacent country rocks and crustal fragments included into the kimberlite, suggesting that the temperature of intrusion is low. This is a function of whether one is dealing with hypabyssal facies or diatreme facies (quenched) kimberlites. The latter crystallize diopside and could not have done this at low temperatures of 200 - 300°C, instead temperatures of approximately 500 to 700°C are more realistic (Clement - in preparation). Hypabyssal facies kimberlite were hotter even at near surface levels as they are known to crystallize monticellite, phlogopite, diopside and possibly olivine as relatively coarse post-emplacement minerals. Harris and Vance (1972), infer from induced graphitisation experiments on diamonds that the temperatures were not in excess of 800°C - 900°C.

Breakage surfaces (conchoidal fractures), on pyrope and chrome diopside commonly display fine textured sculpturing, indicating that fragmentation of pyrope and chrome diopside xenocrysts therefore occurs before the termination of high temperature etching (Plate I60). Fragmentation probably results by mechanical attrition during fluidization. It is concluded that resorption and high temperature etching therefore, post-dates kelyphite formation, and must predate kimberlite groundmass crystallization, which according to Mitchell (1975), takes place at about 600°C.

12.4 Reaction between ilmenite and residual kimberlite fluids

In most kimberlites it must be assumed that the near surface environment is one of complex chemical reaction. Clement (1975), together with many others, (ie. Mitchell, 1970; Robinson, 1972; Dawson and Hawthorne, 1973; and Haggerty, 1975), have suggested that after crystallization of early phenocrysts the residual, ascending kimberlite magma differentiates at relatively high crystal levels into immiscible silicate, carbonatitic and titanium-rich liquids charged with gases. Explosive breaching of the cap rocks by gas accumulation at the head of the magma column, results in a sharp drop in pressure and temperature (quenching).

Reaction between ilmenite and kimberlite groundmass fluids result in the development of mineralogically complex mantles, composed of perovskite, spinel and ferro-magnesian silicates surrounding ilmenite. The reaction rims on ilmenite occur during the build up of CO_2 - rich residual fluid and crystallization of the rapidly quenched kimberlite liquid in response to rapidly changing $f\ O_2$ conditions (Haggerty, 1975; Boctor and Meyer, 1979). Textural evidence indicates that these reaction mantles clearly form at the expense of ilmenite and their development leads to the rough blocky sculptured surfaces commonly found on ilmenite from kimberlites. Sculpturing of ilmenite therefore occurs in the final stages of solidification of kimberlite.

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