A PETROLOGICAL AND MINERALOGICAL STUDY OF PERIDOTITE AND ECLOGITE XENOLITHS FROM CERTAIN KIMBERLITE PIPES

by

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CONTENTS

ABSTRACT

Kimberlite, an ultrabasic diamond-bearing hypabyssal rock-type which has its origin in the Earth's upper mantle, characteristically contains rare, well-rounded xenoliths of peridotite and eclogite. These xenoliths, which undoubtedly originate from some considerable depth below the Earth's surface, possibly represent samples of upper mantle material. They have received much attention from earth scientists and numerous theories as to their origin have been proposed.

Forty-two selected peridotite xenoliths from the Bultfontein, Wesselton, Dutoitspan and Roberts Victor kimberlite pipes of the Kimberley area, South Africa, and 24 eclogite xenoliths from the Roberts Victor pipe have been examined in detail using a variety of petrological and mineralogical techniques. The petrologic research comprises conventional petrographic studies, the determination of accurate modal compositions and the presentation of 22 new whole-rock chemical analyses, nine of which are of garnet peridotite, four of spinel peridotite and nine of eclogite, one being a diamondiferous specimen.

Detailed mineralogical studies of the constituent minerals of the xenoliths comprises descriptive mineralogy, in most cases an estimation of the compositions of these minerals from the measurement of physical properties, X-ray powder diffraction data and the presentation of 21 new chemical analyses of pure mineral separates. This includes five analyses of olivine, five of orthopyroxene, eight of garnet, one of chrome diopside and two of omphacite.

The results of the investigation have shown that the peridotites consist essentially of forsterite and enstatite with minor or trace amounts of one or more of pyrope-rich garnet, chrome diopside, chrome spinel, phlogopite and rarely graphite, and often exhibit features consistent with plastic movement and tectonic deformation. The peridotites are believed to be derived from an ultrabasic upper mantle, which is both chemically and physically zoned.

The eclogite xenoliths, which are composed mainly of pyrope-almandine garnet and omphacitic clinopyroxene and occasionally contain kyanite, corundum and diamond, are not samples of a primary eclogitic upper mantle nor the products of an eclogite fractionation related to kimberlite genesis. Chemically they are not typical of extrusive basalts and probably either represent pockets of partially fractionated basic magma trapped at mantle-level in an eclogite-stable environment or samples of high-grade crustal metamorphic eclogite accidentally incorporated into the Roberts Victor kimberlite.

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I. INTRODUCTION AND AIM

This thesis embodies the results of a detailed petrologic and mineralogical investigation of selected peridotite and eclogite xenoliths from four kimberlite pipes in South Africa. It also expresses the writers view regarding the origin of these xenoliths in the light of this information and, in addition, relates and compares the findings of this investigation to the results and conclusions of other workers in the same field.

Throughout, the main aim has been to record, in quantitative terms, the most important petrologic and mineralogical features of a number of the characteristic peridotite and eclogite xenoliths found in certain pipes of the Kimberley and Boshof districts, South Africa. A search through all the available literature concerning such inclusions in kimberlite has shown that there exists a serious lack of quantitative data concerning them and that which does exist is often of a dubious or unreliable nature. It was felt that with the increasing interest shown in the peridotite and eclogite inclusions from kimberlite a fundamental petrologic and mineralogic analysis of some of these inclusions would form a valuable contribution.

The entire project was undertaken at the Anglo American Research Laboratory, Johannesburg and formed inter alia part of a much broader investigation into the nature and origin of kimberlite and associated rock-types. The writer has had the good fortune to have been actively engaged in research on a number of aspects of kimberlite and consequently is familiar with the nature and problems of these intriguing rocks. Hence it is not without a fairly detailed background to the underlying problems that an attempt has been made to present the following results and to perhaps make a worthwhile contribution to certain aspects of kimberlite geology.

The methods used in this investigation are those employed in normal petrological and mineralogical studies. A brief outline of the nature and a suggested origin of kimberlite is given, followed by a general statement as to the nature and occurrence of peridotite and eclogite xenoliths found in kimberlite. There follows a historical review of research on these xenoliths up to 1936.

Recent research and modern-day thinking is briefly dealt with, as are analytical procedures and techniques used during the course of the investigation. Finally all the results and data obtained are presented and discussed in the light of recent research.

II. THE GENERAL NATURE OF KIMBERLITE

It is necessary, before continuing with the main subject of this thesis, to understand something of the general nature of kimberlite, host rock to the peridotite and eclogite xenoliths.

Ever since the discovery of the first kimberlite diatreme on the farm Jagersfontein, northern Cape, in 1870 (Gardner. F. Williams, 1906), numerous contributions to many aspects of the geology, petrology and mineralogy of kimberlite have appeared in the literature. The more notable of the classical works on the kimberlites of southern Africa are the excellent account by Wagner (1914) and the monumental treatise by Williams (1932). In more recent times, since the discovery of the Yakutian kimberlite province in Siberia (Davidson, 1957, 1964) and the Basutoland kimberlite province in Lesotho, southern Africa (Dawson, 1962; Nixon et al,1963) a tremendous resurgence of interest in the study of kimberlites and associated problems has taken place. The reasons for this interest appear to be four-fold.

Firstly, kimberlite is the only known primary source of terrestrial diamond (diamond has been reported as a primary constituent of other rocks, but never in economic quantities), the demand for which is rapidly increasing.

Secondly, many earth scientists believe that kimberlite diatremes have their origin within the upper mantle of the Earth and hence provide valuable information as to the constitution of the mantle.

Thirdly, the laboratory synthesis of diamond by the General Electric Company (Bundy et al, 1955) provided a much needed stimulus to questions concerning the origin of natural diamonds.

Lastly, the tremendous advances made of late in fundamental research on the origin of magmas and in associated aspects of high pressure-high temperature experimental petrology has no doubt played a key role in stimulating interest in kimberlite.

The discovery of the first kimberlite diatreme in 1870 also heralded the great diamond rush to the Kimberley area and the discovery and opening up of the near-by Kimberley, Bultfontein, Wesselton, De Beers and Dutoitspan pipes. It was only in 1887 however that the name "kimberlite" was first proposed by Professor H. Carvill Lewis for what he regarded as "a serpentinised diamantiferous mica peridotite occurring in diatremes and dikes in the Kimberley area". Since then kimberlite has been variously described by different authors, but all agree on its extreme ultrabasic composition. Holmes (1920) regards it as a brecciated biotite peridotite, occurring in the diamond pipes of South Africa, whilst Shand (1950, p.300) considers it to be "a breccia consisting of fragments of many kinds of rocks enclosed in a matrix of serpentine and carbonates" which occupy the throats of former volcanoes. Hatch et al (1961) refer to kimberlite as a thoroughly brecciated and altered mica peridotite, occurring in deeply eroded volcanic pipes. More recently Dawson (1967a,p.242) states: "Kimberlite may be defined as a serpentinised and carbonated mica peridotite of porphyritic texture, containing nodules of ultrabasic rock-types characterised by such high-pressure minerals as pyrope and jadeitic diopside; it may or may not contain diamonds".

In addition to this it should be mentioned that a characteristic feature of virtually all kimberlites from diatremes is its fluidised texture which has often in the past been ignored. A characteristic suite of heavy minerals (S.G. > 2.90) consisting of vivid red, mauve and orange pyrope-rich garnets, picro-ilmenite, bright green chrome diopside and minute grains of perovskite is invariably present in greater or lesser amounts. Fresh olivine and enstatite are occasionally present. Dawson(1967a) recently presented a review of kimberlites on a world-wide scale.

Kimberlite intrusions occur in the form of relatively small diatremes (more commonly known as pipes) and as dikes (or fissures), often interconnected. In many cases they appear to be closely associated with alkali-undersaturated rock-types such as melilites and nephelinites. They are more typical of the stable shield or cratonic areas, but there are examples of kimberlite occurring in orogenic zones. As regards geographical distribution they are found world-wide although concentrated in southern and East Africa and Siberia.

Broadly three types of kimberlite can be distinguished (Dawson, 1967a); i.e. massive kimberlite (with a basaltic and micaceous variety), intrusive kimberlite breccias (autolithic or heterolithic varieties) and kimberlite tuffs or tuff-breccias. Massive kimberlite is found in diatremes, dikes and rarely sills, whilst the two latter types are practically restricted to diatremes.

The emplacement of kimberlite is a controversial problem of long standing, but to the writer it appears that diatreme kimberlite was initially intruded through the Earth's crust as a solid-liquid system highly charged with volatiles and which at a certain stage, fairly near surface, erupted explosively along zones of weakness. The initial break-through at surface would, amongst other things, result in a very rapid decrease of pressure and the establishment of a highly active gas-solid suspension or fluidised system. At the same time and due to the well-known Joule-Thompson effect, the sudden expansion of the highly pressurised volatile phases (steam and carbon dioxide) would cause a concomittent and equally notable decrease in the temperature of the eruption, hence the virtual lack of thermal metamorphic effects shown by kimberlite. This rapidly emerging material would both enlarge the initial vent by a "sand-blast" effect and build up a volcanic tuff or tuff-breccia cone, possibly rich in carbonate. The more massive kimberlite, probably less charged in volatiles, would follow in depth in the wake of the explosive phase and result in the infilling of the volcanic conduit. As a result of surface denudation since intrusion the original surface expression of virtually all kimberlites has disappeared. Nixon (1969) however regards certain East African volcanic cones to be the surface expression of kimberlites. Kimberlite dikes and the rare sills represent a phase of the kimberlite magma which never reached surface.

The inclusions in kimberlite are perhaps one of its most interesting features and at least three general types can be distinguished. These include:

a) Angular and subangular blocks of country rock, into which the kimberlites are intruded, some of which originated from higher stratigraphical horizons, which have now been eroded away.

b) Rounded and subrounded masses and fragments of lower crustal rocks, often of high metamorphic grade, such as pyroxenites, amphibolites, granulites and possibly certain eclogites.

c) Well-rounded, spheroidal, ovoidal or discoidal masses of basic and ultrabasic rock, often referred to as "cognate xenoliths", composed essentially of varying combinations of olivine, orthopyroxene, clinopyroxene, garnet, spinel, phlogopite and possibly ilmenite. In this group we can distinguish between the peridotite suite (dunite, harzburgite, lherzolite and wehrlite) and the griquaite or eclogite suite. The mineralogy of these rocks clearly indicates their derivation from deep, high-pressure zones and it is with these so-called "cognate xenoliths" that this thesis is concerned.

III. THE PERIDOTITE AND ECLOGITE XENOLITHS FOUND IN KIMBERLITE.

As has already been mentioned, an ever increasing amount of research has been undertaken on various aspects of the geology, mineralogy and chemistry of kimberlites since the latter part of the 1950's and particular attention has been focussed on the peridotite and eclogite inclusions which are typical of almost every occurrence. The reasons for this reawakening to the many problems posed by kimberlite, many of which received much attention during the earlier part of this century, have already been discussed.

This research reached its climax in 1965 in the International Geophysical Year. One of the major tasks undertaken at that time was the study of the Earth's mantle, a problem which has for many years fascinated earth scientists. It has long been believed by a large group of scientists that kimberlite pipes have their roots within the upper mantle of the Earth and that they can, in a way, be regarded as ultradeep drill-holes penetrating the Earth's crust.

If kimberlites do originate within the upper mantle, and there is considerable evidence to indicate that they do, then some of the xenoliths found in kimberlites can possibly be regarded as samples of the upper mantle and lower crust that have been brought to near-surface during intrusion of the kimberlite. The xenolithic rock-types occurring in kimberlite which are possibly of such an exotic origin are obviously the coarse-grained ultrabasic and basic rocks such as peridotites, pyroxenites and eclogites.

As is natural there have been and no doubt still are many scientists whose views are contradictory to this reasoning and who believe that the coarse-grained ultrabasic and basic inclusions in kimberlite originated in a different manner. Some regard them as accidental inclusions derived from metamorphic terrains whilst another concept is that they are cognate or co-magmatic with the kimberlite.

It was with these different points of view in mind that a collection of peridotite and eclogite xenoliths, from several kimberlite pipes, was made and studied.

It is perhaps fitting that the nomenclature of these rock-types should be briefly dealt with before commencing with the description of the xenoliths.

The name eclogite was first used by Haüy (1822) for green diallage and garnet rocks with accessory kyanite, quartz, colourless epidote, amphibole and pyrrhotite found in the Fichtelgebirge. Since then there has been some confusion in the nomenclature of rocks consisting chiefly of garnet and clinopyroxene, various writers suggesting differing definitions, as summarised by Lovering and White (1969). Green and Ringwood (1967a) have defined eclogite as a rock of basaltic chemistry consisting of garnet (almandine-pyrope solid solution) plus clinopyroxene with or without quartz, kyanite, hypersthene or olivine as minor minerals. Plagioclase is absent as a primary phase from rocks strictly classifiable as eclogites and in addition the clinopyroxene of eclogites contains jadeite solid solution and a high jadeite/Tschermak's silicate ratio.

Throughout this investigation the term eclogite is used to describe all the coarse-to medium-grained rocks consisting primarily of clinopyroxene and garnet, and is modified when necessary by the presence of minor constituents, for example, kyanite eclogite or diamond eclogite.

The name griquaite (Beck, 1899) has occasionally been used to describe the eclogitic xenoliths derived from kimberlite, particularly when they are regarded as being cognate segregations derived from the kimberlite magma. Whilst in theory this appears to be quite acceptable, in practice distinction between cognate griquaite segregations and eclogite xenoliths is at present virtually impossible.

Peridotites are defined in this thesis as coarse-to medium-grained ultramafic rocks consisting primarily of olivine (greater than 50 per cent by volume) or its serpentinous alteration products with or without lesser amounts of orthopyroxene (enstatite), clinopyroxene (chrome diopside) and accessory pyrope-rich garnet, chrome spinel, phlogopite or graphite. Feldspar is always absent. Various names have often been given to the different types of peridotite, such as harzburgite or saxonite (olivine plus enstatite), lherzolite (olivine plus enstatite and chrome diopside) and wehrlite (olivine plus chrome diopside). As the presence of only small amounts of chrome diopside in many of the peridotites makes this system of nomenclature rather difficult to apply, it was decided to regard all peridotites with any visible chrome diopside as lherzolites and those with no visible chrome diopside as harzburgites. The presence of accessories such as garnet or spinel are recorded as a prefix attached to the rock name, such as garnet harzburgite or spinel lherzolite.

IV. EARLY RESEARCH ON THE XENOLITHS.

The first mention to any of the so-called "cognate xenoliths" that can be found in the literature is in 1879 when Cohen described an eclogite inclusion from the Jagersfontein Mine.

Twenty years later in 1899, Professor T.G. Bonney recorded the occurrence of numerous diamonds in a specimen of xenolithic eclogite from the Newlands Mine, and reasonably enough stated (p.235) that the eclogite "..... according to the ordinary rules of inference, must be regarded as its (i.e. the diamonds) birth-place". In a later paper Bonney (1907) also mentions that he examined xenolithic specimens of peridotite, namely saxonite, lherzolite and eulysite from the blue ground. It was his hypothesis, based essentially on the rounded and polished nature of the eclogite xenolith, that they represent accidentally included, water-worn boulders of a very coarsely-crystalline and once deep-seated, sporadically diamondiferous eclogite. He considers the boulders to have been derived from a coarse conglomerate, a possible source being the Dwyka Conglomerate (tillite). He dismisses the idea that they were rounded by a sort of 'cup-and-ball' game played by a volcano as practically impossible.

Almost simultaneously with Bonney's first work, Professor Beck (1899) published an account of an examination of a diamond-bearing eclogite, also from the Newlands Mine. Beck however advocated a completely different origin to the eclogite, regarding the garnet-pyroxene aggregate as an early secretion from the kimberlite magma, a theory which had likewise been suggested by Stelzner (1894). It was Beck who proposed the name "griquaite" for the garnet-pyroxene rocks from the blue ground on account of their unusual nature and who also recorded the presence of minute flakes of graphite in eclogite.

Harger (1905) in his discussion of the diamond pipes and fissures of South Africa briefly devotes some space to the eclogite and pyroxenite fragments found in kimberlite. Amongst some interesting features he points out that pyroxenites and lherzolites are usually more plentiful than eclogite, that certain specimens of eclogite from the Jagersfontein Mine contain foliated graphite or diamond and that some specimens of eclogite from the Roberts Victor Mine are kyanite-bearing. As to the origin of the ultramafic xenoliths he has this to say (p.126): "I think there is not the slightest doubt that....... the diamond pipes have intersected ultrabasic zones containing pyroxenites and eclogites and that the latter, being a hard crystalline rock, has been rounded by the bubbling up and 'cup and ball' action of the volcano and has never formed part of an aqueous conglomerate at all". He was also of the opinion (p.125) that the fragments and grains of ferro-magnesian silicates (i.e. mainly olivine, pyroxenes and garnet) contained in the kimberlite originated "from some deep-seated zone which has been shattered to pieces during the bursting through of the pipes and fissures".

Soon after this however Geo. S. Corstophine (1907) described a diamondiferous eclogite from the Roberts Victor Mine and came to the conclusion, as had Beck a few years earlier, that the eclogite inclusions are concretionary nodules formed by segregation or differentiation in the original kimberlitic magma. A similar conclusion was also reached by Voit (1907 a,b) who regarded them as concretions, formed in situ in an absolutely consanguineous magma. In a later paper on another diamondiferous eclogite from the Roberts Victor Mine Corstophine (1911) also suggests that the pyroxene-garnet aggregates may be remnants of late contemporaneous or segregation veins, formed by the intrusion of still molten material into cracks in the already solidified kimberlite, and which have been broken up by brecciation.

In 1907 Johnson presented a contribution entitled "Note on the Lherzolite and Eclogite Boulders of the Roberts Victor Mine" and in the same year Schwarz (1907) described a sapphire-kyanite rock inclusion from the Jagersfontein Mine. This he considered to be of accidental origin, coming from a deeply buried crystalline schist and brought to the surface by the kimberlite.

In the Thirteenth Annual Report of the Geological Commission of the Cape Colony du Toit, (1908), after a petrographic study of nodular inclusions from kimberlites of the north-west Cape, regards the eclogites as varieties of granulite which represent intensely metamorphosed igneous and possibly sedimentary material accidentally incorporated in the kimberlite. He stresses that there is not the slightest justification for considering them to be concretions or segregations formed in the kimberlite and points out that they do not show any affinity to kimberlite, melilite basalt nor to the ultramafic lherzolite and saxonite xenoliths.

Wagner (1914) in his excellent account of the diamond fields of southern Africa deals at length with what he refers to as the cognate xenoliths. He recognises twenty nine types, made up of differing combinations of garnet, diopside, phlogopite, orthopyroxene, olivine, ilmenite and apatite. An interesting feature which he mentions is the development, along the boundaries between the garnet and pyroxene of the eclogites, of thin reaction zones. These are made up of weakly pleochroic hornblende and small flakes of brown mica, whilst in the kyanite-bearing type he records the presence of minute laths of a basic plagioclase (Ab_{25}) and granules of augite and pleonaste (see later, Petrography). As regards the genesis of these xenoliths, Wagner considers the garnet-pyroxene aggregates to be of accidental origin, having been formed by the shattering of schlieren of griquaite or ariegite scattered through the deep-seated peridotite zone in which the kimberlite magma was generated. Other xenoliths he believes could have conceivably formed (p.131) by the "......clotting together, under plutonic conditions, of early products of the consolidation of the kimberlite magma and the breaking up of bodies of rock thus formed. In others it appears almost certain that we have specimens of the plutonic types of which kimberlite represents the hypabyssal or volcanic phase".

Later in another very interesting contribution dealing with xenoliths in kimberlite Wagner (1928) reaffirmed his contention that the peridotite and pyroxenite inclusions represent samples of a deep-seated universal peridotite zone but after studying the work of Penti Eskola on the eclogites of Norway concluded that the eclogite xenoliths are of two types. These are an igneous type, which he regarded as forming bands or schlieren in the universal peridotite layer and a metamorphic type, which possesses a gabbroid affinity and which "...... formed part of a continuous eclogite shell overlying the sima zone and constituting the lower-most part of the zone of amphibolitic, gabbroid and granulitic rocks that is assumed to underlie the platform of granite and gneiss......" (p.138)

In his magnificent account of the kimberlites of southern Africa, Williams (1932) pays considerable attention to the so-called cognate inclusions. The results of his investigations led him to strongly support the theory that the xenoliths are of cognate origin, resulting from the shattering of already solidified bodies of peridotite and pyroxenite formed at depth in a magma which also gave rise to kimberlite.

The last of the earlier workers on the subject of ultramafic xenoliths in kimberlite was Holmes (1936) and Holmes and Paneth (1936). Holmes was in general agreement with Wagner's ideas, that is, that the peridotites and eclogites are not of cognate origin but originate from deep zones of ultramafic rock.

To summarise, it can be seen, from a brief survey of research done during the earlier part of this century, that feelings as to the origin of the ultramafic and eclogite inclusions in kimberlite were divided. Bonney considered the rounded inclusions to be accidentally included water-worn boulders whilst Beck, Corstophine and Williams all regarded them to be of cognate origin directly related to the magma which gave rise to the kimberlite. On the other hand Harger, Du Toit, Wagner and Holmes appear to be of the mind that they represent more or less accidental inclusions of coarsely crystalline material from either a deep-seated peridotite zone or from high-grade metamorphic rocks within the Earth's crust.

V. RECENT RESEARCH ON THE XENOLITHS.

After the work by Holmes in 1936 very little research appears to have been undertaken in the field of inclusions in kimberlite. This is particularly surprising in a country such as South Africa where kimberlites are more abundant than in any other area in the world and where a number of pipes have been continuously exploited for many years.

It was more than twenty years later, that interest, now on a world-wide scale, was renewed in kimberlite, the reasons for this having been outlined previously. As would be expected the **ultramafic** and eclogitic inclusions found in the kimberlite formed one of the major topics of interest.

The result was that in laboratories all over the world these inclusions were studied, not only from their petrographical aspect, but also with regards to their detailed mineralogy, geochemistry and high-pressure melting relationships.

One of the first notable contributions in recent years, dealing with the inclusions in detail, appears to be that of O'Hara and Mercy (1963) who compared the petrology and mineralogy of a suite of peridotite xenoliths from certain kimberlites of South Africa with that of the garnetiferous peridotite masses from the Tafjord district of Norway and from Bellinzona, Switzerland. In brief, O'Hara and Mercy consider the garnet peridotites of Norway, Switzerland and South Africa to be derived from the mantle, but that only the inclusions in kimberlite can be representative of the unmodified composition of the upper mantle. They also consider the eclogite nodules found in kimberlite to be of xenolithic derivation from the upper mantle, the eclogites being partial fusion products of the garnet peridotites, formed and consolidated at great depth. As to the origin of kimberlite itself they suggest that it originated within the upper mantle as a fluidised system of ultramafic xenoliths and xenocrysts, melilite basalt liquid and a volatile phase consisting mainly of water and carbon dioxide and which drilled explosively to surface as a fast moving suspension.

In 1957 the University of Leeds had initiated a programme to study the kimberlite intrusions of Lesotho (then Basutoland), the initial results of which appeared in two doctoral theses (Dawson, 1960; Nixon, 1960). Based mainly on the results from these two theses, portions were later published by Dawson (1962) and by Nixon et al (1963).

In his works Dawson gives special attention to the petrography and mineralogy of the peridotite inclusions (which were found in most pipes of Lesotho) and to rare fragments of eclogite and occasional specimens of granulite-facies rocks found in some pipes. He concludes, somewhat radically, that the coarse-grained ultramafic silicate rocks (i.e. the peridotites) formed within the crust by a reaction between a carbonatite liquid (a magnesite-ankerite carbonate magma rich in water, phosphorus and titania) and granitic material which would yield a residual fluid rich in volatiles, potash, alumina, iron oxide and phosphorus. He proposes that kimberlite is the result of the reaction of this fluid with fragments of the shattered ultrabasic rocks (the larger of which were rounded and intruded with the kimberlite) and that the whole suspension intruded upper crustal levels by a process of fluidisation or gas-solid streaming along fracture zones. He regards the eclogite and granulite xenoliths as accidental inclusions caught up in the kimberlite magma and originating from some highly metamorphosed basic rocks existing at some considerable depth beneath the lavas and sediments of Lesotho. In 1966 Dawson outlined a similar origin for kimberlite when dealing with the kimberlite-carbonatite relationship.

On the other hand Nixon (1960) and Nixon et al (1963), after a detailed study of the Lesotho kimberlites, supports the contention that the ultramafic inclusions in kimberlite are analogous to those in basalts and are probably derived from the mantle, whilst some of the eclogite-type rocks, together with granulite and amphibolite, are of crustal origin and were derived from high-grade metamorphic terrains. They regard certain eclogitic inclusions (griquaite segregations) to be of cognate origin but stress that: "Unfortunately there are insufficient mineralogical and chemical data to delimit with certainty the eclogite xenoliths and the griquaite segregations" (Nixon et al, 1963, p.1128).

Davidson (1957, 1964, 1967b), in publications influenced mainly by dealings with the Yakutian kimberlites, regards both the peridotite and eclogite xenoliths to be of accidental origin and neither representative of upper mantle rocks nor cognate with kimberlite. In his most recent publication the evidence that these rocks are of deep-seated metamorphic origin is presented, apparently based mainly on the fact that: "The entire range of petrographic types amongst the xenoliths can be paralleled in several high-grade metamorphic terrains at the Earth's surface......" (Davidson, 1967b, p.342).

Meanwhile in Russia soon after World War II extensive prospecting for the source of widely scattered alluvial diamonds was carried out in the Western Yakutia, Siberia. It was only in 1954 however that the first kimberlite pipe (the unpayable Zarnitsa pipe) was located. Many more pipes were discovered in the following years, at least several hundred now being known, scattered in small groups over an area of 1.5 million square miles (Davidson, 1967a).

The diamond fields of Yakutia were first briefly described, in English, by Davidson (1957). A digest of a Russian text on the Yakutian diamond fields, prepared in English by Wilson, appeared in 1960. Since the discovery of the kimberlite pipes in the U.S.S.R., Russian scientists have given much attention to questions concerning their petrology and mineralogy and also to inclusions of pyrope-bearing ultramafic rocks and eclogites. In the last ten years Russian scientific publications, dealing with these subjects, have been extremely prolific and it is believed that data accumulated in the field of kimberlite research is tremendous, by far surpassing that of the West.

In 1959 the eminent Russian geologist, V.S. Sobolev, edited a review on the geology of the diamond deposits of Yakutia (Bobrievich et al, 1959). In addition to a detailed account of the kimberlites this text also describes in some detail numerous varieties of xenolithic inclusions found in the Siberian kimberlites. In general these inclusions appear to be very similar to those found in the southern African kimberlites. Four types are defined, which include xenoliths of ultramafic feldspar-free rocks (peridotites, pyroxenites, hornblendites, serpentinites and glimmerites) and xenoliths of crystalline schists (feldspathic eclogite-type rocks, feldspar-free eclogites, granulites and grosspydite). The ultramafic rocks are thought to originate in the peridotite zone whilst a process of eclogitisation of the deep-seated crystalline schists is postulated to account for the many eclogite-type rocks, which are accepted as being of crustal origin.

Bobrievich et al (1960) described in detail a xenolith of diamond-bearing eclogite from the "Mir" pipe. They point out the similarity between this eclogite (which also contains idiomorphic flakes of graphite) and eclogites of metamorphic complexes in general, but note that this rock must have been formed at an exceptionally high pressure and at a great depth, although probably at a higher level than the garnet peridotites.

In 1964 V.S. and N.V. Sobolev described xenoliths of eclogite and peridotite in kimberlite from Yakutia, many specimens of which show a banded stratiform structure and which they regard as likely xenoliths of mantle rocks. Other xenoliths they consider to have formed by high pressure metamorphism of crystalline schists and by processes of eclogitisation and garnetisation.

N.V. Sobolev (1965), recognised as a leading authority on inclusions in kimberlite, described in detail a corundum eclogite (containing about 15 per cent of violet-pink corundum) from the Obnazhennaya pipe and considers it to be a new type of metamorphic rock. In 1968 he presented a paper, at the Twenty-third International Geological Congress in Prague, dealing with xenoliths of eclogite from the kimberlite pipes of Yakutia and their origin as fragments of upper mantle substance. In all, Sobolev recognises six major types within the peridotite-eclogite group of inclusions. These are the so-called eclogite-like rocks (probably garnet granulites), eclogitised ultrabasic rocks, magmatic pyrope peridotites, true eclogites, grosspydite and diamond-bearing eclogites. Sobolev appears to regard the main part of the upper mantle to be composed of pyrope peridotites with separate eclogite lenses, the deeper of which may be more iron-rich and possibly also diamond-bearing. In the uppermost portion of the mantle eclogitised spinel peridotites or true eclogites can be found, overlain by eclogite-like rocks or rocks of the crystalline basement. (Sobolev, 1968a).

Other recent publications from Russia include that of Sobolev et al (1968) dealing with the petrology of grosspydite and associated kyanite eclogite xenoliths from the Zagadochnaya pipe and also the mineralogy of diamond-bearing eclogites (Sobolev and Kuznetsova, 1966).

Returning to the western world again we find that fairly recently several publications dealing with xenoliths from kimberlite have appeared. Harris et al (1967), in a paper dealing with the chemical composition of the upper mantle, indicates the great significance of garnet peridotite inclusions in kimberlite as samples of mantle material.

Schutte (1967) has recently made a detailed study of eclogite and ultramafic xenoliths from the kimberlite of the Barkly West district, South Africa. In all, he recognises sixteen types of xenolith and came to the conclusion that peridotite occurs in a zone between the Mohorovicic discontinuity and approximately 65 km below the continental crust. Below this peridotite zone and extending down to at least 500 km below surface he recognises a world-wide zone of griquaite (eclogite). Similar ideas have been expressed by Frick (1968). Schutte regards his griquaite as the primitive source of all magmas, the nature of the magma being derived from it depending both on temperature and pressure.

For several years an enthusiastic group of workers at the University of Cape Town have been engaged on petrological, mineralogical and geochemical studies on a large portion of the Williams (1932) collection of ultramafic and eclogitic xenoliths and on material collected by themselves. Petrological research recently completed includes that of Berg (1968) on the secondary alteration of eclogite from kimberlite pipes and that of Rickwood et al (1968) on a study of garnet from eclogite and peridotite xenoliths.

This latter account of the xenoliths from 16 kimberlite occurrences in southern and East Africa provides much new quantitative information. These authors suggest a tentative evolutionary scheme which essentially embraces the partial melting, within the mantle, of garnet peridotite to yield liquids which can, under specific pressure-temperature conditions, precipitate a cumulus eclogite phase. These liquids, after subtraction of the eclogite form a kimberlitic fluid of potassic mafic composition or of carbonatitic or alnoitic character. In short they consider the garnet peridotite xenoliths to be of mantle origin, whilst the eclogite inclusions are thought to be of cognate origin, intimately associated with the formation of a kimberlitic magma. In a still more recent contribution Mathias et al(1970)present the detailed mineralogy and petrology of 32 types of ultramafic and eclogitic xenolith, based on an examination of 466 specimens, and which they believe to be reasonably representative of the xenoliths in kimberlite from Lesotho, Rhodesia and South Africa.

The impressive results of this study has led the writers to propose that the peridotite and pyroxenite types have mineralogical proportions suggestive of two, or possibly three disconnected series, whilst the results obtained from the eclogites indicate the possibility of two distinct fractionation trends within the mantle, from a melt formed by the partial fusion of garnet peridotite. They concluded that the upper mantle is largely comprised of garnet peridotite (lherzolite).

Other important publications from this group of workers includes the thesis of Siebert (1968) on the mineralogy and petrology of ultramafic xenoliths, the nature and occurrence of both non-eclogitic ultramafic xenoliths and eclogite xenoliths in the kimberlites of southern Africa (Rickwood, in press and Rickwood et al, also in press, respectively) and ultramafic xenoliths from the Matsoku kimberlite pipe in Lesotho (Mathias and Rickwood, in press).

On the subject of diamondiferous eclogites the work of Rickwood and Mathias (in press) and Gurney et al (in press) can be mentioned. Recent theories on the origin of eclogite inclusions in kimberlite have been presented by Kushiro and Aoki (1968) and MacGregor and Carter (1969). Carswell and Dawson (1970) have recently published the results of numerous chemical analyses of garnet peridotites from kimberlites and discussed their genesis. The genesis of the xenoliths will be dealt with more fully in Chapter X and XI.

Research on the xenoliths has not by any means been restricted to their occurrence, petrology or mineralogy. Melting relationships and phase equilibria studies, on both natural peridotite and eclogite xenoliths have been reported. Although a summary of this aspect is beyond the scope of this investigation, the work of O'Hara (1963a, b, 1965, 1968) and O'Hara and Yoder (1967) deserves special mention, as does that of Ito and Kennedy (1967).

In the field of geochemistry and isotope studies other workers have been active, as is witnessed by the work of people such as Stueber and Murthy (1966), Erlank (1969) and Gurney and Berg (in press).

To summarise it is seen that much interest has been aroused in the study of kimberlites and their unusual xenolithic inclusions. Not surprisingly however no one theory as to the origin of the inclusions is sufficent to provide all the answers and much controversy still exists. Essentially, some regard both the peridotites and eclogites to be of mantle origin whilst others consider them to be derived from high-grade metamorphic terrains. A cognate origin is yet another concept proposed for their origin. It is quite possible that the answer to their origin is a multiple one.

VI. XENOLITHS OF THE PRESENT INVESTIGATION, THEIR SOURCE AND OCCURRENCE.

The specimens originate from three kimberlite pipes (Bultfontein, Wesselton and Dutoitspan) in the Kimberley district, Cape Province, and from one pipe, the Roberts Victor, situated some 80 km north-east of Kimberley, near Boshof, Orange Free State. The pipes of the Kimberley district are intruded through the Dwyka Series of the Karroo System and the Roberts Victor pipe penetrates the Ecca Series of the same System. The Kimberley-Boshof area and the position of these four pipes is shown in Fig. 1.

It is from the three pipes of the Kimberley area, the location of which is shown in Fig. 2, that the bulk of the peridotite specimens originate, whilst all the eclogite specimens, plus several peridotite specimens, come from the Roberts Victor Mine. At present all four mines are producing diamonds.

Most of the specimens were generously made available for this study by the Geological Department of De Beers Consolidated Mines Limited, Kimberley. Several specimens from the Roberts Victor Mine were collected independently and donated by the Bernard Price Institute for Geophysical Research, Johannesburg. A number of specimens, also originating from the Geological Department of De Beers Consolidated Mines Limited, were made available to the writer by Mr. C. van Zyl of Anglo American Research Laboratory.

All specimens from the De Beers Geological Department were either obtained from the "old depositing floors" or from a large collection of nodular inclusions housed near Kimberley. Initially a search for this type of inclusion was made at the majority of the so-called "old depositing floors" and waste-rock dumps of the Bultfontein, Wesselton and Dutoitspan Mines (see Fig. 2). These "old depositing floors" are areas that were set aside for the dumping and weathering of newly mined "blue ground" kimberlite during the earlier part of this century. Short accounts of this process, known as "flooring" or "natural pulverisation", are given by Wagner (1914) and by Williams (1932). Essentially the procedure was to allow fresh, hard kimberlite, spread out thinly over a large area of bare veld, to weather and soften, by atmospheric processes, during a given period of time. When suitably decomposed the kimberlite was sorted and treated in the normal diamond recovery process.

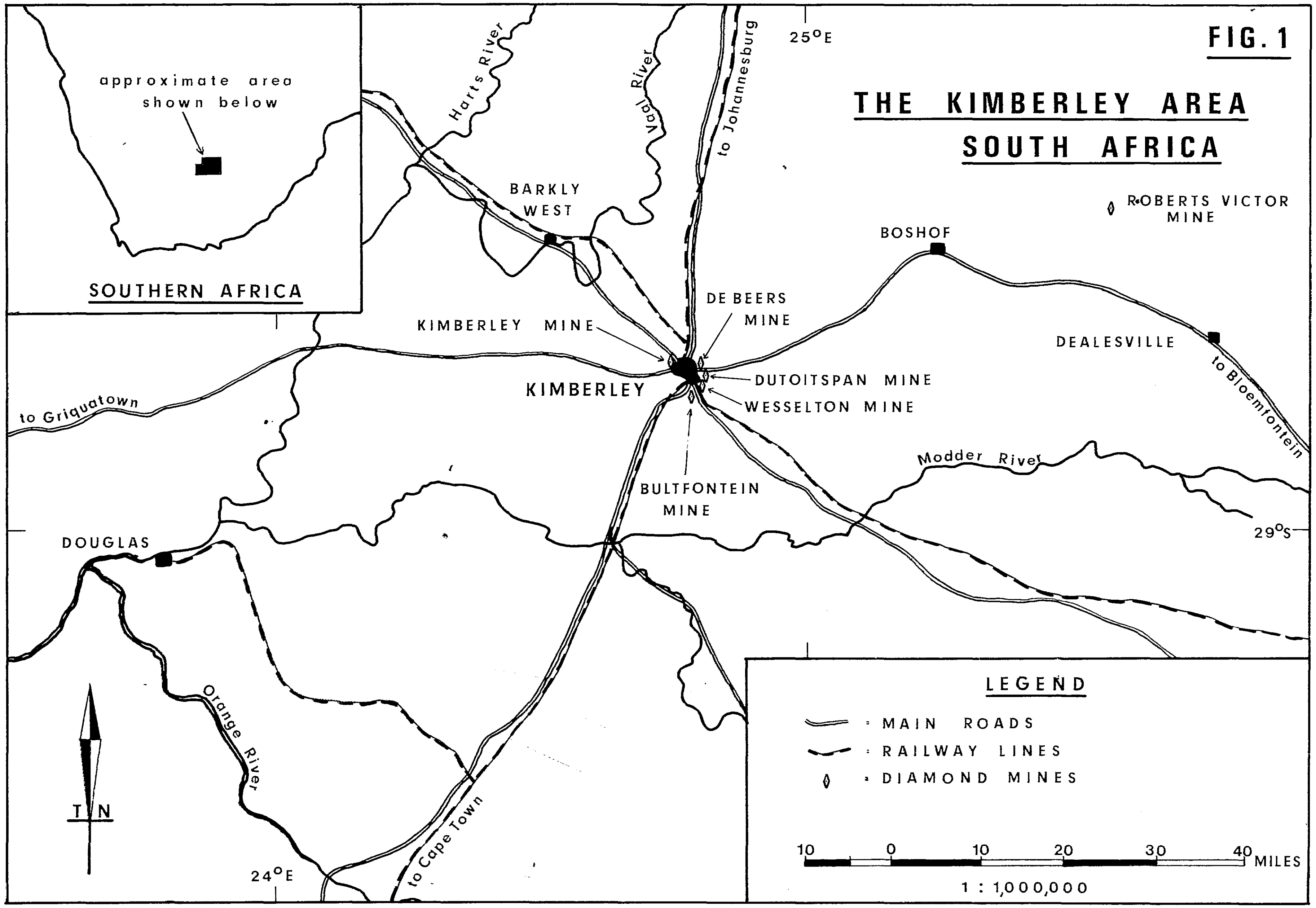
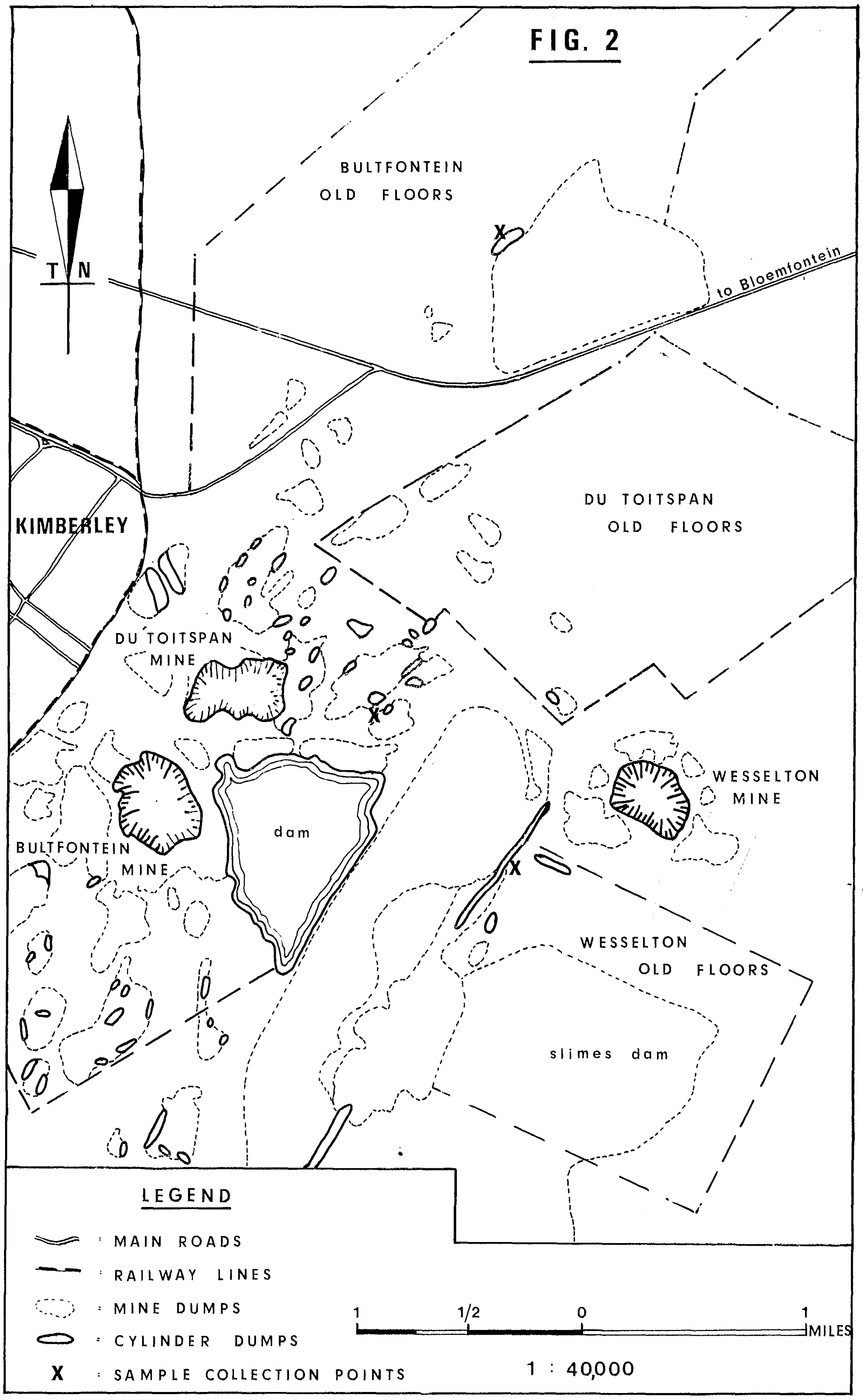


FIG. 1

THE KIMBERLEY AREA
SOUTH AFRICA

FIG. 2



Bultfontein, Du Toitspan and Wesselton Mines, Kimberley, showing dumps and old depositing floors

It appears that during the sorting operation as much of the foreign (i.e. non kimberlite) material as possible was removed from the ore and packed into small elongated dumps, known as "cylinder dumps", many of which are still intact. The main constituent of these dumps is accidental inclusions derived from the Karroo System but they also contain a scattering of ovoid and roughly rounded nodules of deep-seated origin, many being the typical peridotite inclusions.

It is on these rock dumps that many of the peridotite inclusions were collected. Unfortunately these nodules have been exposed to the elements for many years and so show an appreciable degree of surface weathering. However the internal portions of these specimens are relatively fresh and can be used for normal studies.

Similarly the collection of xenoliths housed by the Geological Department of De Beers Consolidated Mines Limited was also initially collected from the depositing floors over forty years ago but as they have been stored under shelter they are much better preserved. It is from this collection that the majority of the specimens were obtained. It is here that a large collection of xenolithic material from the Roberts Victor Mine is also housed and from which all, except for four of the Roberts Victor specimens, were obtained. In all 66 specimens were selected for examination of which 42 are of peridotite (24 garnet peridotites) and 24 of eclogite (including one diamond-bearing xenolith). A list of the specimens, with hand specimen identification and origin, is given in Table 1.

It is very interesting to note that despite a careful search, both on the waste-rock dumps and amongst the inclusions in storage, no eclogite xenoliths from the Kimberley group of pipes were found.

It is rather unfortunate that the original distribution of the inclusions within the enclosing kimberlite is not known, neither is it known from what type of kimberlite each inclusion originated. All that can be said is that the kimberlites of all four mines are generally of the basaltic, brecciated or agglomeratic types and each pipe is made up of a number of different varieties, probably corresponding to different ages of intrusion. For further details on the pipes the reader is referred to the work of Williams (1932).

TABLE I.

LIST OF SPECIMENS EXAMINED, WITH HAND SPECIMEN IDENTIFICATION AND ORIGIN.

Specimen No.	Rock type	Pipe of origin	Specimen No.	Rock type	Pipe of origin
BF. 1	Garnet peridotite	Bultfontein	RV. 1	Eclogite	Roberts Victor
2	" "	"	2	"	"
3	" "	"	3	"	"
4	" "	"	4	Diamond eclogite	"
5	" "	"	5	Eclogite	"
6	" "	"	6	Kyanite eclogite	"
7	" "	"	7	Eclogite	"
8	" "	"	8	"	"
9	" "	"	9	"	"
10	Peridotite	"	10	"	"
			12	Peridotite	"
W. 1	Peridotite	Wesselton	14	"	"
3	"	"	15	Altered peridotite	"
4	"	"	16	Garnet peridotite	"
5	"	"	17	Peridotite	"
6	Garnet peridotite	"	18	Micaceous eclogite	"
7	" "	"	19	Peridotite	"
8	" "	"	20	Eclogite	"
9	" "	"	25	Garnet peridotite	"
10	" "	"	26	Eclogite	"
DT. 2	Altered peridotite	Dutoitspan	27	Kyanite eclogite-eclogite contact	"
3	" "	"			
4	Peridotite	"	29	Eclogite	"
6	Garnet peridotite	"	30	"	"
7	" "	"	31	"	"
8	" "	"	32	"	"
9	Altered peridotite	"	33	"	"
10	" "	"	34	Kyanite eclogite	"
11	Garnet peridotite	"	RVL 2	Eclogite	"
13	Peridotite	"	5	"	"
14	Garnet peridotite	"	10	"	"
15	" "	"	16	"	"
16	Altered peridotite	"			
18	Garnet peridotite	"			
20	" "	"			
21	Altered peridotite	"			

It should also be mentioned here that the collection of peridotite or eclogite xenoliths in situ within the kimberlite would be an extremely ardous and time-consuming task and the assembling of a large number of such inclusions of adequate size would also be virtually impossible. Modern mining methods, in which the kimberlite is crushed underground prior to hoisting to surface, makes a search of the newly-mined kimberlite a rather unrewarding task.

VII. ANALYTICAL PROCEDURES AND TECHNIQUES.

This chapter outlines the various techniques and analytical procedures used in this study. In general the methods used are the standard procedures applied in normal petrographic and mineralogical studies. In this respect a fairly recent text outlining the physical methods of determinative mineralogy (Zussman, 1967) has been found particularly useful. Certain other techniques were developed during the course of the study, both by the writer and by his colleagues at Anglo American Research Laboratory, to enable more specialised tasks to be undertaken or to devise more suitable methods of separation.

1. Optical Investigations.

Examination of thin sections. At least one but normally two or more thin sections, each approximately 3 to 4 sq. cm in area, were prepared from each specimen. These were examined by normal transmitted light techniques using a Leitz Laborlux petrographic microscope. Textures and interesting features were recorded photographically.

Determination of optical constants (2V, $C \wedge \gamma$). Optical constants were accurately determined on suitable selected mineral grains in thin-section using a Leitz four-axis universal stage. The results, obtained by direct reading or from stereographic construction when the former was impossible, are considered to be accurate to within ± 2°.

Determination of refractive indices. All refractive indices were determined on crushed fragments by the immersion method (Kerr, 1959). For the garnets a single-variation technique was used. This technique is similar to the double variation procedure outlined by Emmons (1943) but in this case the temperature was assumed to remain constant and the wavelength of the light varied by use of a monochromator fitted to the microscope. Before the determination of any refractive index the microscope, Abbey refractometer and refractive index liquids were allowed to attain a constant temperature of approximately 68°C by standing for an extended period in an airconditioned room. All operations were carried out in this room at the same temperature. Results, given for the D line (689.3 mμ), were obtained graphically by plotting on single cycle semi-log paper (or a Hartmann net), using refractive index liquids of a known dispersion. In this way the refractive index and the dispersion of the garnets were obtained. The accuracy is thought to be within ± 0.003 for the garnets and within ± 0.005 for the birefringent minerals.

2) Modal Analyses.

The petrographic modal analysis of coarse-grained rocks, such as the ultramafic and eclogite inclusions found in kimberlite, is made difficult by their variable grain-size and their coarse-grained texture. The inhomogeneous nature of the hand specimens, which is reflected in many cases by distinct banding or rude layering, even within a single inclusion, and the variable distribution of the constituent minerals seriously limits the reliability of almost any modal analysis.

It was felt very necessary however to attempt some form of modal analysis on these coarse-grained inclusions as very few quantitative analyses of a similar nature can be found in the literature. Most workers in this field have been content to either ignore a quantitative modal analysis or to roughly estimate the mineral composition of a particular specimen, such as done by Mercy and O'Hara (1965a). They present (p.327) the mineralogical composition of some peridotite inclusions from kimberlite "......... to nearest 5% on the basis of point counting on thin sections cut from hand specimens with very variable grain size and of inhomogeneous character with respect to the distribution of minerals".

On the other hand some writers have gone to the extreme; for example Binns (1967) gives a precise modal analysis, values to the first decimal place, based on measurements of a thin section of eclogite. Rickwood et al (1968), in their study of peridotite and eclogite inclusions in kimberlite, have estimated the volume per cent garnet in each specimen examined by them to the first decimal place, but do clearly indicate the coefficient of variation of these results. In a number of cases this exceeds 20 per cent and in several is greater than 50 per cent.

Chayes (1956) clearly shows the relationship between grain size and measurement area and stresses that the accuracy of any modal analysis is largely dependant on the number of grain sections per measurement area. In other words the coarser-grained a rock is the larger the area of measurement must be to obtain acceptable results.

As a test to whether point counting could be effectively and reliably used in the modal analysis of the coarse-grained peridotite and eclogite inclusions the following experiment was carried out.

From a specimen of fairly coarse-grained garnet harzburgite (specimen BF.8) eight thin slices, all parallel to each other, were cut and thin sections, each measuring approximately 4 sq. cm prepared. An initial examination of the thin sections at once revealed large variations in the relative amounts of olivine, orthopyroxene and garnet. Using a Swift Automatic point-counter with a horizontal stepping distance of 0.5 mm and a vertical stepping distance of 0.3 mm, 1000 points were systematically counted across the surface of each section and the volume per cent of each constituent calculated. These results are given in the table below and clearly indicate the tremendous variation in composition.

Section No.	Volume per cent of major constituents			No. of points counted
	Olivine	Orthopyroxene	Garnet	
1	70.0	27.3	2.7	1000
2	70.1	28.5	1.4	1000
3	84.7	10.3	5.0	1000
4	68.6	23.5	7.9	1000
5	61.5	30.8	7.9	1000
6	67.8	22.1	10.1	1000
7	74.2	22.2	3.6	1000
8	78.6	21.4	-	1000
Mean	71.9	23.3	4.6	8000

In a similar manner, but now using a superimposed transparent perspex grid with 2 mm X 2 mm divisions (equivalent to a 2 mm stepping interval both horizontally and vertically) and a stereoscopic microscope equipped with a traversing head, 900 points were counted across the combined surface of all eight thin sections. Using this method the following modal figures were obtained.

Olivine	Orthopyroxene	Garnet
71%	24%	5%

It is apparent that these results, whilst undoubtedly less precise, compare very favourably with those obtained using the much more laborious and time-consuming automatic point-counter technique. It is also apparent that the stepping interval of 2 mm, both horizontally and vertically, is quite adequate for a reasonable modal analysis of the coarse-grained peridotite and eclogite specimens, so long as the measured area is large enough, in this case approximately 30 sq. cm.

As both the peridotite and eclogite specimens are coarse-grained and essentially contain only a restricted assemblage of easily recognisable minerals (i.e. olivine, orthopyroxene, clinopyroxene, garnet and phlogopite) it was found quite adequate to cut and roughly polish thin slabs (about 1 to 2 cm thick) of the rock and to measure the abundance of each constituent in the following manner.

Over each slab a transparent grid (with 2 mm x 2 mm divisions) was clamped. To improve the clarity of the specimen each slab was initially sprayed, on both sides, with a transparent protective lacquer. The slab, with the superimposed grid, was then clamped onto the stage of a stereoscopic microscope equipped with a traversing microscope head and a strong source of illumination directed onto the specimen. The traversing microscope head was then guided along the traces of the grid and the various minerals corresponding with the grid intersections recorded on a manual counter. When the maximum possible number of points on one side of the slab had been counted, it was reversed and the process repeated. In this manner between 1000 and 1400 points were accumulated for each specimen, this approximately corresponding to a measured area of 35 to 50 sq. cm.

To test the reproducibility of the results a slab of garnet peridotite (specimen BF.8) was analysed five times using this same technique and 1200 points recorded in each run. These results, which are tabulated below, show only a small variation which can be attributed to:

a) mis-identifications by the operator (i.e. between olivine and orthopyroxene)

b) the slab being clamped into slightly different positions for each run.

No. of analysis	Volume per cent constituents			
	Olivine	Orthopyroxene	Garnet	Phlogopite
1	73.5	22.5	4.0	trace
2	74.1	21.6	3.9	0.4
3	72.3	23.0	4.4	0.3
4	71.6	23.8	4.2	0.3
5	72.4	23.1	4.3	0.2
Mean	72.8	22.8	4.2	0.3

In the case of the peridotites a certain difficulty was found in distinguishing olivine from the orthopyroxene on the surface of the slabs. This was overcome by etching the slabs in hot concentrated hydrochloric acid for several minutes. On drying it was found that the numerous serpentine veinlets penetrating the olivine had been leached to leave a superficial white residue which was clearly visible and served to distinguish the olivine from the orthopyroxene. The apparatus used in the point counting analyses is illustrated in Plate 1. Plate 2 illustrates two etched slabs of peridotite used in the point counting analyses.

The results of the volumetric composition of the major constituents are expressed to the nearest per cent for amounts over 10 per cent and to the nearest tenth of a per cent for amounts less than this. In most cases the accuracy of the determinations is probably within two per cent of the given figures. Trace constituents are those which are microscopically visible but which were not recorded during point-counting.

In certain cases the small size of the xenoliths precluded a rock slab being prepared. An estimate of the modal composition of these specimens was obtained from a point count on a thin section, these results therefore being only semi-quantitative.

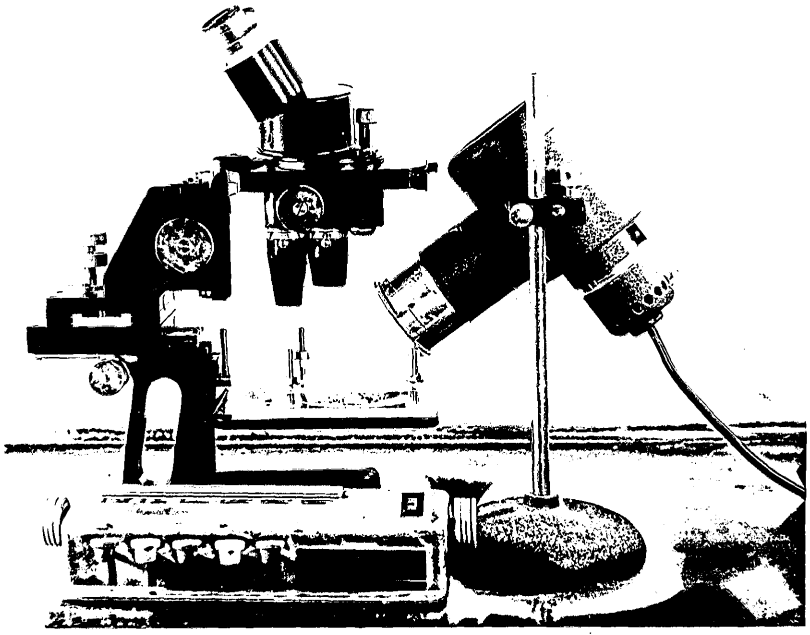


PLATE 1. The apparatus used in the point counting analyses.

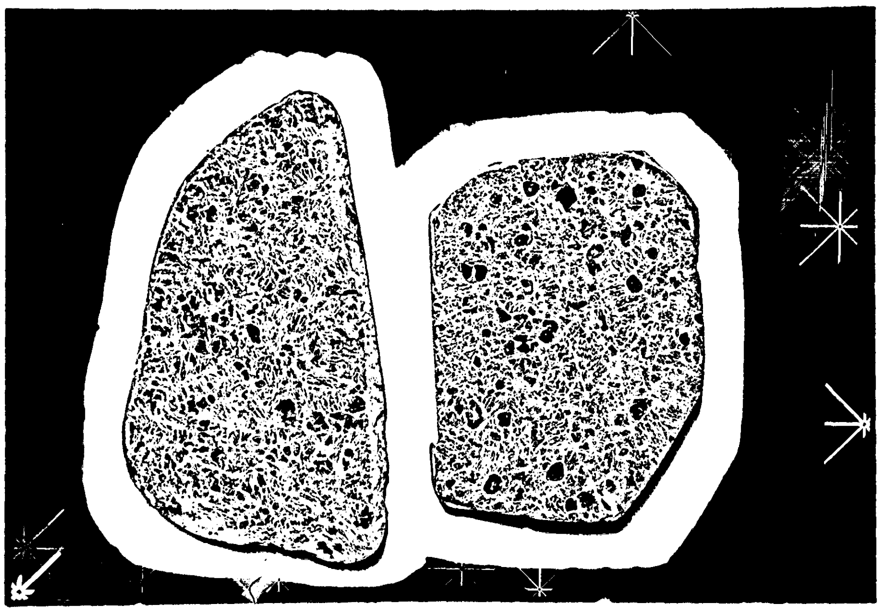


PLATE 2. Two etched slabs of garnet peridotite.
The serpentine veinlets in the olivine are clearly seen and contrast to the unaltered orthopyroxene (green, unaltered) and garnet (dark, red rounded).

3, Mineral Separations.

The chemical and structural analysis of co-existing mineral phases forms a substantial part of this thesis and consequently necessitated the preparation of numerous pure mineral fractions. Also the presence of trace constituents (for example sulphides, spinels, corundum and kyanite) were only detected during the examination of magnetically separated mineral fractions. Separations were accomplished as outlined below.

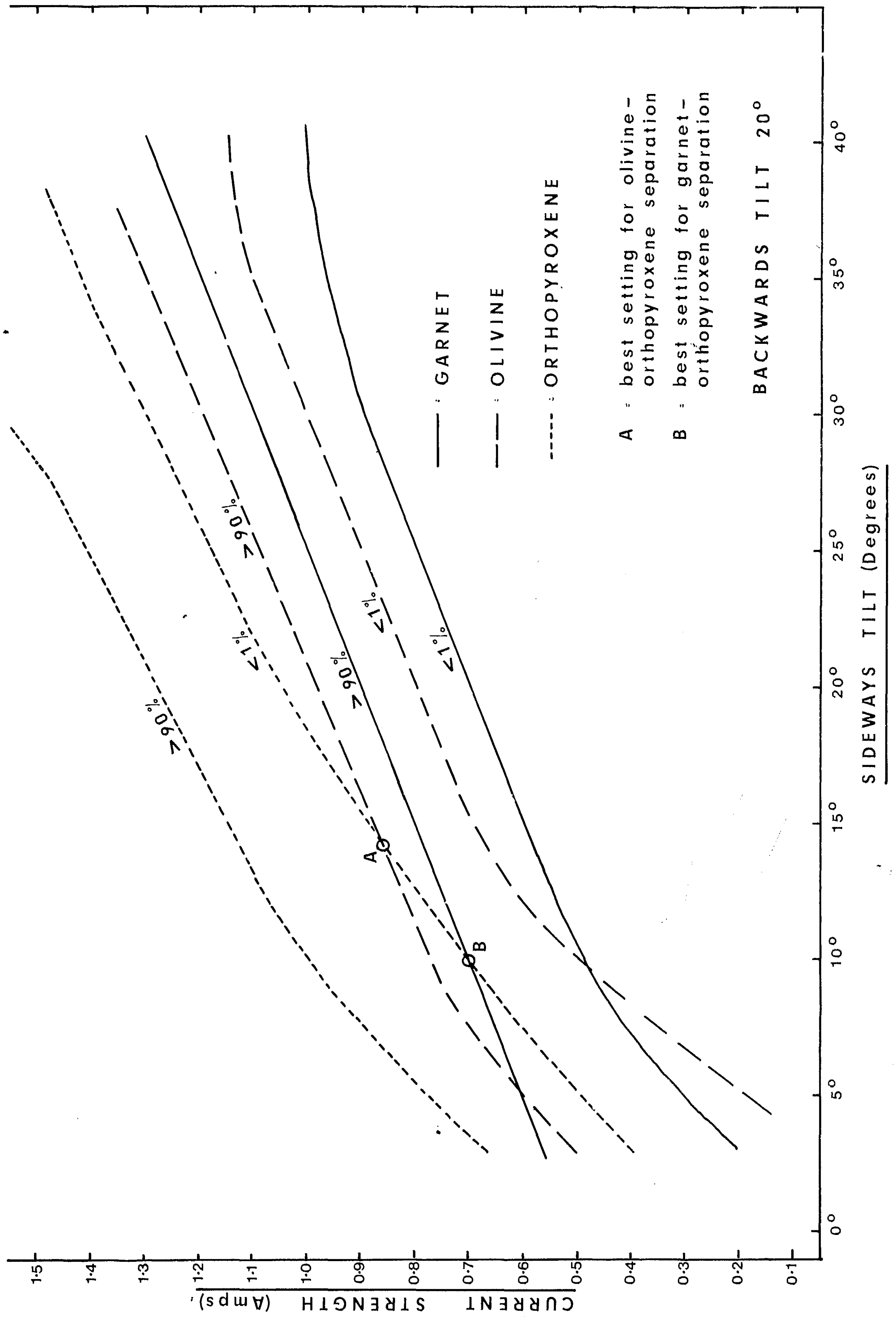
Disaggregation and screening. Initially a portion of the rock to be separated, amounting to roughly between 100 and 200 grams for the eclogite and between 500 and 1000 grams for the peridotite, was crushed to fragments of less than one quarter inch size using a jaw crusher. If the specimen was small enough this process was done by hand using an iron mortar and pestle. All material less than 28 mesh in size was then screened out and the oversize rock and mineral fragments reduced to less than 28 mesh using a disc pulveriser. (NOTE: All screen sizes used are of the Tyler standard type and are constructed of brass).

This crushed material was then deslimed by washing over a 325 mesh stainless steel screen, dried and then manually screened, through both 40 and 100 mesh screens. Both the minus 100 mesh and the plus 40 mesh material was collected and stored. For virtually all separations it was found that the constituent minerals of the remaining minus 40 plus 100 mesh material were completely liberated and quite suitable for the preparation of pure mineral factions. This material was then washed with water and dried with acetone.

Magnetic separations. The highly magnetic material, such as magnetite, tramp iron or pyrrhotite was removed from the clean, well-sized samples with the aid of a hand magnet. The samples were then passed through a Frantz Isodynamic Magnetic Separator at successively stronger magnetic fields and in this way a number of fractions, each normally containing a particular concentration of one, or sometimes two, constituents were obtained. As a guide to the magnetic separation of the more complex peridotite specimens pure mineral fractions, one each of garnet, olivine and orthopyroxene were initially prepared from a garnet peridotite (specimen BF.8).

Using the Frantz Magnetic Separator at a constant downwards tilt of the mineral chute an accurately known amount of a pure mineral fraction was passed

FIG. 3



APPROXIMATE ELECTRO-MAGNETIC SEPARATION FIELDS FOR OLIVINE ORTHOPYROXENE AND PERIDOTITE GARNETS through the machine at varying sideways tilt and coil amperage. The amount of material recovered on the "magnetic" side of the chute after each run was then measured and recorded. In this way a characteristic pattern of magnetic separation could be constructed for a particular constituent. The fields of mineral separation for co-existing olivine, orthopyroxene and garnet (from specimen BF.8) are illustrated in Fig. 3. (It should be noted however that these results are only applicable to a particular magnetic separator as each instrument apparently assumes a character of its own). Strictly, the pattern of magnetic separation is only for the mineral fraction used, but the results can easily be extrapolated to minerals of the same type from other sources, particularly when their chemistry is similar.

A comparison of the magnetic separation fields of the garnet, olivine and orthopyroxene (see Fig. 3) shows that ideal conditions for the separation of one mineral from another will be where the >90 per cent separation area for the one phase coincides with the <1 per cent separation of the other. In practise this ideal condition is often not possible to attain and only impure fractions can be obtained. The presence of alteration products and composite grains further limits its application, but a good indication of the optimum conditions for the magnetic separation of the constituent minerals of the peridotites (olivine, orthopyroxene, garnet and chrome diopside) was obtained in this way and a number of interesting trace constituents detected in the most magnetically unsusceptible fraction.

The eclogite specimens, being virtually bimineralic garnet-clinopyroxene assemblages, did not require nearly as much attention as the peridotites during separation. In their case it was only necessary to find experimentally the most suitable conditions for the garnet-pyroxene separation and to obtain a magnetically unsusceptible fraction (in which the sulphides, kyanite, corundum, rutile and diamond were concentrated).

<u>Heavy liquid separations</u>. As all the minerals required for analysis were "heavy minerals" (i.e. S.G. >2.90) heavy organic liquids were used to great advantage in the separation process. The liquids used were bromoform (S.G.~2.82) and methylene iodide or diodomethane (S.G.~3.25). Secondary minerals such as zeolites, carbonates, silica, and serpentinous and kelyphitic alteration products were removed by treating each crushed sample with bromoform prior to magnetic separation.

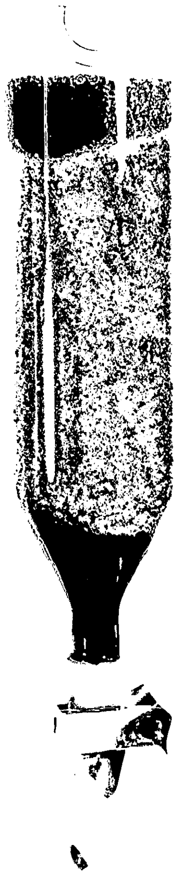


PLATE 3. A typical methylene iodide separation of the constituent minerals of a peridotite. The garnet has sunk to the bottom, the olivine is in suspension and the orthopyroxene and chrome diopside are floating.

After magnetic separation the more refined heavy liquid separations were carried out using methylene iodide. In this way it was often possible to obtain concentrates of fresh material of at least 95 per cent purity. In certain cases cooling of the methylene iodide to slightly above its freezing point (with a resultant increase in its density) enabled more difficult separations to be made, such as that between olivine and orthopyroxene, which have almost identical specific gravities.

The apparatus used for the methylene iodide separations was extremely simple, consisting only of a separating funnel clamped to a stand. The procedure consisted of filling the funnel to a convenient level with methylene iodide and then slowly adding the mixed mineral concentrate, at the same time stirring rapidly. The funnel was then allowed to stand for a suitable period until the separation was complete and the almost pure mineral fractions drained off. A typical separation is illustrated in Plate 3.

Final cleaning of concentrates. The almost pure mineral concentrates were finally cleaned by one or more of a variety of processes which included repeated magnetic separation, hydrochloric acid treatment (to remove tramp metal, carbonates and some secondary materials), hydrofluoric acid treatment (to remove kelyphitic surfaces on garnet grains) and finally, hand-picking with the aid of a stereoscopic microscope.

The mineral fractions thus produced, normally several grams in weight, were virtually 100 per cent pure. Grain counts on these concentrates indicate a purity in excess of 99 per cent.

4. X-ray Diffraction Techniques.

X-ray powder diffraction techniques were employed to identify positively any dubious mineral species and secondly, of much greater importance, to determine the unit cell size and interplanar spacings of various constituents of the rocks.

The fundamental principles and general techniques of X-ray powder diffraction will not be dealt with here as numerous authoritative publications on this aspect are available. The works of Buerger (1956), Nuffield (1966), Zussman (1967) and Azaroff (1968) provide ample background.

Identification of unknown minerals. It was found very useful to use X-ray powder diffraction photographs to identify unknown minerals, particularly when only a trace of the constituent was found. This was done using the method suggested by Hiemstra (1956) and the normal Straumanis film-mounting position (Zussman, 1967). Identifications were then made by comparison against a comprehensive set of standard reference films or by the use of the ASTM Powder Data File and ASTM Index.

Determination of unit cell size. (for garnet only). This was done by both powder photography and powder diffractometry, the former being used when only small amounts of material were available or when it was considered desirable to check a result obtained by diffractometry.

(a) *X-ray powder photography.*

The "ball mount" specimen preparation technique suggested by Hiemstra (1956) was employed together with a technique similar to that described by Coetzee (1963). This involved crushing, between two microscope slides, a small grain of garnet placed in a drop of rubber solution and forming a small ball of the resultant powder. The ball, less than 0.5 mm in diameter, was then mounted on a thin nylon hair, placed in the powder camera and carefully centred. Using the Straumanis film setting and finely-collimated iron-filtered cobalt radiation the specimen was exposed to X-rays for two to three hours.

After development and drying of the films they were accurately measured on a fluorescent screen using a vernier measuring device that permits estimation to the nearest 0.05 mm. A shrinkage or expansion correction factor for each individual film could then be calculated and, if necessary, applied to the measurements. Poor quality films were rejected.

Once corrected the apparent unit cell size was calculated using the $K\alpha_1$, and $K\alpha_2$ lines of the four strongest back reflections, their Miller indices being (880), (884) (12.2.0) and(10.6.4). As garnet possesses a cubic symmetry this was a relatively simple procedure, the following formula being used:

$$a = d_{hkl} \times \sqrt[2]{h^2 + k^2 + l^2}$$

where a = apparent unit cell size

d = interplanar spacing (in Angstrom Units) for a particular reflection

hkl = Miller indices for a particular reflection.

Error caused by absorption and divergent radiation was minimised by means of an extrapolation function, $^1/_2 \left(\frac{\mathrm{Cos}^2\theta}{\mathrm{Sin}\theta} + \frac{\mathrm{Cos}^{\ }\theta}{\theta}\right)$, obtained from tables compiled by Nelson and Riley (1945), and the a_o value obtained. For most specimens examined in this way the unit cell of the garnet was calculated from three or more different grains and the mean value obtained. The maximum variation was found to be of the order of $\pm$ 0.003Å .

(b) X-ray powder diffractometry.

This rapid method is inherently more accurate than the powder photograph method and when enough material was available it was invariably utilised for structural determinations of the garnet, olivine and pyroxenes.

Approximately 0.5 grams of a clean mineral fraction was very finely crushed in acetone, together with approximately 0.1 to 0.2 grams of pure AR silicon powder to act as an accurately calibrated internal standard.

The resultant powder, when dry, was then packed and flattened into a shallow, recessed perspex sample holder and mounted in the diffractometer specimen chamber. The peak positions of the X-ray reflections, both of the mineral and the silicon, were recorded on a chart. The X-ray run was repeated several times, on each occasion using iron-filtered cobalt radiation with a goniometer speed of 1° 2θ per minute. For better resolution of certain peaks a goniometer speed of $^1/_4{}^{\circ}$ 2θ per minute was employed. The position of the peaks was corrected for any experimental error by reference to those of the internal silicon standard and the corresponding interplanar spacings obtained from tables.

For the determination of the unit cell of the garnets by this method the position of both the $K\alpha_1$, and $K\alpha_2$ peaks of almost all the back reflections were measured, the interplanar spacing determined and the a_o value for each reflection calculated in the normal manner (for the $K\alpha_2$ reflections a small correction factor had to be applied). By using this method no further correction was necessary as most analytical errors were compensated for by the use of an internal standard. Indications are that the variation in the determined unit cell size is of the order of ± 0.001 Å, a value which is considerably better than that obtained by the photographic method.

X-ray equipment and settings.

(a) Powder photography.

Camera : Philips Debye-Scherrer, radius 57.28 mm.
Radiation : Co, Fe filtered
KV, mA : 32 KV, 15 mA
Collimators : fine
Temperature : ~ 68°F
Exposure time : 2 - 3 hours

(b) Powder diffractometry.

Diffractometer : Philips vertical goniometer, model PW1050
Radiation : Co, Fe filtered
KV, mA : 40 KV, 20 mA
Collimator slits : fine
Temperature : ~ 68°F
Goniometer speed : 1° 2θ/min, for better resolution $^1/_4$ 2θ/min.

5. Chemical Analyses.

All major element analyses, except for alkalis, ferrous oxide, water and carbon dioxide were carried out by X-ray fluorescence spectrographic techniques, the other constituents being determined by normal chemical methods. Trace elements were determined by both X-ray fluorescence and emmission spectrographic techniques. Chromium was determined by wet chemical and X-ray methods.

Methods of chemical analysis by X-ray fluorescence techniques have been developed at Anglo American Research Laboratory over a number of years using Philips X-ray fluorescence equipment. Whilst a description of the techniques is beyond the scope of this thesis a comprehensive background to practical X-ray spectrometry can be found in a recent text by Jenkins and de Vries (1967). Advantages of the X-ray fluorescence analysis of rocks compared with the classical wet chemical methods are numerous; some that come to mind include:

a) rapidity - a single rock sample can be prepared and completely analysed for all major elements in approximately four hours, provided the operators are experienced and calibration data exists.

b) accuracy - the accuracy attainable is equal to, if not greater than that of wet-chemical analyses, provided of course reliable calibration standards are used.

c) sample size - only a small amount of material is required for a complete rock analysis, normally of the order of several grams.

d) records - the sample is permanently prepared in the form of a glass disc or briquette and can always be referred to.

The method employed in the analysis of both rock and mineral specimens quoted in this thesis consists essentially of finely pulverising (in a tungsten carbide mill) a representative portion of the material and then fusing a known amount together with a known quantity of flux in either a platinum-gold or graphite crucible at 1000°C. The flux, consisting of lithium tetraborate ($Li_2B_4O_7$) and lanthanum oxide (La_2O_3) is mixed with the sample in the ratio 85:15. Once the sample has been completely fused (approximately 30 mins) the molten glass is cast into a round, flat disc in a graphite mould, allowed to harden and cool and is then given a rough polish on one side to form the smooth analytical surface.

The disc can then be analysed by X-rays and the results calculated and calibrated with internationally accepted standards such as those of the United States Geological Survey, the Canadian Association for Applied Spectroscopy, the United States National Bureau of Standards and the British Chemical Society.

6. Specific Gravity Determinations.

The specific gravity of each rock specimen was determined, as well as that of individual mineral species. These determinations were carried out as indicated below.

Rock specimens. As all the rocks are coarse-grained, it was necessary for fairly large samples to be used in the determination. In practice it was found suitable to use a slab of the specimen, weighing between 400 to 600 grams, with as much of the weathered material as possible removed. Of course when the specimen was smaller than this a proportionately smaller fragment had to be used.

A displacement method was employed to determine the specific gravities (see Muller, in Zussman, 1967). The procedure was as follows:

The specimen was first weighed in air (W_1). After weighing a beaker of water on a rough chemical balance (W_2) the rock specimen was completely suspended in the water with the aid of a thin nylon thread, making sure that all air bubbles had been removed. The weight of the beaker plus water was found again (W_3), and $W_3 - W_2$ gives the weight of the water displaced by the specimen. The specific gravity is therefore given by the formula $\frac{W_1}{W_3-W_2}$ i.e. the weight of the specimen divided by the weight of an equal volume of water. Accuracy of this method when used on fresh, non-porous material is the order of ± one per cent.

Mineral concentrates. The specific gravity of mineral concentrates was done by the well-known pyknometer method. Basically it consists of using a known weight of a pure mineral concentrate and comparing with the weight of an equal volume of a liquid, benzene, toluene or alcohol normally being used. The results obtained by this method have the advantage of being the mean value of all the grains in the concentrate.

Individual grains. In practise the method used consisted of dropping a small grain (less than 28 mesh in size) into a small beaker of concentrated Clerici solution and diluting drop by drop with water until the grain is in complete equilibrium with the liquid. The specific gravity of the liquid, which is also that of the grain, was then determined by standard pyknometry, or by the refractive index method of Jahns (1939).

VIII. PETROLOGY OF THE XENOLITHS.

In the following sections the petrography, modal compositions and chemistry of 42 peridotite and 24 eclogite xenoliths are dealt with in some detail. A summary of these findings and their significance is dealt with in the final section. Details pertaining to the constituent minerals are presented in Chapter IX.

1. Petrography.

A. PERIDOTITES.

Initially all specimens were examined macroscopically and particular note was made of colour, structure, nature and degree of weathering and any forms of alteration. These observations, together with brief petrographic notes, are incorporated in Table 2 (garnet peridotites) and Table 3 (spinel, altered and unusual peridotites). It was found that the peridotites could be conveniently grouped into:

a) garnet-bearing peridotite
b) spinel-bearing peridotite
c) highly altered peridotite plus several unusual types.

As the garnet and spinel peridotites are so similar in both mineralogical composition and appearance they can be described together. The highly altered and mineralogically unusual specimens are described separately. Although in hand specimen certain differences are apparent an examination of thin sections of both the garnet peridotites and spinel-bearing peridotites reveals their essential similarity. Consequently detailed petrographic descriptions of individual specimens would serve no useful purpose. A generalised description of all the peridotites is given below.

General description: The garnet and spinel peridotites are phanerocrystalline, medium- to coarse-grained rocks, normally showing a greyish to somewhat olive or yellowish green colour on fresh surfaces. When weathered the surface takes on an ochrous or khaki colouration, extending into the xenolith to a maximum depth of about 1 cm. Due to differential weathering of the constituent minerals

TABLE 2.

PETROGRAPHIC NOTES ON THE GARNET PERIDOTITE XENOLITHS.

NOTE: The maximum estimated size of the garnet grains, in millimetres, is indicated in brackets.

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
BF.1	Garnet lherzolite	3.07	Well-rounded xenolith, thin zone of superficial ochrous weathering. Fresh surfaces greenish grey.	Olivine appreciably serpentinised, slightly "granulated", shows uneven extinction. Orthopyroxene and chrome diopside show uneven extinction. Garnet (2 mm) well-rounded, fractured, thin kelyphitic rims. Phlogopite possibly primary.
BF.2	Garnet lherzolite	3.06	Superficial ochrous weathering, fresh surfaces yellowish green with prominent red garnet.	Olivine extensively "granulated", slightly serpentinised. Birefringent minerals all show uneven extinction. Garnet (5 mm) mainly rounded, some subhedral, all fractured, thin kelyphitic rims. Phlogopite (primary?), bent and distorted.
BF.3	Garnet lherzolite	3.01	Well-rounded xenolith, thin zone of superficial ochrous weathering. Fresh surfaces grey-green, slight gneissose appearance.	Olivine slightly "granulated", typically serpentinised. Birefringent minerals show uneven extinction. Garnet (2 mm) rounded, subhedral or elongated.
BF.4	Garnet harzburgite	3.06	Fresh appearance, only slight serpentinisation. Yellowish green on fresh surfaces. Garnet concentrated in patches.	Olivine very slightly "granulated", marked uneven extinction. Orthopyroxene bent, contains kink bands, inversion (?) lamellae. Garnet irregular aggregates, occasionally >10mm.
BF.5	Garnet lherzolite	2.99	Roughly rounded xenolith, fresh surfaces dark greyish green. Surface weathering extends about 5 mm into rock.	Olivine extensively serpentinised, appreciable "granulation". Birefringent minerals show uneven extinction. Garnet (3 mm) rounded, subhedral or elongated, thin kelyphitic rims.

TABLE 2 (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
BF.6	Garnet lherzolite	3.03	Xenolith smoothly rounded, thin zone of weathering. Fresh surfaces greyish green.	Olivine typically serpentinised, "granulation" absent. Garnet (3 mm) rounded or irregular, no kelyphitic borders.
BF.7	Garnet lherzolite	2.99	Xenolith of blocky shape, surface shows ochrous weathering, fresh surfaces grey-green.	Olivine appreciably serpentinised and fractured, slightly "granulated". Orthopyroxene contains kink bands. All birefringent minerals show uneven extinction. Garnet (2 mm) rounded, subhedral or irregular, often enclosed in orthopyroxene.
BF.8	Garnet harzburgite	3.00	Large, well-rounded xenolith, rough ochrous surface. Fresh surfaces greyish green with prominent reddish garnets.	Olivine serpentinised and fractured, "granulation" slight. Orthopyroxene bent, contain kink bands. All birefringent minerals have uneven optical extinction. Garnet (5 mm) fractured, rounded to subhedral, no kelyphitic margins, contain olivine inclusions.
BF.9	Garnet harzburgite	3.09	Large,well-rounded xenolith, rough weathered surface. Fresh surfaces grey-green. Garnet concentrated in patches, similar to BF.4.	Olivine slightly "granulated", fractured, uneven extinction. Orthopyroxene, occasional kink bands, uneven extinction. Garnet (6 mm) relatively large irregular grains Trace chrome spinel detected.
W.6	Garnet lherzolite	3.10	Thick zone of surface weathering. Fresh material dark grey-green.	Olivine, marked marginal "granulation", uneven optical extinction, serpentinised. Orthopyroxene bent, contain kink bands and inversion (?) lamellae. Garnet (3 mm) rounded, fractured thin micaceous kelyphite.

TABLE 2. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
W.7	Garnet lherzolite	2.99	Well-rounded xenolith, dark grey on fresh surfaces, contains abundant mica flakes.	Olivine not "granulated", shows slight uneven extinction, appreciable serpentinisation and secondary serpentine veinlets. Garnet (2 mm) irregular to rounded, thick micaceous kelyphitic rims. Phlogopite probably secondary.
W.8	Garnet lherzolite	2.98	Very roughly rounded, thick ochrous weathering zone. Dark grey-green on fresh surfaces.	Olivine, fractured and serpentinised, no "granulation", slight uneven extinction in olivine and orthopyroxene. Garnet (2 mm) irregular to rounded. Phlogopite possibly primary.
W.9	Garnet lherzolite	3.17	Slight surface weathering roughly pitted surface, fresh surfaces yellowish green, exceptionally coarse-grained.	Olivine "granulated", fractured, exhibits intragranular recrystallisation features, uneven extinction. Orthopyroxene shows uneven extinction. Garnet (8 mm) rounded, fractured, concentrated in certain areas, thick opaque kelyphitic margins.
W.10	Garnet harzburgite	3.02	Xenolith roughly rounded, fresh surfaces dark grey-green. Olivine blackish, contrasts with unaltered orthopyroxene. Slightly gneissose.	Olivine not "granulated", slight uneven extinction, extensively fractured and serpentinised. Fractures contains abundant dust-like iron oxide (?), hence blackish colour. Garnet (3mm) well-rounded, fractured, with micaceous kelyphite.
DT.6	Garnet harzburgite	3.01	Well-rounded, thin surface weathering, fresh surfaces greenish grey.	Olivine extensively fractured and "granulated", exhibits intragranular recrystallisation features, uneven extinction. Orthopyroxene, bent crystals, kinks bands and inversion (?) lamellae. Garnet (1 mm) rounded, thin micaceous kelyphitic rims. Trace idiomorphic chrome spinel detected.

TABLE 2. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
DT.7	Garnet lherzolite	3.08	Xenolith rounded, only slight surface weathering. Rock has fresh appearance.	Olivine fractured, only very slight "granulation" and intragranular recrystallisation, typical uneven extinction. Orthopyroxene, occasional kinks bands, slight uneven extinction. Garnet (2 mm) rounded to angular, thin opaque kelyphite, fractured.
DT.8	Garnet lherzolite	3.05	Roughly rounded, pitted surface, gneissose, orthopyroxene prominent. Fresh surfaces greyish black.	Olivine shows uneven extinction, extensively fractured, "granulated", exhibits intragranular recrystallisation. Fractures contain abundant dust-like iron oxide (?), hence blackish colour. Orthopyroxene, uneven extinction, bent, kinks, inversion (?) lamellae. Garnet (3 mm). rounded to irregular, fractured, virtually no kelyphitic margins.
DT.11	Garnet lherzolite	3.10	Roughly rounded, thin zone of surface weathering, fresh surfaces greyish green, occasional mica flakes.	Olivine fractured, slightly serpentinised, uneven extinction, no "granulation". Orthopyroxene, slight uneven extinction. Chrome diopside shows prominent parting. Garnets (5 mm) rounded to irregular, thin micaceous kelyphite. Some phlogopite possibly primary.
DT.14	Garnet lherzolite	3.04	Blocky, rounded outline, thin zone of weathered material, fresh surfaces greyish green.	Olivine, appreciably veined by serpentine, fractured, "granulated" and recrystallised in places, shows uneven extinction. Orthopyroxene slightly weathered, bent crystals, uneven extinction, shows kink bands. Garnet (3 mm) fractured, rimmed by thin opaque and micaceous kelyphite.

TABLE 2. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
DT.15	Garnet harzburgite	2.94	Ochrous, weathered surface, smoothly rounded. Fresh surfaces are greenish grey.	Olivine, uneven extinction, "granulation", intragranular recrystallisation, serpentine veining. Orthopyroxene, slight uneven extinction, intergrown with trace chrome diopside. Garnet (2 mm) rounded, fractured, thick opaque and micaceous kelyphite. Phlogopite probably secondary.
DT.18	Garnet harzburgite	3.04	Xenolith smoothly rounded, thin surface weathering zone, grey-green on fresh surfaces, fairly fine-grained in places.	Olivine extensively recrystallised, shown by "granulation" and intragranular recrystallisation, original olivine shows uneven extinction. Orthopyroxene bent, contains deformation kink bands, inversion (?) lamellae, shows uneven extinction. Garnet (2 mm) irregular or rounded, extensive marginal alteration. Abundant secondary phlogopite.
DT.20	Garnet harzburgite	3.05	Very similar to DT.15. Thin ochrous surface, well-rounded xenolith. Fresh surfaces greenish grey.	Olivine shows slight "granulation", uneven extinction, intragranular recrystallisation, fractures. Orthopyroxene has uneven extinction, kink bands, possible inversion (?) lamellae, associated with trace chrome diopside. Garnets (2 mm). irregular, fractured, thick opaque and micaceous kelyphite. Phlogopite appears secondary.
RV.16	Garnet lherzolite	3.08	Well-rounded, rough pitted surface. Weathering up to 10 mm into the xenolith. Fresh rock is dark greenish grey.	Olivine fractured, slightly serpentinised and "granulated", shows uneven extinction and deformation structures. Orthopyroxene shows uneven extinction, kink bands, possible inversion lamellae. Garnet (2 mm) roundish to angular, fractured, thick opaque kelyphitic rims.

TABLE 2. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.25	Garnet lherzolite	3.06	Well-rounded xenolith, fresh surfaces yellowish green.	Olivine appreciably "granulated", fractured and serpentinised, shows uneven extinction, occasional intragranular recrystallisation. Orthopyroxene shows bent crystals, uneven extinction, kink bands. Garnet (2 mm) roundish or angular, fractured, thick opaque kelyphitic rims.

TABLE 3.

PETROGRAPHIC NOTES ON THE SPINEL AND ALTERED PERIDOTITE XENOLITHS.

* Altered or unusual xenoliths which have not been represented diagramatically nor used in the estimations of "average" compositions.

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
BF.10	Spinel harzburgite	3.10	Roughly rounded, fresh appearance. Orthopyroxene yellowish green.	Olivine slightly serpentinised, fractured, kink bands, uneven extinction, no "granulation". Orthopyroxene uneven extinction, shows occasional lamellar structure. Spinel-pyroxene symplectite.
W.1	Spinel lherzolite	3.08	Fresh material of slightly altered appearance, pale grey-green. Prominent mica flakes.	Olivine highly fractured, slightly "granulated", contains intragranular recrystallisation, shows uneven extinction. Orthopyroxene partly altered, fractured, shows uneven extinction. Serpentine veinlets abundant. Phlogopite possibly primary. Spinel small, subhedral, opaque grains.
W.3	Spinel lherzolite	2.96	Well-rounded xenolith, fresh surfaces dark greenish grey, of altered appearance.	Olivine extensively fractured, faint deformation lamellae, uneven extinction. Orthopyroxene, incipient alteration, uneven extinction. Spinel subhedral, opaque grains. Phlogopite shows uneven extinction, possibly primary.
W.4	Spinel harzburgite	2.97	Xenolith well-rounded, thin ochrous alteration on surface. Fresh surfaces appear slightly altered. Prominent orthopyroxene parting, yellowish green.	Olivine, uneven extinction, kink bands, deformation lamellae, typically serpentinised. Orthopyroxene shows lamellar structure, very uneven extinction. Spinel-pyroxene symplectite.

TABLE 3. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
W.5	Spinel harzburgite	2.98	Xenolith roughly rounded, fresh surfaces dark grey-black with prominent altered orthopyroxene.	Olivine extensively fractured, dust-like alteration on fractures, slight uneven extinction. Orthopyroxene altered to semi-opaque material, lamellar structure visible, rimmed by phlogopite. Spinel-phlogopite symplectite.
DT.2	Altered lherzolite*	2.90	Well-rounded, smooth xenolith, altered appearance, dark grey on fresh surfaces.	Olivine extensively fractured, "granulated", shows intragranular recrystallisation, uneven extinction, deformation lamallae. Abundant secondary serpentine, calcite and phlogopite. Orthopyroxene fractured, partly replaced, intergrown with chrome diopside. Rock approaches pyroxenite in composition.
DT.3	Altered harzburgite *	2.85	Rounded xenolith, rough pitted surface. Thick zone of surface weathering.	Olivine extensively serpentinised, fractured, shows abundant intragranular and intergranular recrystallisation. Orthopyroxene altered to talcose and chloritic material, shows uneven extinction.
DT.4	Spinel lherzolite	2.81	Well-rounded xenolith, thick weathered zone. On fresh surfaces greenish grey and altered appearance.	Olivine extensively fractured and serpentinised, no signs of tectonic deformation. Orthopyroxene appreciably altered to talc and chlorite. Spinel as rounded or euhedral grains, maximum size 2 mm.
DT.9	Altered spinel wehrlite*	2.97	Well-rounded rough xenolith, dark grey, appreciably altered. Abundant chrome diopside.	Olivine typically fractured and partly serpentinised, shows no deformation structures. Abundant serpentine veining and secondary phlogopite. Chrome spinel associated with pale green chrome diopside, often partly altered. Occasional minute garnet grains detected.

TABLE 3. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
DT.10	Recrystallised peridotite*	3.07	Smoothly rounded xenolith, blackish fresh surfaces, texture unlike the normal peridotites.	Completely recrystallised to a fine-grained, granular mosaic of olivine with interstitial serpentine, iron oxide and phlogopite. Relicts of original olivine present.
DT.13	Spinel lherzolite	2.97	Smooth well-rounded xenolith, thin zone of surface weathering. Fresh surfaces greenish grey, contains scattered mica flakes.	Olivine slightly "granulated", extensively fractured, shows kink bands, deformation lamellae, intragranular recrystallisation. Orthopyroxene slightly altered, shows kink bands, uneven extinction and possible clinoenstatite inversion lamellae. Phlogopite probably secondary. Chrome spinel, small rounded grains.
DT.16	Recrystallised peridotite*	3.00	Well-rounded, pitted xenolith, extensively weathered, thick zone of ochrous material. Fresh surfaces are very fine-grained, blackish.	Olivine has been almost completely recrystallised to a fine-grained, granular mosaic, with interstitial serpentine and phlogopite. Remnants of the original olivine are scattered through the rock.
DT.21	Altered lherzolite*	2.85	Ochrous, pitted surface. Unweathered material is dark green-grey, appears altered.	Olivine extensively serpentinised and fractured, very slight uneven extinction. Abundant secondary serpentine, phlogopite, minor calcite. Orthopyroxene altered to talcose material. Trace of spinel, opaque grains.
RV.12	Spinel harzburgite	2.99	Well-rounded, smooth surface, thin ochrous weathered material. Fresh rock, greenish grey.	Olivine fractured, slightly serpentinised, shows kink bands and occasional intragranular recrystallisation features. Orthopyroxene shows occasional kink bands and slight lamellar structure. Phlogopite (in places enclosed by olivine) possibly primary. Spinel occurs as euhedral, opaque grains.

TABLE 3. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.14	Spinel lherzolite	3.02	Typical well-rounded xenolith, thin ochrous surface alteration zone. Fresh material is greenish grey	Olivine slightly "granulated", contains intragranular recrystallisation, shows uneven extinction, deformation lamellae. Orthopyroxene, bent crystals, uneven extinction. Phlogopite (in places enclosed by olivine) possibly primary. Spinel, small euhedral to rounded, opaque grains.
RV.15	Phlogopite-spinel lherzolite*	3.07	Blocky, roughly rounded xenolith, very little surface weathering. Fresh surfaces are greenish grey with abundant mica flakes.	Olivine fractured, very slightly serpentinised. Orthopyroxene slightly altered, shows lamellar structure, associated with with clinopyroxene. Abundant phlogopite, often as inclusions in olivine, possibly primary. Spinel, small subhedral grains, often occur in mica.
RV.17	Spinel lherzolite	3.03	Rough, rounded surface, very little weathering. Fresh rock in yellowish green with green orthopyroxene.	Olivine typical fractured, partly serpentinised, faint kink bands. Orthopyroxene slightly altered to talcose material, shows uneven extinction, lamellar structure. Thin serpentine-phlogopite veinlets. Spinel-pyroxene symplectite.
RV.19	Spinel harzburgite	2.97	Typical well-rounded xenolith, thin ochrous surface weathering. Fresh surfaces green-grey with occasional mica flakes.	Olivine extensively fractured, slightly serpentinised, shows occasional kink bands, uneven extinction. Orthopyroxene very slightly altered, shows faint lamellar structure. Phlogopite laths occur within olivine grains, possibly primary. Spinel opaque, subhedral.

and also possibly attrition or corrosion within the kimberlite at the time of intrusion, the harder or more resistant minerals, such as orthopyroxene and garnet, stand up in relief on the rounded surfaces of any of the xenoliths, the olivine grains forming finely honeycombed pits.

Individual xenoliths vary considerably in shape but are generally of a well-rounded, ellipsoidal outline, often showing a tendency to be slightly flattened or elongated along one direction, suggesting a gneissose structure within the xenoliths. It is interesting to note that accidental xenoliths of Karroo dolerite, also incorporated in the same kimberlites of the Kimberley district, are well-rounded and of spheroidal outline, presumably due to the random orientation of the constituents. Recent research on the petrofabrics of lherzolite, pyroxenite and eclogite inclusions from kimberlite pipes in Utah and Arizona (Helmstaedt and Anderson, 1969) suggest that the tectonic deformation of these rocks took place in a crustal environment prior to incorporation in the kimberlite.

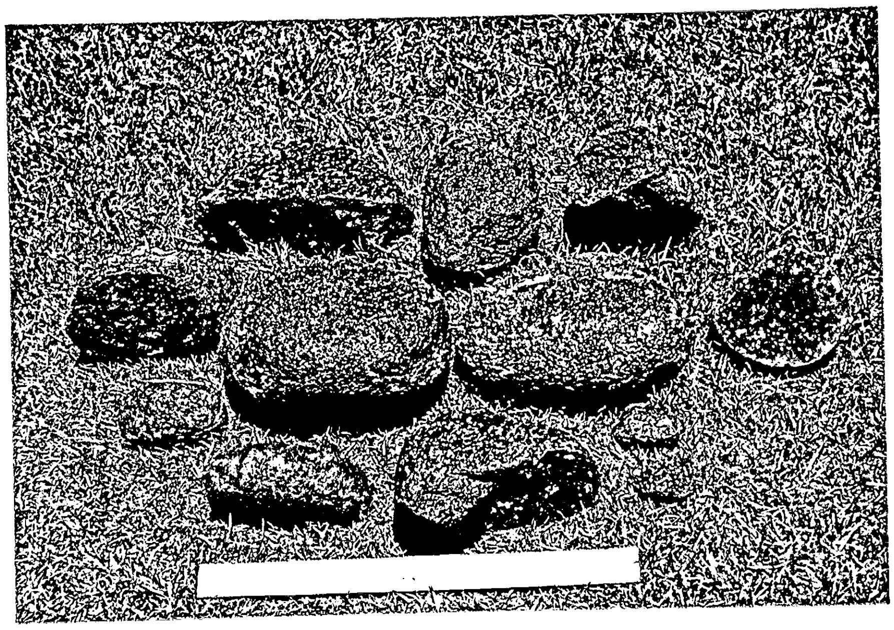


Plate 4. Typical xenoliths from kimberlite. Note particularly the variation in size and the smooth, well-rounded surfaces. The scale is 45 cm in length.

Considerable differences in size exist, ranging from specimens with a longest diameter of approximately 30 cm to those with a longest diameter of 15 cm. A selection of both peridotite and eclogite xenoliths, illustrated in Plate 4, clearly shows their variable shape and size.

The fabric of the peridotites is essentially equigranular allotriomorphic but modified on occasions by a tendency towards a seriate texture. Usually the rocks are of a striking appearance and contrast with most other varieties of igneous and metamorphic rocks. Perhaps the most noticeable features are the rounded grains of dark reddish garnet which are scattered throughout the garnet-bearing variety and the minor amount of vivid green chrome diopside found in most xenoliths. The textures of several typical garnet peridotite xenoliths is illustrated in Plates 5 to 9. These photomicrographs clearly show the allotriomorphic textures and the relationships between the constituent minerals. The spinel-bearing peridotites are not illustrated, but, except for the absence of garnet, are virtually identical with the garnetiferous variety.

Thin-section studies have shown that the peridotites are essentially compact mosaics of interlocking olivine and orthopyroxene grains and can be regarded as harzburgites. In most xenoliths a small amount of clinopyroxene (chrome diopside), varying from several per cent to only a trace, is present, which gives the specimens a distinct lherzolitic character. O'Hara (personal communication) suggests that the presence of chrome diopside, even in minute amounts, is indicative that the assemblage belongs within the lherzolite stability field and hence all specimens which contain even a trace of clinopyroxene should correctly be termed lherzolites. However, as the chrome diopside is often only a very minor and widely dispersed constituent the identification of such peridotites with true lherzolites is often impractical. Although the xenoliths are identified as such in Tables 2 and 3 for the rest of the study they will be simply regarded as peridotites.

In addition to the chrome diopside other accessory minerals include roundish grains of red garnet (usually surrounded by thin kelyphitic borders), chrome spinel (often intergrown in a vermicular or symplectic manner with diopside), flakes of phlogopite and occasional traces of sulphides and

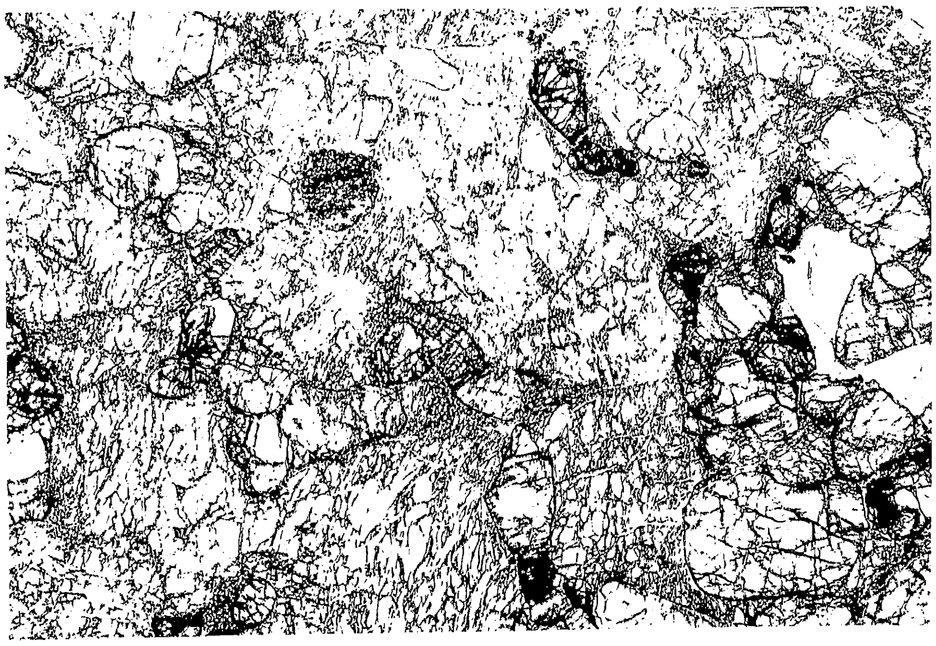
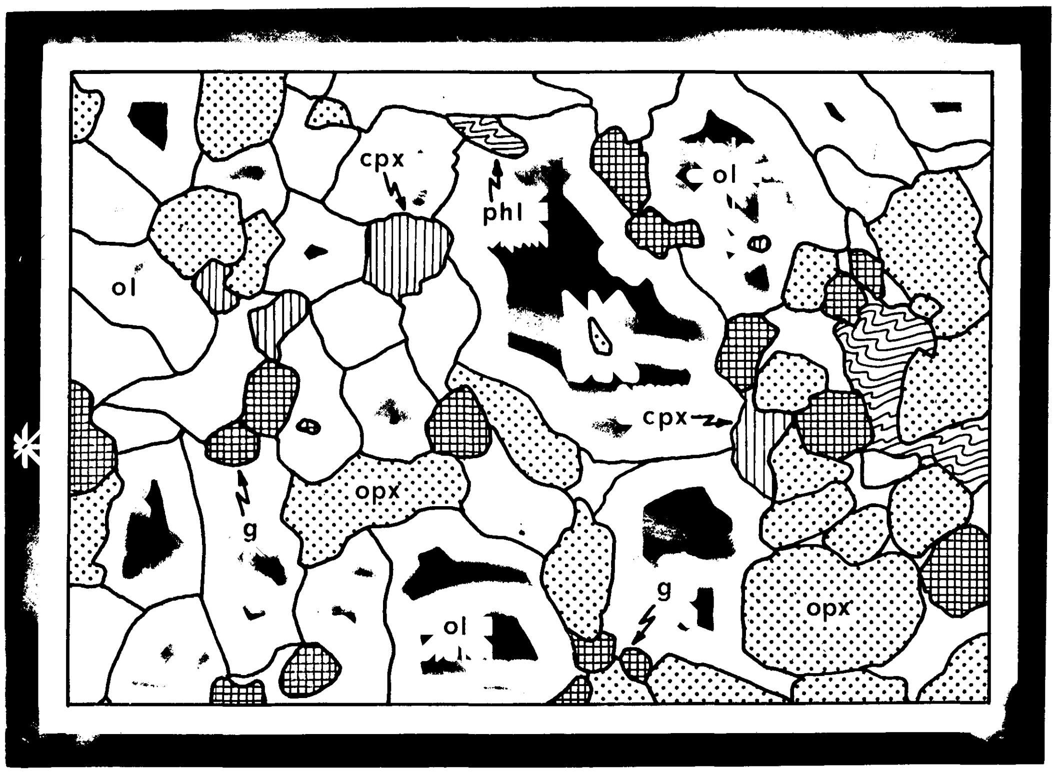


Plate 5. Garnet peridotite BF.1. Notice the somewhat rounded orthopyroxene and the patches of phlogopite. The olivine is extensively veined by serpentine. Magnification X5, ordinary light.



Key to Plate 5. olivine (ol), orthopyroxene (opx), garnet (g), chrome diopside (cpx), phlogopite (phl).

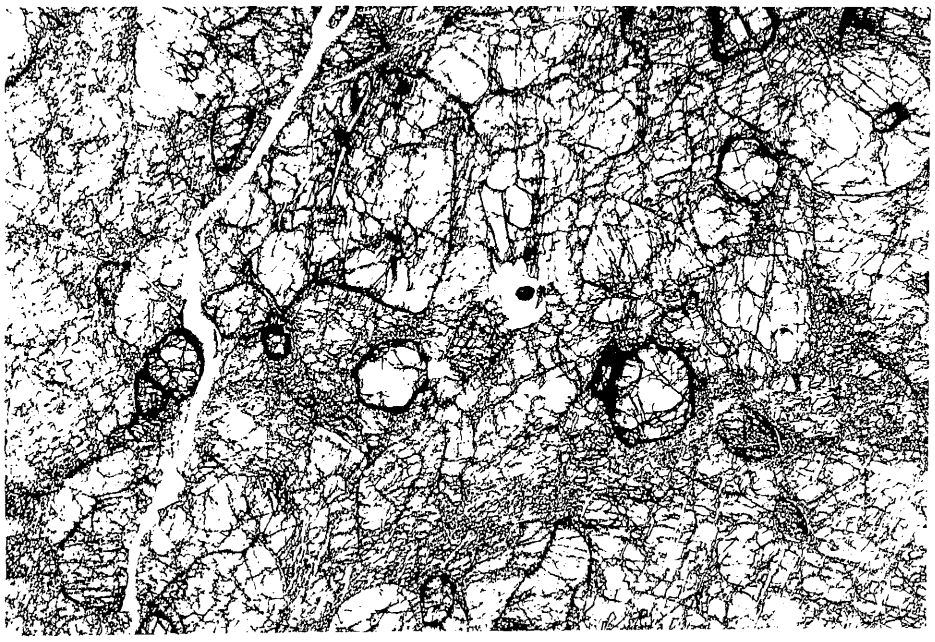
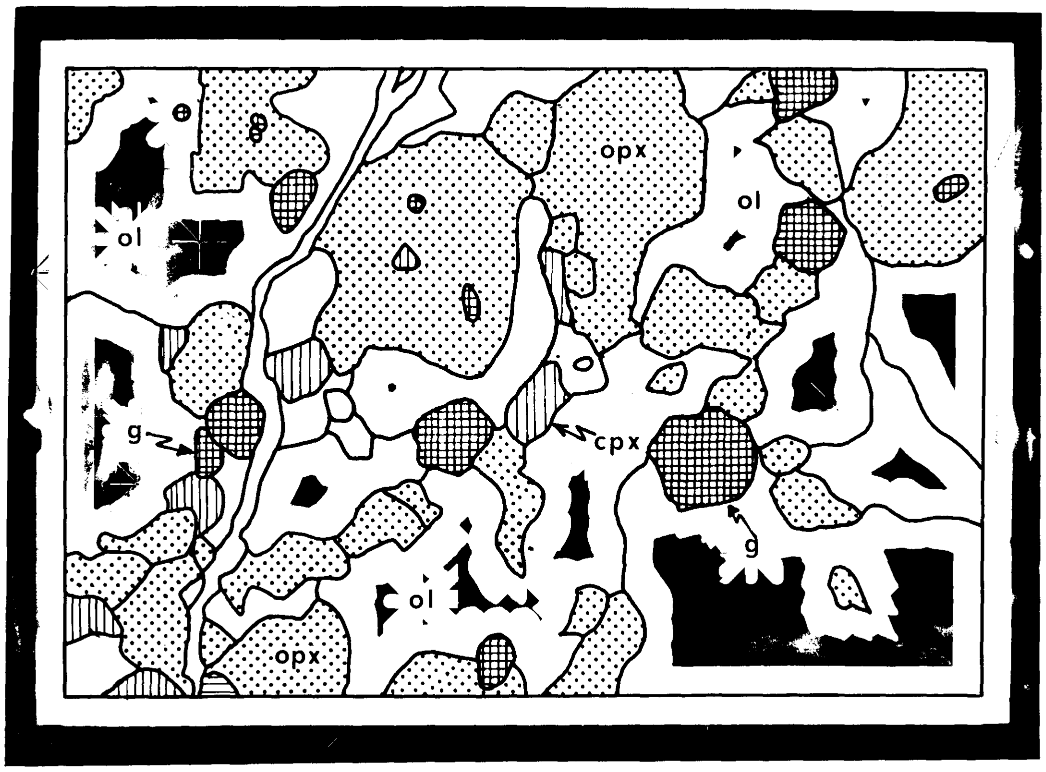


Plate 6. Garnet peridotite BF.3. A small amount of chrome diopside can be seen. Notice also the small garnet inclusions in the orthopyroxene.
Magnification X5, ordinary light.



Key to Plate 6. olivine (ol), orthopyroxene (opx), garnet (g), chrome diopside (cpx).

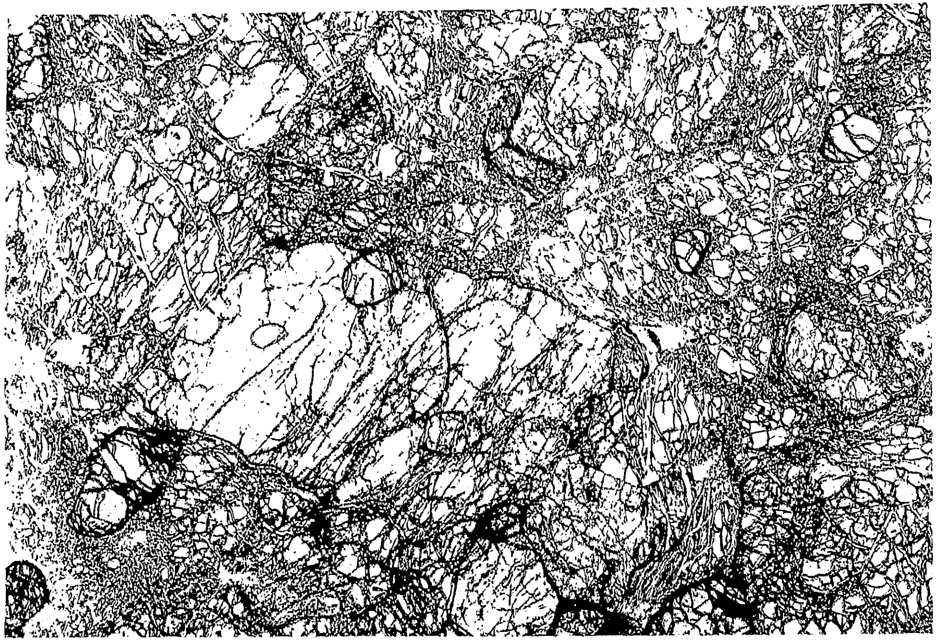
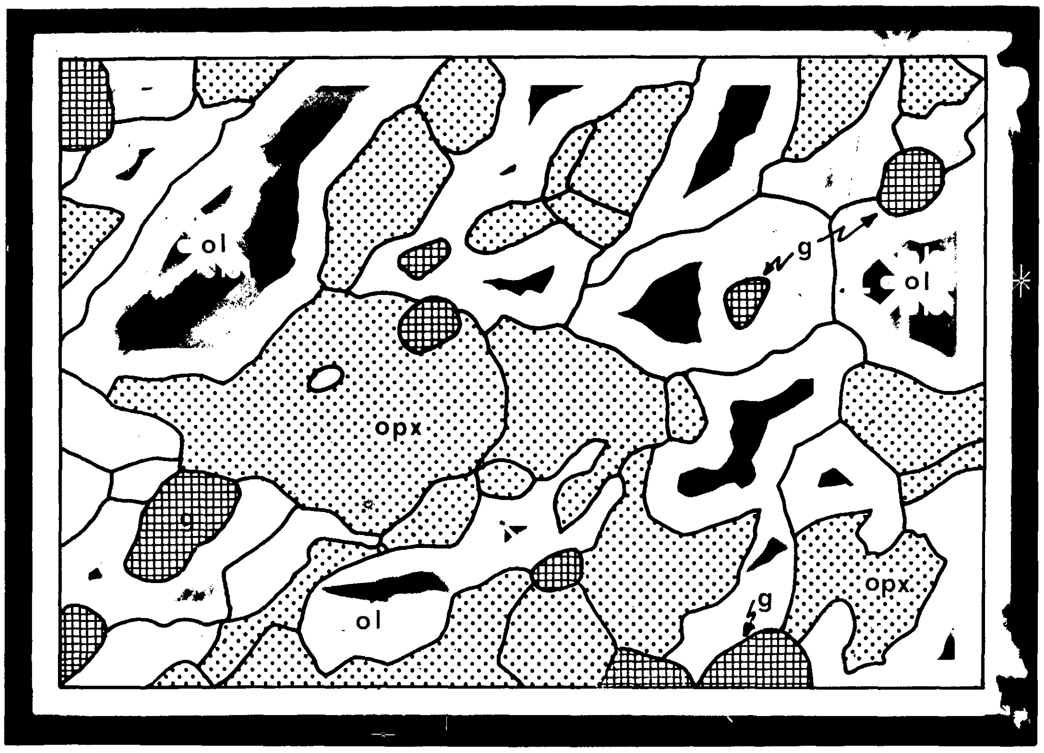


Plate 7. Garnet peridotite BF.5. The serpentinisation and granulation of the olivine is well shown while the orthopyroxene remains unaffected.
Magnification X5, ordinary light.



Key to Plate 7. olivine (ol), orthopyroxene (opx), garnet (g).

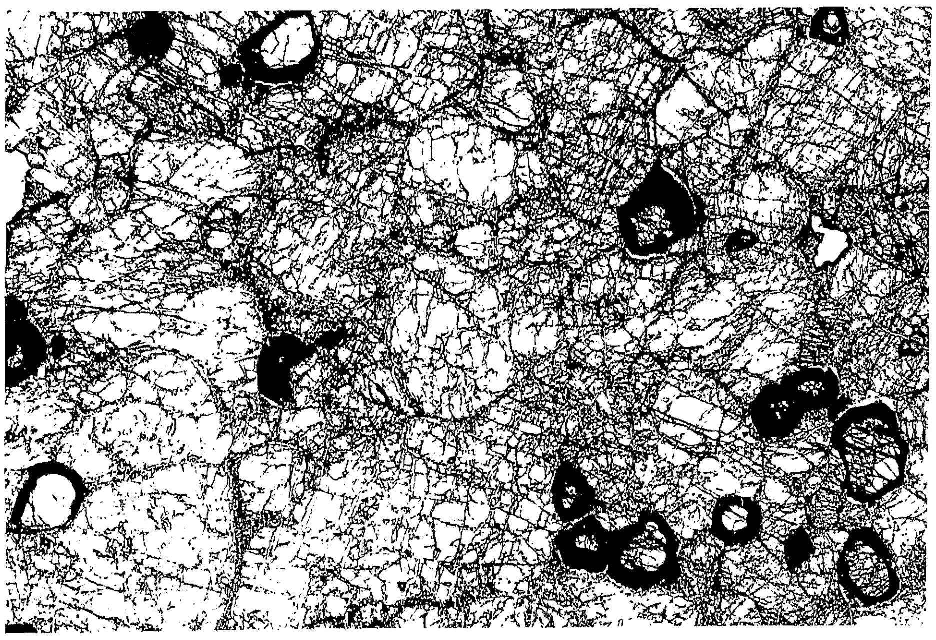
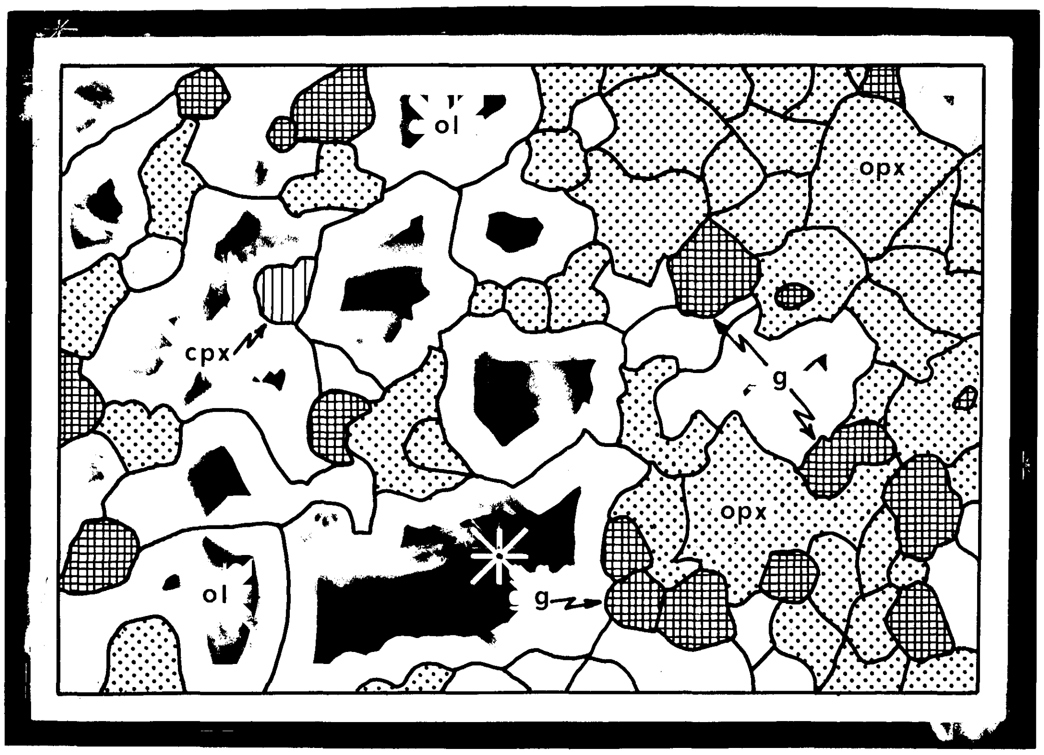


Plate 8. Garnet peridotite RV.16. The garnets in this rock are surrounded by a thick kelyphitic rim (black). Magnification X5, ordinary light.



Key to Plate 8. olivine (ol), orthopyroxene (opx), garnet (g), chrome diopside (cpx).

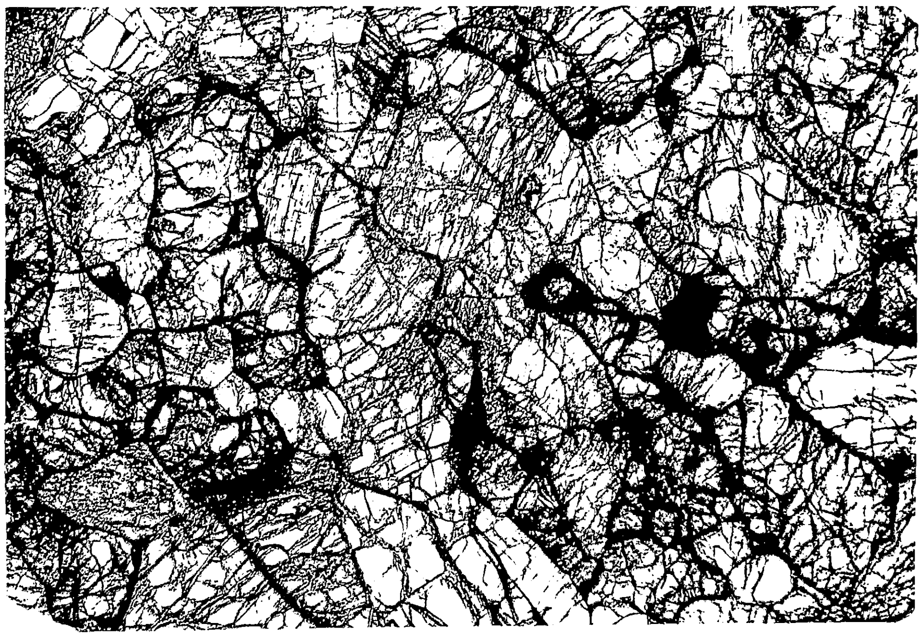
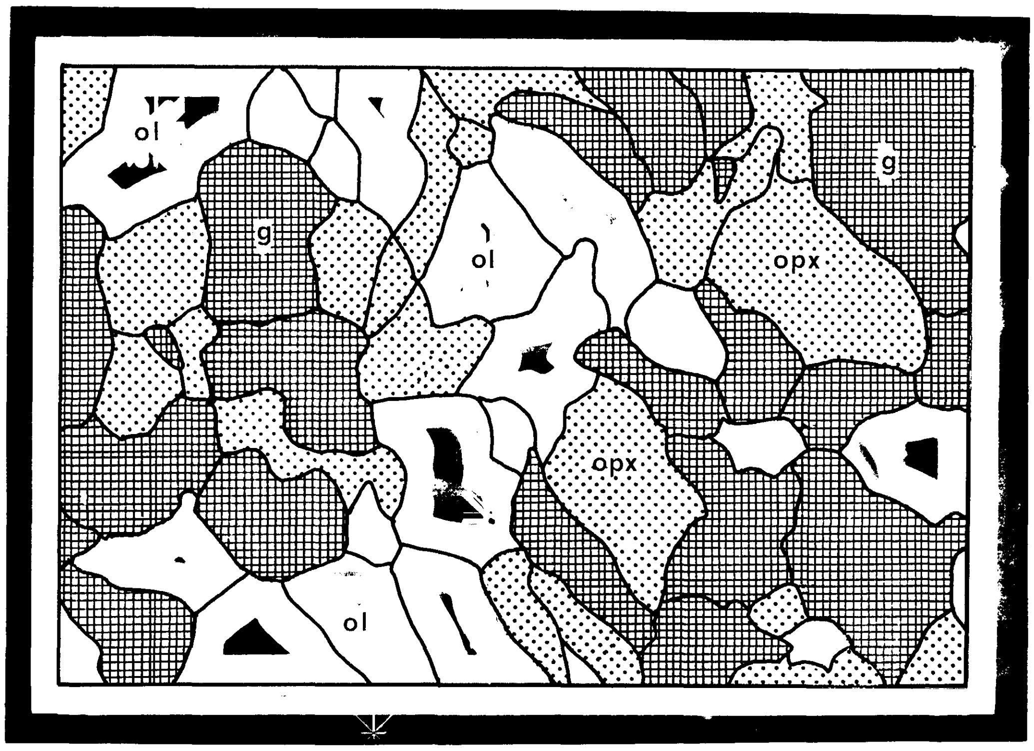


Plate 9. Garnet peridotite BF.4, showing an area unusually rich in irregular garnet.
Magnification X8, ordinary light.



Key to Plate 9. olivine (ol), orthopyroxene (opx), garnet (g).

graphite. One specimen contains a very small amount of ilmenite. Thin, secondary carbonate and serpentine veins are not uncommon. Compared with the garnet in the garnet peridotites the spinel in the spinel peridotites constitutes a much smaller amount (see Modal Analyses). Individual minerals are described more fully in Chapter IX.

Many of the peridotite xenoliths show microscopic features typical of stress and tectonic deformation, such as uneven extinction of the constituent minerals between crossed nicols, the development of bent crystals, kink bands, possible inversion products and recrystallisation. These features are also dealt with in much greater detail in Chapter IX.

The state of preservation of each rock varies from specimen to specimen but all have undergone an appreciable period of serpentinisation and carbonatisation during the intrusion of the kimberlite. Other alteration features include the formation of zeolites and phlogopite.

The highly altered peridotite xenoliths, several of which are extensively "granulated" and approach a dunite in composition, are similar in shape and size to the xenoliths of garnet- and spinel-bearing types. Unusual peridotites include two containing exceptionally large amounts of clinopyroxene (DT.2, DT.9) and one which contains abundant mica (RV.15). Typical textural features of the highly "granulated" types are illustrated in Plates 10 and 11. Mineralogic data from altered and unusual types have not been used in the calculations of the "average" compositions, nor included in the diagrams.

All altered and unusual xenoliths (except one, RV.15) originate from the Dutoitspan Mine, a feature which may be of some significance. The "granulated" xenoliths are fine-grained, in contrast with the much coarser-grained normal types, and contain neither spinel nor garnet. Of the remaining xenoliths spinel is found in only two rocks, one of which also contains a trace of garnet. In the "granulated" xenoliths only relicts of the original olivine are present; orthopyroxene, where evident, is highly altered and phlogopite is a common constituent. Indications are that the so-called "granulation" is not essentially a physical disintergration of the rock under stress but rather a recrystallisation of the olivine under conditions of high temperature and stress. This could not have taken place within the kimberlite

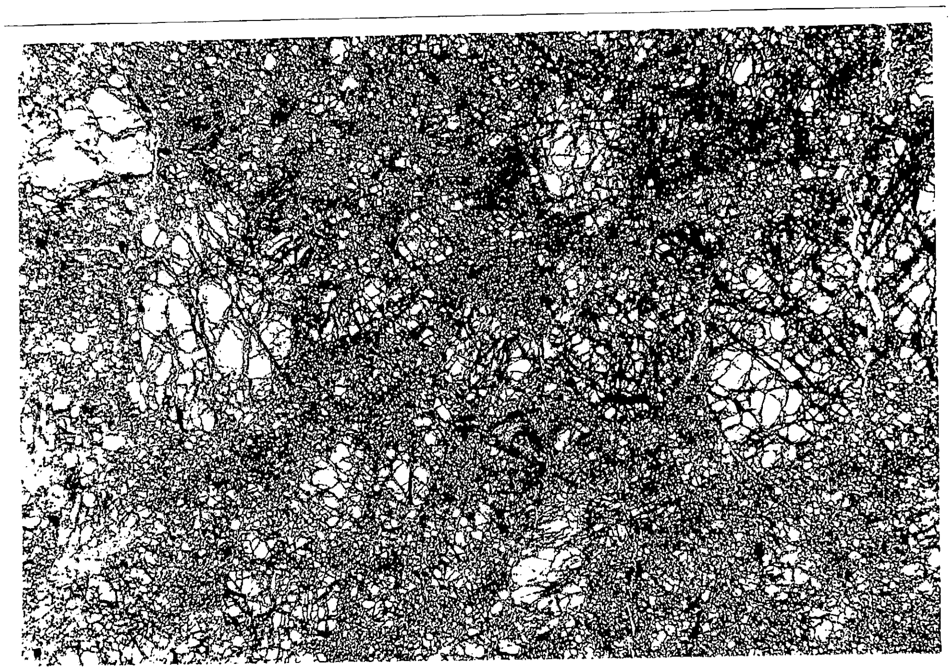


PLATE 10 . Altered peridotite DT.16, highly "granulated" and partly serpentinised. Only relicts of the original olivine are present.
Magnification X 6.5, ordinary light.

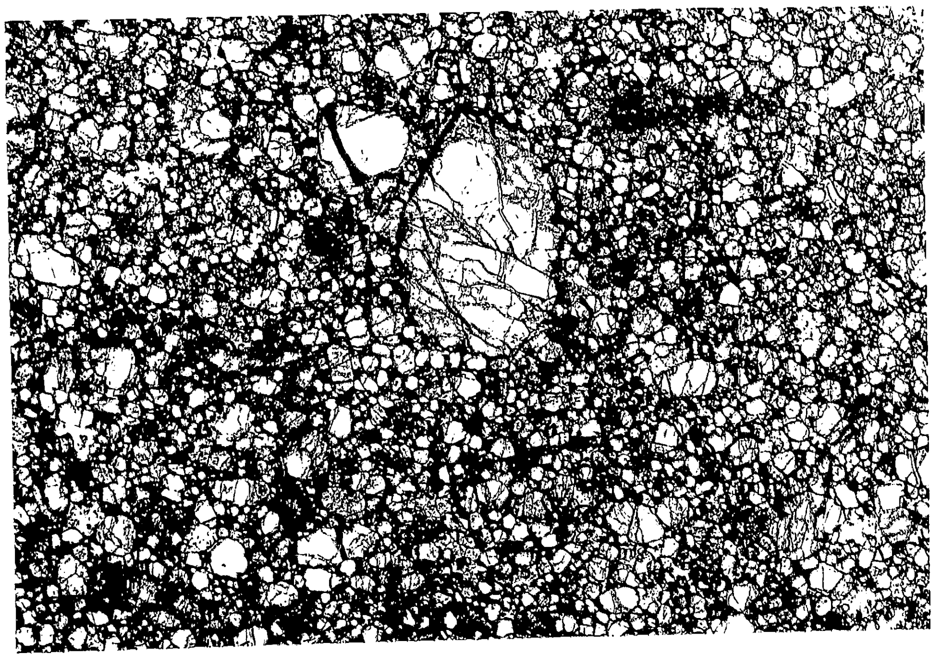


PLATE 11 . Altered peridotite DT.10, very similar to DT.16 above. A relict of the original olivine is visible. The intergranular serpentine is almost opaque, being highly charged with dust-like iron oxide.
Magnification X 6.5, ordinary light.

and must represent tectonic recrystallisation at depth (see also Olivine and Orthopyroxene, Chapter IX). Serpentinisation and phlogopitisation would have taken place during the intrusion of the kimberlite.

B. ECLOGITES.

As in the case of the peridotites all eclogite specimens were initially examined macroscopically and notes made of their structure, colour and forms of alteration. These observations are incorporated in Table 4. This superficial examination clearly showed that the eclogite suite consisted of several distinct types which differed from each other by:

a) slight changes in the colour of the constituent minerals, particularly the garnet, and

b) distinctive mineral additions to the basic garnet-clinopyroxene composition, as witnessed by the presence of kyanite, corundum, rutile or diamond.

The distinct differences recorded by MacGregor and Carter (1969), who recognised two groups of eclogite xenoliths from the Roberts Victor Mine on textural considerations, could not be clearly seen by the writer. Their first group consists of large, subhedral to rounded garnets in a matrix of anhedral to interstitial clinopyroxene and their second group of anhedral, irregular garnet and clinopyroxene with a tightly interlocking fabric. Support of this simple two-fold textural grouping of the eclogite xenoliths was not forthcoming from a careful study by the present writer of all specimens available.

Even though there are distinct differences in the structure of a number of the eclogite xenoliths, many for example exhibiting a rudimentary layering, their texture shows no consistent variation. Consequently, only a general description of the xenoliths is given here, while more detailed petrographic notes, summarising the major differences and noting features of interest, are presented in Table 4.

The eclogite xenoliths are well-rounded and generally ellipsoidal or ovate in outline. Several typical xenoliths are illustrated in Plate 4. Compared with the peridotite xenoliths they often show a considerably greater flattening in one direction, with the result that some xenoliths are almost

TABLE 4.

PETROGRAPHIC NOTES ON THE ECLOGITE XENOLITHS.

NOTE: The maximum estimated size of the garnet grains and the colour of both the garnet and clinopyroxene is indicated in brackets

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.1	Eclogite	3.41	Garnet unevenly distributed, occurs in bands and patches.	Garnet (pale pinkish orange, 5 mm) turbid, irregular, anhedral grains with abundant fractures and occasional faint anisotropism. Thin micaceous kelyphitic rims. Clinopyroxene (pale blue-green) generally interstitial to garnet, highly altered to ultrafine semi-opaque aggregates, only relicts of original material remain.
RV.2	Eclogite	3.30	Garnet fairly evenly distributed, grains tend to cluster in places.	Garnet (reddish orange, 7 mm) angular to rounded, fractured, contain minute oriented anisotropic spindles (unidentified), altered in places. Thin micaceous kelyphite. Clinopyroxene (dark green) appears interstitial, fine alteration on partings.
RV.3	Eclogite	3.38	Xenolith has rudely banded appearance, similar to RV.1. Garnet unevenly distributed, grains vary in size.	Garnet (pale pinkish orange, 5 mm) turbid, irregular to rounded, completely anhedral, abundant sub-parallel fractures, slight alteration, very faint anisotropism. Clinopyroxene (pale green) extensively altered to ultrafine semi-opaque material, relicts of original pyroxene. Kelyphitic material contains minute feldspar laths.
RV.4	Diamond eclogite	3.18	Xenolith roughly discoidal, very rough surface, diamonds visible, gneissose appearance.	Garnet (pale orange, 4 mm) elongated, subhedral to anhedral, sub-parallel fractures, turbid in places. Clinopyroxene (pale green) extensively altered to fine-grained, semi-opaque aggregates concentrated along fractures and partings. Rutile and diamond are accessories. Kelyphite contains feldspar microlites. Secondary quartz.

TABLE 4. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.5	Eclogite	3.54	Discoidal, well-polished xenolith, garnet concentrated in places, similar to RV.1.	Garnet (pale orange, 6 mm) rounded to angular, anhedral, turbid, subparallel fractures, in places very faintly anisotropic, contain clinopyroxene inclusions. Clinopyroxene (pale green) distinctly interstitial, partly altered to whitish semi-opaque aggregates, especially on cracks.
RV.6	Kyanite-corundum eclogite	3.09	Xenolith rounded, rough surface, banded. Two distinct types of eclogite evident in hand specimen, one containing kyanite predominates	Garnet (orange, 5 mm) irregular, anhedral, subparallel fractures, kyanite-corundum inclusions, turbid in places. Clinopyroxene mainly altered to very fine-grained semi-opaque material. Kyanite occurs as rounded or irregular grains, contains mauve corundum. Glassy material, with feldspar crystallites, occurs within the altered clinopyroxene. Trace of rutile present.
RV.7	Eclogite	3.43	Garnet irregularly distributed, very similar to RV.1, occurs in segregated areas.	Garnet (pale pinkish orange) fractured, turbid, anhedral grains, rounded to irregular. Clinopyroxene (bluish green) highly altered to ultrafine-grained, opaque aggregates. Glassy material occurs as thin veins, (associated with kelyphite), contains feldspar laths, amphibole, spinel, mica. Pyroxene distinctly interstitial.
RV.8	Eclogite	3.35	Rough, uneven surface, slightly weathered, garnet fairly evenly distributed through the rock.	Garnet (reddish orange, 6 mm) anhedral, roundish, slightly fractured, incipient alteration visible, faint anisotropism in places. Clinopyroxene (dark green), interstitial to garnet, contains small garnet inclusions, partly altered to ultrafine-grained aggregates. Kelphitic margins very micaceous, traces of glassy material in places.

TABLE 4. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.9	Eclogite	3.25	Exceptionally rich in garnet, pyroxene extensively altered.	Garnet (pale pinkish orange, 5 mm) anhedral, roundish to irregular, abundant subparallel fractures, turbid in places. Clinopyroxene highly altered to ultrafine-grained semi-opaque aggregates, in places shows signs of melting and formation of feldspar laths. Kelyphitic material borders some garnets.
RV.10	Eclogite	3.26	Garnet and pyroxene evenly distributed, no banding evident.	Garnet (brownish red, 6 mm) angular, subhedral to anhedral grains, subparallel fractures, turbid alteration in places, contain minute birefringent oriented spindles. Clinopyroxene (green) not typically interstitial, slightly altered, shows distinct twinning on (100) parting. Micaceous kelyphite.
RV.18	Altered eclogite	3.03	Well-rounded xenolith, not banded, abundant micaceous material, garnet evenly distributed through rock.	Garnet (pale pink, 5 mm) rounded to elongated fractured, extensively altered, anhedral, in places only relicts remain. Clinopyroxene largely replaced by dark mica , fine-grained relicts of earlier material remain. Other secondary minerals include pale green amphibole and occasional feldspar laths.
RV.20	Eclogite	3.22	Well-rounded, discoidal xenolith, slightly finer-grained than most xenoliths. Similar to RV.10.	Garnet (brownish pink, 3 mm) angular and elongated, fractured, subhedral to anhedral, evenly distributed. Rimmed by opaque and micaceous kelyphite. Clinopyroxene (pale green) not interstitial, abundant subparallel fractures. Mica probably secondary.

TABLE 4. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.26	Eclogite	3.31	Xenolith elongated, angular. Finer-grained than most xenoliths. Similar to RV.2, RV.8.	Garnet (reddish orange, 3 mm) roundish to irregular anhedral grains, slightly fractured, turbid in places, very faintly anisotropic. Thin kelyphitic borders. Clinopyroxene (dark green) appreciably altered, especially along fractures and partings, to very fine-grained semi-opaque materials. Occasional small garnet inclusion in pyroxene.
RV.27	Contact:eclogite-kyanite eclogite	n.d.	Roughly rounded xenolith, two distinct types clearly visible, sharp contact (see Plate 13).	(a) Eclogite: Garnet (brownish orange, 5 mm) roundish or irregular, anhedral, turbid, extensively fractured. Clinopyroxene (dark green) partly altered to typical fine-grained products, appears interstitial. (b) Kyanite eclotite: Garnet (orange, 4 mm) roundish to elongated, anhedral or vaguely subhedral, turbid, fractured. Clinopyroxene completely altered to opaque very fine-grained material, glassy in places, shows feldspar crystallites. Kyanite (blue) rounded to irregular grains included in both garnet and pyroxene.
RV.29	Altered eclogite	3.02	Well-rounded xenolith, extensively replaced by mica. Similar to RV.18.	Garnet (pinkish orange, 5 mm) rounded to irregular, anhedral, surrounded by extensive dark mica (secondary). Clinopyroxene (dark green) highly altered, relicts of original material remain. Mica, reddish brown, probably biotite.

n.d. = not determined.

TABLE 4. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.30	Eclogite	3.41	Large, discoidal xenolith. Garnet and clinopyroxene evenly distributed, clustered in groups of several grains. Rock has a fresh appearance, similar to RV.2, RV.8, RV.26.	Garnet (reddish orange, 5 mm) rounded to irregular, anhedral, slightly fractured, turbid, thin kelyphite, faintly anisotropic in places. Clinopyroxene (dark green) extensively altered to opaque materials, occasionally contain small, rounded garnet inclusions.
RV.31	Eclogite	3.32	Xenolith distinctly banded into two eclogite types, very rough surface (one type occurs only in minor amount).	Garnet (pale orange, 5 mm) rounded to irregular, fractured anhedral, thin rims of kelyphitic material. Clinopyroxene (pale green) interstitial, almost completely altered to very fine-grained, whitish, semi-opaque material. Glassy material and feldspar microlites in places. Secondary quartz.
RV.32	Eclogite	3.43	Well-rounded, flattend, rough surface, gneissose structure.	Garnet (reddish orange, 6 mm) angular, elongated, often subhedral, contain oriented spindles (unidentified), subparallel fractures, slightly turbid. Clinopyroxene (very dark green) not typically interstitial, partly altered to very fine-grained materials, especially on fractures and partings, contains rutile (?) inclusions. Slight melting in places.
RV.33	Eclogite	3.39	Extremely rough surface, xenolith vaguely rounded, surface material weathered.	Garnet (pale orange, 5 mm) roundish to irregular, anhedral, subparallel fractures, slight anomalous extinction, thin micaceous kelyphitic rims contains occasional feldspar laths. Clinopyroxene (green) extensively altered in typical fashion. Secondary quartz occurs in minor amounts, glassy material in places.

TABLE 4. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RV.34	Kyanite eclogite	3.15	Typical kyanite-bearing specimen. (See Plate 21). Slightly weathered surface.	Garnet (reddish orange, 4 mm) rounded to subhedral, slightly fractured, turbid in places. Clinopyroxene completely opaque, very fine-grained greyish aggregate, traces of original pyroxene (pale green) visible, melting has occurred in places. Kyanite (blue) generally rounded or subhedral.
RVL.2	Eclogite	3.27	Smoothly rounded, weathered surface. Garnet evenly distributed.	Garnet (pinkish orange, 5 mm) irregular to rounded, occasionally subhedral, slightly fractured, turbid in places. Clinopyroxene (dark green) extensively altered, particularly along fractures. Veinlets of glassy material (with feldspar and amphibole) associated with kelyphitic material.
RVL.5	Eclogite	3.44	Well-polished surface, thin surface alteration, garnet evenly distributed.	Garnet (reddish orange, 5 mm) slightly anisotropic, roundish, anhedral to subhedral, slightly fractured, thin kelyphite. Clinopyroxene (green) fairly fresh, altered to fine-grained material mainly on fractures and partings, pyroxene is not generally interstitial.
RVL.10	Eclogite	3.35	Well-rounded, polished xenolith, thin surface alteration.	Garnet (reddish orange, 6 mm) rounded to irregular, anhedral, fractured, turbid, thin kelyphitic rims. Clinopyroxene (dark green) slightly altered in typical manner, occasional small garnet inclusions.

TABLE 4. (continued)

Specimen No.	Rock type	S.G.	Macroscopic examination	Microscopic examination
RVL.16	Eclogite	3.47	Xenolith is of fresh appearance, well rounded.	Garnet (dark orange, 5 mm) rounded to angular, elongated, subhedral. Clinopyroxene (dark green) not interstitial, slightly altered to fine-grained products. Garnet-pyroxene symplectite in places, other garnet occurs as thin stringers on pyroxene grain boundaries (exsolution feature?). Garnets also contain oriented birefringent spindles, clinopyroxene contains rutile prisms.

discoidal. This is thought to be due to the gneissose or layered structure exhibited by many of the rocks, a fine example of which is illustrated in Plate 12. This xenolith, of which only a portion is shown, also clearly illustrates the high degree of rounding and well-polished surfaces of many of these inclusions. In many other specimens which possess a less well defined layering, garnet is inhomogeneously distributed through the rock and occurs as clusters, often several centimetres across. Whilst the original surface of many of the xenoliths is exceptionally smooth and polished, others are roughly pitted.

Plate 13 illustrates a very unusual feature - the contact between a normal eclogite and a kyanite eclogite. It is interesting to note that the colour of the garnets in each type differ considerably, as does the nature of the clinopyroxene. Dawson (1968) has described a similar specimen and Mathias <u>et al</u> (1970) refer to thin alternating bands of kyanite and kyanite-free eclogite in one xenolith examined by them.

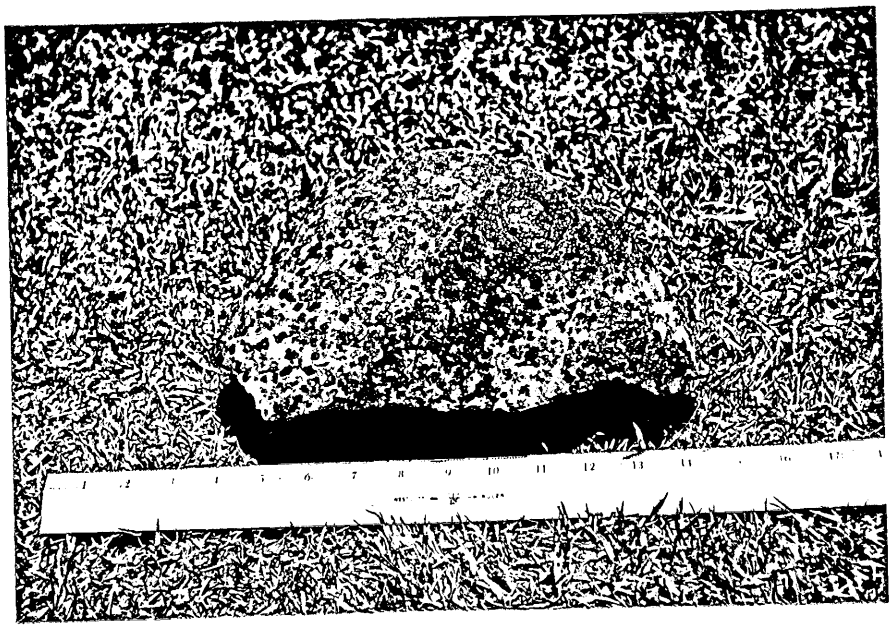


Plate 12. A portion of a well-layered eclogite xenolith RVL.2. Notice the distinct garnet-rich layers. The xenolith is considerably flattened in a direction parallel to the plane of the paper, which corresponds roughly to the layering.

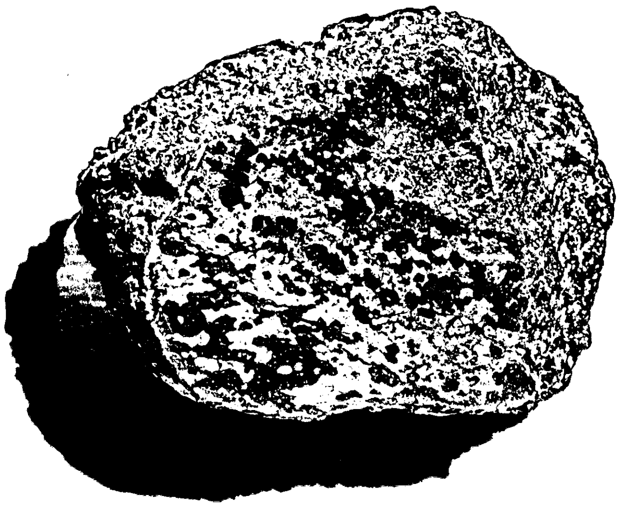


Plate 13. Layered eclogite RV.27, showing the contact between a normal clinopyroxene-garnet assemblage and a clinopyroxene-garnet-kyanite rock. The xenolith has a maximum diameter of approximately 14 cm.

The size of individual xenoliths varies considerably but, when complete, their longest dimension is generally of the order of 10 to 20 cm. In some cases only a portion of a xenolith was available for examination and it was impossible to estimate the size of the original specimen with accuracy.

Close examination of the eclogites shows that they are essentially phanerocrystalline, medium- to coarse-grained aggregates of brownish, orange or red garnet and dark green clinopyroxene. Their fabric, which can be described as allotriomorphic, consists of a compact interlocking mosaic of irregular to rounded anhedral grains. As would be expected from their cubic symmetry the garnet grains are more rounded than the clinopyroxene but very rarely show any sign of distinct subhedral outline. Many of the garnet grains are also completely irregular. In most cases the pyroxene appears to be interstitial to the garnet suggesting that the garnet formed before the pyroxene. This texture may however be deceptive as garnet exerts a much stronger crystallising force than pyroxenes, even in the solid state (Harker, 1950).

Two rock slabs showing the typical texture of eclogite are illustrated in Plate 14. A range of textures, seen microscopically, is illustrated by photomicrographs in Plates 15 to 20. Points to note, other than the textural features, are the abundant sub-parallel fractures in the garnet (Plates 16 to 18), thought to be due to tectonism, the highly altered nature of much of the clinopyroxene (Plates 15, 16, 18 and 20) and the presence of laths of mica associated with the kelyphitic material (Plate 17.)

Three specimens of kyanite-bearing eclogite were identified, one being the striking rock (RV.34) whown in Plate 21. Switzer and Melson (1969) have recently described, in detail, a partially melted kyanite eclogite from the Roberts Victor pipe. The xenoliths of kyanite eclogites are characterised by an intense alteration of the clinopyroxene to a very fine-grained grey, opaque matrix in which only traces of the original material are still present (see Plate 20). X-ray diffraction clearly shows that the crystalline structure of this material, whilst poorly developed, is still essentially that of a clinopyroxene. Blue kyanite occurs as irregular, rounded or subhedral grains

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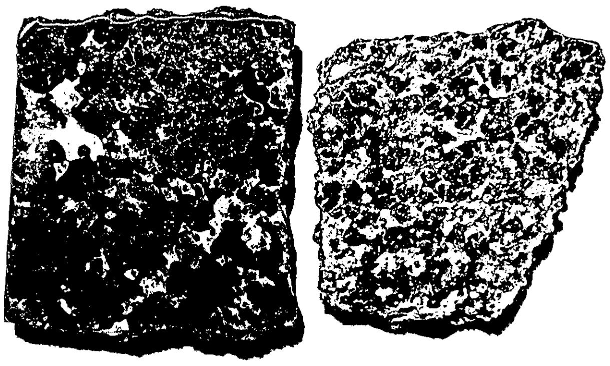


Plate 14. Slabs of eclogite [RV.32 (left) and RV.33 (right)] used in modal analyses, illustrating the typical macroscopically visible textures. The slabs are approximately 7 cm across.

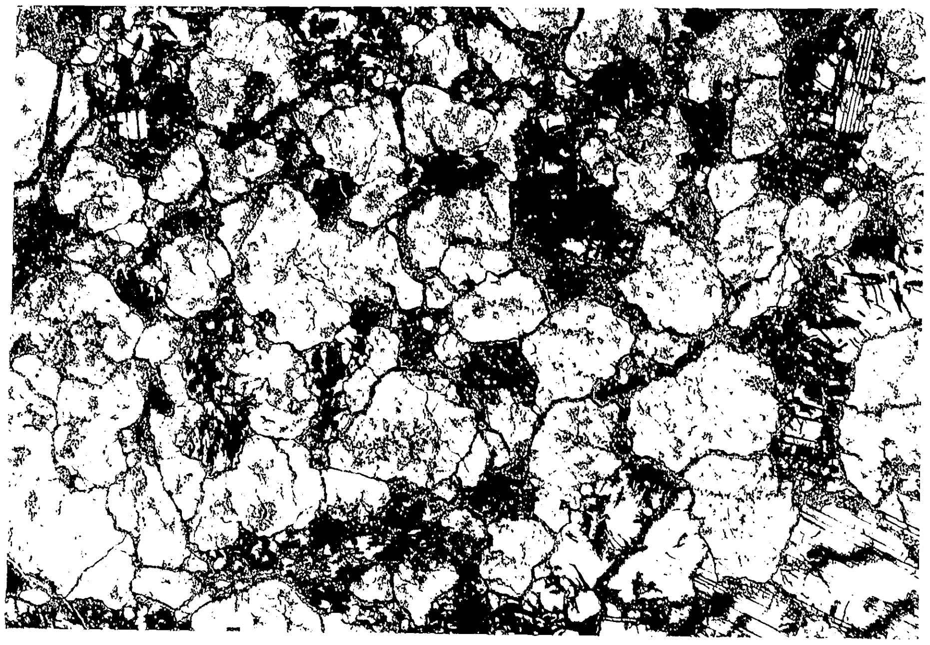
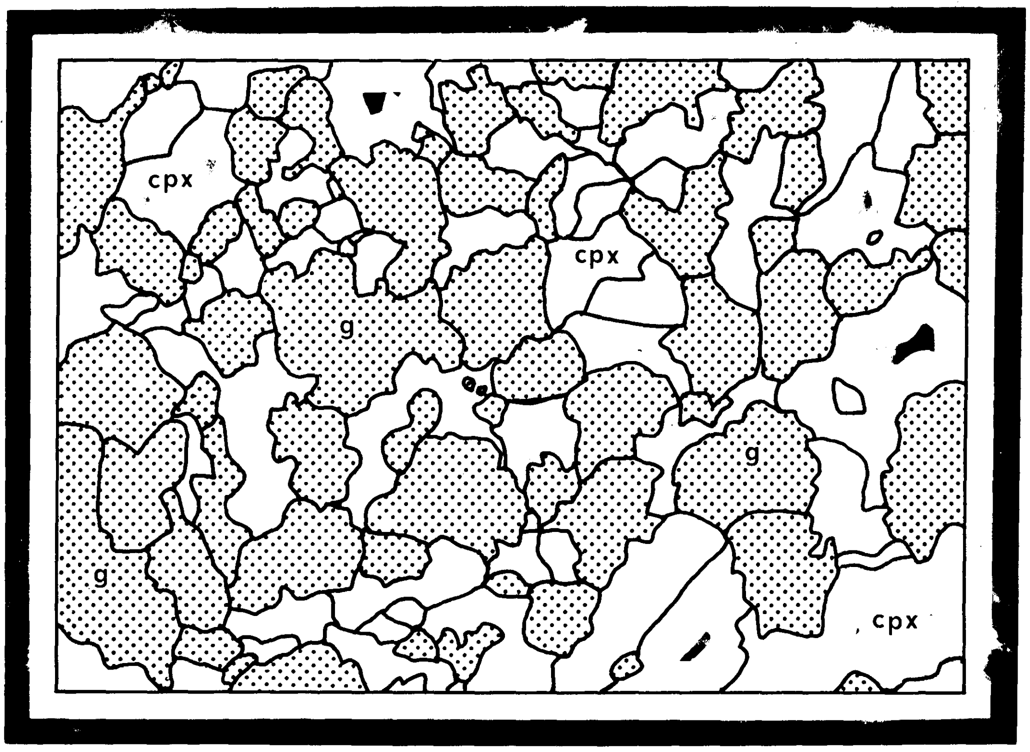


Plate 15. Eclogite RV.1. Notice the extensive alteration of the clinopyroxene and the irregular shape of the garnet. Magnification X5, ordinary light.



Key to Plate 15. clinopyroxene (cpx), garnet (g).

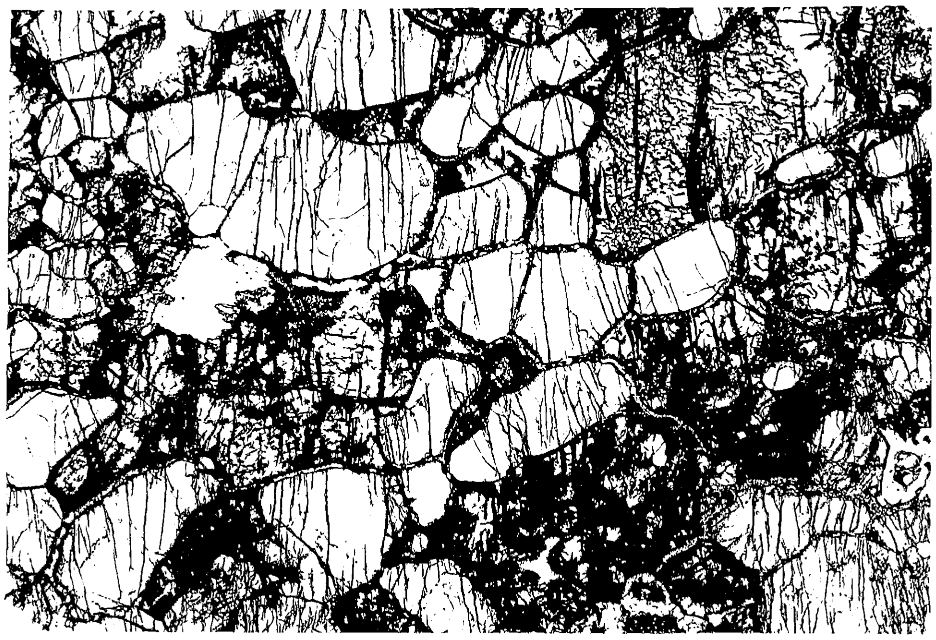


Plate 16. Diamondiferous eclogite RV.4. The sub-parallel fractures in the garnet are particularly outstanding.

Magnification X5, ordinary light.

Key to Plate 16. clinopyroxene (cpx), garnet (g), quartz (q).

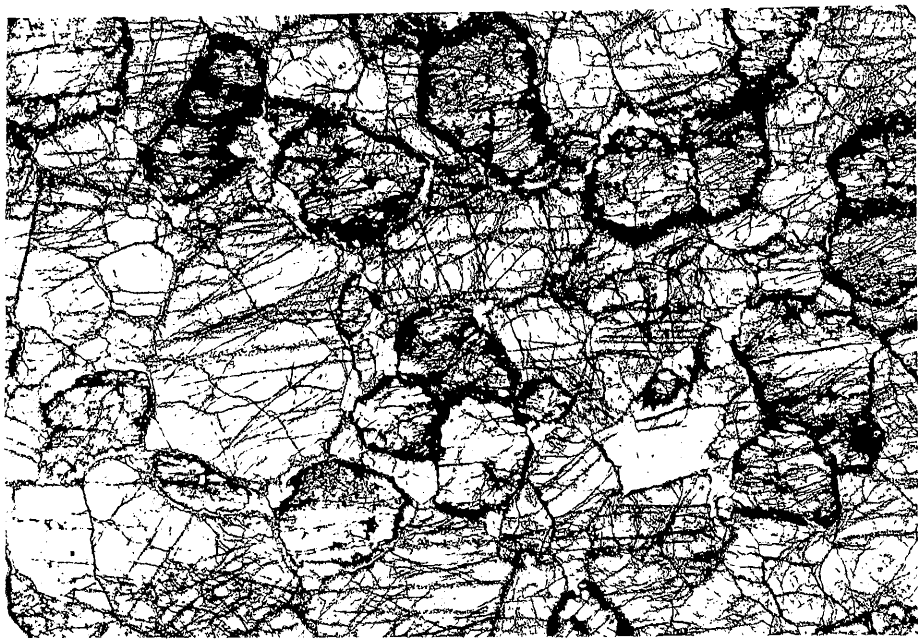
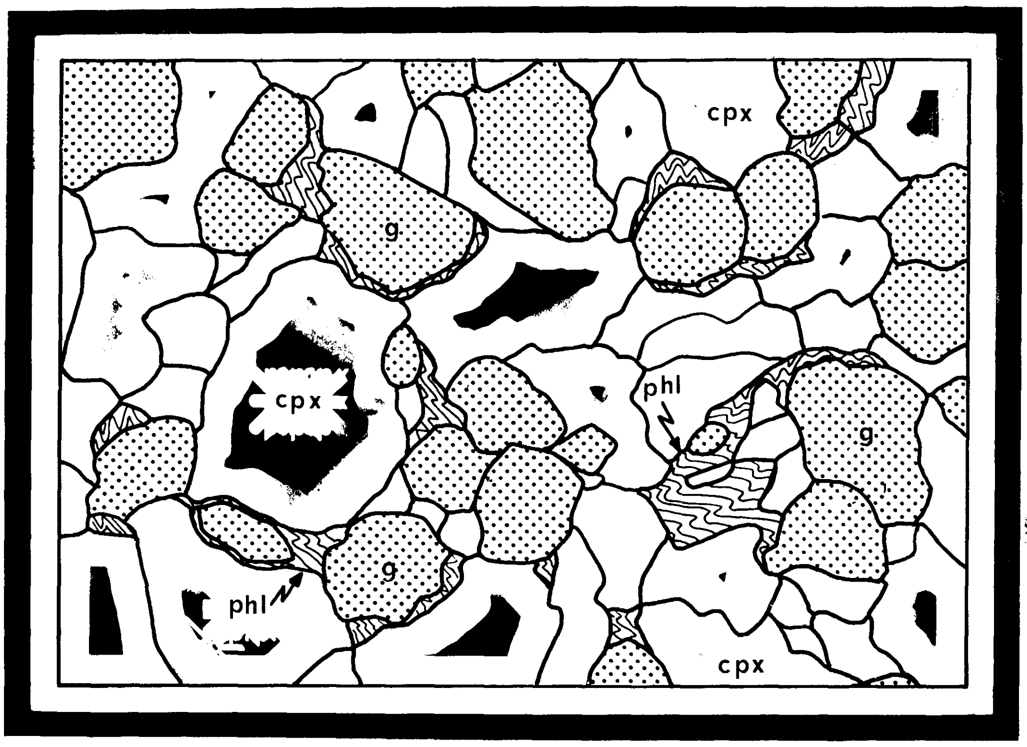


Plate 17. Eclogite RV.20. Flakes and patches of mica, probably of secondary origin, are closely associated with the kelyphitic rims of the garnet.
Magnification X5, ordinary light.



Key to Plate 17. clinopyroxene (cpx), garnet (g), phlogopite (phl).

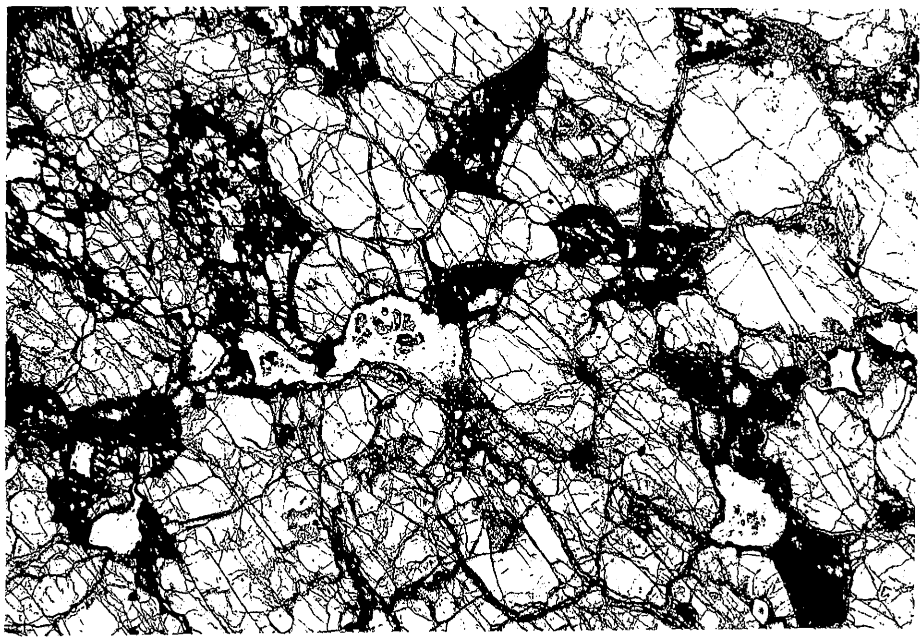
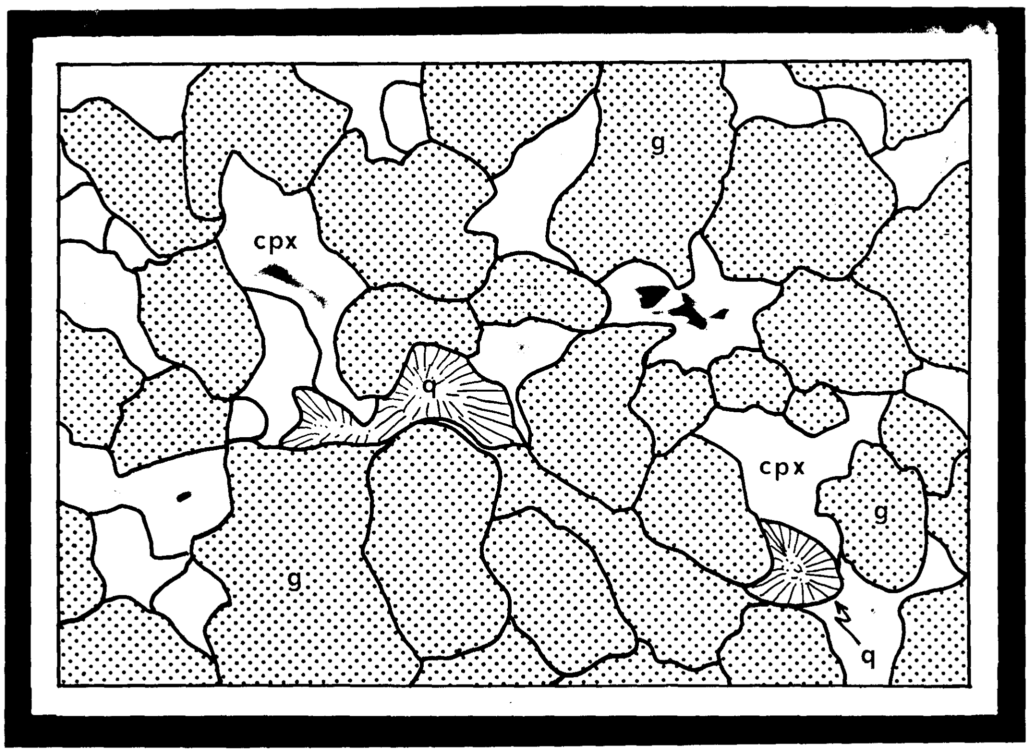


Plate 18. Eclogite RV.33. The extensive alteration of the clinopyroxene is very marked, as are the subparallel fractures in the garnet. Notice also the patches of secondary chalcedonic quartz. Magnification X5, ordinary light.



Key to Plate 18. clinopyroxene (cpx), garnet (g), secondary quartz (q).

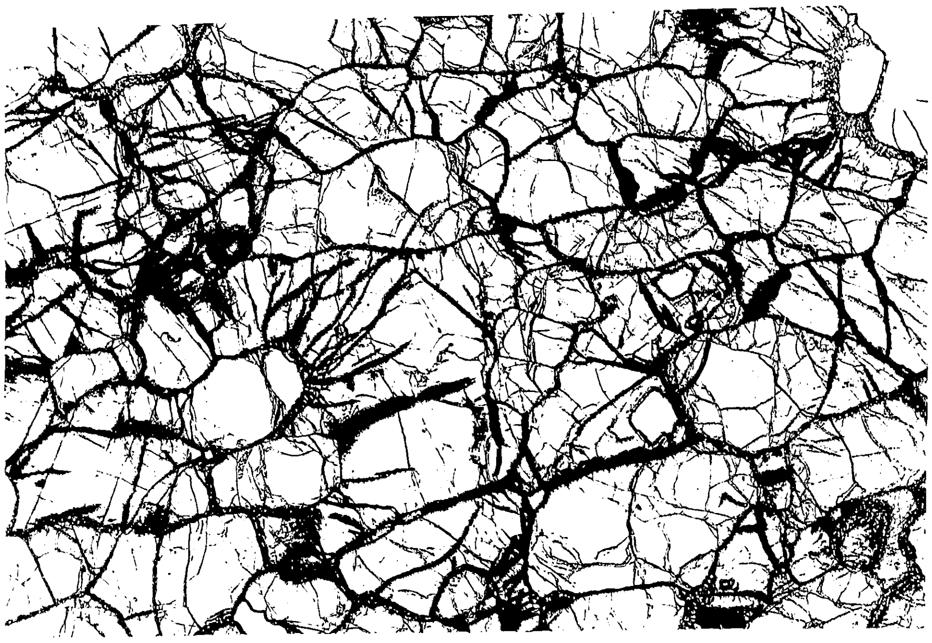


Plate 19. Eclogite RVL.16. An unusually fresh specimen of eclogite, showing only slight alteration of the clinopyroxene. Magnification X5, ordinary light.

Key to Plate 19. clinopyroxene (cpx), garnet (g).

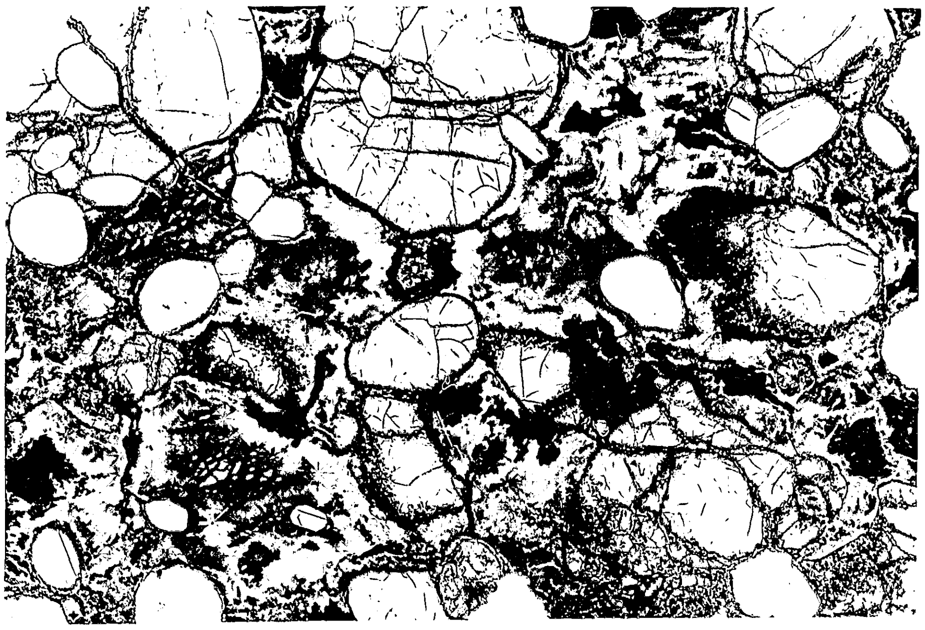
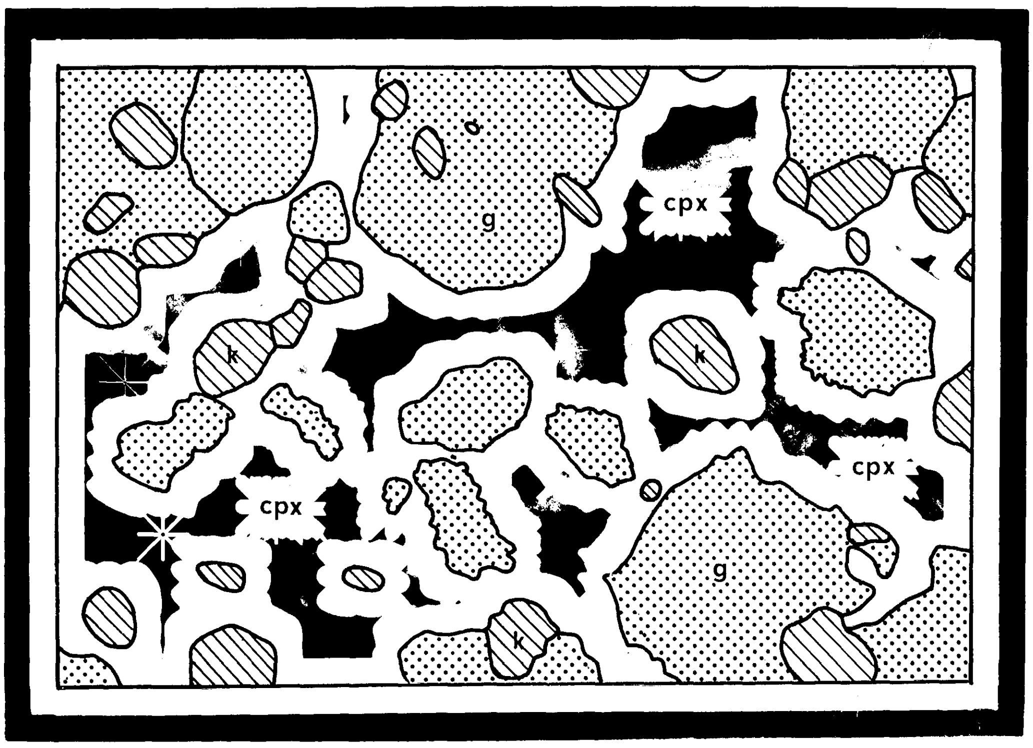


Plate 20. Kyanite eclogite RV.34. Notice the rounded or subhedral grains of kyanite and the opaque, completely altered nature of the clinopyroxene.
Magnification X5, ordinary light.



Key to Plate 20. clinopyroxene (cpx), garnet (g), kyanite (k).

often showing a good cleavage. In places it is poikiloblastically enclosed by the garnet. In specimen RV.6 the kyanite is associated with a minor amount of mauve, lath-shaped corundum, which introduces a primary four-phase association. Similar clinopyroxene-garnet-kyanite-corundum associations have recently been reported by Sobolev et al (1968) from the Zagadochnaya pipe in Yakutia and by Mathias et al (1970) from the Crown Mine (South Africa).

One specimen of diamond-bearing eclogite, RV.4, calls for special mention. In appearance and texture this rock closely resembles the other eclogites. The complete xenolith, discoidal in shape (approximately 13 x 10 x 5 cm), has a distinctly gneissose structure and the rounded to elongated, pale orange-coloured garnets show prominent sub-parallel fractures (Plate 16); some grains show an ill-defined crystal shape. The clinopyroxene is poorly preserved, only occasional pale green relict grains being visible, the remainder of the material forming a soft, khaki-coloured, earthy matrix. Diamonds, ranging in size from a maximum of approximately 4 mm across to less than 1 mm, are scattered throughout the rock. Compared with a diamondiferous kimberlite, this eclogite is fabulously rich. Two typical diamonds are illustrated in Plates 22 and 23. The shapes of the diamonds vary from single well-formed octahedra (Plate 22) to irregular crystalline aggregates (Plate 23), while in colour they change from glass-clear to blackish. The results of a more detailed study of the diamonds are given in Chapter IX. It is interesting to note that rutile, showing minute, orientated, opaque inclusions, is a minor accessory of the rock and appears identical with the rutile found as an inclusion in diamond from eclogite (Gurney et al, in press).

One of the most interesting features, seen to a greater or lesser degree in almost every eclogite, is the presence of small, localised amounts of interstitial, brownish, glassy material (often containing feldspar crystallites) or very fine-grained, secondary, plagioclase-amphibole (or plagioclase-mica) aggregates. Similar features have been reported by Switzer and Melson (1969) and Frick (1970). The glassy material and feldspar crystallites, illustrated in Plate 24, are best developed in the clinopyroxene, which shows the effects of appreciable melting, and in the kelyphitic material along the contact between garnet and pyroxene. The partial melting of the eclogites and the formation of constituents stable at lower pressure is thought

Plate 21. Kyanite eclogite RV.34. The kyanite (blue) and the garnet (orange) are set in an opaque, greyish matrix of altered clinopyroxene. Magnification X1.5.

to be due to a sudden relief of pressure, probably on the rapid and explosive intrusion of the kimberlite and the subsequent chilling of minor amounts of glassy material formed.

Other than melting, changes in the eclogites are shown by typical kelyphitic margins around the garnet. These kelyphitic margins normally consist of a very fine intergrowth of a pale brown amphibole, phlogopite, green spinel and occasionally feldspar and glass. Alteration of the clinopyroxene results in the formation of areas of ultra fine-grained, whitish aggregates. This altered material, found in the pyroxene of almost every specimen in varying amounts, is especially concentrated along fractures and partings and in places has assumed almost a "saw-toothed" pattern. The nature of this secondary material is dealt with in more detail in Chapter IX.

Other changes attributed to hydrothermal alteration and weathering include the formation of patches of secondary, chalcedonic quartz and small amounts of minerals such as analcime, a stilbite-like mineral and red, jaspery silica. In some xenoliths brownish micaceous material is an important constituent.

In conclusion, a brief mention of the observed primary eclogitic mineral associations can be made. In their recent study Mathias et al (1970) list 15 distinct eclogite associations occurring in the kimberlites of Lesotho, Rhodesia, South Africa and Tanzania. The following four mineral assemblages were recognised in the xenoliths of the present investigation:

1. clinopyroxene - garnet.
2. clinopyroxene - garnet - kyanite.
3. clinopyroxene - garnet - kyanite - corundum.
4. clinopyroxene - garnet - diamond.

In addition to the minerals mentioned above, trace amounts of other primary phases were detected in many of the rocks but it was considered that these did not warrant definition as essential constituents. These minerals include rutile (normally containing minute, orientated, opaque inclusions), sulphides (pyrite, marcasite and a polydymite-type mineral) and rarely traces of corundum, kyanite, chrome spinel and ilmenite. Chalcedonic quartz, slightly milky in appearance, is an accessory in five of the rocks and is considered to be of secondary origin.

A more detailed description of the individual minerals and quantitative optical, chemical and physical data are presented in Chapter IX.

Plate 22. A clear, well-formed octahedral diamond on the surface of eclogite RV.4.
Magnification X5.

Plate 23. A clear but irregular aggregate of diamond embedded in eclogite RV.4.
Magnification X5.

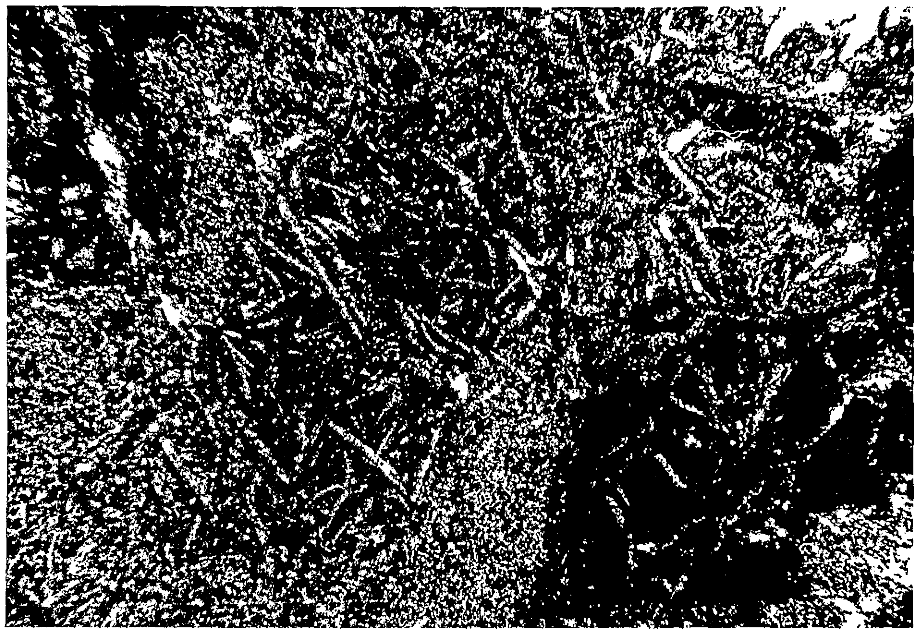


Plate 24. The glassy material in eclogite RV.6. Note the feldspar crystallites.
Magnification X63, polarised light.

Plate 25. A patch of glassy material in eclogite RV.7. Greenish, weakly pleochroic amphibole, spinel and calcite have developed in a glassy groundmass. Magnification X90, ordinary light.

2. Modal Analyses.

The results of modal analyses of the peridotites and eclogites are presented in Table 5 (garnet peridotites), Table 6 (spinel and altered peridotites) and Table 8 (eclogites). The volumetric percentage of the major constituents, that is, those greater than 10 per cent by volume, have been rounded off to the nearest one per cent and the figure for the minor constituents (those less than 10 per cent by volume) to the nearest one-tenth per cent. It must be understood, however, that due to the coarse-grained and inhomogeneous nature of the xenoliths these values are not necessarily always highly accurate, but in most cases, unless specifically indicated, the accuracy is thought to be within five per cent relative of the amount present for the major constituents and within 10 per cent for the accessory minerals.

A. PERIDOTITES.

The results of the garnet peridotite analyses, tabulated in Table 5, are presented graphically in Fig. 4, in which the values are plotted on a triangular diagram using olivine, total pyroxene (orthopyroxene plus any accessory amounts of chrome diopside) and garnet as the end-members. Where phlogopite does not exceed half of one per cent by volume it is combined with the garnet end-member but when in excess of this amount it is ignored and the sum of the other constituents recalculated to a total of one hundred per cent. This has been done as it is considered that the bulk of the phlogopite is of secondary origin (however, see Phlogopite, Chapter IX). Fig. 5 is a diagrammatic representation of the essential mineralogical composition of a number of typical garnet peridotite xenoliths based on the results found in Table 4. This diagram gives some indication of the range in mineralogical composition of the garnet peridotites, whilst the histograms shown in Fig. 6 illustrate the distribution frequency of the four main constituents.

The composition of the spinel peridotites is also presented graphically in Fig. 4 but the nature of the altered peridotites makes them unsuitable for

TABLE 5.

MODAL ANALYSES OF THE GARNET PERIDOTITE XENOLITHS.

Specimen No.	Volume percentage*					Trace constituents
	Olivine	Ortho-pyroxene	Garnet	Chrome diopside	Phlogopite	
BF.1	68	26	3.7	1.2	1.2	
2	80	13	4.5	1.9	0.4	
3	68	26	3.6	2.0	0.2	sulphides
4	59	33	7.4	-	-	graphite
5	71	21	4.0	1.4	2.7	
6	63	31	5.2	0.2	0.4	
7	75	21	3.7	0.5	-	
8	74	23	4.0	-	tr	
9	62	32	6.3	-	tr	chrome spinel, graphite
W.6	55	39	5.9	0.2	tr	
7	52	38	4.7	tr	5.6	chrome spinel
8	73	23	2.9	0.7	0.8	
9	58	37	3.6	1.6	-	sulphides
10	66	29	5.0	-	tr	
DT.6	77	20	2.4	-	0.1	chrome spinel
7	61	33	5.8	0.2	tr	
8	70	25	4.8	tr	tr	
11	65	22	5.9	5.0	1.2	
14	59	35	5.6	0.5	0.4	
15	64	30**	5.2	-	0.2	
18	65	26	3.8	-	4.2	chrome spinel, sulphides
20	64	31**	3.9	-	0.6	
RV.16	57	37	4.9	1.0	-	
25	59	36	4.1	0.7	tr	

* Various alteration products are included with the original constituent i.e. serpentine combined with olivine, kelyphite with garnet.

** Small amounts of chrome diopside are associated with the orthopyroxene.

tr : trace.

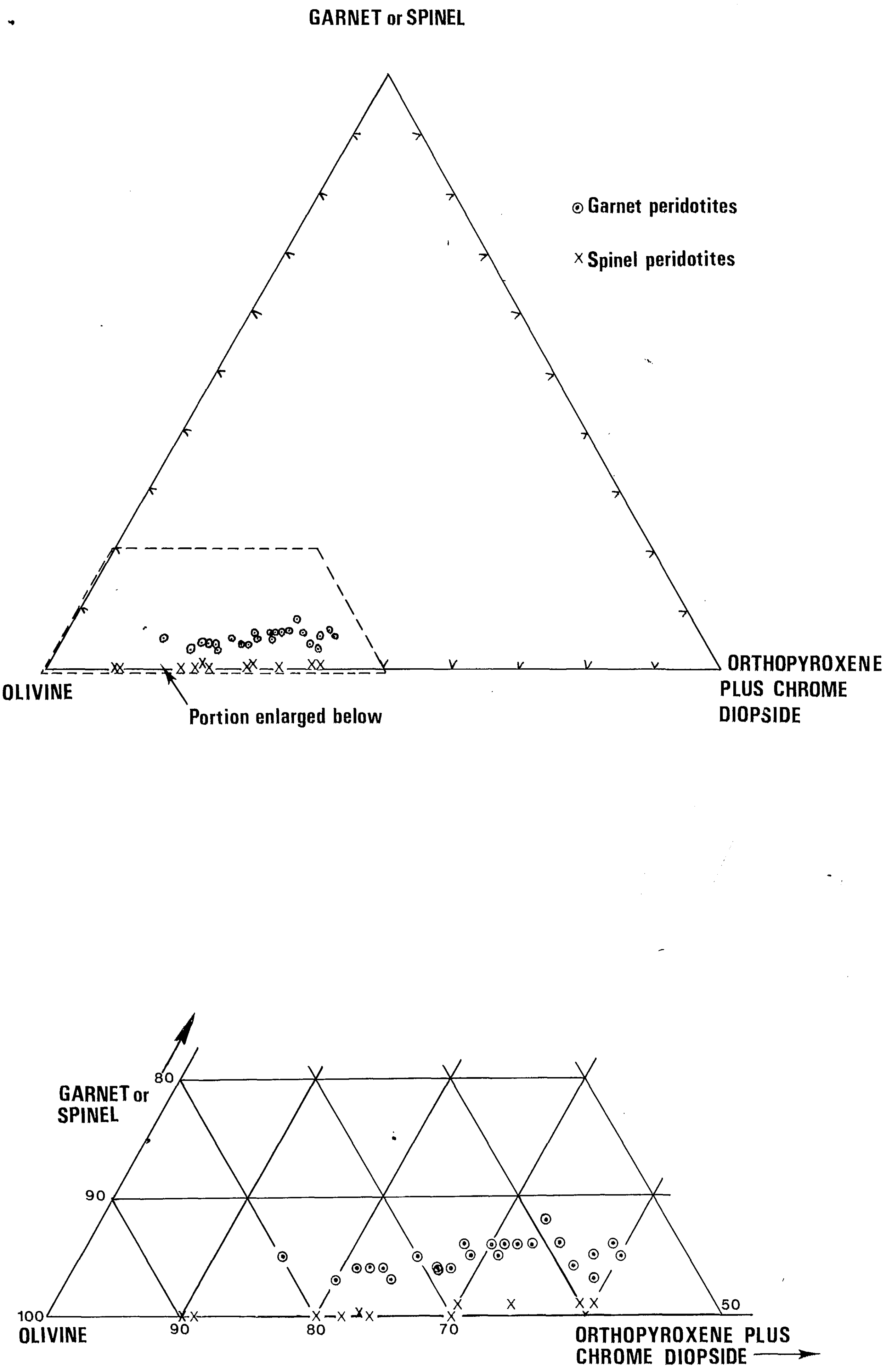
TABLE 6.

MODAL ANALYSES OF THE SPINEL PERIDOTITE AND ALTERED PERIDOTITE XENOLITHS.

Specimen No.	Volume percentage +					Trace constituents
	Olivine	Ortho-pyroxene	Chrome diopside	Phlogopite	Spinel	
BF.10	59	40	-	-	0.6	
W. 1	55	35**	tr	9.4	0.6	
3	75	21	0.5	3.2	0.3	garnet, sulphide
4	65	34**	-	-	0.6	garnet
5	68	31**	-	tr	0.6	
DT. 2*	39	45ø		1.6	-	
3*	82	18	-	-	-	
4	89	11	0.2	0.3	0.3	garnet
9*	80	-	13.6	6.4	tr	garnet, sulphides
10*	95	remainder alteration products				ilmenite
13	89	11	0.3	1.4	0.2	
16*	94	4	-	2.0	-	
21*	91	7	1.2	-	0.3	garnet, sulphides
RV.12	78	21	-	0.2	0.1	
14	71	23	0.3	5.9	0.2	garnet
15*	63	tr	6.7	30	0.1	
17	69	30	0.1	0.8	0.1	
19	78	19	-	2.8	0.3	

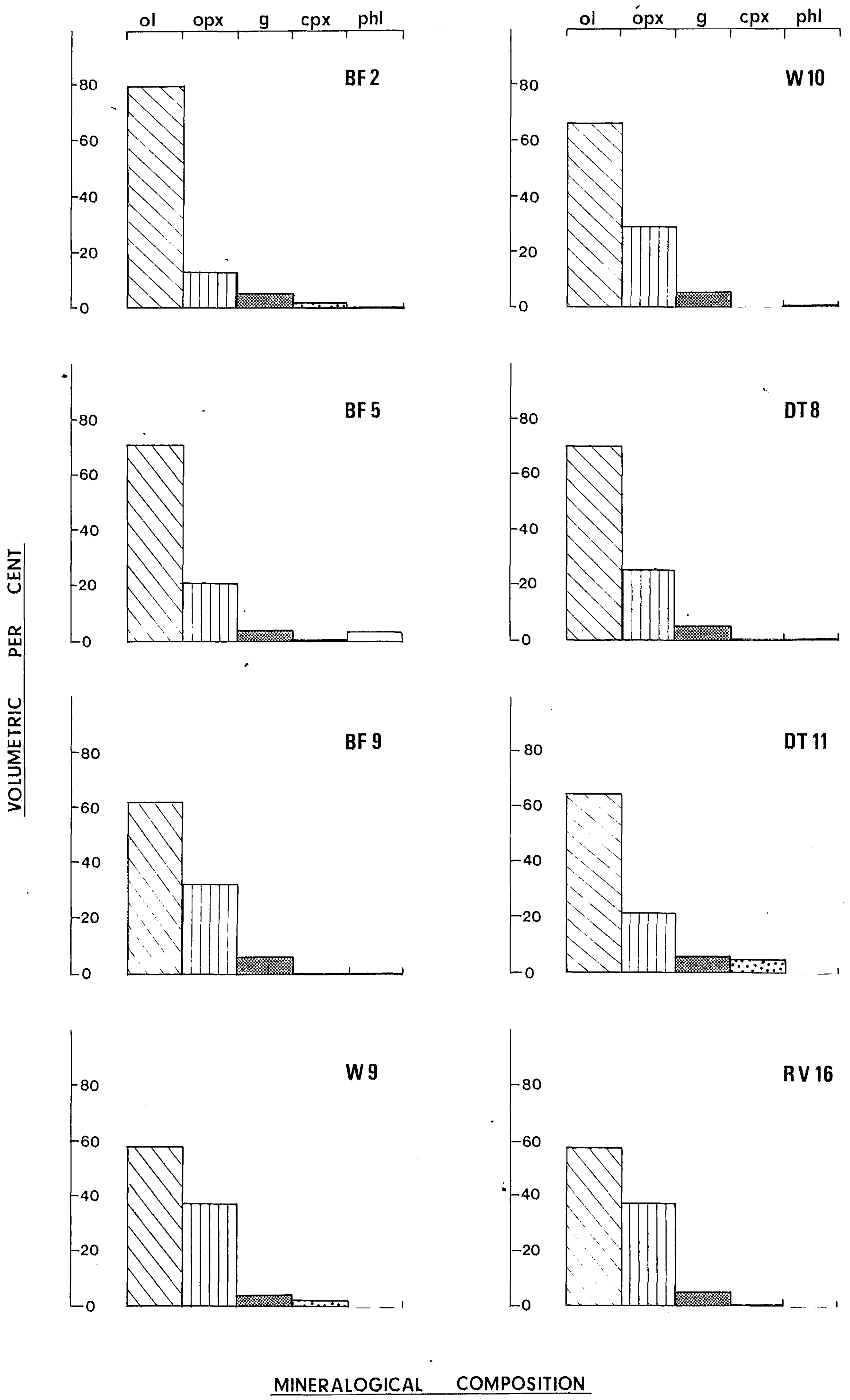
*	altered peridotites.
**	small amounts of chrome diopside are associated with orthopyroxene.
ø	consists of intergrown orthopyroxene and chrome diopside.
+	various alteration products are included with the original constituent.
tr :	trace.

FIG. 4



Diagrammatic representation of the modal analyses of the Peridotite Xenoliths using Olivine, Garnet [or Spinel] and total Pyroxene as end-members

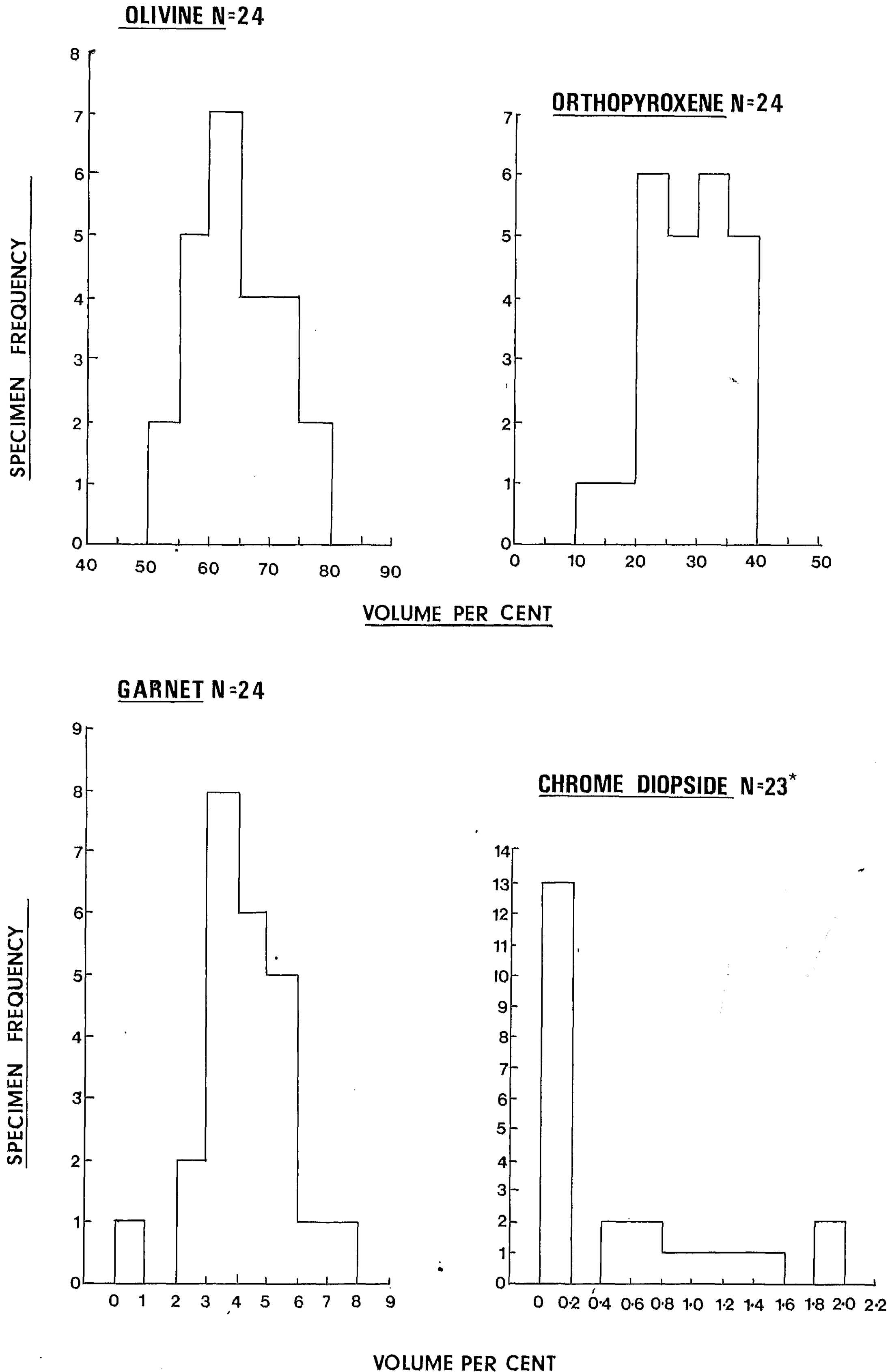
FIG. 5



AN ILLUSTRATION OF THE ESSENTIAL MINERALOGICAL COMPOSITION OF SELECTED GARNET PERIDOTITE XENOLITHS

ol = olivine
opx = orthopyroxene
cpx = clinopyroxene
g = garnet
phl = phlogopite

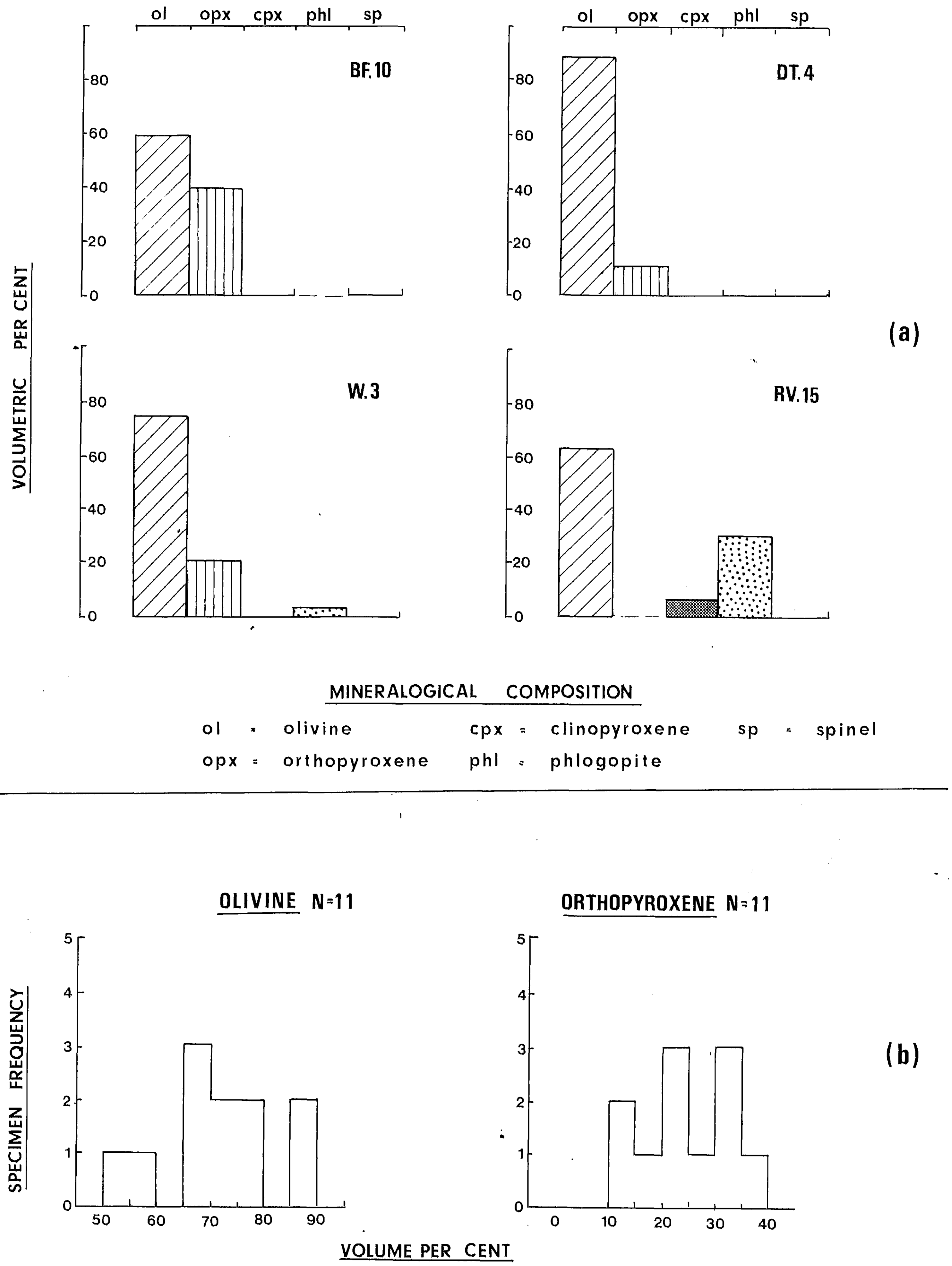
FIG. 6



*One specimen (DT 11) not included

Histograms illustrating the distribution frequency of the major constituents in the Garnet Peridotite Xenoliths

FIG. 7



(a) AN ILLUSTRATION OF THE ESSENTIAL MINERALOGICAL COMPOSITION OF SELECTED SPINEL PERIDOTITE XENOLITHS

(b) HISTOGRAMS SHOWING THE DISTRIBUTION FREQUENCY OF OLIVINE AND ORTHOPYROXENE IN THE SPINEL PERIDOTITES diagrammatic representation. In the case of the spinel peridotites spinel has been substituted for the garnet end-member and the diagram should be read thus. Phlogopite was similarly combined as for the garnet peridotite analyses. The essential mineralogical composition of a number of the spinel peridotites, but not the highly altered material, is also shown in Fig. 7(a) whilst histograms showing the distribution frequency of olivine and orthopyroxene in the spinel peridotites are presented in Fig. 7(b). Chrome diopside, usually present in only small or trace amounts, is not shown.

The essential results of the modal analyses of the garnet peridotites are summarised in Table 7 (Section A). It is apparent from the analyses that on the basis of mineralogical composition the garnet peridotites show a large and more or less continuous range. Although no one particular composition dominates the group, there is a distinct tendency for the calculated average composition to be most abundant (Table 7). A possible inference to be drawn from these results, if the garnet peridotite xenoliths are regarded as being samples of the upper mantle, is that beneath the Kimberley area of southern Africa the upper mantle is relatively inhomogeneous and possibly layered.

The essential results of the modal analyses of the spinel and altered peridotites are summarised in Sections B and C respectively of Table 7. This illustrates that the spinel-bearing types are broadly similar to the garnet peridotites and similar conclusions regarding the possible nature of the upper mantle can be drawn. There is however a noticeable increase in the average amount of olivine in the spinel peridotites (72%) as compared with the garnet peridotites (65%);the altered peridotites appear to have contained an even greater amount of olivine (average 84%).

B. ECLOGITES.

The results obtained from a modal analysis of 24 specimens of eclogite are listed in Table 8, together with trace constituents in these rocks, and are shown graphically in Fig. 8(a) and (b). In the first triangular diagram [Fig. 8(a)] the three end-members are clinopyroxene, garnet and "others", "others" including all kelyphitic reaction rims, micaceous material, kyanite and secondary products. In Fig. 8(b) the three end-members are clinopyroxene, garnet plus kelyphitic and micaceous material and "others", which now includes

TABLE 7.

SUMMARY OF THE ESSENTIAL RESULTS OF THE MODAL ANALYSES OF THE PERIDOTITE XENOLITHS.

Constituent	Range in volumetric composition (%)	Average composition (%)	Histogram maximum (%)
A. GARNET PERIDOTITES	(24 specimens)		
Olivine	52 - 80	65	61 - 65
Orthopyroxene	12 - 39	29	21 - 25 and 31 - 35
Chrome diopside	Nil - 50	0.7	0 - 0.2
Garnet	2.4 - 7.4	4.6	3.0 - 4.0
Phlogopite	Nil - 6.4	1.0	n.d.
Spinel	trace in four xenoliths		
B. SPINEL PERIDOTITES	(11 specimens)		
Olivine	55 - 89	72	66 - 70
Orthopyroxene	11 - 40	25	21 - 25 and 31 - 35
Chrome diopside	tr - 0.5	0.1	n.d.
Spinel	0.1 - 0.6	0.4	n.d.
Phlogopite	Nil - 9.4	2.2	n.d.
Garnet	trace in four xenoliths		
C. ALTERED PERIDOTITES	(6 specimens)*		
Olivine (altered)	82 - 95	84	n.d.
Orthopyroxene }	present but highly altered		-
Chrome diopside }			
Garnet	trace in two xenoliths		-
Spinel	Nil - 0.3	n.d.	n.d.
Phlogopite	Nil - 30	n.d.	n.d.
Ilmenite	trace in one xenolith		-

tr : trace
n.d. : not determined
* · DT.2 not included

TABLE 8.

MODAL ANALYSES OF THE ECLOGITE XENOLITHS.

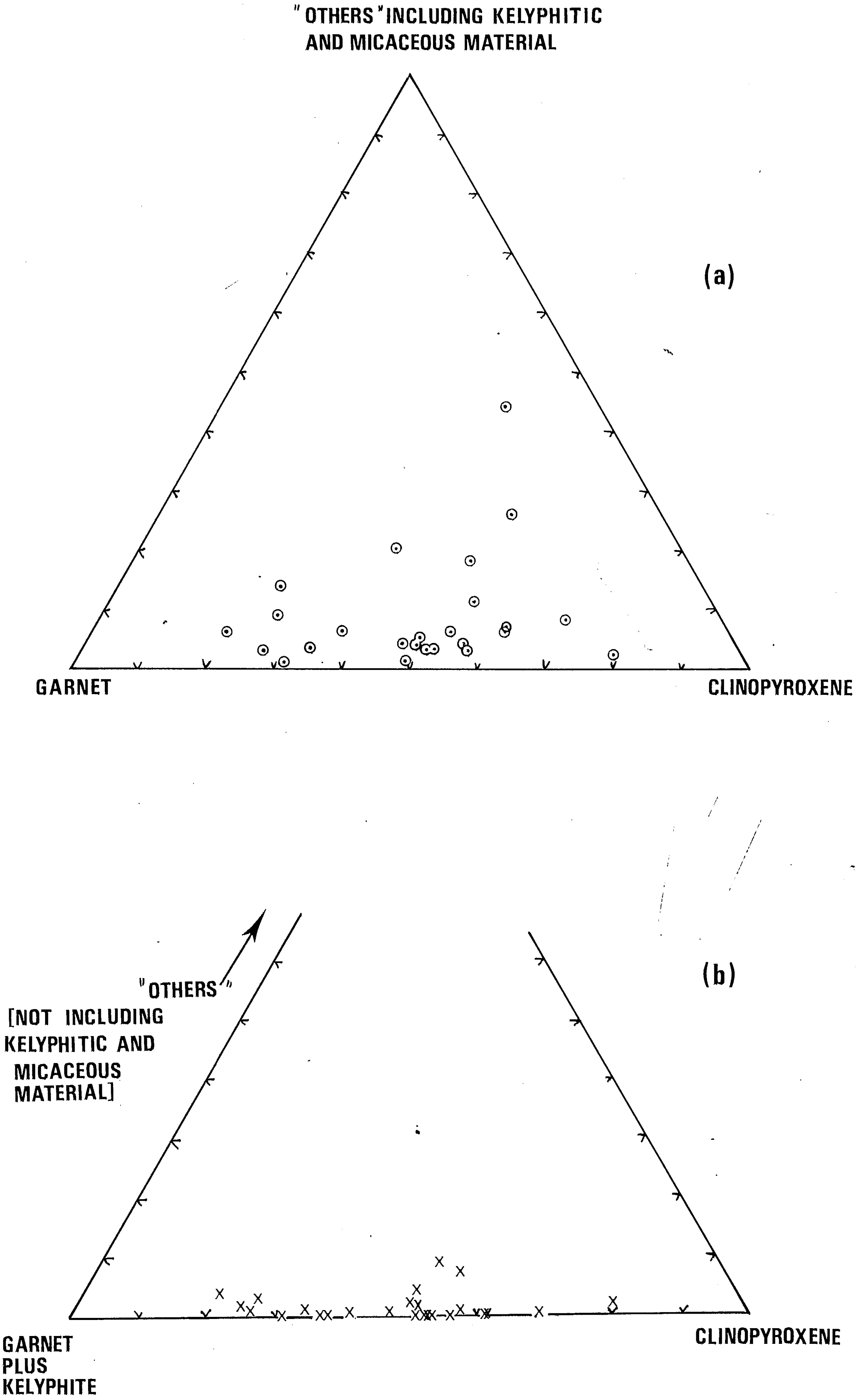
Specimen No.	Volume percentage				Trace constituents
	Garnet	Clinopyroxene	Micaceous material	Others*	
RV.1	62	24	12	2.1	kyanite, sulphides
2	33	61	5.7	tr	sulphides
3	57	37	5.9	tr	sulphides
4	50	49	tr	1.4	diamond, rutile
5	68	31	0.7	tr	spinel
6	47	49	tr	3.7	(includes 3.3% kyanite) corundum, rutile.
7	65	26	8.2	1.5	sulphides
8	40	56	3.8	tr	sulphides, rutile
9	70	27	0.5	2.7	kyanite, sulphides
10	42	38	20	tr	
18	22	52	26	tr	
20	23	69	8.0	tr	
26	32	61	6.9	tr	sulphides
27	(49	47	3.9	tr	
	(35	54	4.4	7.0	(includes 3.9% kyanite)
29	14	42	44	-	
30	46	49	3.1	1.9	corundum, kyanite sulphides, rutile
31	74	20	1.2	4.4	sulphides
32	41	53	6.0	tr	
33	63	34	2.2	1.0	sulphides
34**	32	50	9	9	(9% kyanite)
RVL.2	19	79	tr	1.6	rutile, ilmenite
5	45	52	2.7	tr	rutile
10**	40	57	3	tr	rutile, sulphides
16**	46	51	3	tr	

* "Others" consists mainly of secondary veining, quartz, zeolites and calcite.

** results from thin sections.

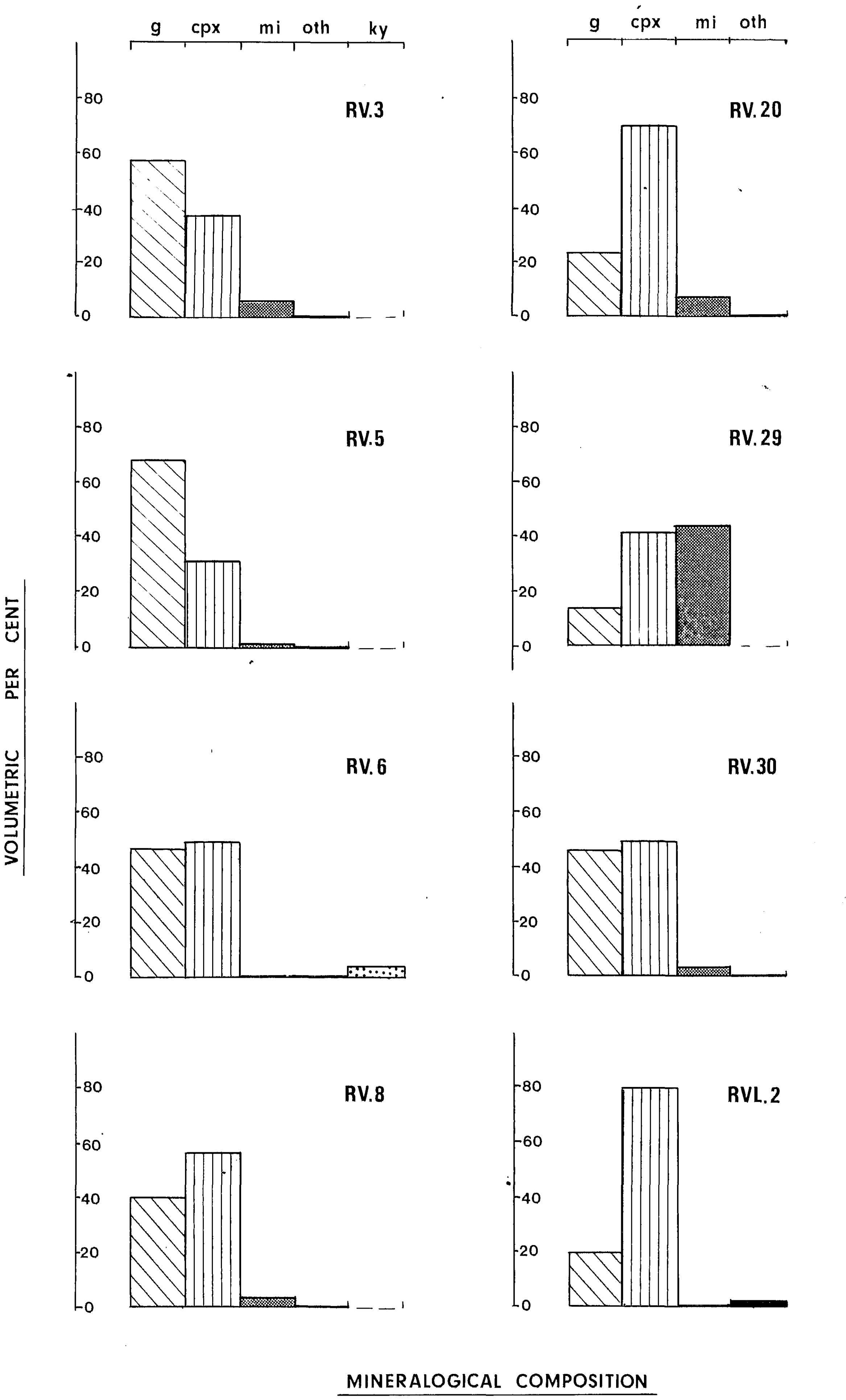
tr : trace.

FIG. 8



Diagrammatic representation of the modal analyses of the Eclogite Xenoliths using the end-members indicated (for explanation see text)

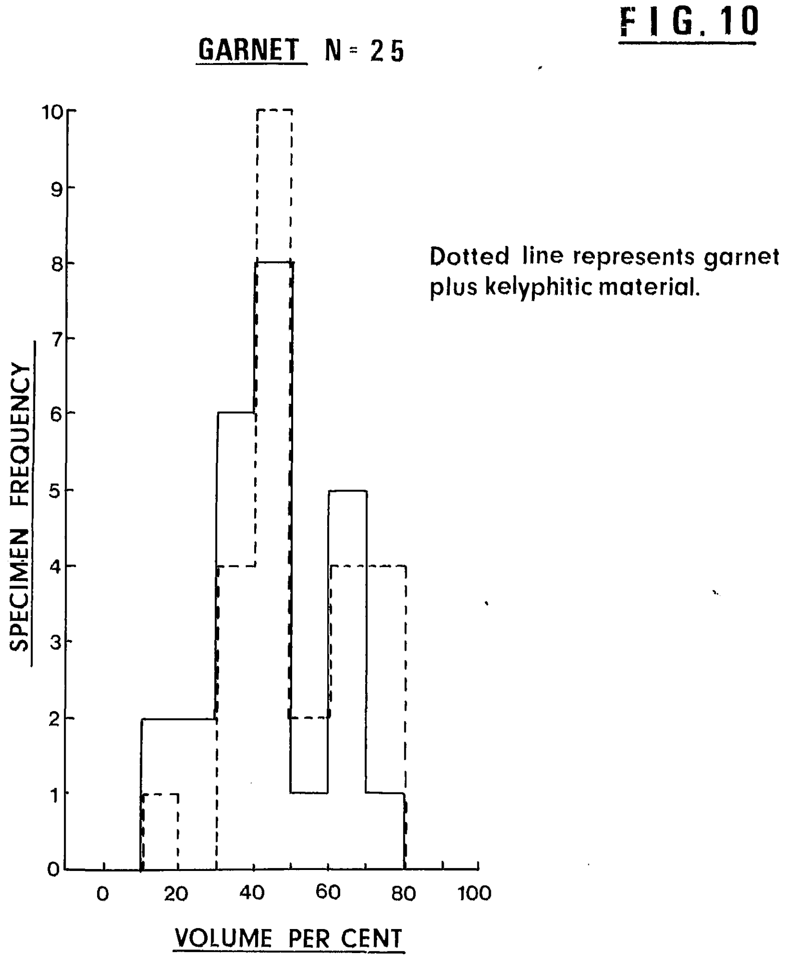
FIG. 9

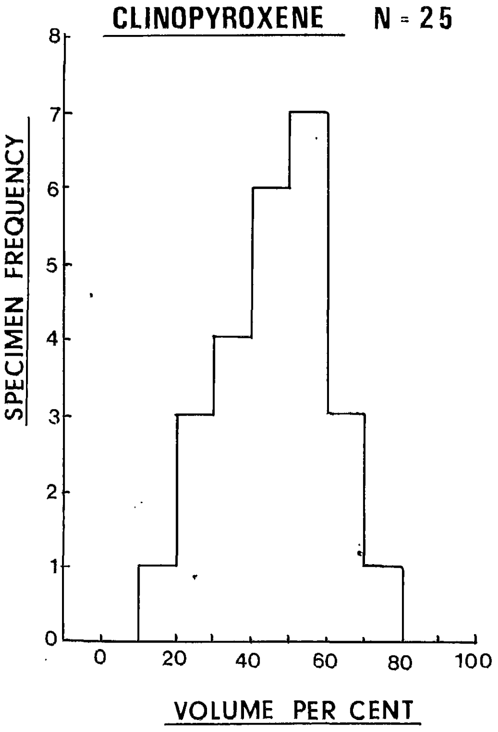


AN ILLUSTRATION OF THE ESSENTIAL MINERALOGICAL COMPOSITION OF SELECTED ECLOGITE XENOLITHS

g = garnet
cpx = clinopyroxene
mi = micaceous material
oth = "others", mainly secondary products
ky = kyanite

FIG. 10





Histograms illustrating the distribution frequency of garnet and clinopyroxene in the Eclogite Xenoliths only kyanite, secondary quartz and veining. This has been done as it is considered that the bulk of the kelyphitic and micaceous material has been derived from the garnet.

The modal composition of eight specimens of eclogite is illustrated in Fig. 9 and clearly shows the large range in mineralogical composition that exists. Histograms showing the distribution frequency of clinopyroxene, garnet and garnet plus kelyphitic material are presented in Fig. 10, whilst a summary of the essential results is given in Table 9.

It is evident that on the basis of mineralogical composition alone no reliable grouping of the eclogite xenoliths can be attempted and no distinct types of eclogite can be defined.

The distribution frequency of the garnet is clearly bimodal but that of the clinopyroxene unimodal. The wide variation in the mineralogical composition of the eclogites, which is very much greater than that shown by the peridotites, suggests that either the eclogite xenoliths originated from an inhomogeneous source (or sources) or that during eclogite formation within the upper mantle, conditions of formation fluctuated over an appreciable range, resulting in eclogite of variable composition. The origin of the eclogite xenoliths is dealt with more fully in Chapter XI.

TABLE 9.

SUMMARY OF THE ESSENTIAL RESULTS OF THE MODAL ANALYSES OF THE ECLOGITE XENOLITHS.

Constituent	Range in volumetric composition (%)	Average* composition (%)	Histogram maximum (%)
Garnet	14 - 74	45	41 - 45, 61 - 70
Clinopyroxene	20 - 79	47	51 - 60
Micaceous material	trace - 44	7.3	n.d.
Others	Nil - 9.0	1.5	n.d.
Kyanite (3 specimens only)	3.3 - 9.0	5.4	n.d.

n.d. : not determined.

* average composition includes the three kyanite-bearing types.

3. Chemistry

Introduction.

As many of the eclogite and peridotite xenoliths have been appreciably altered, either within the kimberlite or by surface weathering, the number of inclusions that could be used for reliable chemical analyses was considerably less than the total number of xenoliths examined during the course of this investigation. Of the 42 peridotite and 24 eclogite xenoliths studied, nine garnet peridotites, four spinel peridotites and nine eclogites were selected for detailed chemical analysis. None of the appreciably altered peridotites or eclogites were analysed and zones of weathering were as far as possible, removed from the selected xenoliths prior to analysis. In the selection of the peridotites a number of other considerations also had to be kept in mind, namely, that each kimberlite pipe be represented and that the analyses should, as far as possible, be representative of distinct mineralogical variations within the rock-types. Reference to the modal analyses will show that for the garnet peridotites the analysed rocks are spread over a considerable range of mineralogical composition, as are the spinel peridotites. The selection of the eclogite xenoliths was, to a large extent, controlled by the estimated garnet compositions (see Chapter IX) and by the presence of accessory minerals, such as kyanite and diamond. Consequently both a diamondiferous and a kyanite-bearing eclogite were selected, in addition to selecting the least altered xenoliths representative of the different estimated garnet compositions.

The results of the major element analyses, carried out using the techniques described in Chapter VII, are listed in Table 10 (garnet peridotites), Table 11 (spinel peridotites) and Table 12 (eclogites). The X-ray fluorescence analyses were carried out by the staff of the X-ray Analytical Laboratory and the wet-chemical analyses by the Analytical Section, both of Anglo American Research Laboratory.

It is immediately apparent from these analyses that the peridotites have a very restricted range of composition whilst the eclogites show a much greater range. The results of a semi-quantitative trace element analysis of these xenoliths are presented in Tables 20 and 21.

TABLE 10.

CHEMICAL ANALYSES OF SELECTED GARNET PERIDOTITE XENOLITHS[*]

	BF.2	BF.5	BF.8	BF.9	W.9	W.10	DT.7	DT.8	RV.16
SiO_2	41.17	42.97	43.83	45.46	46.61	44.15	45.31	45.51	44.56
TiO_2	0.05	0.05	0.03	0.04	0.05	0.11	0.09	0.04	0.08
Al_2O_3	1.08	0.78	1.29	1.19	0.60	1.04	1.56	1.47	1.48
Cr_2O_3	0.31	0.23	0.18	0.23	0.18	0.17	0.19	0.21	0.20
Fe_2O_3	0.91	2.75	2.23	1.73	1.62	1.58	1.83	1.17	1.83
FeO	5.66	4.25	4.58	4.47	4.81	4.83	4.29	4.81	4.74
MnO	0.11	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.11
NiO	0.32	0.34	0.32	0.32	0.34	0.34	0.31	0.31	0.32
MgO	44.01	41.96	41.30	41.60	42.24	41.19	41.62	41.90	41.31
CaO	0.82	0.51	0.54	0.49	0.85	0.46	0.78	0.69	0.91
K_2O	0.13	0.22	0.07	0.07	0.12	0.12	0.17	0.10	0.14
Na_2O	0.44	0.35	0.09	0.12	0.24	0.18	0.11	0.12	0.11
P_2O_5	0.01	<0.01	<0.01	0.01	0.03	<0.01	0.02	-	0.04
H_2O^+	3.52	4.73	3.91	2.44	1.33	3.38	2.59	3.18	3.02
H_2O^-	0.42	0.66	0.64	0.51	0.33	0.63	0.62	0.78	0.59
CO_2	0.38	0.22	0.20	0.20	0.12	0.28	0.22	0.17	0.21
	99.34	100.12	99.32	98.99	99.58	98.57	99.82	100.57	99.65

[*] Analyses by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

TABLE II.

CHEMICAL ANALYSES OF SELECTED SPINEL PERIDOTITE XENOLITHS*

	BF.10	W.4	DT.4	RV.12
SiO_2	45.46	41.93	39.78	42.63
TiO_2	0.03	0.03	0.11	0.18
Al_2O_3	1.37	0.80	0.07	0.36
Cr_2O_3	0.29	0.17	0.10	0.16
Fe_2O_3	2.55	1.22	2.36	2.06
FeO	3.88	4.49	3.24	4.51
MnO	0.10	0.09	0.08	0.09
NiO	0.31	0.33	0.35	0.34
MgO	42.19	42.44	42.61	43.80
CaO	0.48	0.42	0.43	0.78
K_2O	0.04	0.05	0.10	0.30
Na_2O	0.07	0.09	0.07	0.16
P_2O_5	<0.01	<0.01	0.05	0.05
H_2O^+	3.01	3.55	7.44	4.06
H_2O^-	0.45	0.72	1.27	0.73
CO_2	0.16	0.23	0.39	0.37
	100.39	96.56	98.45	101.03

* Analyses by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

TABLE 12.

CHEMICAL ANALYSES OF SELECTED ECLOGITE XENOLITHS*

	RV.1	RV.4	RV.5	RV.6	RV.8	RV.10	RV.32	RVL.5	RVL.10
SiO_2	43.43	45.89	43.12	42.27	46.13	43.93	44.90	46.40	46.89
TiO_2	0.32	0.32	0.30	0.46	0.31	0.20	0.27	0.37	0.48
Al_2O_3	18.19	18.89	18.30	22.16	13.64	14.23	15.26	15.09	12.58
Cr_2O_3	0.06	0.08	0.08	0.03	0.09	0.13	0.06	0.08	0.08
Fe_2O_3	2.57	3.94	1.68	1.18	4.63	2.37	4.11	2.51	3.79
FeO	9.08	5.37	10.37	6.63	8.83	5.22	9.39	10.12	8.07
MnO	0.28	0.15	0.29	0.25	0.53	0.17	0.26	0.27	0.24
NiO	0.05	0.03	0.03	0.02	0.04	0.07	0.03	0.04	0.04
MgO	12.79	11.81	12.99	6.51	13.66	16.26	9.63	13.16	12.17
CaO	8.47	8.48	8.27	9.75	9.36	13.25	11.82	8.49	10.79
K_2O	0.47	0.63	0.39	0.70	0.41	0.87	0.28	0.54	0.23
Na_2O	1.27	1.89	1.00	4.31	2.13	0.82	2.43	1.40	2.40
P_2O_5	0.05	0.02	-	0.01	0.01	0.03	-	<0.01	0.01
H_2O^+	0.62	1.12	0.41	2.12	1.03	1.21	0.47	0.19	0.47
H_2O^-	0.39	1.04	0.27	0.77	0.80	0.51	0.30	0.26	0.30
CO_2	0.30	0.08	0.08	0.39	0.08	0.19	0.21	0.21	0.07
	98.34	99.74	97.58	97.56	101.68	99.46	99.42	99.13	98.61

* Analyses by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

C.I.P.W. norms and Niggli values, calculated from the major element analyses using conventional methods (Burri, 1964) are compared in Table 13 (garnet peridotites), Table 14 (spinel peridotites) and Table 15 (eclogites). As both the eclogite and peridotite xenoliths have been subjected to appreciable changes, both within the kimberlite and after extraction from it, as is witnessed by the development of secondary hydrated minerals and carbonates, it was considered that to obtain a more realistic impression of their original chemical composition the chemical analyses should be recalculated on a water- and carbon dioxide-free basis. Recalculated analyses of the garnet and spinel peridotites are found in Tables 16 and 17 respectively and those of the eclogites in Table 18. All diagrams used in illustrating the chemistry of these rocks have been prepared using the adjusted values; figures quoted in the discussion of the petrochemistry are similarly based on the recalculated values and not on the original analyses. Table 19 summarises the essential chemical data, giving the average chemical composition of the peridotites and eclogites and indicating the compositional range for all types.

C.I.P.W. norms and Niggli values.

According to the C.I.P.W. norms calculated from the original analyses (shown in Tables 13 to 15) all the garnet and spinel peridotites are enstatite and olivine normative and consequently fall into the undersatured olivine tholeiite field (Yoder and Tilley, 1962, Fig. 2). Complete melting of the peridotites would thus form a picritic basaltic liquid. An inspection of the eclogite norms shows that most of them are also enstatite and olivine normative (and hence they similarly fall into the olivine tholeiite field) but three specimens are olivine and nepheline normative, which places them in the alkalic basaltic field. The presence of corundum in the norms of many of the peridotites and eclogites suggests a relationship to the high-alumina basalts, but it is interesting to note that two spinel peridotites contain normative acmite reflecting a deficiency of alumina.

The eclogite norms are also characterised by high diopside, anorthite and albite values whilst values for the peridotites are low or even zero. The forsterite/fayalite ratio of the peridotites is high compared with that of the eclogites (indicating that magnesium greatly exceeds iron in the peridotites)

TABLE 13.

C.I.P.W. NORMS AND NIGGLI VALUES OF THE ANALYSED GARNET PERIDOTITE XENOLITHS.*

	BF.2	BF.5	BF.8	BF.9	W.9	W.10	DT.7	DT.8	RV.16
(A)	C.I.P.W. NORMS.								
or	0.56	1.11	0.56	0.56	0.56	0.56	1.11	0.56	0.56
ab	3.14	3.14	0.52	1.05	2.10	1.57	1.05	1.05	1.05
an	1.11	-	1.11	1.11	0.28	0.28	2.50	2.50	3.06
di	0.22	0.86	-	-	2.63	-	-	-	-
en	9.80	23.30	32.80	35.90	33.00	32.00	33.10	33.00	31.00
of	0.79	1.19	2.11	2.24	2.38	2.38	1.98	2.38	2.11
fo	69.44	56.28	48.72	47.18	49.56	49.14	49.14	49.70	49.98
fa	6.73	3.26	3.47	3.26	3.88	4.06	3.26	3.88	3.88
mt	1.39	4.18	3.25	2.55	2.32	2.32	2.78	2.55	2.55
il	0.15	0.15	0.15	-	0.15	0.15	0.15	-	0.15
cc	0.90	0.50	0.50	0.50	0.20	0.70	0.50	0.30	0.50
C	-		0.71	0.51	-	0.51	0.31	0.31	0.10
(B)	NIGGLI VALUES.								
al	0.89	0.68	1.12	1.04	0.51	0.87	1.37	1.26	1.29
fm	97.40	97.88	97.93	97.93	97.79	98.09	97.09	97.45	97.08
c	1.14	0.76	0.78	0.78	1.27	0.70	1.20	1.02	1.37
alk	0.57	0.68	0.17	0.26	0.42	0.35	0.34	0.26	0.26
si	55.60	60.61	62.95	65.37	65.82	63.91	64.61	64.46	63.75
mg	0.91	0.90	0.90	0.91	0.91	0.91	0.91	0.91	0.91
k	0.14	0.25	0.50	0.33	0.20	0.33	0.50	0.33	0.33
ti	0.08	0.08	0.09	-	0.08	0.09	0.09	-	-
qz	-46.7	-42.1	-37.7	-35.7	-35.5	-36.8	36.6	-36.6	-37.3
$^{c}/fm$	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

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* Calculated from data given in Table 10.

TABLE 14.

C.I.P.W. NORMS AND NIGGLI VALUES OF THE ANALYSED SPINEL PERIDOTITE XENOLITHS.*

	BF.10	W.4	DT.7	RV.12
(A) C.I.P.W. NORMS.				
o~~f~~	-	0.56	0.56	1.67
ab	0.52	1.05	-	0.52
an	1.67	0.28	-	-
di	-	-	-	0.65
ac	-	-	0.46	0.92
en	38.10	23.60	20.70	20.30
of	1.72	1.58	0.92	1.19
fo	46.62	57.26	59.50	61.60
fa	2.45	4.28	2.86	4.08
mt	3.71	1.86	3.25	2.55
il	-	-	0.15	0.46
cc	0.30	0.60	0.50	0.80
ap	-	-	0.34	0.34
C	0.71	0.41	-	-
(B) NIGGLI VALUES.				
al	1.19	0.69	0.09	0.33
fm	97.95	98.46	99.05	98.03
c	0.77	0.60	0.69	1.14
alk	0.09	0.26	0.17	0.49
si	64.54	59.81	57.06	58.24
mg	0.91	0.92	0.92	0.91
k	-	0.33	0.50	0.50
ti	-	-	0.09	0.25
qz	-35.8	41.2	-43.5	-43.2
c/fm	0.01	0.01	0.01	0.01

* Calculated from data given in Table 11.

TABLE 15.

C.I.P.W. NORMS AND NIGGLI VALUES OF THE ANALYSED ECLOGITE XENOLITHS.*

	RV.1	RV.4	RV.5	RV.6	RV.8	RV.10	RV.32	RVL.5	RVL.10
(A) C.I.P.W. NORMS.									
or	2.78	3.34	7.23	3.89	2.22	5.00	1.67	2.78	1.11
ab	10.48	16.24	8.38	13.10	17.82	2.10	15.72	12.05	20.44
ne	-	-	-	12.50	-	2.56	2.56	-	-
an	39.20	41.14	40.31	34.47	26.41	32.53	30.02	33.36	23.07
di	-	0.43	-	8.48	15.60	25.04	21.88	6.05	24.07
en	11.80	12.60	4.00	-	4.60	-	-	14.80	2.20
of	5.28	2.64	2.11	-	1.58	-	-	7.13	0.79
fo	14.00	11.62	19.74	6.73	16.66	21.14	12.04	11.06	13.72
fa	6.94	2.65	11.63	13.10	6.73	4.08	7.34	6.12	5.51
mt	3.71	5.57	2.55	1.86	6.73	3.48	6.03	3.71	5.57
il	0.61	0.61	0.61	0.91	0.61	0.46	0.61	0.76	0.91
cc	0.70	0.20	0.20	0.90	0.20	0.50	0.50	0.50	0.20
ap	0.34	-	-	-	-	-	-	-	-
C	1.33	-	0.61	1.84	-	-	-	-	-
(B) NIGGLI VALUES.									
al	21.23	23.10	21.00	29.11	15.18	15.17	17.94	14.89	17.64
fm	57.89	53.31	58.46	37.52	61.42	56.66	51.91	57.02	60.90
c	17.91	18.98	17.15	23.23	19.06	25.76	25.12	23.17	18.12
alk	2.97	4.62	3.38	10.15	4.38	2.40	5.02	4.92	3.34
si	85.77	95.38	83.78	93.99	87.67	79.80	89.47	93.76	92.13
mg	0.74	0.69	0.64	0.57	0.63	0.78	0.55	0.63	0.64
k	0.20	0.16	0.45	0.09	0.11	0.41	0.07	0.05	0.17
ti	0.47	0.50	0.51	0.80	0.46	0.33	0.48	0.72	0.60
qz	-26.1	-23.1	-29.7	-46.6	-29.9	-29.8	-30.6	-25.9	-21.2
c/fm	0.31	0.36	0.29	0.62	0.31	0.45	0.48	0.41	0.30

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* Calculated from data given in Table 12.

TABLE 16.

RECALCULATED* CHEMICAL ANALYSES OF THE GARNET PERIDOTITE XENOLITHS.

	BF.2	BF.5	BF.8	BF.9	W.9	W.10	DT.7	DT.8	RV.16
SiO_2	43.33	45.47	46.35	47.43	47.66	46.83	47.00	47.19	46.50
TiO_2	0.05	0.05	0.03	0.04	0.05	0.12	0.09	0.04	0.08
Al_2O_3	1.14	0.83	1.36	1.24	0.61	1.10	1.62	1.52	1.54
Cr_2O_3	0.33	0.24	0.19	0.24	0.18	0.18	0.20	0.22	0.21
Fe_2O_3	0.96	2.91	2.36	1.81	1.66	1.68	1.90	1.21	1.91
FeO	5.96	4.50	4.84	4.66	4.92	5.12	4.45	4.99	4.95
MnO	0.12	0.10	0.12	0.11	0.11	0.12	0.11	0.11	0.11
NiO	0.34	0.36	0.34	0.33	0.35	0.36	0.32	0.32	0.33
MgO	46.31	44.10	43.67	43.41	43.19	43.69	43.18	43.45	43.11
CaO	0.86	0.54	0.57	0.51	0.87	0.49	0.81	0.72	0.95
K_2O	0.14	0.23	0.07	0.07	0.12	0.13	0.18	0.10	0.15
Na_2O	0.46	0.37	0.10	0.13	0.25	0.19	0.11	0.12	0.11
P_2O_5	0.01	<0.01	<0.01	0.01	0.03	<0.01	0.02	-	0.04
$FeO:Fe_2O_3$	6.21	1.55	2.05	2.57	2.96	3.05	2.34	4.12	2.59
FeO**	6.82	7.12	6.96	6.29	6.41	6.63	6.16	6.08	6.67
MgO:FeO**	6.79	6.24	6.27	6.90	6.74	6.59	7.01	7.15	6.46

* Recalculated to 100.0% after elimination of all H_2O and CO_2.

** Total iron expressed as FeO.

TABLE 17.

RECALCULATED* CHEMICAL ANALYSES OF THE SPINEL PERIDOTITE XENOLITHS.

	BF.10	W.4	DT.4	RV.12
SiO_2	46.98	45.54	44.52	44.68
TiO_2	0.03	0.03	0.12	0.19
Al_2O_3	1.42	0.87	0.08	0.38
Cr_2O_3	0.30	0.18	0.11	0.17
Fe_2O_3	2.64	1.32	2.64	2.16
FeO	4.01	4.88	3.63	4.73
MnO	0.10	0.10	0.09	0.09
NiO	0.32	0.36	0.39	0.36
MgO	43.60	46.10	47.69	45.90
CaO	0.50	0.46	0.48	0.82
K_2O	0.04	0.05	0.11	0.31
Na_2O	0.07	0.10	0.08	0.17
P_2O_5	<0.01	<0.01	0.06	0.05
$FeO:Fe_2O_3$	1.52	3.70	1.38	2.19
FeO**	6.39	6.07	6.01	6.67
MgO:FeO**	6.82	7.59	7.94	6.88

* Recalculated to 100.0% after elimination of all H_2O and CO_2.

** Total iron expressed as FeO.

TABLE 18.

RECALCULATED* CHEMICAL ANALYSES OF THE ECLOGITE XENOLITHS.

	RV.1	RV.4	RV.5	RV.6	RV.8	RV.10	RV.32	RVL.5	RVL.10
SiO_2	44.76	47.07	44.54	44.83	46.24	45.03	45.61	47.12	47.96
TiO_2	0.33	0.33	0.31	0.49	0.31	0.21	0.27	0.38	0.49
Al_2O_3	18.75	19.37	18.90	23.50	13.67	14.59	15.50	15.32	12.87
Cr_2O_3	0.06	0.08	0.08	0.03	0.09	0.13	0.06	0.08	0.08
Fe_2O_3	2.65	4.04	1.74	1.25	4.64	2.43	4.18	2.55	3.88
FeO	9.36	5.51	10.71	7.03	8.85	5.35	9.54	10.28	8.25
MnO	0.29	0.15	0.30	0.27	0.53	0.17	0.26	0.27	0.25
NiO	0.05	0.03	0.03	0.02	0.04	0.07	0.03	0.04	0.04
MgO	13.18	12.11	13.42	6.90	13.69	16.67	9.78	13.36	12.45
CaO	8.73	8.70	8.54	10.34	9.38	13.58	12.01	8.62	11.04
K_2O	0.48	0.65	0.40	0.74	0.41	0.89	0.28	0.55	0.24
Na_2O	1.31	1.94	1.03	4.57	2.13	0.84	2.47	1.42	2.45
P_2O_5	0.05	0.02	-	0.01	0.01	0.03	-	<0.01	0.01
$FeO:Fe_2O_3$	3.53	1.36	6.16	5.62	1.91	2.20	2.28	4.03	2.13
FeO**	11.74	9.15	12.28	8.15	13.03	7.54	13.30	12.57	11.74
MgO:FeO**	1.12	1.32	1.09	0.85	1.05	2.21	0.74	1.06	1.06

* Recalculated to 100.0% after elimination of all H_2O and CO_2.

** Total iron expressed as FeO.

but in the case of the kyanite-bearing eclogite (RV.6) normative fayalite actually exceeds forsterite. The presence of olivine in all the norms indicates that they are all undersaturated with respect to silica.

The Niggli values show that the al, alk and c values for the peridotites are all very low, with a consequent very high fm value (usually >97). The high mg values indicate the magnesium-rich nature of these rocks and the negative qz values shows their undersaturated nature. A study of the Niggli values for the eclogites shows that whilst fm is still predominant both al and c are appreciable and a minor amount of alk is also evident. These Niggli values suggests that the rocks have an essentially basic composition.

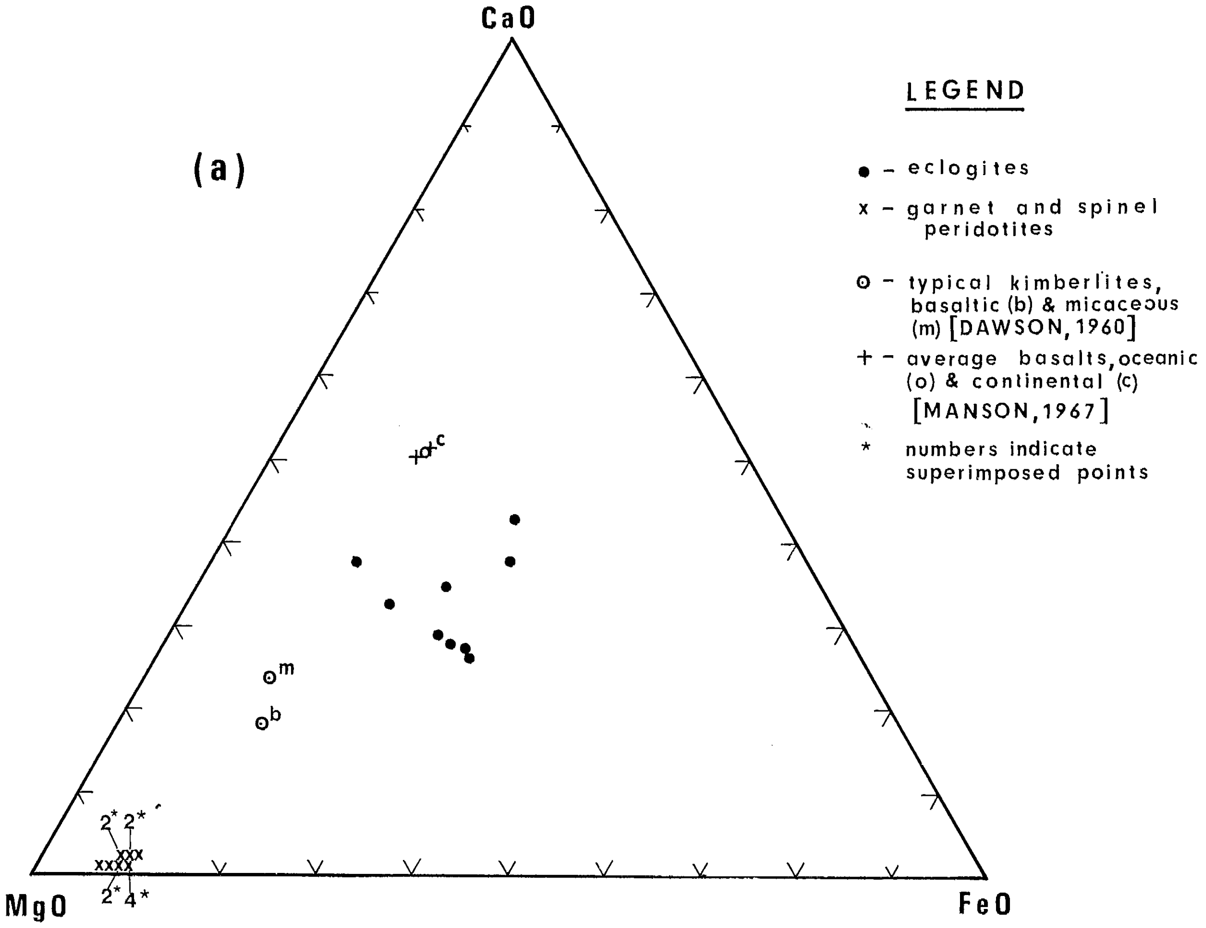
Diagrammatic representation of analyses.

Variations in the major element chemistry of the eclogite and peridotite specimens can be adequately represented within a double tetrahedron, the apices corresponding to CaO, MgO, FeO, (Al_2O_3 + Fe_2O_3) and (Na_2O + K_2O), as shown in Fig. 11(b). The range in silica content of the rocks is so small that it need not be considered. The variation of any three-component system within the double tetrahedron can be illustrated by projecting the values onto the relevant triangular face. In this way the variation in the amounts of the following components have been selected for projection and appear in the figures shown. The method of plotting is that used for normal triangular diagrams, the sum of the three selected components being recalculated proportionately to total 100 per cent and plotted on an equilateral triangle. (Burri, 1964, p.21).

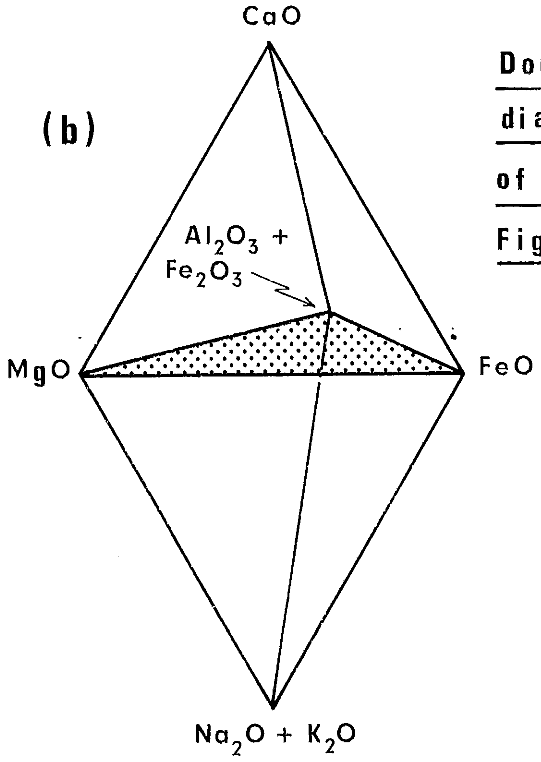
Mgo - Feo - CaO : Fig. 11(a).
Mgo - FeO - (Na_2O + K_2O) : Fig. 12(a).
Mgo - Feo - (Al_2O_3 + Fe_2O_3) : Fig. 12(b).

In all three triangular variation diagrams the very restricted chemical composition of the peridotites is clearly shown and no distinction can be made between the garnet- and spinel-bearing types. The composition of the peridotites is in fact so similar that certain values are superimposed on each other in the triangular diagrams. The variation in the eclogites, however, is much wider but it is difficult to detect any distinct trends. Whilst the majority of the eclogite analyses plot within a fairly small area a number of them consistently fall outside

FIG. 11

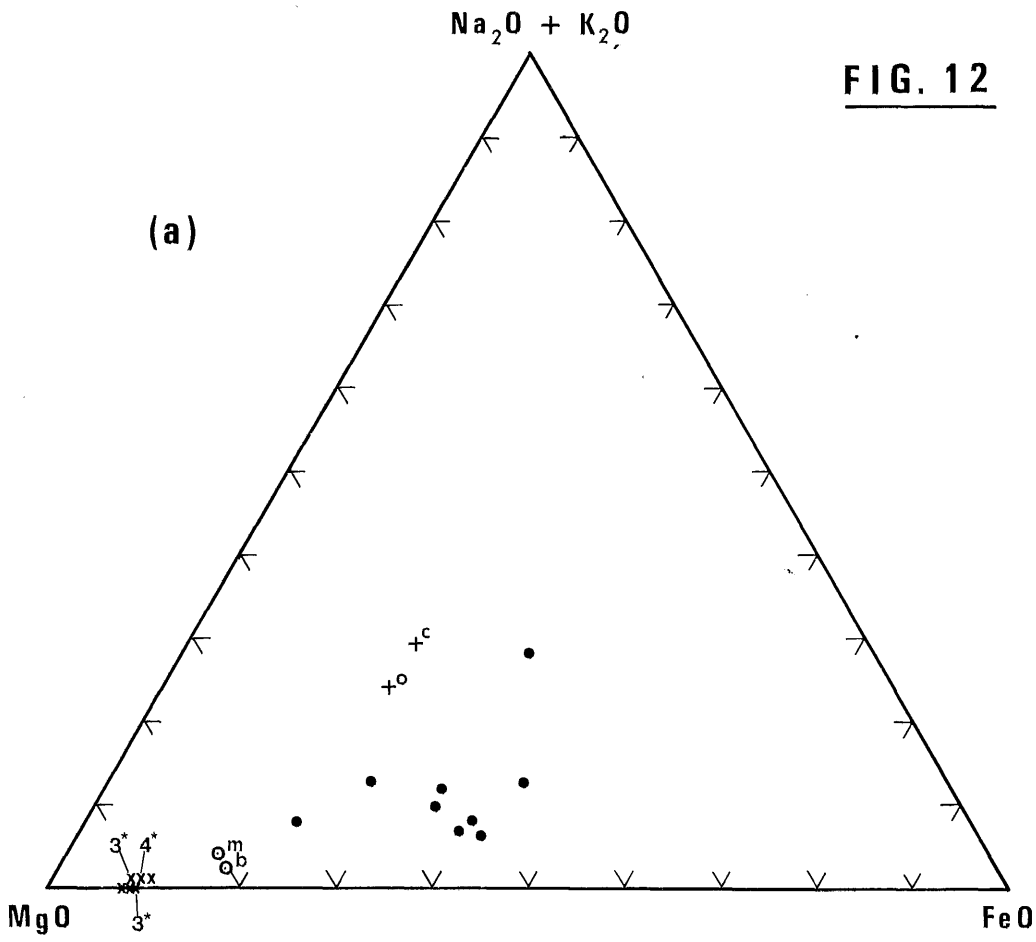


Variation in the MgO, FeO and CaO content of the Eclogite and Peridotite Xenoliths

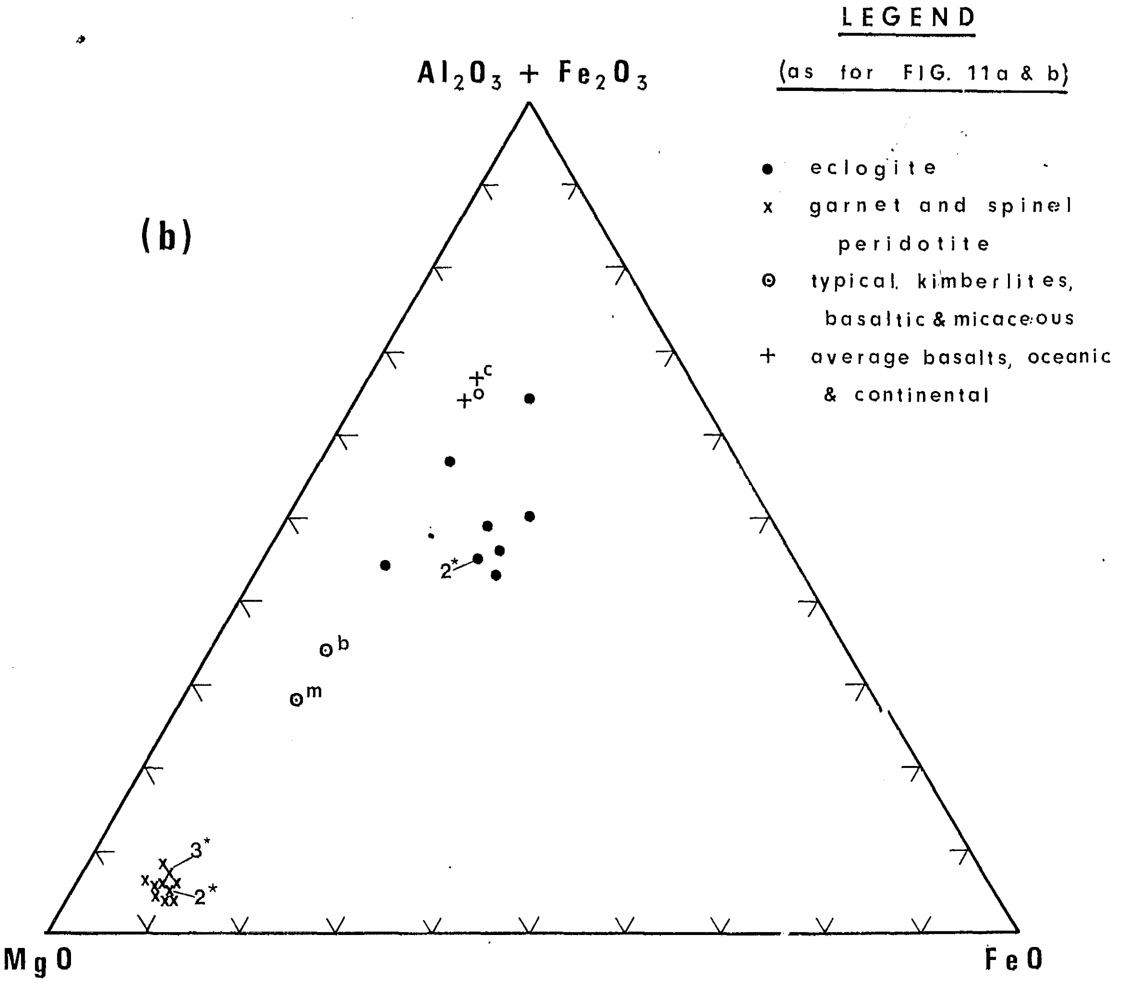


Double tetrahedron used for the diagrammatic representation of the analyses (as shown in Figs. 11a & 12)

FIG. 12



Variation in the MgO, FeO and $Na_2O + K_2O$ content of the Eclogite and Peridotite Xenoliths



Variation in the MgO, FeO and $Al_2O_3 + Fe_2O_3$ content of the Eclogite and Peridotite Xenoliths this area and perhaps constitue a number of chemically distinct eclogite-types. Before any definite conclusions along these lines can be made many more analyses of all types of eclogite derived from kimberlite will be required. On the triangular diagrams the variations apparent in several other rock types are shown for comparative purposes. These include average continental and oceanic basalts (Manson, 1967, p.222) and typical basaltic and micaceous kimberlites (Dawson, 1960, Table 4).

Fig. 13 illustrates the variation in alkali:silica ratio for all specimens and, for comparative purposes, includes the value for average oceanic basalt. Typical kimberlites and average continental basalt cannot be shown due to the restricted silica range. From this diagram, using the line defining the boundary between the alkalic and tholeiitic fields taken from the alkali:silica diagram of Macdonald and Katsura (1964, p.87) the bulk of the eclogites fall within the tholeiitic field, only two specimens being alkalic. All the peridotites plot in the tholeiitic field. This supports a similar conclusion made from a study of the C.I.P.W. norms.

Shown in Fig. 14 is the variation in MgO and FeO. In this case the FeO represents the total iron, i.e. ferrous iron plus ferric iron recalculated as ferrous. The clustering of the peridotites is a conspicuous feature whilst the eclogites cover a much larger area and show a wider distribution.

An attempt at illustrating the petrochemistry using the Niggli values proved to be of no more value than the diagrams already shown. Plotting the values on the al-alk-c-fm tetrahedron showed that the peridotites clustered tightly around the fm apex and the eclogites in a relatively small area nearby. In general the similarity of composition between the various types of eclogite and peridotite and the absence of any consistent variations or trends makes these analyses rather unsuitable for diagrammatic representation.

Major and minor element variation.

The average compositions and compositional ranges of the peridotite specimens can be found in Table 19 and these results are represented graphically in Fig. 15. These figures are based on the recalculated analyses found in Tables 16, 17 and 18. Individual major and minor elements are dealt with briefly in the following sections. Where comparisons with element abundances of other igneous

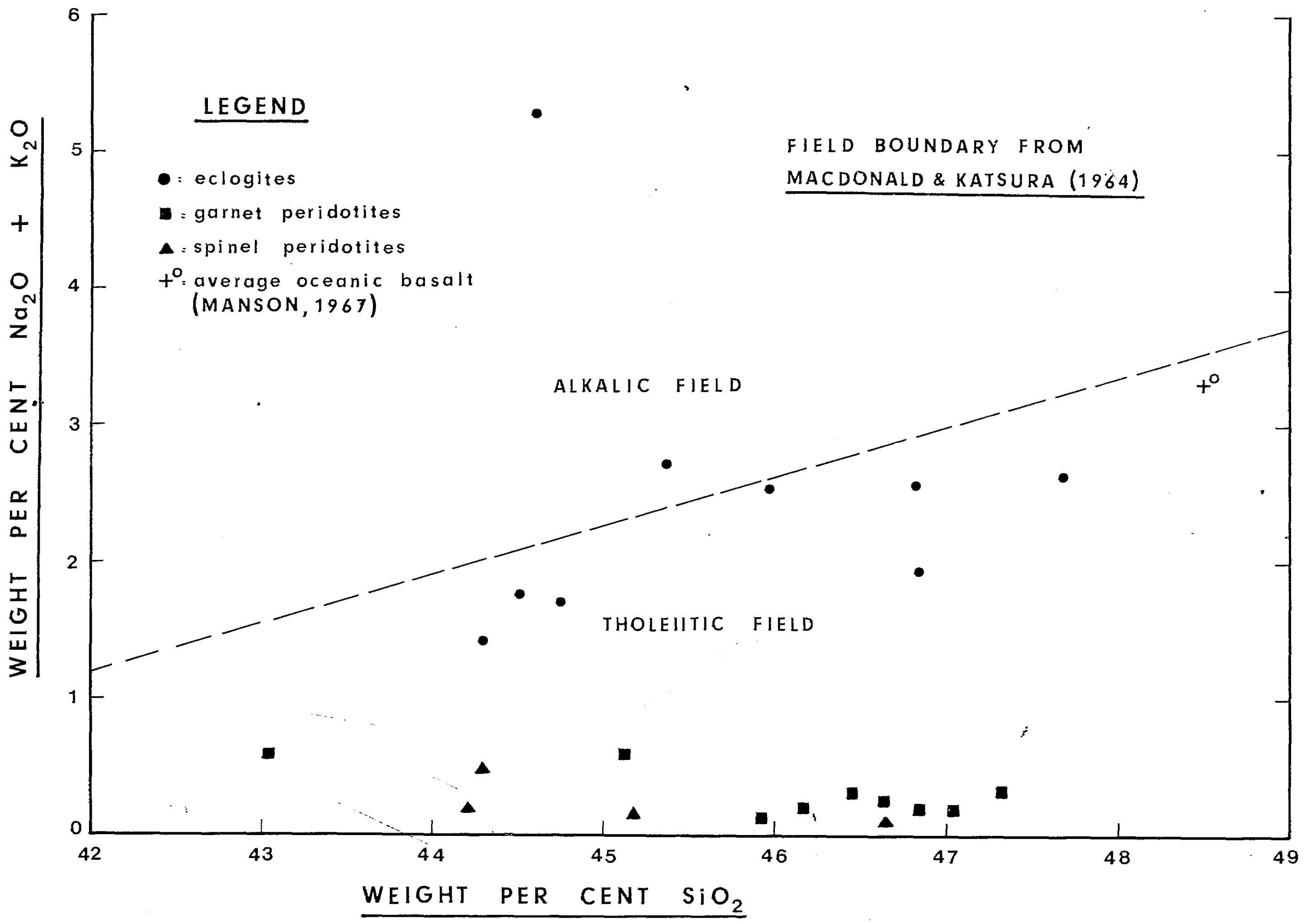


FIG. 13

THE VARIATION IN THE ALKALI : SILICA RATIO FOR THE ECLOGITE AND PERIDOTITE XENOLITHS

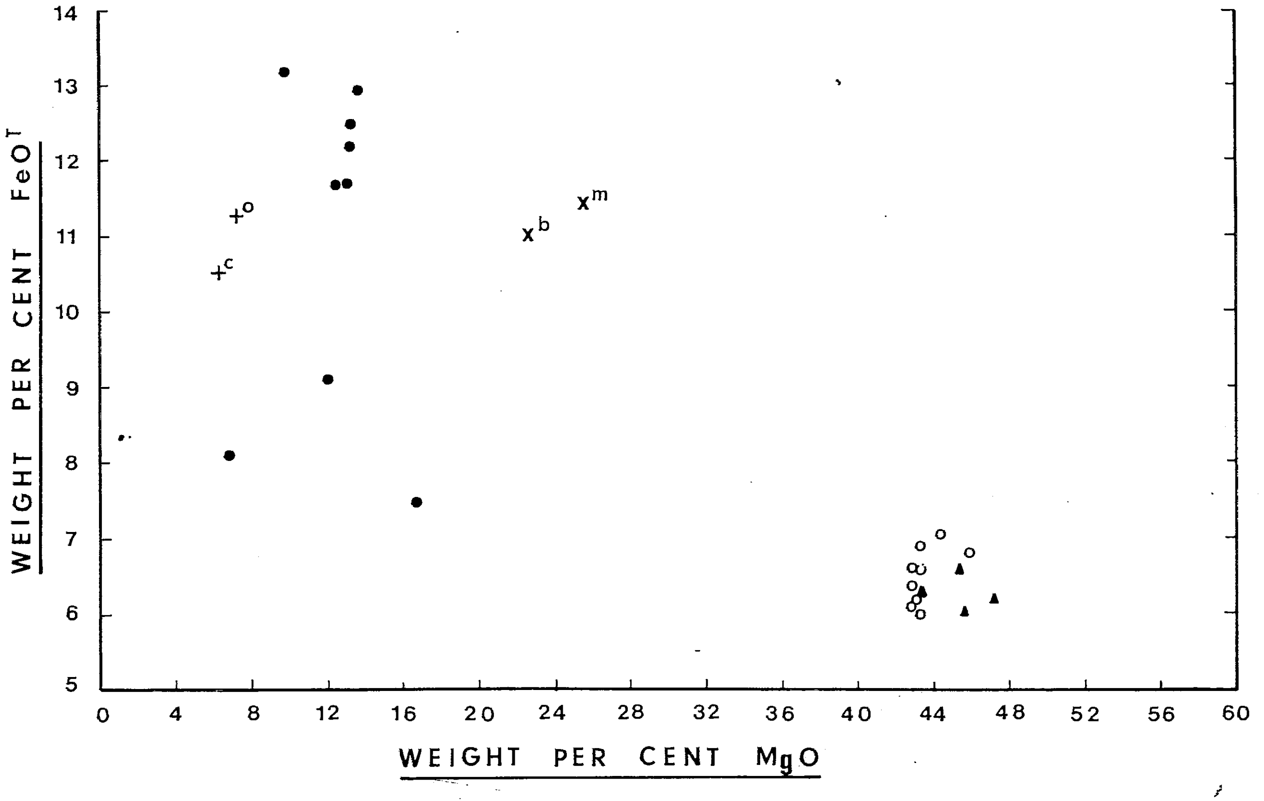


FIG. 14

THE VARIATION IN THE MgO : FeO^T RATIO FOR THE ECLOGITE AND PERIDOTITE XENOLITHS

(FeO^T = Total iron as FeO)

rock-types are made, the values adopted are those listed by Dawson (1967b, p.271 and 273).

Silica. Both the peridotites and eclogites are undersatured rocks, as shown by the presence of olivine and nepheline in the C.I.P.W. norms and the negative qz Niggli values. The amount of silica is surprisingly similar in both peridotites and eclogites and the range relatively small. The amount of silica in these rocks, is however, appreciably higher than in their host, kimberlite.

Titania. This element is found in only trace amounts in the peridotites and in most cases does not exceed 0.1 per cent. Strictly, it should be regarded as a trace element. In the eclogites the average titania content is 0.33 per cent but comes nowhere near the values reported for kimberlite, which are of the order of two per cent. Indications are therefore that kimberlite is not the product of complete melting of either peridotite or eclogite.

Alumina. In the peridotites alumina occurs in only minor amounts, generally of the order of one per cent, a figure considerably less than that found in kimberlites. The garnet peridotites appear to be slightly enriched in alumina compared to the spinel peridotites and this is probably reflected in the presence of garnet. Alumina forms a major constituent of the eclogites and shows a considerable range from approximately 13 per cent to 19 per cent. As would be expected, the kyanite-bearing specimen is unusually rich in alumina, exceeding 23 per cent. The average alumina content of the eclogites (excluding the kyanite eclogite) is similar to that of basic and intermediate rocks, the average alumina content of the peridotites is approximately that found in ultrabasic rocks.

Chromia. This element is usually present in minor amounts in ultrabasic rocks (~ 2400 ppm Cr; Goles, 1967) and in trace amounts in basic rocks (~ 200 ppm Cr; Dawson, 1967b). The chromia contents of both the peridotites (average, 0.2 per cent Cr_2O_3) and the eclogites (average, 0.08 per cent Cr_2O_3) are approximately in keeping with those of ultrabasic and basic rocks respectively, whilst the range of chromia content in both the peridotites and eclogites does not generally exceed 0.1 per cent Cr_2O_3. Comparison of the chromia values with those of other analysed peridotite xenoliths (O'Hara and Mercy, 1963; Carwell and Dawson, 1970) and eclogite xenoliths (Kushiro and Aoki, 1968) show that they are of the same order, but slightly lower. The chromia content of the peridotite xenoliths are also similar to those for kimberlite. The chrome is present in the form of chrome diopside, chrome-rich garnet, chrome spinel and to a lesser extent in the orthopyroxene.

Ferric and ferrous iron. The amount of total iron in the peridotites (expressed as FeO) is remarkably constant, ranging from approximately six per cent to seven per cent. The spinel peridotites appears to contain slightly less iron than the garnetiferous type. In the peridotites ferric iron varies over a slightly wider range, this being thought to be mainly due to varying degrees of alteration. No consistent variation in $FeO:Fe_2O_3$ ratio of the peridotites nor eclogites is apparent, values ranging from 1.36 to 6.21. On the other hand, compared with the peridotites, the eclogites show a much wider range both in total iron content (from approximately 7 per cent to 13 per cent) and in the amount of ferric iron. The total iron content of the peridotites is appreciably less than that quoted by Dawson (1967b) for ultrabasic rocks (12.6 per cent FeO) but the eclogites contain approximately the same amount of iron as basic rocks (10.9 per cent).

Magnesia. Magnesia constitutes approximately 43 to 47 per cent of the peridotites, with an average of 43 per cent for the garnetiferous rocks and 45 per cent for the spinel-bearing types. These figures match fairly well the magnesia content of ultrabasic rocks. Although the $MgO:FeO^*$ratios are exceptionally high, reflecting the relatively low iron content of the peridotites, they are consistently of the order of six to 7.5. The magnesia is accommodated mainly within the olivine and orthopyroxene. The magnesia content of the eclogites is considerably less than that of the peridotites but appreciably more than that typical of basic rocks. The average value is of the order of 13 per cent, whilst for the kyanite eclogite it is approximately seven per cent. The $MgO:FeO^*$ratio of the eclogites is considerably less than that of the peridotites and slightly larger than that for basic rocks. In the eclogites the magnesia occurs both within the garnets and the clinopyroxene. (NOTE: * indicates total iron expressed as FeO).

Lime. The amount of lime in the peridotites does not exceed one per cent whilst in the eclogites it averages 10 per cent. Both figures are much the same as the average amounts found in ultrabasic and basic rocks. The lime content of the eclogites is also similar to that found in kimberlites. As with magnesia, lime occurs within the garnet and clinopyroxene of the eclogites. The lime content of many of the xenoliths, particularly the peridotites, may have been enhanced by

TABLE 19.

AVERAGE CHEMICAL COMPOSITIONS AND COMPOSITIONAL RANGES OF THE PERIDOTITE AND ECLOGITE XENOLITHS.

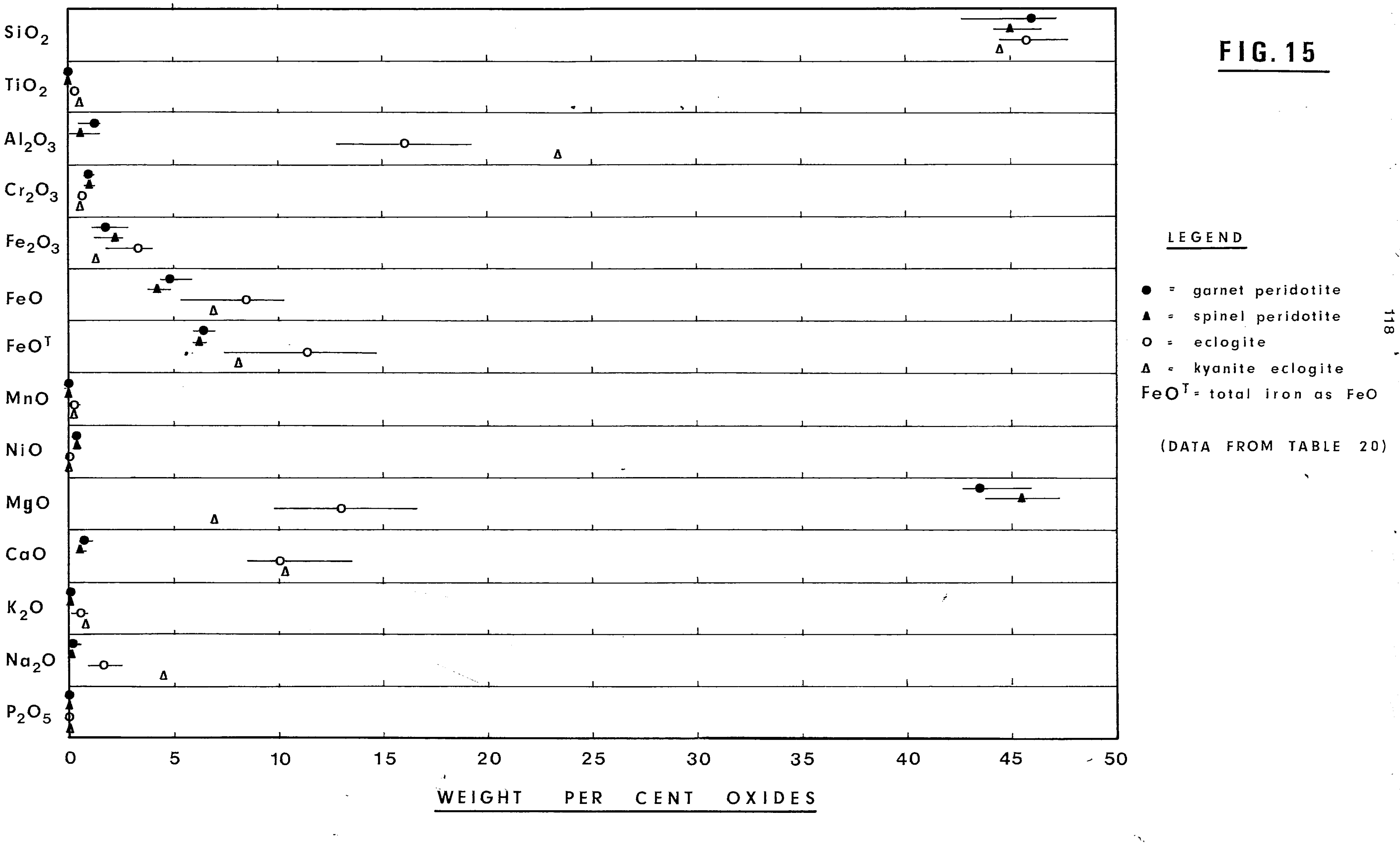
	Garnet peridotite (9 xenoliths)		Spinel peridotite (4 xenoliths)		Eclogite* (8 xenoliths)		Kyanite eclogite (1 xenolith)
	Average	Range	Average	Range	Average	Range	
SiO_2	46.42	44.33 - 47.66	45.43	44.52 - 46.98	46.04	44.54 - 47.96	44.83
TiO_2	0.06	0.03 - 0.12	0.09	0.03 - 0.19	0.33	0.21 - 0.49	0.49
Al_2O_3	1.22	0.83 - 1.62	0.68	0.08 - 1.42	16.12	12.87 - 19.37	23.50
Cr_2O_3	0.25	0.18 - 0.33	0.19	0.11 - 0.30	0.08	0.06 - 0.13	0.03
Fe_2O_3	1.82	1.21 - 2.91	2.19	1.32 - 2.64	3.26	1.74 - 4.64	1.25
FeO	4.93	4.45 - 5.96	4.31	3.63 - 4.88	8.49	5.35 - 10.71	7.03
MnO	0.11	0.10 - 0.12	0.10	0.09 - 0.10	0.28	0.15 - 0.53	0.27
NiO	0.34	0.32 - 0.36	0.36	0.32 - 0.39	0.04	0.03 - 0.07	0.02
MgO	43.82	43.11 - 46.31	45.82	43.60 - 47.69	13.08	9.78 - 13.69	6.90
CaO	0.70	0.49 - 0.95	0.57	0.46 - 0.82	10.08	8.54 - 13.58	10.34
K_2O	0.13	0.07 - 0.23	0.13	0.04 - 0.31	0.49	0.24 - 0.89	0.74
Na_2O	0.20	0.10 - 0.46	0.11	0.07 - 0.17	1.70	0.84 - 2.47	4.57
P_2O_5	0.01	Nil - 0.04	0.03	<0.01 - 0.06	0.02	Nil - 0.05	0.01
$FeO:Fe_2O_3$	2.71	1.55 - 6.21	1.97	1.38 - 2.19	2.60	1.36 - 6.16	5.62
FeO*	6.57	6.08 - 7.12	6.28	6.01 - 6.67	11.42	7.54 - 13.30	8.15
MgO:FeO**	6.67	6.24 - 7.15	7.30	6.82 - 7.94	1.15	0.74 - 2.21	0.85

* Kyanite-bearing eclogite (RV.6) excluded

** Total iron expressed as FeO.

Diagrammatic comparison of the major element composition of the "average" Peridotite and Eclogite Xenoliths

FIG. 15



the presence of secondary calcite.

Alkalis. Alkalis are present in only minor to trace amounts in the peridotites, soda being approximately equal to or in excess of potash and both being more or less of the order of that found in ultrabasic rocks. The low potash content of the peridotites contrasts with the relatively high potash content of kimberlite (approximately one to two per cent). Some potash is evidently of secondary origin and was probably introduced into the peridotites in the form of phlogopite. The eclogites contain a much larger amount of soda, averaging 1.7 per cent for the garnet-clinopyroxene rocks and 4.60 per cent for kyanite-bearing type. Potash is also much more abundant in the eclogites, averaging about 0.5 per cent.

Phosphate. This constituent is either absent or present in only trace amounts. It is probably of secondary origin having been introduced by the kimberlite.

Volatiles. All peridotite analyses show an unusually high volatile content, predominantly in the form of water but including a minor amount of carbon dioxide. As no primary water-bearing minerals occur in the peridotites (except possibly for minor amounts of phlogopite in some specimens) the bulk of water occurs in the secondary serpentine and was probably introduced during the period of kimberlite intrusion. The eclogites contain much less water but a similar amount of carbon dioxide. They too contain no primary water-bearing minerals and as for the peridotites, a similar conclusion can be made.

Trace element content.

The results of semi-quantitative trace element analyses of the xenoliths are presented in Table 20 (peridotites) and Table 21 (eclogites). These analyses, except where indicated, were done by emission spectrographic techniques* and their accuracy is somewhat limited. It is estimated that the concentration of these elements ranges between twice the given value to one half of that value. The values for Ni, Cu and Zn, were determined by X-ray fluorescence techniques.**

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* Emission spectrographic analyses done by the Analytical Research Section, Anglo American Research Laboratory.

** X-ray fluorescence analyses done by the X-ray Analytical Laboratory, Anglo American Research Laboratory.

TABLE 20.

SEMI-QUANTITATIVE TRACE ELEMENT CONTENT OF THE PERIDOTITE XENOLITHS.+

(values in parts per million)

	B	Co	Ni*	Cu*	Zn*	Zr	Mo	Sn
BF.2	10	170	2520	50	45	25	10	10
BF.5	10	120	2710	30	45	20	8	10
BF.8	10	150	2505	30	40	20	1	10
BF.9	10	200	2495	65	45	30	<1	15
W.9	<10	150	2670	55	40	30	2	15
W.10	10	170	2640	85	40	35	<1	20
DT.7	<10	200	2400	40	40	25	<1	15
DT.8	<10	170	2500	50	40	30	<1	15
RV.16	10	200	2500	90	40	40	<1	30
BF.10	10	200	2430	35	40	25	1	20
W.4	10	170	2560	55	40	30	<1	20
DT.4	10	120	2755	40	40	20	1	10
RV.12	10	120	2655	55	45	35	<1	15
Limit of detection	10	10	5	5	5	10	1	10

In all peridotite specimens

Li < 50
Be < 0.5
V < 50
Ge < 10
As <100
Sr < 10
Y < 10
Nd < 10
Ag < 0.1

Cd < 10
Sb < 10
Ba <100
La <100
Pt < 50
Au < 5
Pb < 10
Bi < 5

* Quantitative values, determined by X-ray fluorescence techniques.

\+ Analyses by Analytical Research Section and X-ray Analytical Laboratory, Anglo American Research Laboratory.

TABLE 21.

SEMI-QUANTITATIVE TRACE ELEMENT CONTENT OF THE ECLOGITE XENOLITHS.+

	V	Co	Ni*	Cu*	Zn*	Sr	Y	Zr	Nb	Mo	Sn	Ba
RV.1	<50	200	380	90	55	60	<10	50	10	4	30	200
RV.4	<50	200	240	65	70	80	<10	40	<10	<1	20	170
RV.5	<50	250	210	40	60	90	<10	55	10	3	30	400
RV.6	<50	150	180	30	55	200	<10	45	<10	<1	20	700
RV.8	50	170	350	145	60	90	<10	50	<10	1	30	100
RV.10	<50	200	540	30	35	80	<10	45	<10	1	25	300
RV.32	<50	220	260	65	70	100	<10	60	<10	2	30	200
RVL.5	50	200	350	65	65	200	15	50	<10	1	25	220
RVL.10	<50	200	330	120	85	100	15	50	<10	1	25	150
Limits of detection	50	10	5	5	5	10	10	10	10	1	10	100

In all eclogite specimens:

Li	< 50	Sb	< 10
Be	<0.5	La	<100
B	< 10	Pt	< 50
Ge	< 10	Au	< 5
As	<100	Pb	< 10
Ag	<0.1	Bi	< 5
Cd	< 10		

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* Quantitative values, determined by X-ray fluorescence techniques.

\+ Analyses by Analytical Research Section and X-ray Analytical Laboratory, Anglo American Research Laboratory.

and can be regarded as quantitative (variation ± 10 parts per million). The results have been compared with the average trace element content of other rock-types, given by Dawson(1967b, p.273) and Gole's "average" ultrabasic rock (1967, p.354). The trace element contents of both the garnet and spinel peridotites show no consistent differences and are typical of those of ultrabasic rocks. This suite is characterised by high Ni, Cr and Co values. The relatively high Sn and, in some cases, Cu and Mo are probably due to instrumental errors inherent to the technique used.

The eclogites on the other hand show values more appropriate of basic rocks. Ni, Cr and Co are much lower than in the peridotites. Sr, Y, Zr and Nb values are consistently lower than those of basic rocks. An interesting feature shown by the peridotites and eclogites is that, in comparison with their host rock, kimberlite, they have exceptionally low Ba, Sr and Nb contents.

4. Summary and Discussion.

A. PERIDOTITES.

It has been shown that the garnet- and spinel-bearing peridotite xenoliths are phanerocrystalline, medium- to coarse-grained aggregates consisting essentially of a mosaic of primary olivine and orthopyroxene with minor amounts of one or more of garnet, clinopyroxene, spinel and possibly phlogopite. The non-garnetiferous peridotites always contain small amounts of spinel, either as discrete grains or as spinel-pyroxene symplectic intergrowths. The fabric of the peridotites is allotriomorphic and no textural differences between the two main types appears to exist.

The xenoliths are generally well-rounded, ellipsoidal in outline and often display a slight gneissose structure. Those xenoliths examined range considerably in size, from about 15 cm to 30 cm across their longest diameter. A characteristic feature of most of the peridotite xenoliths is the effects of tectonic deformation, either within the upper mantle or lower crust, this being reflected by recrystallisation of the olivine and the development of typical deformation phenomena such as kink bands, deformation lamellae, uneven optical extinction and possible inversion products.

Alteration of the xenoliths is shown by the presence of abundant secondary serpentine. In addition phlogopite, talc, carbonates, iron oxides, kelyphitic material and occasionally zeolites occur as alteration products. The alteration is considered to have taken place either during the intrusion of the kimberlite or by deep-weathering processes after intrusion.

In addition to the normal garnet and spinel peridotites a number of highly altered or unusual xenoliths have also been examined. These consist of completely recrystallised peridotites or xenoliths so extensively altered that their original mineralogical composition cannot be accurately assessed. One specimen contains an abnormally large amount of phlogopite, much of which may be primary, whilst another contains a very minor amount of ilmenite.

As has already been mentioned no significant textural differences exist between the spinel and garnet peridotites. This suggests that they have a similar origin, the only difference being whether the peridotite formed in a garnet-stable environment or not (see Chapters X and XI.) It is notable that the average specific gravity of the garnet peridotite xenoliths is 3.03, compared to that of spinel peridotites, 2.99. If the garnet and spinel peridotites are considered to represent upper mantle material originating from different depths this slight but very significant change in the average density of these two rock-types may have a marked effect on the variation of seismic velocity within the upper mantle.

A study of the results shows that all four kimberlite pipes sampled produced both spinel- and garnet-bearing types, although not always in the same amounts. A reliable frequency distribution of the two main peridotite types in the kimberlites will require that many more samples be examined (to constitute a representative collection). Ideally xenoliths should be collected in situ to eliminate any sampling bias but this is, as has been explained, virtually impossible.

Assuming that the xenoliths are samples of upper mantle material, it seems possible that beneath the Kimberley area of the African Shield the mantle consists of both garnet and spinel peridotite and that the garnetiferous type occurs at greater depth. Similar conclusions have been drawn from the results of experimental studies of the stability fields of garnet "pyrolite" (peridotite) and aluminous pyroxene plus spinel "pyrolite" (spinel peridotite) by Green and Ringwood (1967b). They consider that beneath the Precambrian Shields there may be an extremely limited zone near the base of the crust where a rock of "pyrolite" (essentially undepleted peridotite) composition would form an olivine-aluminous orthopyroxene-clinopyroxene assemblage. Below 35 - 40 km they suggest that "pyrolite" would yield an olivine-alumina-poor orthopyroxene-clinopyroxene and garnet assemblage (i.e. garnet lherzolite). Green and Ringwood also point out, however, that along the Precambrian Shield geotherm the probability of chemical zoning would limit the possible assemblages and that no regular change in mineralogy would occur.

Ito and Kennedy (1967), from a study of the phase relations of a natural peridotite point out that experimental evidence indicates that in the upper mantle below the Precambrian Shields, garnet peridotite is stable and spinel peridotite is unstable. The results of this present study suggest that this is not necessarily the case. In addition in four garnet peridotites spinel was found and in six of the spinel and altered peridotites traces of garnet were detected. This suggests that a transition region from garnet peridotite to spinel peridotite may occur, probably over a small range of temperature and pressure conditions.

However, if the upper mantle consists mainly of garnet peridotite the average mineralogical composition of the garnet peridotites of the present investigation may be compared with estimates of upper mantle composition from the results of other workers. Calculations by Harris et al (1967) give the average composition in Column 1 below and the estimate of Mathias et al (1970) is shown in Column 2. Column 3 is the average garnet peridotite from the present investigation whilst Column 4 is the composition of the most chrome diopside-rich garnet lherzolite (DT.11) examined in this study (and which may most closely approach the composition of the unmodified upper mantle).

	Volume per cent			
	1	2	3	4
Olivine	67	64	65	65
Orthopyroxene	12	27	29	22
Clinopyroxene	11	3	0.7	5.0
Garnet	10	6	4.6	5.9
Phlogopite	-	-	1.0	1.2

A more detailed discussion of the origin of the peridotite xenoliths is given in Chapter X.

A more detailed look at the various mineral associations found in the peridotites can now be made. Of the 24 garnet peridotite xenoliths 16 are garnet lherzolites and eight garnet harzburgites. The amount of clinopyroxene (chrome diopside) in the lherzolitic rocks varies from a trace to approximately five per cent, with an average of a little over one per cent. Except for the presence of chrome diopside, the garnet lherzolites show no distinctive petrographic characteristics when compared with the garnet harzburgites. Of the garnetiferous xenoliths examined those from the Kimberley mines include both varieties but the Roberts Victor Mine produced only garnet lherzolite. The total number of garnet peridotite samples, however, is much too small for the results to be reliably used for any frequency distribution analysis.

Of the spinel peridotites, 6 xenoliths are lherzolitic, the remaining 5 being harzburgites. The true distribution of these varieties between the 4 kimberlite pipes sampled cannot be reliably decided, the number of xenoliths examined being too small for statistical interpretation. Xenoliths from the Wesselton and Roberts Victor Mines, both of which have 4 samples each of spinel peridotite, are divided equally between harzburgites and lherzolites.

Before briefly discussing the petrochemistry of the peridotites it should be noted that generally the xenoliths from the Roberts Victor Mine are identical with those from the Kimberley mines, approximately 80 km distant. Another feature of some significance may be the fact that both the spinel peridotites and the unusual or altered xenoliths, which originate from the Dutoitspan Mine, are significantly richer in olivine [except for one altered xenolith (DT.2) which has a pyroxenitic character]. Only one xenolith of (altered) wehrlitic composition was recognised, this also being from the Dutoitspan Mine.

Chemically the peridotites are all very similar to one another and fall into the olivine tholeiite field. Individual analyses of the spinel- and garnet-bearing types show no significant characteristic variations, except perhaps for a slight decrease in the amount of alumina in the spinel peridotites. Average values (Table 19) show that the spinel-bearing rocks are also deficient in silica (relative to the garnet peridotites), a fact that is reflected in a generally higher olivine content (see Table 7). However, the difference may be due to unrepresentative sampling. It should also be borne in mind that, especially under the Precambrian Shields the supposed higher-level spinel peridotite zone may consist of a greater proportion of refractory residual peridotite, that is, peridotite depleted in the more readily fusible constituents. Before any distinct trends or variations between the two types of peridotites can be accurately made many more reliable analyses will be necessary.

Chemical variations between the garnet harzburgites and garnet lherzolites are small or even non-existent. The lime content of the lherzolitic variety appears to be slightly higher than the harzburgites, a feature which would be expected.

The essential similarity in both major and trace element chemistry of all the analysed peridotite xenoliths strongly suggests that they originate from a common relatively homogeneous source, possibly from two different levels. It is considered that the upper mantle would provide the ideal source. If this is so the analyses suggest that chemical variations in the upper mantle beneath Precambrian Shield areas are surprisingly small. It is much more difficult to imagine that rocks of such similar chemistry could have formed as a cognate phase of a kimberlite magma. This aspect is also dealt with in Chapter X.

In conclusion petrologic studies of both the spinel peridotite and garnet peridotite xenoliths have adequately demonstrated their very similar but distinct nature,and within the limits posed by the rather inadequate sampling have also illustrated the essential variation in mineralogical and chemical composition of what may represent a portion of the upper mantle beneath the Precambrian Shield of South Africa. These facts should be borne in mind when the origin of the xenoliths is discussed.

B. ECLOGITES.

The examination of the eclogites has shown them to be essentially medium-to coarse-grained, phanerocrystalline aggregates of garnet and clinopyroxene and occasionally containing an accessory amount of kyanite and traces of corundum, rutile and diamond. Their fabric can be described as allotriomorphic but considerable variations in the textures shown by individual xenoliths are apparent. The garnet varies in shape from irregular to rounded and occasionally angular or subhedral whilst the clinopyroxene is irregular to angular and often of an interstitial nature. The distribution of the garnet and clinopyroxene varies considerably from specimen to specimen; in some instances garnet has segregated into clustered patches or distinct bands and in others it is evenly distributed throughout the rock. From textural considerations alone it appears unwise to attempt any grouping of the eclogite xenoliths.

The xenoliths are generally well-rounded and often display a polished surface but angular, rough-surfaced xenoliths are not uncommon. Their size is of the same order of that shown by the peridotite xenoliths and gneissose structures have often been developed. Thin-section studies have shown that the garnets and the clinopyroxene are often highly fractured, a feature taken to be indicative of tectonic deformation, either within the upper mantle or the crust. Slight anisotropism of the garnets leads to a similar conclusion. That the eclogites formed under extremely high pressure conditions cannot be disputed (this is reflected in the presence of diamond) and evidence for a rapid release of pressure is shown by the presence of glassy material (often with feldspar crystallites) in many of the xenoliths. The kelyphitic material surrounding the garnets typically contains, in addition to mica, twinned feldspar microlites and pale secondary amphibole. It is considered possible that slight melting of the clinopyroxene, and possibly even of the garnet, would have been accentuated on the garnet-pyroxene contact by the presence of traces of water on the interface. This phase would have drastically lowered the melting point of the silicates and also resulted in the crystallisation of the amphibole. Extensive alteration of the clinopyroxene to ultra-fine-grained aggregates (consisting of poorly crystalline pyroxene, feldspar and zeolite) is typical and is probably related to the period of intrusion of the kimberlite.

A major aspect of the petrologic study of the eclogite xenoliths has been to define some criterion which can be used to group the eclogites, preferably one of some genetic significance. Textural considerations have been found to be unsuitable but study of the rocks in hand specimen clearly indicated that a broad distinction between three main groups could be made on the basis of variations in the colour of the constituent minerals (particularly the garnet) and the degree of alteration of the pyroxene. This petrographic grouping, which is only descriptive, defines the following three groups:

<u>Group 1</u>. Garnets dark reddish or brownish orange, usually clear; clinopyroxene dark green and only partly altered.

<u>Group 2</u>. Garnets pale orange, pinkish orange or pink and often turbid; clinopyroxene pale green, usually extensively altered. Diamond may be a rare accessory.

<u>Group 3</u>. Garnets bright orange, usually clear; clinopyroxene almost completely altered. Kyanite is a constant accessory, more rarely corundum.

A study of the modal compositions of the 24 xenoliths shows that the amount of garnet varies tremendously, from about 14 per cent to 74 per cent and that the distribution frequency of the garnet is bimodal (see Fig. 10). Although no obvious grouping of the xenoliths, using the modal values, can be made, there are definite indications that Group 1 eclogites do not contain more than 50 per cent garnet whilst Group 2 eclogites invariably contain 50 per cent or more. The Group 3 eclogites, characterised by the presence of kyanite, contain less than 50 per cent garnet. Using the modal ananlyses presented in Table 8 (garnet includes micaceous material), combined with the tentative grouping described above, the following "average" mineralogical compositions of the 3 groups are given:

	Volume per cent		
Major constituents	Group 1 (10 specimens)	Group 2 (12 specimens)	Group 3 (3 specimens)
Garnet	43	62	42
Clinopyroxene	57	37	51
Kyanite	-	-	5.4
Others	0.3	1.1	1.0
Average S.G.	3.37	3.29	3.12

Chemically the eclogites show much greater variation than the peridotites; alumina, lime, iron magnesia and soda exhibit relatively large ranges. Normative calculations show that only three of the nine analysed xenoliths are nepheline normative and hence fall into the alkalic field. The remainder are olivine tholeiitic and show high alumina. Complete melting of the eclogites would not yield liquids of typically basaltic character. This indicates that eclogite xenoliths do not simply represent a high pressure isochemical transformation of gabbro. Complete melting of the eclogites would produce a liquid of picrite or allivalite composition.

The inhomogeneous and variable nature of the eclogite xenoliths suggests that they represent either scattered eclogite segregations within the upper mantle or a cumulative phase (resulting from eclogite fractionation) related to the formation of kimberlite. As only the Roberts Victor Mine (of the four mines sampled) has produced eclogite xenoliths in any abundance the former suggestion appears the more likely. Their origin as highly metamorphosed crustal rocks cannot be overlooked. The origin of the eclogites is discussed more fully in Chapter XI.

IX. MINERALOGY OF THE XENOLITHS.

As has already been stated the peridotites consist almost exclusively of olivine and orthopyroxene with minor or trace amounts of one or more of clinopyroxene, garnet, spinel, phlogopite, graphite and sulphides. The eclogites consist essentially of clinopyroxene and garnet with minor or trace amounts of kyanite, corundum, rutile, sulphides, diamond and mica. In the following sections each of these mineral species is dealt with in some detail, this including a general description of each type, a note on features of alteration and tectonic deformation and the determination of accurate optical, physical and chemical properties. The significance of these findings is discussed in the final section, with special reference to the origin of the xenoliths.

1. Olivine.

By definition olivine (or its serpentinous alteration product) is the major constituent of all the peridotite specimens. No olivine was found in any of the eclogites. I agree!

General description.

In hand specimen the olivine appears a glassy grey-green, but on crushing it becomes almost colourless, with a slight greenish yellow tinge. Observations in thin-section show that it forms large, colourless anhedral grains, usually smoothly irregular but occasionally equant or rounded in shape. Many grains are angular and in places occur interstitially to the orthopyroxene. Small well-rounded crystals of olivine are sometimes included within the orthopyroxene (see Plate 29) or in the garnet (see Plate 33). In size the olivine grains vary considerably, some being more than 1 cm across, but most are of the order of 5 mm. The size and shape of the individual olivine grains in the peridotites are well illustrated in Plates 5 to 11. Granulation and recrystallisation of the olivine is typical of many specimens and will be dealt with in more detail in a following section.

Serpentinisation of the olivine.

The olivine grains invariably exhibit a characteristic anastomosing pattern of irregular cracks and fractures along which yellowish secondary serpentine has formed. This serpentine is usually free of typical dust-like particles of iron oxide thus indicating the magnesium-rich composition of the olivine. This secondary serpentine, probably of the antigorite variety, is found in smaller or greater amounts in all specimens, particularly along grain boundaries. In some cases large portions of a grain have been altered to the pale yellowish material, leaving only small isolated relicts of the original olivine in the secondary mass. This extensive serpentinisation of the olivine is particularly well developed in proximity to secondary veining. The anastomosing pattern of the serpentine is well illustrated in Plate 2 where peridotite slabs have been etched by hydrochloric acid.

The serpentinisation is no doubt a late-stage hydrothermal phenomenon. In the presence of water and at moderate to low pressures Bowen and Tuttle (1949) found that serpentine could only be prepared below 500°C. Serpentinisation of olivine by water can only be achieved at temperatures below 400°C (Deer et al 1962, vol. 3). Indications are therefore that the alteration of the olivine took place mainly on early-formed fractures and cleavages, either during the intrusion of the kimberlite when the temperature dropped below 400°C or by a deep-weathering process in the upper portions of a consolidated kimberlite.

Deformation and recrystallisation structures.

When examined in thin-section under crossed nicols the olivine of many of the peridotite xenoliths shows a very noticeable wavy or uneven optical extinction. Individual olivine grains often extinguish over a range of 30° or more. This clearly indicates that the peridotites were, at some stage, subjected to considerable stress deformation, a feature also evidenced by the formation of kink bands and thin deformation lamellae within the olivine grains. Raleigh (1967, 1968) has studied the mechanism of plastic deformation in experimentally deformed olivine grains at high temperatures and high pressures and has demonstrated that the deformation is due to slip along a number of systems. At all temperatures and pressures kink bands and plastic bending occur by a mechanism of discontinuous slip along translation glide planes, the kink band boundaries occuring in three principal crystallographic directions, approximately parallel to (100), (010) and (001). Deformation lamellae found in experimentally deformed olivine form parallel to the active slip planes.

In naturally deformed olivine grains it appears that the predominant glide mechanism involves slip in the [100] direction, with (010) being the slip plane. Experimentally this feature is confined to grains deformed at temperatures above 1000°C. Raleigh concludes that the slip mechanism is therefore favoured by high temperature.

The micro-deformation structures described by Raleigh appear to be very similar to those observed in many of the naturally deformed olivine grains in the peridotite xenoliths. Similar plastic deformation structures in olivine have also been described by Chudoba and **Frechen** (1950). It is therefore concluded that plastic flow of the olivine has taken place by tectonic deformation at high temperatures, probably in excess of 1000°C.

The suggestion of Challis (1967) that the deformation lamellae in olivine are produced mainly in the last stages of crystallisation where rapidly growing olivine crystals are competing for space (i.e. by crystallisation pressure), is not supported in the light of the extensive recrystallisation of the olivine and the deformed nature of the other silicate constituents. It should also be mentioned that Raleigh goes as far as to say that one of the principal mechanisms of flow in the upper mantle is by slip in olivine.

Another very interesting feature of the olivine from many of the peridotite xenoliths is the fine marginal granulation of many of the grains, illustrated in Plate 26. It is most noticeable that this granulation has only affected the olivine while adjacent grains of orthopyroxene or garnet are unaffected. This "mylonitisation" of the olivine appears to be a form of recrystallisation induced by stress, possibly accompanying intergranular movement; the large original grains show all the features characteristic of plastic deformation but the newly crystallised granular material is completely free of these features. The degree to which this granulation or recrystallisation has developed undoubtedly depends on the stress involved. While generally confined to the periphery of the olivine grains (as illustrated in Plate 26) specimens showing almost complete recrystallisation of the olivine are found (see Plates 10 and 11). In rocks such as these only relicts of the original olivine are present.

Yet another feature, also undoubtedly due to recrystallisation, is apparent in some of the deformed olivine grains. Large individual grains of olivine have partly or completely recrystallised into numerous lath-like olivine

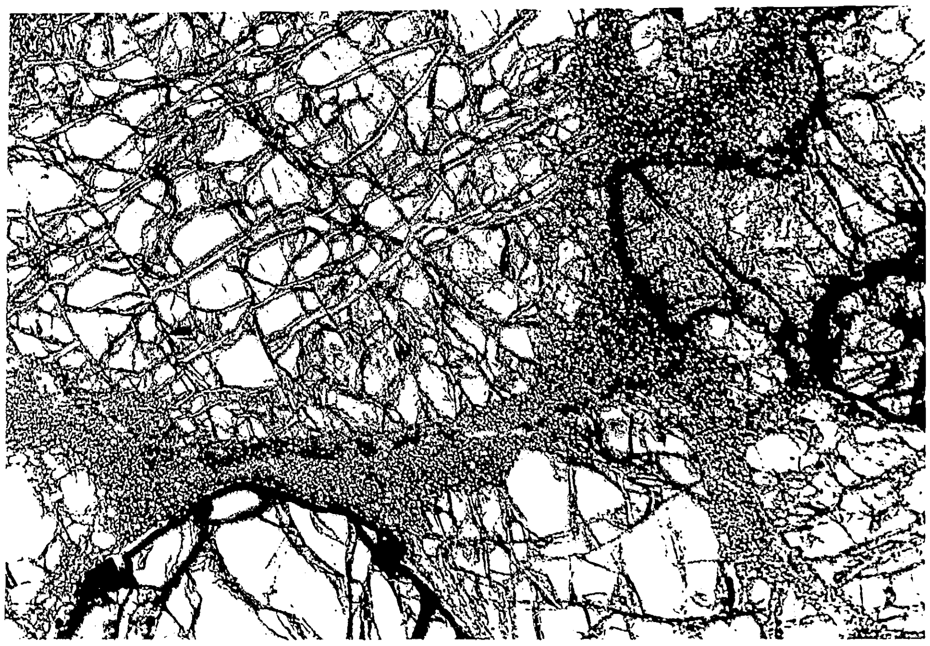


PLATE 26. Peridotite BF.2 showing the marginal granulation of olivine in contact with orthopyroxene and garnet. Magnification X 25, ordinary light.

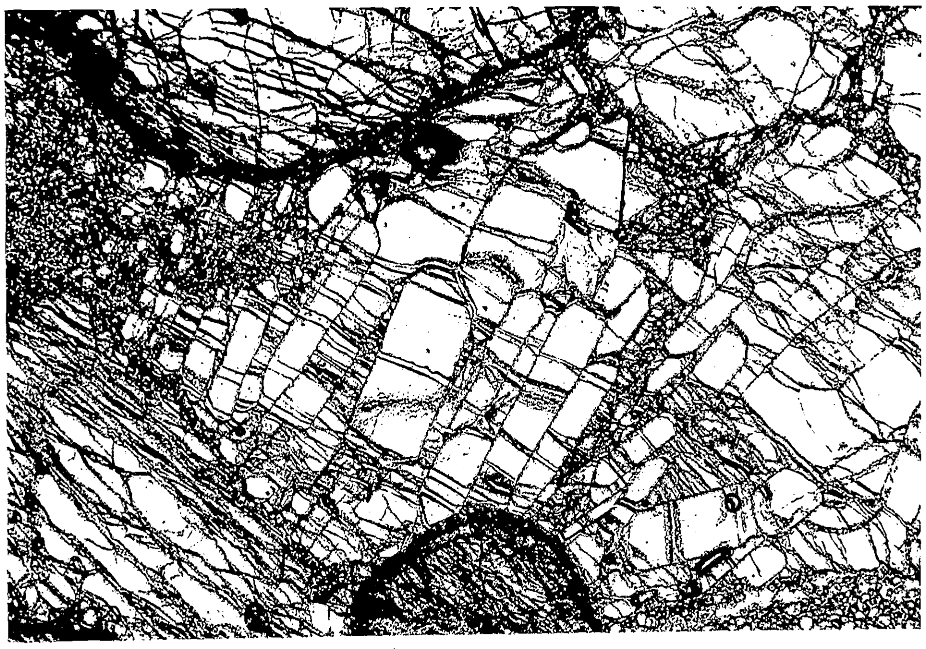


PLATE 27. Newly formed (recrystallised) lath-like olivine grains in peridotite W.9. Note in particular their sub-parallel alignment and subhedral outline. Magnification X 21, ordinary light.

crystals, often of subhedral or euhedral outline. The end-result of this feature, an intragranular olivine recrystallisation, is very well illustrated in Plate 27. These newly formed olivine crystals often show a tendency towards a clustered, subparallel alignment but individually exhibit none of the characteristic features of stress or strain, even though they may be entirely enclosed within a grain showing uneven extinction. The alignment of these grains suggests that recrystallisation, has been induced by tectonic deformation, also probably at high temperatures.

In conclusion it is very interesting to note that Jackson (1968) suggests that recrystallisation may be an important mechanism of flow within the upper mantle. In a very recent publication Ave'Lallemant and Carter (1970) discuss recrystallisation of olivine and modes of flow in the upper mantle and conclude (p.2215) "........ that an important or dominant mode of flow in the upper mantle is syntectonic recrystallisation. Plastic deformation .... must certainly contribute to the deformation but, as observed in the 'upper mantle' rocks, cannot account for large creep strains". The recognition of recrystallisation and deformation structures in the peridotite xenoliths of the present investigation, which are likely to be of mantle origin (see Chapter X), supports this hypothesis.

Lastly it can be mentioned that shock waves can also induce both deformation and transformation in minerals. Müller and Hornemunn (1968, 1969) have recorded distinctive planar structures in experimentally shock-loaded olivine grains and in natural olivine grains from chondritic meteorites. Similar structures were not detected in any of the olivine of the peridotite xenoliths and this suggests that shock metamorphism has had little or no effect on the xenoliths, either in their original source or in the kimberlite.

Physical properties and composition of the olivine.

The composition of the olivine from every peridotite has been estimated by two or more techniques and these results are presented in Table 21. Techniques applied included the accurate determination of refractive index (in most cases only the β value) and the measurement of the optical axial angle ($2V_{\gamma}$); graphical estimation of the Mg content was made from data given by Deer et al (1962, vol. 1, Fig. 11). These results were checked by the X-ray determinative method of Yoder and Sahama (1957), using an internal standard. The X-ray determinative method described by Heckroodt (1958) was also tested using olivine from the 10 Bultfontein peridotites. As these results were found to be consistently

TABLE 21.

OPTICAL PROPERTIES AND d_{130} INTERPLANAR SPACING FOR OLIVINE FROM THE PERIDOTITE XENOLITHS, WITH ESTIMATED COMPOSITIONS.

Specimen No.	Refractive indices (± 0.005)				Optic axial angle (± 2°)		d_{130} interplanar spacing	
	α	β	γ	Atom.% Mg*	$2V_{\gamma}$	Vol % Mg*	d_{130}(Å)	% Fo**
BF.1	-	1.668	-	92	-	-	2.7710	91
2	1.647	1.669	1.685	91	88°	90	2.7703	92
3	-	1.668	-	92	-	-	2.7703	92
4	-	1.667	-	93	-	-	2.7689	93
5	1.649	1.669	1.684	91	88°	90	2.7703	92
6	-	1.669	-	91	-	-	2.7703	92
7	-	1.668	-	92	-	-	2.7689	93
8	1.650	1.667	1.687	93	87°	92	2.7689	93
9	1.648	1.668	1.683	92	88°	90	2.7703	92
10	1.647	1.668	1.683	92	87°	92	2.7689	93
W.1	-	1.670	-	91	-	-	2.7703	92
3	-	1.669	-	91	-	-	2.7689	93
4	-	1.667	-	93	-	-	2.7696	92
5	-	1.668	-	92	-	-	2.7668	94
6	-	1.670	-	91	-	-	2.7676	92
7	-	1.668	-	92	-	-	2.7689	93
8	-	1.668	-	92	-	-	2.7696	92
9	-	1.668	-	92	-	-	2.7682	93
10	-	1.668	-	92	-	-	2.7682	93
DT.2	-	1.666	-	94	-	-	2.7696	92
3	-	1.666	-	94	-	-	2.7682	93
4	-	1.667	-	93	-	-	2.7703	92
6	-	1.667	-	93	-	-	2.7689	93
7	-	1.669	-	91	-	-	2.7689	93
8	-	1.667	-	93	-	-	2.7696	92
9	-	1.667	-	93	-	-	2.7696	92
10	-	1.668	-	92	-	-	2.7710	91
11	-	1.668	-	92	-	-	2.7696	92
13	-	1.668	-	92	-	-	2.7689	93
14	-	1.668	-	92	-	-	2.7689	93
15	-	1.668	-	92	-	-	2.7689	93
16	-	1.670	-	91	-	-	2.7732	89
18	-	1.667	-	93	-	-	2.7689	93
20	-	1.669	-	91	-	-	2.7689	93
21	-	1.667	-	93	-	-	2.7689	93
RV.12	-	1.666	-	94	-	-	2.7682	93
14	-	1.668	-	92	-	-	2.7682	93
15	-	1.667	-	93	-	-	2.7696	92
16	-	1.667	-	93	-	-	2.7682	93
17	-	1.668	-	92	-	-	2.7696	92
19	-	1.668	-	92	-	-	2.7689	93
25	-	1.667	-	93	-	-	2.7696	92

* Estimated graphically using values from Deer et al, (1962, vol. 1, Fig. 11).

** Estimated graphically using the olivine X-ray determinative curve from Yoder and Sahama (1957).

higher (of the order of two to four per cent forsterite) than those estimated from optical measurements and from the Yoder and Sahama X-ray diffraction method, this technique was not applied further. Excellent agreement was obtained between the compositions inferred from both optical and X-ray properties. Complete optical properties (α, β, γ and $2V_{\gamma}$) are given only for the chemically analysed olivine samples, that is, olivine from xenoliths BF.2, BF.5, BF.8, BF.9 and BF.10.

What is immediately striking from a study of Table 21 is the almost identical mineral composition of the olivine in every peridotite, the forsterite content ranging from 91 to 94 per cent. Whether the xenoliths are garnetiferous, spinel-bearing or altered apparently makes no difference, neither does whether they are harzburgites or lherzolitic.

Table 22 gives the results of a full chemical analysis of five pure olivine separates, two being from garnet lherzolites (BF.2, BF.5), two from garnet harzburgites (BF.8, BF.9) and one from a spinel harzburgite (BF.10). A structural formula has been calculated for each analysis using the method described by Deer et al (1966, p.515-517) and gives the number of ions on the basis of 4 oxygens. In the calculations of the Fe^{2+} and Mg atomic ratios all iron has been expressed in the divalent form (FeO). These analyses clearly support the compositions inferred from the physical properties (Table 21), the Mg atomic per cent ranging between 90.9 to 92.3, that is, approximately 91 to 92 per cent forsterite. Specific gravities of the analysed olivines are also given.

In Table 23 the results of a semi-quantitative trace element analysis of the same olivine concentrates are presented. Other than Ni and Cr (see Table 22) these results show that the only trace elements of any significance are Co, Zr, Mo and Sn.

It is significant to note that all minor elements (with the exception of manganese and nickel) are present in extremely low concentrations. For olivine the ferric iron content is somewhat high; this can be attributed to the appreciable serpentinisation of the olivine. Although the analysed olivine concentrates were virtually free of any secondary serpentine a substantial amount of the primary Fe^{2+} has apparently oxidised to Fe^{3+}.

The analytical results indicate that the minor element distribution in the analysed olivines is in accordance with the results of Simkin and Smith

TABLE 22.

CHEMICAL ANALYSES, STRUCTURAL FORMULAE AND ATOMIC RATIOS OF OLIVINE.+

	BF.2	BF.5	BF.8	BF.9	BF.10
(A) CHEMICAL ANALYSES:					
SiO_2	41.09	40.09	41.56	41.06	40.87
TiO_2	0.02	0.02	0.01	<0.01	0.02
Al_2O_3	<0.01	<0.01	<0.01	<0.01	0.05
Cr_2O_3	0.04	0.06	0.05	0.02	0.01
Fe_2O_3	1.10	8.90*	1.56	1.10	1.33
FeO	6.93		7.00	6.46	6.84
MnO	0.10	0.10	0.10	0.08	0.10
NiO	0.37	0.39	0.45	0.46	0.42
MgO	50.4	50.3	50.9	51.3	50.2
CaO	0.03	0.03	0.03	<0.01	<0.01
K_2O	0.01	<0.01	0.02	<0.01	0.01
P_2O_5	0.01	0.01	<0.01	<0.01	<0.01
	100.10	99.90	101.68	100.48	99.85
FeO*	7.92	8.90	8.40	7.45	8.04
(B) STRUCTURAL FORMULAE**					
Si	0.997)=1.00	0.983)=0.98	0.994)=0.99	0.992)=0.99	0.996)=1.00
Al	-	-	-	-	0.003
Cr	0.002)=2.00	0.003)=2.03	0.003)=2.00	-)=2.01	-)=1.99
Fe^{3+}	0.020	-	0.029	0.020	0.023
Fe^{2+}	0.140	0.183	0.139	0.131	0.134
Mn	0.002	0.002	0.001	0.002	0.002
Ni	0.007	0.007	0.009	0.009	0.007
Mg	1.822	1.836	1.813	1.844	1.821
Ca	0.002	0.002	0.001	-	-
(C) ATOMIC RATIOS (%)					
Fe^{2+}*	8.2	9.1	8.7	7.7	8.3
Mg	91.8	90.9	91.3	92.3	91.7
S.G.	3.31	3.32	3.31	3.31	3.28

* Total iron expressed as FeO.

** Structural formulae calculated as the number of anions on the basis of 4 oxygens.

\+ Analyses by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

TABLE 23.

SEMI-QUANTITATIVE TRACE ELEMENT ANALYSIS OF OLIVINE FROM THE PERIDOTITE XENOLITHS.+

(in parts per million)

Specimen No.	Co	Zr	Mo	Sn
BF.2	200	30	10	15
3	200	30	<10	20
8	150	30	10	20
9	200	30	10	15
10	150	30	<10	15
Limit of detection	10	10	1	10

In all olivine specimens

B	< 10	Bi	< 5
Li	< 50	Cd	< 10
Be	<0.5	Sb	< 10
V	< 50	Ba	<100
Ge	< 10	La	<100
As	<100	Pt	< 50
Sr	< 50	Cu	< 10
Y	< 10	Zn	< 50
Nb	< 10	Au	< 5
Ag	<0.1	Pb	< 10

+ Analyses by Analytical Research Section, Anglo American Research Laboratory.

TABLE 24.

X-RAY DIFFRACTION DATA FOR OLIVINE FROM PERIDOTITES BF.8 AND BF.10.

ASTM card No. 7-74 Forsterite			Olivine BF.8		Olivine BF.10	
d(Å)	I	hkl	d(Å)	I*	d(Å)	I*
5.10	50	020	5.09	MS	5.09	MS
4.30	10	110	-	-	-	-
3.883	70	021	3.894	S^{3}	3.879	S^{3}
3.723	10	101	3.719	VW	3.724	VW
3.496	10	111	3.490	W	3.490	W
3.478	20	120				
3.007	10	121	2.996	W	2.993	W
2.992	10	002				
-	-	-	2.878	VVW	2.876	VVW
2.768	60	130	2.769	VS	2.769	VS
2.512	70	131	2.513	VS^{2}	2.514	VS^{2}
2.458	100	112	2.460	VS^{1}	2.461	VS^{1}
2.383	5	200	-	-	-	-
2.347	20	041	2.349	W	2.347	VW
2.316	10	210	2.310	VVW	2.317	VVW
2.269	40	122	2.270	MS	2.271	MS
2.250	30	140	2.251	MS	2.251	MS
2.161	10	220,211	2.162	W	2.161	VW
2.032	5	132	2.033	VVW	2.033	VVW
1.876	20	150	1.877	VW	1.877	VW
1.785	5	151	1.791	VVW	1.792	VVW
1.750	40	222	1.749	S	1.748	S
1.740	10	240	1.740	VW	1.740	VW
1.731	10	123	1.731	VVW	1.731	VVW
1.671	10	241	1.671	VW	1.671	VW
1.636	10	061	-	-	-	-
1.634	10	232	-	-	-	-
1.619	20	133	1.619	W	1.618	VVW
1.590	5	152	1.592	VVW	1.591	VVW
-	-	-	1.572	VW	1.572	VW
1.497	20	004	1.497	MS	1.496	MS
1.479	20	062	1.480	S	1.480	MS
1.397	10	170,233	1.395	W	1.395	W
1.388	S	312	1.389	VVW	1.388	VVW
1.351	20	322	1.352	VW	1.352	VW
1.316	10	134	1.317	VW	1.317	VW
-	-	-	1.295	VVW	1.295	VVW

d interplanar spacings

I intensity of reflections

* estimated intensity, using the following scale:

VS = very strong
S = strong
MS = moderately strong
W = weak
VW = very weak
VVW = very, very weak

hkl Miller indices

^{1,2,3} indicates strongest, second strongest and third strongest reflections respectively.

(1970) who have shown that for olivine in general relatively high nickel correlates with high magnesium, low manganese correlates with low iron and extremely low calcium agrees with a deep-seated crystallisation environment.

No distinct major or minor element differences exist between the olivine from the garnet or spinel peridotites with the exception that the olivine from the spinel peridotite contains a slightly smaller amount of chrome and is fractionally richer in alumina.

Interplanar (d) spacings.

X-ray powder diffraction data of two analysed olivines (BF.8, BF.10) are presented in Table 24. These results, determined by powder diffraction techniques using an internal silicon standard, are compared with an ASTM reference standard of forsterite (card No. 7-74). The d-spacings and estimated intensities shown by these two olivines are virtually identical to the reference material. Miller indices are assumed to be the same as for the standard.

A study of the interplanar spacings of the olivine was done to determine whether olivine from a high pressure environment shows any anomalous diffraction property which would serve as a petrogenic indicator. The study has indicated that this is not the case, the structure of the olivine apparently being controlled only by the chemical composition. Crystal structure studies of natural olivines by Birle *et al* (1968) have similarly indicated (p.822) that "...... the structural parameters (of olivine) are quite regular and apparently immune to crystallisation history. Only chemical parameters seem to be of value".

2. Orthopyroxene.

In virtually every xenolith of peridotite, orthopyroxene is the second-most abundant constituent. As with the olivine no orthopyroxene was detected in any of the eclogite xenoliths.

General description.

The orthopyroxene, being more resistant to weathering than the olivine, often forms prominent grains on the weathered surface of the xenoliths. On fresh surfaces it is greenish to yellowish-green and in a number of the xenoliths displays a well-developed parting. The characteristic pyroxene cleavages are normally well-developed. Study in thin-section has shown that in general the orthopyroxene forms anhedral grains, usually more irregular in outline than the olivine grains, with which it forms an interlocking mozaic (see Plates 5 to 9). In size the orthopyroxene grains are similar to the olivine but considerable differences exist from xenolith to xenolith. Inspection of numerous thin-sections of the peridotites leaves one with the impression that in most cases the orthopyroxene crystallised out at a slightly later stage than the olivine, but before the clinopyroxene. This is also borne out by the fact that orthopyroxene crystals often contain inclusions of both olivine and garnet while the reverse is rare. Plates 28 and 29 illustrate respectively garnet and olivine inclusions in orthopyroxene.

In thin-section the orthopyroxene grains are virtually colourless or very pale yellowish, when compared with the olivine. In hand specimen the orthopyroxene from the spinel peridotites is noticeably greener than that from the garnetiferous rocks and is, as will be shown, an indication of the higher chrome content of this orthopyroxene. The orthopyroxene grains are typically fractured, cracked and show incipient alteration. Features due to tectonic deformation are common and will be dealt with in a following section.

It is of some significance to record that whilst all the orthopyroxene from the garnet peridotites appears "clean", that occurring in the spinel peridotite xenoliths often shows very fine but distinct lamellae of another phase parallel to the (100) parting direction. This is the typical lamellar structure characteristic of orthopyroxene of the Bushveld type. While individual lamellae are much too fine for optical identification, indications are that they probably represent lamellae of a calcium-rich phase exsolved at lower temperatures (and pressures?).

Alteration of the orthopyroxene.

Unlike the olivine the orthopyroxene shows very little in the way of alteration. A fine "dustiness" or slight turbidity is evident within most of the grains and appears concentrated on fractures and cleavages. Alteration of the orthopyroxene, while not common, is shown by the development of semi-fibrous talcose, chloritic and serpentinous aggregates, particularly in the highly serpentinised rocks. In one xenolith (W.5) the orthopyroxene is exceptionally turbid and brownish in colour. This orthopyroxene (illustrated in Plate 30) is typically rimmed by numerous pale

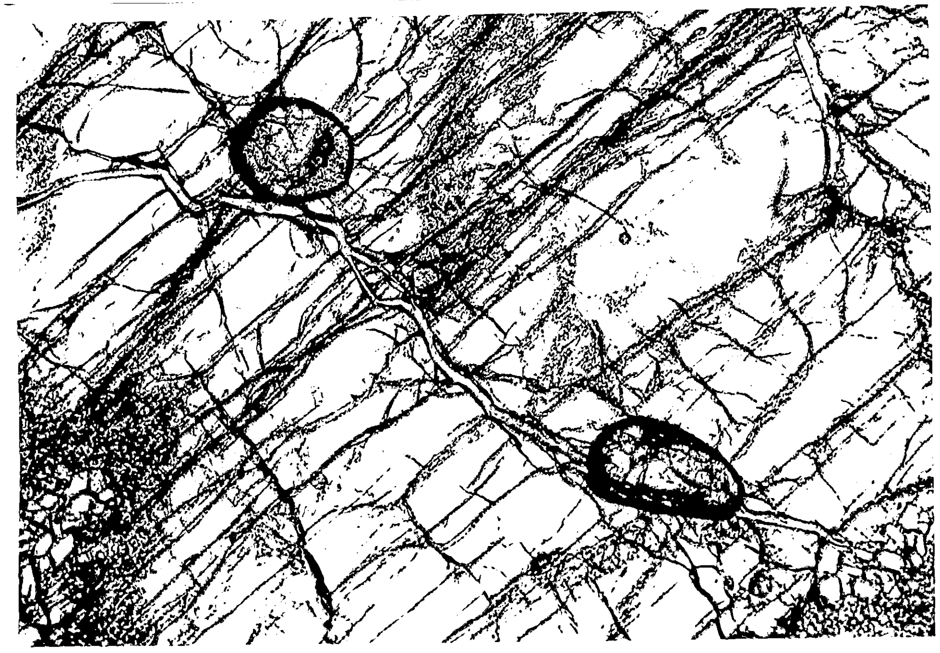


PLATE 28. Orthopyroxene displaying typical fractures and cleavage traces as well as two rounded inclusions of garnet (W.9).
Magnification X 19, ordinary light.

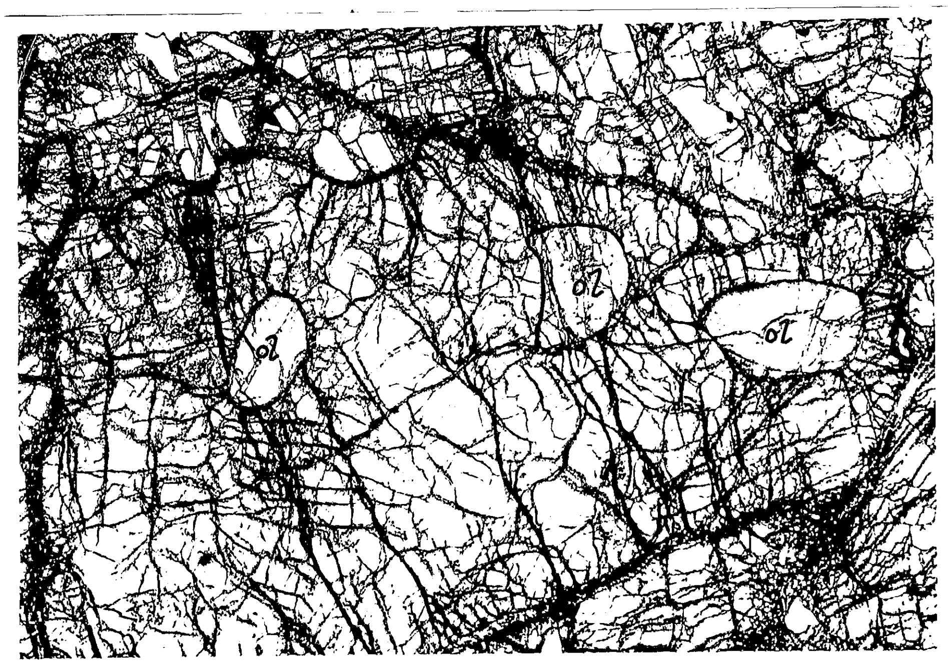


PLATE 29. A large irregular grain of orthopyroxene in peridotite W.9 with several roundish inclusions of olivine (ol).
Magnification X 8.5, ordinary light.

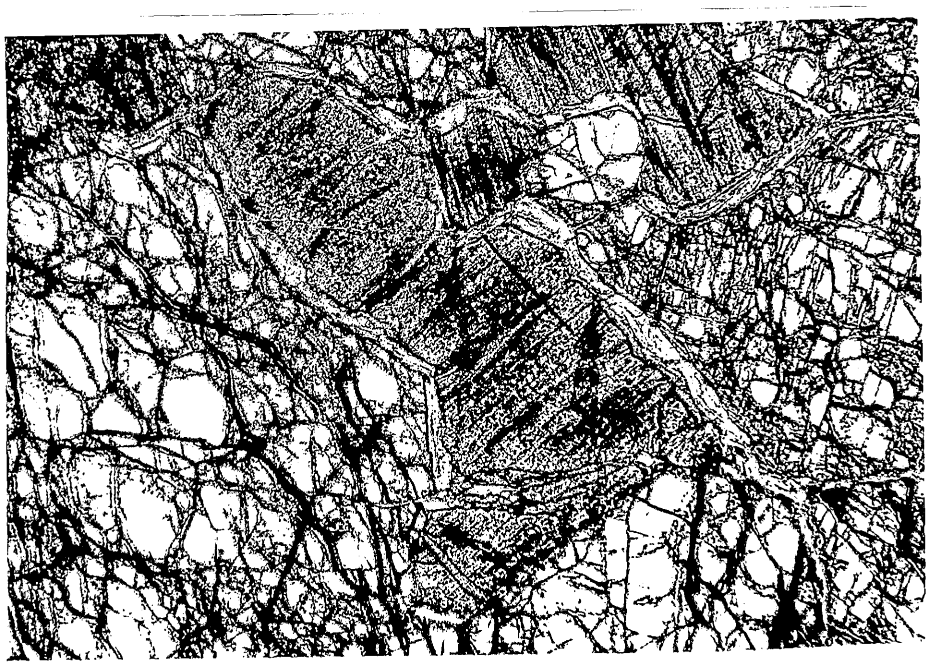


PLATE 30. An unusual type of alteration in orthopyroxene. The pyroxene is light brown, turbid and shows a well-developed parting. The grains are almost completely surrounded by laths of phlogopite. From peridotite W.5. Magnification X 14, ordinary light.

brown phlogopite laths and also displays a very well-developed parting. Indications are that the orthopyroxene has been partially altered to the mica, by a process of phlogopitisation.

Deformation and inversion features.

Evidence of stress and tectonic deformation is found in the orthopyroxene of many of the peridotite xenoliths. These features are invariably accompanied by the previously described deformation and recrystallisation structures in the coexisting olivine grains.

The deformation shows itself by uneven optical extinction, bent crystals, kink bands and evidence of a possible orthopyroxene ——> clinopyroxene inversion. Two typical examples of deformation are illustrated in Plates 31 and 32. The uneven optical extinction and the bending of the orthopyroxene grains (as revealed by bent cleavage traces) are self explanatory but the development of kink bands and possible polymorphism calls for special attention.

The microscopic effects accompanying the experimental deformation of orthopyroxene (enstatite) have been described by Turner et al (1960), Borg and Handin (1966) and Riecker and Rooney (1967). All these workers obtained clear evidence of intergranular plastic deformation, such as the bending of enstatite crystals, the development of kink bands and the inversion of enstatite (orthorhombic symmetry) to clinoenstatite (monoclinic symmetry); all agree that the kink bands form on the slip system (100) [001] by a translation gliding mechanism.

In several peridotite xenoliths occasional grains of well-kinked orthopyroxene appear to contain lamellae of a very slightly different nature. These lamellae, which show up with a slightly higher relief and fractionally higher polarisation colours, are considered likely to represent clinoenstatite inversions. They are of similar appearance to the inversion lamellae produced experimentally and to those recently recognised as occurring in terrestrial bronzite crystals (Trommsdorff and Wenk, 1968). Unfortunately the lamellae are very thin and could not be satisfactorily analysed by optical methods. Refractive index measurements point to the lamellae having the same composition as the host orthopyroxene. Clearly detailed research along this line is indicated.

From recent studies (Boyd and England, 1965) it appears that enstatite is the stable high temperature-high pressure form (which can persist metastably under

PLATE 31(a). A typical deformed orthopyroxene grain from xenolith BF.4 The grain is slightly bent, contains numerous kink bands and possible clinoenstatite inversion lamellae (arrowed). Magnification X 15, ordinary light.

PLATE 31(b). The same grain illustrated above but now observed in polarised light. Notice the uneven extinction and the well-developed kink bands.
Magnification X 15, polarised light.

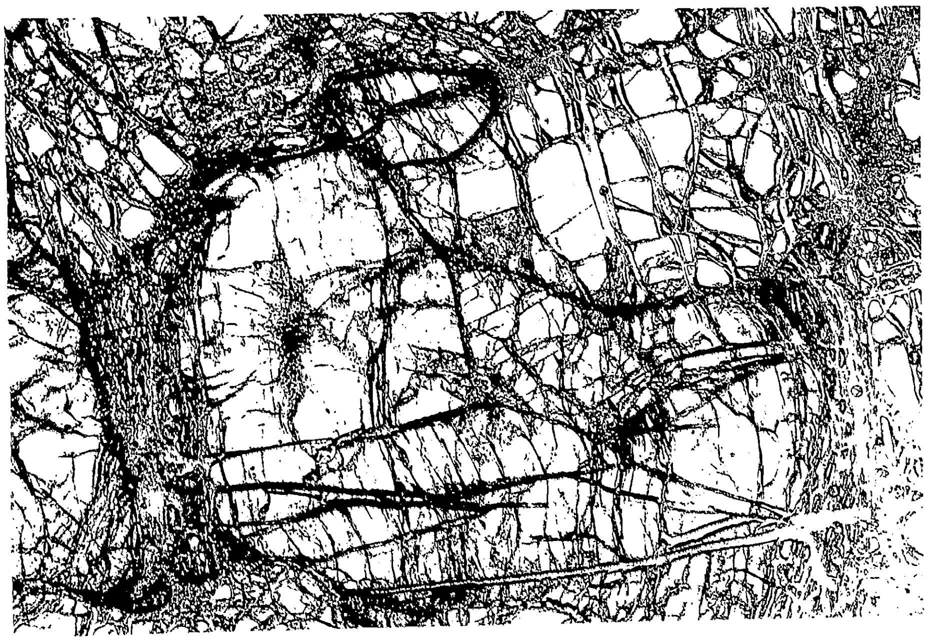


PLATE 32(a). Another deformed orthopyroxene grain from xenolith BF.8. Numerous kink bands are evident. Magnification X 16, ordinary light.

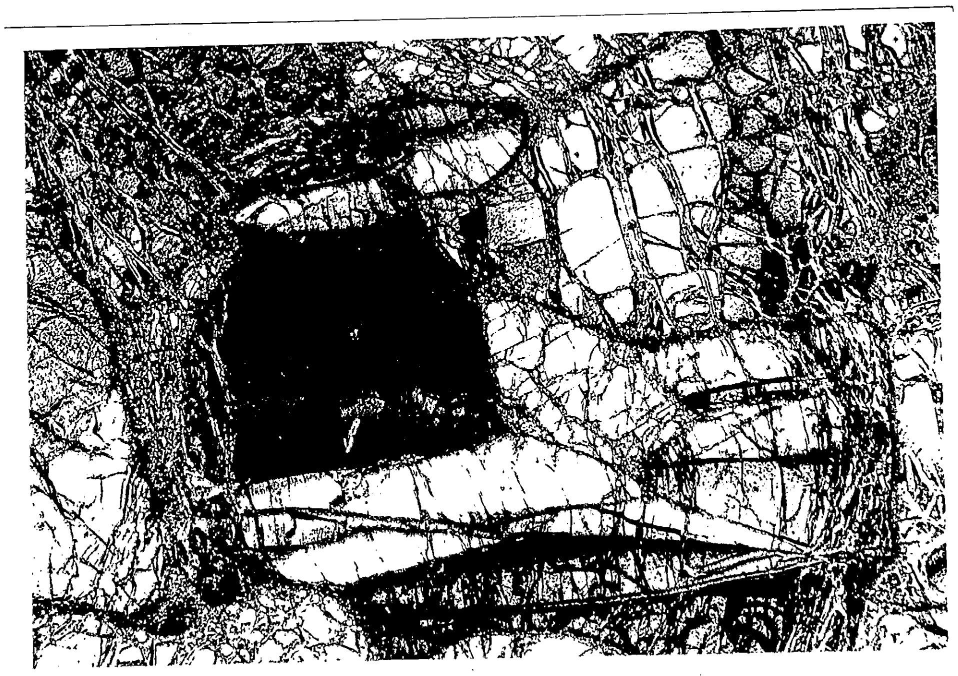


PLATE 32(b). The same grain illustrated above, but now seen in polarised light. The kink bands are more conspicuous. Magnification X 16, polarised light.

other conditions) whilst clinoenstatite is a high pressure-low temperature phase. It has been demonstrated that under the appropriate conditions of high shear strain experimentally stressed enstatite can invert to clinoenstatite. The concept of "stress minerals" has been discussed by Harker (1950, p.150); the occurrence of enstatite $\longrightarrow$ clinoenstatite inversion supplies proof of the validity of this concept and also demonstrates the effect of a large shearing stress on the polymorphism of enstatite.

The presence of the abovementioned deformation structures in the orthopyroxene undoubtedly demonstrates (as do the olivine deformations) the high stress that these rocks have experienced, either within the upper mantle or lower crust. The possible presence of clinoenstatite inversion products (coupled with the resultant small volume change that would take place) in naturally deformed terrestrial rocks of deep-seated origin has tremendous tectonic implications, particularly in the production of seismic energy (Randall, 1964). The finding of clinoenstatite in mantle-type rocks supports the conclusion of Riecker and Rooney (1967, p.1051) who suggest "..... the inversion of rhombic to monoclinic enstatite should be considered as a possible source mechanism for some intermediate- and deep-focus earthquakes".

Physical properties and composition of the orthopyroxene.

The composition of the orthopyroxene from almost every peridotite (except those that are completely recrystallised or extensively altered) has been estimated by one or more optical techniques. These included the accurate determination of the γ refractive index and the measurement of the optic axial angle ($2V_{\alpha}$). The compositions were estimated graphically from data given by Deer et al (1962, vol. 2, Fig. 10). These results appear in Table 25. The refractive index and optic axial angle of five analysed orthopyroxenes (BF.2, BF.5, BF.8, BF.9 and BF.10) are also given. Excellent agreement was found between compositions estimated by the two optical methods and those chemically analysed (see Table 26).

As with the olivine the most striking feature about these results is the almost identical composition of the orthopyroxene from the different xenoliths, which in all cases corresponds to that of enstatite, ranging from En_{94} to En_{88}. Indications are that the Mg content of the enstatite from the spinel peridotites may be fractionally less than that from the garnet peridotites.

TABLE 25.

OPTICAL PROPERTIES AND ESTIMATED COMPOSITIONS OF ORTHOPYROXENE FROM THE PERIDOTITE XENOLITHS.

Specimen No.	Refractive indices (± 0.005)		Optical axial angle (±2°)	Inferred composition	
	α	γ	$2V_\alpha$	A*	B*
BF. 1	-	1.673	-	92	-
2	1.662	1.673	104°	92	93
3	-	1.672	-	93	-
4	-	1.671	-	94	-
5	1.663	1.674	105°	91	93
6	-	1.672	-	93	-
7	-	1.672	-	93	-
8	1.661	1.673	105°	92	93
9	1.660	1.672	104°	93	93
10	1.667	1.677	102°	88	92
W. 1	-	1.674	-	91	-
3	-	1.673	104°	92	93
4	-	1.677	102°	88	92
5	-	~1.67	-	~93	-
6	-	1.673	-	92	-
7	-	1.673	-	92	-
8	-	1.673	106°	92	94
9	-	1.673	-	92	-
10	-	1.673	-	92	-
DT. 2	-	-	-	-	-
3	-	-	-	-	-
4	-	1.674	104°	91	93
6	-	1.673	-	92	-
7	-	1.675	-	90	-
8	-	1.672	-	93	-
9	-	-	-	-	-
10	-	-	-	-	-
11	-	1.672	-	93	-
13	-	1.673	102°	92	92
14	-	1.674	-	91	-
15	-	1.674	106°	91	94
16	-	-	-	-	-
DT.18	-	1.672	-	93	-
20	-	1.675	104°	90	93
21	-	-	-	-	-
RV.12	-	1.672	-	93	-
14	-	1.673	-	92	-
15	-	1.672	-	93	-
16	-	1.672	-	93	-
17	-	1.677	102°	88	92
19	-	1.671	-	94	-
25	-	1.674	105°	91	93

A: Estimated from γ refractive index

B Estimated from $2V_\alpha$

* Both estimations are based on data from Deer *et al* (1962, vol. 2, Fig. 10) and are expressed as 100 Mg : Mg + Fe^{2+} + Mn.

Differences between harzburgites and lherzolites are non-existent.

The results of a complete chemical analysis of five pure enstatite separates are given in Table 26, together with structural formulae calculated for the number of anions on the basis of 6 oxygens (Deer et al, 1966, p.515-517). Atomic ratios (% Fe^{2+}, Mg and Ca) and specific gravities are also given.

One of the most important features of the orthopyroxene analyses is the low alumina content of those from the garnet peridotites which contrasts with the relatively high alumina content of the enstatite from the spinel peridotite. Early experimental work by Boyd and England (1960) indicated that orthopyroxenes from a high pressure alumina-bearing environment might contain large amounts of alumina. It has been subsequently shown by Boyd and England (1964), during an examination of the system enstatite-pyrope, that the alumina content of an enstatite in equilibrium with pyrope is a function of both temperature and pressure. Increase of pressure greatly reduces the solubility of alumina in enstatite and results in the formation of pyrope by the following simplified reaction:

$$\text{Aluminous enstatite} \rightleftarrows \text{Alumina-poor enstatite} + \text{pyrope}$$

The results obtained from the present study are in keeping with this experimental work and clearly demonstrate that the enstatite in the spinel peridotites was formed in a region of lower pressure than the enstatite in the garnet peridotites. The inference is that the garnet peridotites formed under higher pressure conditions than the spinel peridotites.

The orthopyroxenes also contain an exceptionally high chromium content, a feature which is in keeping with enstatite from peridotites in general. It is significant to note that the chromia content of the enstatite from the spinel peridotite is approximately twice that of the garnet peridotite enstatites. The lime distribution follows the same trend and as would be expected the magnesia content of the spinel peridotite enstatite is slightly lower than that for the garnet peridotites. The relatively high lime content of the spinel peridotite enstatites is also demonstrated by the presence of a fine lamellar structure in many of these pyroxenes. These fine lamellae are considered to represent an exsolved Ca-rich phase. The lamellae are entirely absent from the alumina-poor garnet peridotite enstatites, the excess lime having no doubt entered the garnet structure.

TABLE 26.

CHEMICAL ANALYSES, STRUCTURAL FORMULAE AND ATOMIC RATIOS OF ORTHOPYROXENE. +

	BF.2	BF.5	BF.8	BF.9	BF.10
(A) CHEMICAL ANALYSES					
SiO_2	57.24	56.42	57.22	56.98	55.76
TiO_2	0.04	0.02	0.04	0.02	0.02
Al_2O_3	0.73	0.68	0.77	0.90	2.88
Cr_2O_3	0.42	0.38	0.35	0.37	0.80
Fe_2O_3	5.10*	5.91*	0.46	0.03	<0.01
FeO			4.65	4.74	4.79
MnO	0.11	0.12	0.11	0.10	0.12
NiO	0.09	0.13	0.12	0.12	0.10
MgO	35.7	35.1	35.4	35.6	34.3
CaO	0.51	0.53	0.58	0.35	0.96
K_2O	0.02	0.02	0.01	0.02	0.03
P_2O_5	0.01	<0.01	0.02	0.05	0.03
	99.97	99.31	99.73	99.28	99.79
FeO*	5.10	5.91	5.06	4.77	4.79
(B) STRUCTURAL FORMULAE**					
Si	1.966	1.964	1.952	1.972	1.923
	=2.00	=1.99	=1.99	=2.00	=2.00
Al	0.029	0.029	0.033	0.028	0.077
Al	-	-	-	0.009	0.039
Cr	0.021	0.008	0.008	0.008	0.025
Fe^{3+}	-	-	0.012	-	-
Fe^{2+}	0.146	0.172	0.135	0.137	0.139
Mn	0.002 =2.02	0.002 =2.03	0.002 =2.00	0.002 =2.01	0.002 =2.01
Ni	0.002	0.002	0.002	0.002	0.002
Mg	1.825	1.822	1.817	1.835	1.763
Ca	0.019	0.019	0.023	0.013	0.037
(C) ATOMIC RATIOS (%)					
Fe^{2+}*	7.3	8.5	6.8	6.9	7.2
Mg	91.7	90.5	92.0	92.4	90.9
Ca	1.0	0.9	1.2	0.7	1.9
S.G.	3.24	3.23	3.25	3.22	3.27

* Total iron expressed as FeO.

** Structural formulae calculated as the number of anions on the basis of 6 oxygens.

\+ Analyses by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

The relatively high alumina, lime and chromia content of the spinel peridotite enstatites is of considerable petrologic importance. Whole rock chemistry and olivine compositions show no essential differences between the two major peridotite types. Indications are that the mineralogical changes are only pressure dependant. Experimental verification is obtained in the high pressure-high temperature work of Green and Ringwood (1967b) who, using material of pyrolite composition (a synthetic garnet peridotite composition), have shown that garnet appears only when the pressure is sufficient to cause the aluminous pyroxene to break down to garnet plus a less-aluminous pyroxene.

The results of a semi-quantitative trace element analysis of the five analysed enstatites is presented in Table 27 and indicate that, as with the olivine, only Co, Zr and Sn are of any importance. It is interesting to note that the minor element content of the enstatites follows a different pattern to that of the olivine. It is particularly noticeable in the low nickel and high chromium, lime and alumina contents of the enstatites in comparison with those of the olivines, where the situation is reversed. As with the olivines the titania, potash and phosphate contents are negligible.

Finally it should be mentioned that the structural formulae of the enstatites, except for one case, show a slight excess of cations over the expected figure of four per formula unit. Mercy and O'Hara (1965b), in a study of olivines and orthopyroxenes from garnetiferous peridotites, suggest that the departure from the ideal formulae is due to the presence of minor amounts of the olivine molecule in solid solution in the orthopyroxene and indicate that these results are consistent with the deduction that the garnet peridotites attained equilibrium at relatively low temperatures. By analogy a similar deduction can be made for the peridotites of the present investigation.

Interplanar (d) spacings.

Two of the enstatite separates have been analysed by normal X-ray diffraction techniques using silicon as a precisely calibrated internal standard. These results are listed in Table 28 and are compared with an ASTM reference standard of enstatite (card No. 7-216). Miller indices are assumed to be the same as for the reference material. The d-spacings of enstatite BF.8 are in close agreement with those of the reference material (a meteoric enstatite with low Fe, Ca and Al). The interplanar spacings of enstatite BF.10 show a slight but consistent decrease

TABLE 27.

SEMI-QUANTITATIVE TRACE ELEMENT ANALYSIS OF ORTHOPYROXENE FROM THE PERIDOTITE XENOLITHS.*

(in parts per million)

Specimen No.	Co	Zr	Sn
BF. 2	60	20	10
5	60	20	10
8	80	20	10
9	80	20	10
10	60	20	10
Limit of detection	10	10	10

In all orthopyroxene specimens

B < 10
Li < 50
Be <0.5
V < 50
Ge < 10
As <100
Sr < 50
Y < 10
Nb < 10
Ag <0.1
Mo < 10

Bi < 5
Cd < 10
Sb < 10
Ba <100
La <100
Pt < 50
Cu < 10
Zr < 50
An < 5
Pb < 10

* Analyses by Analytical Research Section,
Anglo American Research Laboratory.

TABLE 28.

X-RAY DIFFRACTION DATA FOR ORTHOPYROXENE FROM PERIDOTITES BF.8 AND BF.10.

ASTM card No. 7-74 Enstatite			Enstatite BF.8		Enstatite BF.10	
d(Å)	I	hkl	d(Å)	I*	d(Å)**	I*
6.33	<1	210	6.33	VW	6.30	As for BF.8
4.41	14	020	4.41	W	4.39	
3.303	35	121	3.303	W	3.297	
3.167	100	420,221	3.167	VS[1]	3.164	
2.941	45	321	2.941	MS	2.938	
2.872	85	610	2.872	VS[2]	2.872	
2.825	25	511	2.827	W	2.825	
2.706	25	421	2.704	MS	2.696	
2.534	45	131	2.533	S[3]	2.529	
2.494	50	202	2.495	MS	2.494	
2.471	30	430,521	2.471	S	2.468	
2.385	8	331	2.385	VVW	2.385	
-	-	-	2.357	VVW	2.356	
2.280	6	800	2.278	VVW	2.273	
2.252	8	402,621	2.251	VW	2.252	
2.232	8	431	2.232	VVW	2.229	
2.114	25	630	2.113	MS	2.111	
2.096	20	531	2.095	MS	2.092	
2.058	14	721,512	2.058	W	2.056	
-	-	-	2.027	VVW	2.027	
-	-	-	2.022	VVW	-	
2.019	10	820,422	2.019	VW	2.013	
1.984	14	241	1.984	MS	1.979	
1.968	25	631	1.958	MS	1.956	
1.926	4	341,612	-	-	-	
1.887	6	821	1.887	VW	1.886	
1.854	4	441,332	1.853	VVW	-	
-	-	-	1.839	VVW	-	
1.800	8	622,830	1.802	VVW	-	
1.786	10	640,10.1.0	1.786	W	1.786	
1.773	8	541	1.774	VW	1.771	
1.732	8	921	1.733	W	1.729	
1.702	10	831	1.700	VW	1.701	
1.698	8	722	-	-	-	
1.679	10	812,142	1.682	VVW	-	
1.649	7	741	-	-	-	
-	-	-	1.610	VVW	-	
1.603	20	10.2.1.	1.603	VVW	-	
-	-	-	1.598	VVW	-	
1.588	10	931	1.589	W	1.587	
-	-	-	1.586	VW	-	
1.525	7	551	1.527	MS	1.524	
1.520	14		1.521	W	-	
1.485	34	remainder not indexed	1.486	MS	1.485	
1.470	22		1.471	MS	1.468	
1.418	6		1.419	VVW	1.418	
-	-		1.398	VW	1.397	
1.392	17		1.392	MS	1.391	
1.379	6		1.380	VVW	-	
-	-		1.377	VVW	-	
1.360	2		1.358	VW	-	
-	-		1.339	VVW	-	
1.307	6		1.307	VW	1.307	
-	-		1.298	VW	-	
-	-		1.295	VW	-	
-	-		1.289	W	-	
1.267	8		1.268	W	1.266	

d interplanar spacings.
I intensity of reflection.
* estimated intensity, using the following scale:

VS : very strong.
S : strong.
MS : moderately strong.
W : weak.
VW : very weak.
VVW : very, very weak.
hkl : Miller indices

1,2,3 indicates strongest, second strongest and third strongest reflections respectively.
** numerous very weak reflections omitted.

and it is thought to be due to a slight increase in the Ca and Al content of this pyroxene, a feature which will noticeably affect the cell parameters (Hess 1952; Kuno, 1954).

3. Garnets.

As the peridotites and eclogites each contain garnet which is distinct in both appearance and mineralogical composition it is convenient to deal with each type separately.

A) THE GARNETS OF THE PERIDOTITES.

General description.

It has been shown that garnet is a minor yet essential constituent of the garnet peridotite xenoliths and that trace amounts are also present in some of the spinel and altered peridotite xenoliths. In the garnet peridotites it occurs in a fairly constant amount, ranging between two and six per cent by volume (Chapter VIII, Modal Analyses, p.84).

On the rounded, weathered surfaces of the xenoliths the resistant garnets normally stand up in fairly high relief as scattered, dark red grains. Close examination of fresh rock surfaces and the prepared rock-slabs shows that the garnets are unevenly distributed and are often, although not exclusively, in contact with, or in close proximity to grains of orthopyroxene. Examination in thin-section has also shown that occasionally small, rounded crystals of garnet are included in the orthopyroxene grains (Plate 28).

The shape of the garnets varies from roundish to irregular with rare grains exhibiting distinct crystal faces. Well-rounded grains predominate but in some xenoliths large irregular patches of garnet are found (Plate 9). In size the rounded grains vary from approximately 1 to 4 millimetres. The shape, size and textural relationships of the garnet to the other constituents of the peridotites is illustrated in Plates 5 to 9.

In hand specimen all garnets are dark wine-red but on separation from the host rock and examination with the aid of a stereoscopic microscope it is seen that they are all a very characteristic intense, lustrous pink. Slight variations from mauvish pink through magenta-pink to a slight orange-pink are evident. Bragg (1958) has suggested that variations in the colour of pyrope-rich garnets can be related to their chromium content. Results obtained during this study indicate that this is true, at least in part. Analysed garnets (Table 29) have colours ranging from mauve-pink (BF.5, 2.35 per cent Cr_2O_3) to magenta-pink (BF.2 and BF.8, 1.88 and 1.03 per cent Cr_2O_3 respectively) and pale mauve-pink (BF.9, 0.50 per cent Cr_2O_3). The very distinctive and vivid colours of all the garnets can be exactly matched by those derived from the kimberlite matrix.

The garnet grains are always extensively fractured, as illustrated in Plate 33. This fracturing can be attributed to tectonic deformation of the peridotites in depth (as shown by the deformation structures in the other constituents) followed by a rapid release of pressure on the eruption of the kimberlite. Garnet grains occasionally show small rounded olivine inclusions which on serpentination have caused the development of sub-radiating expansion cracks. Other inclusions, so common in garnets from high-grade metamorphic terrains, are completely missing.

Seen in thin-section the garnets are very pale mauvish pink and except for those from a few of the peridotite xenoliths, are completely isotropic. The garnets from several of the peridotites which show extensive deformation structures show very faint anisotropism. Prolonged etching in hydrofluoric acid of polished thin slices of garnet from a tectonically deformed peridotite failed to produce the tangled dislocation structures, recognised by Carstens (1969, 1970), occurring in pyrope-rich garnets of orogenic garnet peridotites. Only a slight etching of the surface was seen.

Alteration of the garnet normally occurs in the form of thin kelyphitic borders. These reaction rims, consisting of opaque to semi-opaque, very fine-grained secondary materials, vary from incipient rims to fairly extensive zones in which more than half the garnet has altered (see Plates 33 and 34). In incident light the kelyphite is khaki-coloured and in transmitted light it is virtually opaque. The kelyphite normally consists of minute grains of brownish spinel and very fine micaceous material and orthopyroxene. In places where garnet grains have been highly fractured the kelyphitic material has also formed along certain cracks.

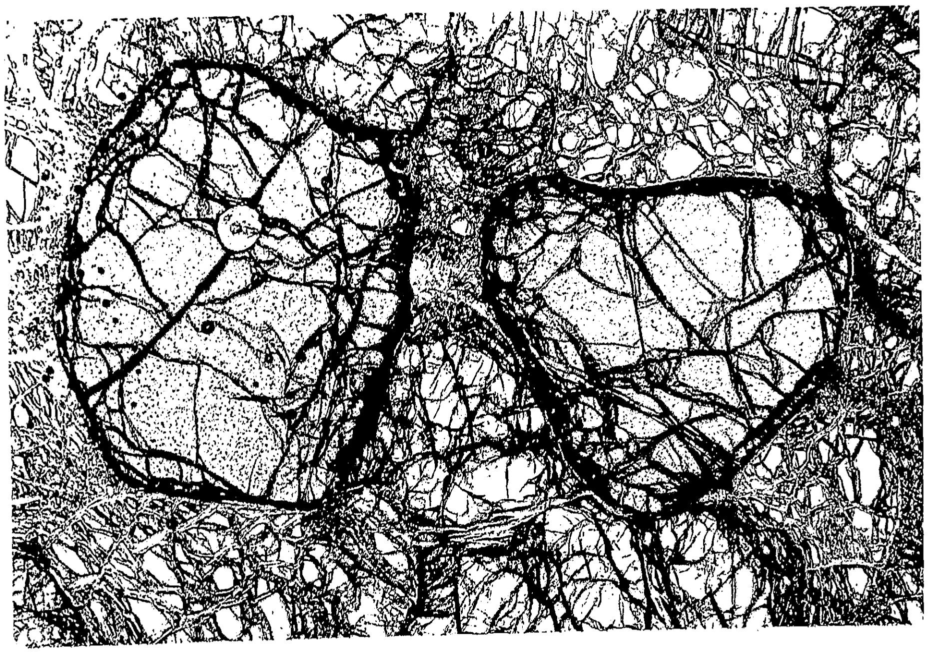


PLATE 33. Garnets from peridotite BF.8. Both grains are extensively fractured and one contains a small, rounded serpentinised olivine inclusion. Only thin kelyphitic rims have formed.
Magnification X 15, ordinary light.

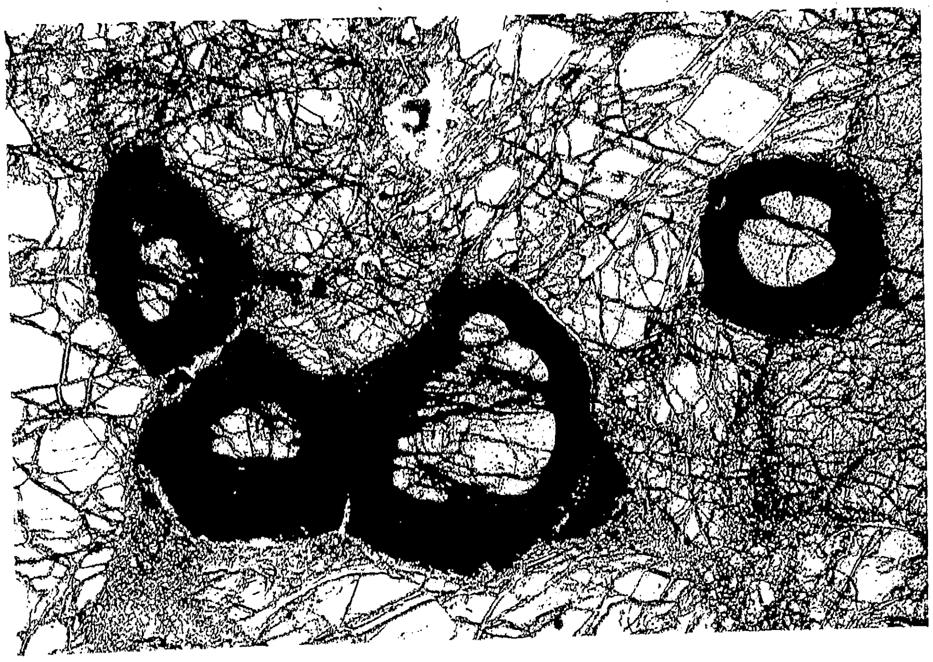


PLATE 34. Garnets from peridotite RV.25. Besides being fractured the grains have been extensively replaced by earthy, opaque kelyphite (shown as black rims).
Magnification X 19, ordinary light.

Physical properties and composition of garnet.

The refractive index and unit cell size of the garnets from all garnet-bearing peridotites are listed in Table 29 together with estimated end-member molecular percentages. This includes values for garnets which are both an essential and a trace constituent. These results are presented graphically in Fig. 16. Diagrams relating the physical properties of garnets to their composition have been devised by Winchell (1958) in which the refractive index is plotted against unit cell size and density is plotted as contours on the surfaces of the projected solid defined by the position of the pyrope, almandine, grossularite, spessartite and andradite end-members. Any graphical solution of this type gives only an approximation of the end-member composition.

Rickwood et al (1968), in their study of garnets from peridotite and eclogite xenoliths, have shown that garnets from the peridotite/pyroxenite suite of xenoliths can be largely described as consisting of a solid solution of the pyrope, almandine, andradite and uvarovite end-members. More recent analyses of garnets by Carswell and Dawson (1970), after recalculation to molecular percentages by the method of Rickwood (1968), are in agreement with this conclusion. The small amounts of grossularite and spessartite present have been ignored.

In the present study, following the lead of Rickwood et al (1968), the determination of only two physical properties (refractive index and unit cell size) has enabled an estimation of three components using the pyrope-almandine-andradite triangle of Winchell's diagram. It is fortunate however that uvarovite and andradite have similar physical properties and plot nearby on Winchell's diagram. Consequently for the purposes of compositional estimation it should be understood that end-member molecular percentages determined represent pyrope-almandine-andradite plus uvarovite.

The garnets plot in a relatively narrow, straight band, the long axis of which is directed to the pyrope end-member. In several cases multiple compositions within one xenolith were recognised (BF.4, BF.9, DT.21). The most conspicuous variations in compositions are those of pyrope which ranges from 80 to 65 per cent and almandine which shows a range from 20 to 9 per cent. The andradite plus uvarovite component shows a variation from 15 to 8 per cent. Whilst the accuracy of these results is of course seriously limited by the

TABLE 29.

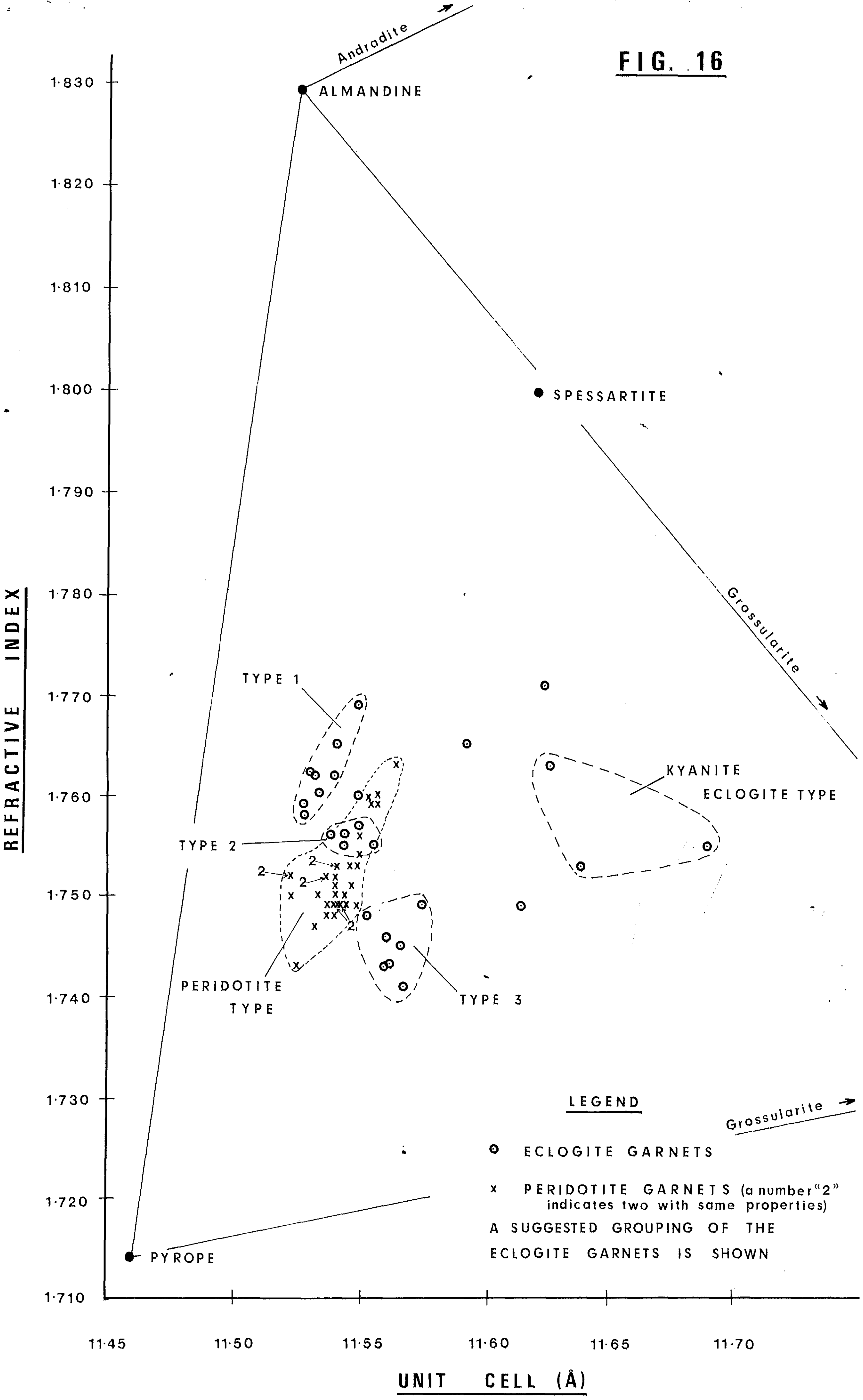
PHYSICAL PROPERTIES AND ESTIMATED END-MEMBER COMPOSITIONS OF GARNETS FROM THE PERIDOTITE XENOLITHS.

Specimen No.	Refractive index (± 0.003)	Unit cell size (Å)	Estimated composition*			S.G.
			Py	Al	An + Uv	
BF. 1	1.753	11.547	73	14	13	-
2	1.760	11.554	67	20	13	3.73
3	1.752	11.541	73	15	12	-
4	1.749	11.542	76	12	12	-
	1.753	11.542	72	16	12	-
5	1.763	11.565	65	20	15	3.73
6	1.752	11.541	73	15	12	-
7	1.752	11.538	73	15	12	-
8	1.754	11.551	73	14	13	3.72
9	1.748	11.538	77	11	12	3.66
	1.753	11.538	72	16	12	
W. 3	1.753	11.550**	73	18	14	-
4	1.749	11.550**	77	9	14	-
6	1.748	11.541	77	11	12	-
7	1.751	11.548**	75	11	14	-
8	1.750	11.541	75	13	12	-
9	1.759	11.557	68	19	13	-
10	1.756	11.551	69	20	11	-
DT. 4	1.750	11.535**	74	15	11	-
6	1.752	11.523	72	20	8	-
7	1.749	11.538	76	12	12	-
8	1.750	11.545	76	11	13	-
9	1.752	11.538**	73	15	12	-
11	1.747	11.533	77	12	11	-
14	1.749	11.543	77	10	13	-
15	1.750	11.523	73	18	9	-
18	1.759	11.556	68	19	13	-
20	1.749	11.541	75	13	12	-
21	1.760	11.559**	67	18	15	-
	1.743	11.527**	80	10	10	-
RV.14	1.749	11.544**	76	11	13	-
16	1.749	11.543	77	10	13	-
25	1.748	11.545**	76	10	14	-

* Estimated end-member compositions calculated using pyrope (Py), almandine (Al) and andradite (An) plus uvarovite (Uv) (see text for explanation).

** Determined using X-ray powder photographic methods [results: ± 0.003 Å]; others by X-ray diffractometer techniques [results: ± 0.001 Å].

FIG. 16



Graph of Refractive Index versus Unit Cell Size for Garnets from the Eclogite and Peridotite Xenoliths restriction imposed in using only two variables they do indicate the similar, pyrope-rich composition of the garnets from all the peridotites. As with their appearance, the refractive index and unit cell size values can be exactly matched by garnets from the kimberlite matrix.

Four pure garnet concentrates were selected for detailed chemical analysis, two being from garnet lherzolites and two from garnet harzburgites. These results, together with structural formulae (Deer et al, 1966, p.515-517) and the percentage garnet end-member molecules calculated according to the procedure outlined by Rickwood (1968) are presented in Table 30. The specific gravities of these analysed garnets are given in Table 29.

The analyses, conducted by the procedures outlined in Chapter VII, have unfortunately resulted in anomalous results. Comparison of the analyses in Table 30 with those of garnets from other garnet peridotite xenoliths (O'Hara and Mercy 1963; Nixon et al, 1963; Carswell and Dawson, 1970) clearly reveals that the silica values are too high (of the order of one to 1.5 per cent) and that the alumina values are too low (of the order of one to two per cent). The remaining analyses give comparable values. The discrepencies are further borne out by the structural formulae (calculated only for those two analyses where ferric iron has been determined). These two structural formulae deviate strongly from structural ideality, the R^{4+} component (Si) being excessively high and the R^{3+} component (Al, Ti, Cr, Fe^{3+}) abnormally low.

It is considered (C.E. Feather, personal communication) that the error is an analytical one due to inter-element enhancement and depression effects when using X-ray fluorescence analytical techniques. The determination of high silica in the presence of high alumina and magnesia will result in excessive silica values; similarly the determination of alumina would be depressed. Fortunately it is thought that only the silica and alumina determinations are anomalous and the remaining results are considered true analytical values. Consequently if silica and alumina are disregarded the recasting of the garnet analyses into end-member molecules using the procedure of Rickwood (1968) can be made.

Acquisition, in the not too distant future, of computer-correction facilities, will enable resolution of this analytical problem and it is hoped to re-analyse the fusion disks at a later stage.

TABLE 30.

CHEMICAL ANALYSES, STRUCTURAL FORMULAE AND END-MEMBER COMPOSITIONS OF PERIDOTITE GARNETS.+

	BF.2	BF.5	BF.8	BF.9
(A) CHEMICAL ANALYSES				
SiO_2	44.50	43.10	43.04	42.99
TiO_2	0.11	0.07	0.11	0.02
Al_2O_3	19.10	17.81	19.03	20.55
Cr_2O_3	1.88	2.35	1.03	0.50
Fe_2O_3	1.57	8.67*	2.79	7.24*
FeO	6.13		5.10	
MnO	0.38	0.38	0.35	0.37
NiO	<0.01	<0.01	<0.01	<0.01
MgO	20.6	20.0	20.6	22.3
CaO	5.56	5.96	5.51	4.21
K_2O	<0.01	0.01	0.01	0.01
P_2O_5	0.06	0.08	0.06	0.10
	99.89	99.40	97.63	99.10
FeO*	7.54	8.67	7.61	7.24
(B) STRUCTURAL FORMULAE**		Not calculated as Fe^{3+} not determined		Not calculated as Fe^{3+} not determined
Si	6.324)=6.32		6.255)=6.26	
Ti	0.009)		0.008)	
Al	3.192)		3.245)	
Cr	0.205)=3.58		0.105)=3.67	
Fe^{3+}	0.171)		0.315)	
Fe^{2+}	0.725)		0.619)	
Mn	0.051)=5.98		0.043)=5.98	
Mg	4.361)		4.458)	
Ca	0.845)		0.855)	
(C) END-MEMBER COMPOSITION (MOLECULAR PERCENTAGES)				
Pyrope ($Mg_3Al_2Si_3O_{12}$	73.0	Not calculated as Fe^{3+} not determined	74.2	Not calculated as Fe^{3+} not determined
Almandine ($Fe^{2+}_3Al_2Si_3O_{12}$)	12.0		10.5	
Spessartite $Mn_3Al_2Si_3O_{12}$)	0.9		0.9	
Grossularite ($Ca_3Al_2Si_3O_{12}$)	4.7		3.9	
Andradite ($Ca_3Fe^{3+}_2Si_3O_{12}$)	4.3		7.9	
Uvarovite ($Ca_3Cr^{3+}_2Si_3O_{12}$)	5.2		2.6	

* Total iron expressed as FeO.

** Structural formulae calculated as the number of anions on the basis of 24 oxygens.

\+ Analyses by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

Interesting features arising out of the analyses are the relatively high and variable chromia values (reflected as an appreciable uvarovite content), variable ferric iron (shown up by a variable andradite content) and fairly constant total iron, manganese, magnesia and lime contents. Except for the rather high grossularite percentage the calculated end-member compositions are in close agreement with the calculated composition of the mean of 40 garnet analyses from garnet peridotite xenoliths derived from kimberlite (Carswell and Dawson, 1970, Table 5).

A semi-quantitative trace element analysis of both the peridotite and eclogite garnets is presented in Table 31. The only trace elements of any significance in both suites are Sn, Ni, Co, V and Zr.

Interplanar (d) spacings.

X-ray diffraction data of two analysed garnets (BF.5, BF.8) are presented in Table 32, and are compared with an ASTM reference standard of synthetic pyrope (card No. 2-1008). Excellent agreement was obtained for the d spacings of the two analysed garnets (which indicates their very similar composition, see Table 30). They both compare well with the standard pyrope. Diffractometric patterns were run using a silicon internal standard.

B, THE GARNETS OF THE ECLOGITES.

General description.

Unlike the peridotite garnets, garnet forms a major constituent of the eclogites, varying between approximately twenty and seventysix volumetric per cent, with two rather ill-defined maxima at about fifty and sixtyfive per cent (Chapter VIII, Modal Analyses).

As with the peridotites the garnets tend to stand up in higher relief on weathered or rounded surfaces and are usually well-polished. Examination of hand specimens and prepared rock slabs shows that the garnet distribution varies considerably and that in some xenoliths the garnets are segregated into layers or patches.

In shape the grains are almost always anhedral and vary from roundish to elongated to irregular. Very rarely do any grains exhibit distinct crystal morphology. In size the garnets vary from about 2 to 6 millimetres. Typical eclogites, illustrated in Plates 15 to 20, show the shape, size and textural

TABLE 31.

SEMI-QUANTITATIVE TRACE ELEMENT ANALYSIS OF GARNET FROM THE PERIDOTITE AND ECLOGITE XENOLITHS.+

(in parts per million)

Specimen No.	Co	V	Zn	Sn	Mo	Y	Zr
BF. 2	40	50	<50	10	<10	<10	50
5	40	50	<50	15	<10	10	50
8	40	50	<50	15	<10	<10	60
9	40	50	<50	10	<10	10	40
RV. 4	60	<50	50	20	10	10	40
5	60	<50	<50	20	10	10	40
32	60	<50	<50	30	10	10	40
RVL. 5	60	50	50	30	15	<10	
Limit of detection	10	50	50	10	10	10	10

In all garnet specimens.

B <10
Li <50
Be <0.5
Ge <10
As <100
Sr <50

Nb <10
Ag <0.1
Bi < 5
Cd <10
Sb <10
Ba <100

La <100
Pt < 50
Cu < 10
Au < 5
Pb < 10

\+ Analyses by Analytical Research Section, Anglo American Research Laboratory.

TABLE 32.

X-RAY DIFFRACTION DATA FOR GARNET FROM PERIDOTITES BF. 5 AND BF.8.

ASTM card No. 2-1008 Byrope			Garnet BF.5		Garnet BF.8	
d(Å)	I	hkl	d(Å)	I*	d(Å)	I*
-	-	-	10.6	VVW	-	-
-	-	-	5.1	VVW	-	-
-	-	-	3.88	VVW	3.88	VVW
2.88	60	400	2.890	S^2	2.887	S^2
-	-	-	2.766	VVW	-	-
2.58	100	420	2.586	VS^1	2.584	VS^1
-	-	-	2.515	VW	2.509	VVW
2.46	30	332	2.467	MS	2.462	MS
2.35	30	422	2.361	MS	2.358	MS
2.26	30	510	2.270	MS	2.267	MS
2.10	20	521	2.111	W	2.110	W
2.03	5	440	-	-	-	-
1.87	40	611	1.876	MS	1.874	W
1.82	10	620	1.829	VW	1.827	VW
1.66	30	444	1.669	W	1.667	W
1.60	60	640	1.603	MS	1.602	MS
1.54	100	642	1.545	S^3	1.543	S^3
1.44	30	800	1.445	W	1.444	VW
1.42	5	811	-	-	-	-
1.29	40	840	1.293	W	1.291	W
1.26	60	842	1.262	W	1.260	W
1.24	5	921	-	-	-	-
1.23	40	664	1.233	VW	1.232	W
1.22	10	930	1.168	VVW	1.167	VW
1.16	30	941	-	-	-	-
1.13	10	862	-	-	-	-
1.07	70	666	1.073	MS	1.073	MS
1.05	60	10.4.2.	1.056	W	1.054	W
1.02	60	880	1.022	W	1.021	W
0.96	20	12.0.0.	0.964	VW	0.963	VW
0.95	20	12.2.0.	0.950	W	0.950	W
0.94	60	10.6.4.	0.938	MS	0.937	MS

d : interplanar spacings.
I : intensity of reflections.
* estimated intensity, using the following scale:

VS : very strong.
S : strong.
MS : moderately strong.
W : weak.
VW : very weak.
VVW : very, very weak.

^{1,2,3} indicates strongest, second strongest and third strongest reflections respectively.

hkl : Miller indices.

relationships of the garnets.

The colour of the garnets varies considerably from a pale orange through pinkish browns to fairly dark reddish browns. The dark mauves, pinks and reds of typical peridotite and kimberlite garnets are absent. On separation and microscopic examination the analysed garnets show colours of pale orange (RV.4), pale pinkish orange (RV.5) to dark reddish brown or dark orange (RV.32 and RVL.5 respectively). The chemical analyses (Table 34) all show very little chromium and it is doubtful whether this element contributes much to the colour (except possibly in the case of RVL.5). There is however a noticeable increase in the amount of both total iron and ferric iron which probably manifests itself by a darkening of the colour.

The garnet grains are often extensively fractured, sometimes in a sub-parallel fashion. This can probably be related to intense tectonic deformation or stress, a feature which is also shown by slight anisotropism of many of the grains when viewed under crossed nicols. In thin-section the garnets show a very faint pinkish or orange tint and in a number of instances exhibit abundant orientated, needle-like inclusions. These hair-like inclusions, illustrated in Plate 35, which are highly birefringent and are regularly orientated in at least three directions, probably parallel to the (111) planes of the host. They also exhibit an inclined extinction. Such inclusions, which appear to be exsolution bodies, could be one of a number of minerals, of which rutile, kyanite, sillimanite and clinopyroxene come to mind. The fact that they show inclined optical extinction suggests however that they are either clinopyroxene or kyanite.

Alteration of the garnet occurs in the form of thin kelyphitic rims and thin veinlets of melted material where in contact with the clinopyroxene. The kelyphitic borders normally consist of a very fine mixture of pale brown mica, green spinel and in places pale amphibole, feldspar microlites and glassy material. Many of the garnets are turbid and show incipient dust-like alteration on fracture surfaces.

Physical properties and composition of garnet.

The refractive index and unit cell size of the garnets from the eclogites are listed in Table 33 together with estimated end-member molecular percentages. These results are presented graphically in Fig. 16.

TABLE 33.

PHYSICAL PROPERTIES AND ESTIMATED END-MEMBER COMPOSITIONS OF GARNETS FROM THE ECLOGITE XENOLITHS.

Specimen No.	Refractive Index (± 0.003)	Unit cell size (Å)	Estimated compositions*			S.G.
			Py	Al	Gro	
RV. 1	1.755	11.556	52	29	19	-
2	1.762	11.532	49	39	12	-
3	1.756	11.539	52	33	15	-
4	1.749	11.576	49	26	25	3.77
5	1.756	11.545	50	34	16	3.78
6	1.763	11.626**	28	35	37	-
7	1.755	11.544	52	32	16	-
8	1.760	11.534	48	39	13	-
9	1.743	11.561	57	21	22	-
	1.746	11.561	55	23	22	-
10	1.745	11.567	54	23	23	-
18	1.749	11.615**	40	25	35	-
20	1.748	11.553 +	54	26	20	-
26	1.758	11.528	50	37	13	-
27 K	1.753	11.639**	32	26	42	-
	1.757	11.550**	48	35	17	-
	1.760	11.550	46	38	16	-
29	1.769	11.550	39	46	15	-
30	1.762	11.539	46	40	14	-
31	1.741	11.568+	56	19	25	-
32	1.765	11.593	32	40	28	3.82
33	1.743	11.562	56	22	22	-
34	1.755	11.689**	20	25	55	-
RVL. 2	1.759	11.528	51	37	12	-
5	1.762	11.531	48	40	12	3.84
10	1.765	11.541	44	42	14	-
16	1.771	11.624**	22	43	35	-

* Estimated end-member compositions calculated using pyrope (Py), almandine (Al) and grossularite (Gro) (see text for explanation).

** Determined by X-ray powder photographic methods (results : ± 0.003Å); all others by X-ray diffractometer techniques (results : ± 0.001Å).

\+ Diffuse X-ray reflections.

K : Garnet from kyanite-bearing portion.

The estimation of garnet composition from physical properties has already been dealt with (p.158). Studies by Rickwood et al (1968) and Kushiro and Aoki (1968) have shown that eclogite garnets can largely be described using the pyrope, almandine and grossularite end-members. In this study a measurement of only two physical properties (refractive index and unit cell size) has enabled an estimation of these three components to be made, using the pyrope-alamandine-grossularite triangle of Winchell's diagram. Small amounts of andradite, uvarovite and spessartite have been ignored.

A study of Fig. 16 (p.159) shows that, in contrast to the peridotite garnets, those from eclogite plot over a very much wider range, indicating a fairly wide variation in chemical composition. The amount of pyrope varies from twentytwo to fiftyseven per cent, the almandine from twentytwo to fortysix per cent and grossularite from twelve to fiftyfive per cent. Garnets from two eclogites (RV.9, RV.27) show a small range in physical properties. The data for the eclogite garnets, illustrated in Fig. 16, allows a tentative grouping of the majority of the garnets to be made. At least three types, defined as follows, can be recognised:

Type 1 (8 garnets) : Garnets are clear, dark reddish orange in colour.
Average estimated composition : PY_{47} Al_{40} Gro_{14}.
Range in estimated composition : $PY_{39-54}Al_{37-46}$ Gro_{12-15}

Type 2 (5 garnets) : Garnets usually turbid, pinkish or brownish orange.
Average estimated composition : PY_{51} Al_{33} Gro_{17}
Range in estimated composition : PY_{48-52} Al_{29-35} Gro_{15-19}

Type 3 (6 garnets) : Garnets usually turbid, pale pinkish or orange.
Average estimated composition : PY_{55} Al_{23} Gro_{23}
Range in estimated composition : PY_{49-56} Al_{19-56} Gro_{20-25}

Only seven garnets do not fall into one of these three types, three of these coming from kyanite or kyanite-corundum eclogites. It is interesting to note that the Type 1 garnets, as defined in this Chapter, correlate fairly well with the Group 1 eclogites discussed in Chapter VIII, Summary and Discussion. Garnets falling into Types 2 and 3 are only found in the Group 2 eclogites (with two exceptions). The garnets from the kyanite eclogites (Eclogite Group 3) have not been grouped as they plot over a considerable range of values.

Rickwood et al (1968) have similarly attempted a grouping of eclogite garnets on the basis of physical properties. Although their grouping is broadly similar it does not coincide strictly with that obtained during the present study. They did however deal with many more xenoliths from numerous kimberlites. An inspection of their Fig. 5 (p.287) leaves one with the impression that their attempted grouping has been too bold. For example, it is indeed difficult to see the justification for including all the points in their Group II within one field; similarly the wisdom of including those garnets plotting in the area defined by $n<1.75$ and $a_o <11.55$ in their Group I is doubtful.

Four pure garnet concentrates (one each from Type 1, 2 and 3 and one ungrouped garnet, RV.32) were selected for a detailed chemical analysis. These results, together with structural formulae (Deer et al, 1966, p.515-517) and the percentage garnet end-member molecules calculated according to the method of Rickwood (1968) are given in Table 34. Specific gravities of these analysed garnets are given in Table 33.

These results are much more consistent than those of the peridotite garnets (Table 30) and are of the same order as those of eclogite garnets analysed by Kushiro and Aoki (1968). The calculation of structural formulae, which do not deviate markedly from ideality, support the correctness of the analyses.

The calculated end-member compositions show the essential and fairly constant pyrope-rich composition of the garnets, whilst the almandine, andradite and grossularite contents varies considerably. The calculated end-member compositions are in fairly good agreement with those estimated from physical properties. A noticeable feature of the analyses is the variable total iron and lime content and the very low chromia values (which contrasts with the peridotite garnets).

A semi-quantitative trace element analysis of the four analysed garnets is given in Table 31.

Interplanar (d) spacings.

X-ray powder diffraction data of two analysed eclogite garnets (RV.4, RVL.5) are presented in Table 35. These results, determined by X-ray powder diffractometric techniques using an internal silicon standard, are compared with

TABLE 34.

CHEMICAL ANALYSES, STRUCTURAL FORMULAE AND END-MEMBER COMPOSITIONS OF ECLOGITE GARNETS.+

	RV.4	RV.5	RV.32	RVL.5
(A) CHEMICAL ANALYSES				
SiO_2	40.61	40.20	39.10	40.40
TiO_2	0.25	0.26	0.15	0.31
Al_2O_3	21.99	21.57	21.36	21.37
Cr_2O_3	0.05	0.06	0.07	0.11
Fe_2O_3	2.01	2.40	2.97	3.26
FeO	11.33	13.89	17.41	16.26
MnO	0.22	0.41	0.44	0.39
NiO	<0.01	<0.01	<0.01	<0.01
MgO	14.1	14.7	9.4	14.5
CaO	9.03	5.77	9.17	4.00
K_2O	0.06	0.10	0.02	0.02
P_2O_5	0.08	0.08	0.04	0.03
	99.73	99.44	100.13	100.65
FeO*	13.14	16.05	20.08	19.19
(B) STRUCTURAL FORMULAE**				
Si Al	5.954)=6.00 0.046)	5.954)=6.00 0.046)	5.918)=6.00 0.082)	5.960)=6.00 0.040)
Al Fe^{3+} Ti	3.759) 0.229)=4.02 0.035)	3.734) 0.267)=4.03 0.027)	3.736) 0.345)=4.11 0.027)	3.659) 0.372)=4.07 0.036)
Fe^{2+} Mn Mg Ca	1.392) 0.026)=5.92 3.083) 1.418)	1.721) 0.053)=5.97 3.254) 0.918)	2.200) 0.054)=5.86 2.118) 1.491)	2.001) 0.053)=5.87 3.188) 0.629)
(C) END-MEMBER COMPOSITIONS (MOLECULAR PERCENTAGES)				
Pyrope $Mg_3Al_2Si_3O_{12}$	49.0	55.0	28.7	49.6
Almandine $(Fe_3^2{+}Al_2Si_3O\ _2)$	22.2	28.8	29.8	31.0
Spessartite $(Mn_3Al_2Si_3O_{12})$	0.8	0.9	0.7	0.8
Grossularite $Ca_3Al_2Si_3O_{12}$	22.6	8.6	30.1	9.9
Andradite $Ca_3Fe_2^3{+}Si_3O_{12})$	5.4	7.8	10.6	8.7

* Total iron expressed as FeO

** Structural formulae calculated as the number of anions on the basis of 24 oxygens.

\+ Analysed by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

TABLE 35.

X-RAY DIFFRACTION DATA FOR GARNET FROM ECLOGITES RV.4 AND RVL.5.

ASTM card No. 9-427 Almandine			Garnet RVL.5		Garnet RV.4	
d(Å)	I	hkl	d(Å)	I*	d(Å)	I*
4.04	30	220	-	-	-	-
-	-	-	3.35	VVW	3.34	VVW
2.873	40	400	2.881	S^2	2.890	S^2
2.569	100	420	2.578	VS^1	2.588	VS^1
2.447	5	332	2.457	W	2.468	MS
2.348	20	422	2.352	MS	2.362	MS
2.257	20	510	2.261	MS	2.270	MS
2.102	20	521	2.104	W	2.112	W
2.043	10	440	2.038	VVW	2.045	VVW
1.866	30	611	1.869	MS	1.876	MS
-	-	-	1.823	VW	1.829	VVW
-	-	-	1.700	VVW	-	-
1.660	30	444	1.663	W	1.670	W
1.599	40	640	1.598	MS	1.604	MS
1.540	50	642	1.540	S^3	1.546	S^3
1.441	20	800	1.441	W	1.446	W
-	-	-	1.418	VVW	1.424	VVW
-	-	-	1.377	VVW	1.384	VVW
1.287	20	840	1.289	W	1.294	W
-	-	-	1.258	W	1.263	W
-	-	-	1.243	VVW	1.248	VVW
1.228	10	664	1.225	W	1.234	VW
-	-	-	1.215	VVW	1.220	VVW
1.167	5	941	1.165	VW	1.169	VW
-	-	-	1.131	VVW	1.135	VVW
1.070	20	10.2.2.	1.071	MS	1.075	W
1.051	10	10.4.2.	1.053	W	1.057	W
1.019	10	880	1.019	W	1.023	W
-	-	-	0.961	W	0.963	VVW
0.947	5	12.2.0.	0.948	W	0.952	VW
0.935	10	11.5.2.	0.935	MS	0.939	MS
Plus other lines						

d : interplanar spacings.
I : intensity of reflections.
* estimated intensity, using the following scale:

VS : very strong.
S : strong.
MS : moderately strong.
W : weak.
VW : very weak.
VVW : very, very weak.

hkl : Miller indices.

1,2,3 indicates strongest, second strongest and third strongest lines respectively.

an ASTM reference standard of almandine (card No. 9-427). A comparison of these results with those in Table 32 should also be made. The small differences that are apparent reflect the compositional variations.

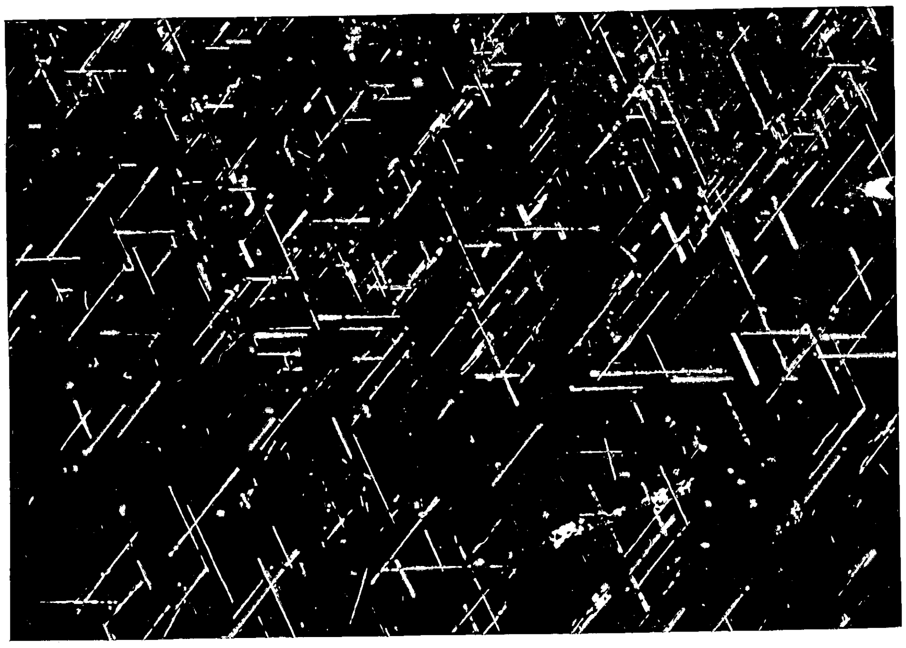


PLATE 35. Minute, orientated, needle-like inclusions in the garnet of eclogite RV.10. These are possibly exsolved clinopyroxene or kyanite bodies. Magnification X 100, crossed nicols.

4. Clinopyroxenes.

As with the garnets the peridotites and eclogites contain clinopyroxene which in both appearance and mineralogical composition is distinctive. That from the lherzolitic peridotites is commonly known as chrome diopside while the clinopyroxene of the eclogites is considered to be of omphacitic composition. It is convenient to deal with each type separately.

A. THE CLINOPYROXENES OF THE PERIDOTITES (CHROME DIOPSIDE).

General description.

By definition chrome diopside is only found in the lherzolitic peridotites, and then in only minor amounts. In only two xenoliths examined (DT.2 and DT.9, one of which is a wehrlite) does chrome diopside form a major constituent; the mean content of chrome diopside in the garnet peridotite xenoliths is 0.7 per cent and for the garnet lherzolites alone approximately one per cent (see Chapter VIII, Modal Analyses).

The small amounts of chrome diopside show up on fresh rock surfaces as small, scattered vivid green specks. Close examination shows that the chrome diopside is usually closely associated with either the enstatite or the garnet. The textural features and distribution of the chrome diopside in the garnet peridotites is illustrated in Plates 5 to 9. The grains are always anhedral and only very rarely show inclusions.

In colour the chrome diopside is a characteristic, intense, bright green and shows only slight colour variation. The unusual green colouration is no doubt due mainly to the substantial amount of chromium in the structure (see Table 37). The very distinctive colour of the chrome diopside can be exactly matched by that of the chrome diopside derived from the kimberlite matrix.

In thin section the chrome diopside is faintly pleochroic in shades of yellowish green to green. The grains show extensive fracturing and the typical pyroxene cleavages; occasionally they show the development of twin lamellae and an indistinct parting. Slight granulation of the chrome diopside is evident in places but in general the grains do not show any extensive deformation although the lamellar structure may represent a deformation feature (Raleigh and Talbot, 1967). Examination in polarised light reveals that the majority of the grains show only a very slight uneven extinction, if at all.

Alteration of the chrome diopside, which is generally slight, is shown up by a turbid appearance or dustiness. Where more intense the grains show replacement by chloritic material, spinel and micaceous matter.

Physical properties and composition.

Optical properties have been measured for a selection of the chrome diopside grains, including those of an analysed sample, and are reported in Table 36. Both Nixon et al (1963) and Mathias et al (1970) have noted that optical properties of the chrome diopside cannot be accurately correlated with chemical composition but it is known that substitution by chromium in a crystal lattice will increase refractive indices (Ahrens, 1958). In the light of the fact that the optical properties are not diagnostic for compositional variation it was considered that a detailed study of the optical properties of the chrome diopside from all the present xenoliths would, at this stage, prove of little value.

The measured optical properties (Table 36) can be seen to vary slightly suggesting that the chemical composition of the chrome diopside from the xenoliths show only minor variations. The result of an analysis of one pure mineral separate of chrome diopside from peridotite BF.5 is presented in Table 37, together with the calculated structural formula (Deer et al, 1966), atomic ratios and specific gravity.

What is immediately striking from the analysis are the high soda and chromia contents. In addition a normative calculation shows that magnesia is in excess after making up the diopside formula and results in an appreciable amount of enstatite in the norm, a feature also recognised by Nixon et al (1963). In other words a significant amount of enstatite is held in solid solution in the diopside, this indicating that high temperature was necessary for its formation (Boyd and Schairer, 1964).

In a recent electron microprobe study of chrome diopsides from kimberlites and associated peridotite xenoliths Boyd (1969) has stressed the solid solution relationships of enstatite in diopside (see also Davis and Boyd, 1966). His results have shown that in the kimberlitic diopsides there exists a wide range of solid solution towards enstatite, this being evidently

TABLE 36.

OPTICAL PROPERTIES OF CLINOPYROXENE FROM SELECTED PERIDOTITE AND ECLOGITE XENOLITHS.

Specimen No.	Optical properties		
	n_β *	$2V_\gamma$ **	$c \wedge \gamma$ **
A. CHROME DIOPSIDE.			
BF.11	1.682	-	35°
BF. 2	1.685	-	37°
BF. 5	1.684	65°	37°
W. 6	1.681	-	40°
DT. 7	1.686	-	40°
DT.11	1.687	-	41°
RV.16	1.686	-	40°
RV.25	1.687	-	39°
B. OMPHACITE.			
RV. 1	1.679	-	37°
RV. 4	1.671	-	39°
RV. 5	1.678	-	38°
RV. 8	1.681	-	39°
RV.10	1.679	-	40°
RV.32	1.681	66°	41°
RVL.5	1.680	64°	41°

* Results ± 0.005

** Results ± 2°

TABLE 37.

CHEMICAL ANALYSES, STRUCTURAL FORMULAE AND ATOMIC RATIOS OF CLINOPYROXENE FROM THE PERIDOTITE AND ECLOGITE XENOLITHS.+

	Chrome diopside BF.5	Omphacite RV.32	Omphacite RVL.5
(A) CHEMICAL ANALYSES			
SiO_2	54.48	53.47	53.78
TiO_2	0.02	0.36	0.44
Al_2O_3	2.09	9.25	6.98
Cr_2O_3	2.09	0.04	0.08
Fe_2O_3 FeO	1.12*	7.26*	6.67*
MnO	0.06	0.04	0.09
NiO	0.02	0.04	0.06
MgO	17.7	9.4	11.5
CaO	19.33	14.99	14.20
K_2O	0.04	0.03	0.18
Na_2O	1.93	4.8	4.1
P_2O_5	0.02	0.04	0.06
	98.90	99.72	98.33
(B) STRUCTURAL FORMULAE**			
Si	1.979 =2.00	1.897 =2.00	1.977 =2.00
Al	0.021	0.103	0.023
Al	0.070	0.285	0.282
Cr	0.061	-	-
Fe^{3+}	- =1.12	- =1.08	0.053 =1.13
Ti	-	0.090	0.011
Fe^{2+}	0.033	0.215	0.150
Mn	0.002	-	0.002
Mg	0.958	0.497	0.629
Ca	0.753 =0.89	0.569 =0.90	0.558 =0.86++
Na	0.136	0.328	0.292
(C) ATOMIC RATIOS			
Al^{3+},Fe^{3+},Cr,Ti	6.5	18.9	17.4
Fe^{2+},Mn	1.7	10.8	7.7
Ca	37.4	28.7	28.1
Na,K	6.8	16.5	15.1
S.G.	3.30	3.32	3.34

* Total iron as FeO.

** Structural formulae calculated as the number of anions on the basis of 6 oxygens.

++ Includes K 0.008.

\+ Analysed by X-ray Analytical Laboratory and Analytical Section, Anglo American Research Laboratory.

due to variation in the depth of subsolidus equilibrium (which will be affected by the temperature and pressure of equilibration). Boyd has used the distribution of the ratio Ca/Ca + Mg (atomic per cent) in the diopside to indicate the temperature of formation (see Boyd, 1969, Fig. 2). Using the same procedure the chrome diopside analysed during the present study gives a Ca/Ca + Mg ratio of 0.439, indicating a temperature of formation of about 1075°C (at a pressure of approximately 30 kb). This result is slightly higher than those for the bulk of kimberlite diopsides (950 to 1000°C) and indicates a slightly greater depth of formation, at approximately 125 km on the Precambrian Shield geotherm.

Using the chemical composition of pyroxene O'Hara (1967) has also devised a scheme in which an assessment of conditions of equilibrium in ultramafic assemblages can be made. Using two compositional variants for clinopyroxene (α_c and β_c) an estimation of equilibrium conditions can be made (see O'Hara, 1967, Figs. 12.4 and 12.6). Application of this hypothesis to the analysed chrome diopside suggests that the material (and hence the garnet lherzolite xenolith, BF.5) equilibrated at conditions of 36.5 kb and 1150°C, equivalent to a depth of approximately 125 km. This result is also consistent with those of other peridotite xenoliths in kimberlite (see O'Hara, Fig. 12.6) and is in excellent agreement with results determined on the basis of the Ca/Ca + Mg ratio (Boyd, 1969).

The results of a semi-quantitative analysis for trace elements of one sample of chrome diopside (from xenolith BF.1) is given in Table 38, together with the results of two eclogitic clinopyroxenes. For the chrome diopside the only elements of significance are Nb, Co, V, Sr and Zr.

Interplanar (d) spacings.

X-ray powder diffraction data of one unanalysed chrome diopside (from xenolith BF.1) is presented in Table 39 together with similar data for one eclogite clinopyroxene. These results are compared with those for diopside (ASTM card No. 11-654) and omphacite (ASTM card No. 17-522) respectively. The chrome diopside data shows appreciable divergence from that of the reference diopside.

TABLE 38.

SEMI-QUANTITATIVE TRACE ELEMENT ANALYSIS OF CLINOPYROXENE FROM THE PERIDOTITE AND ECLOGITE XENOLITHS.+

(in parts per million)

	Sn	Nb	Cu	Co	V	Sr	Zr
Chrome diopside BF.1	<10	10	<10	20	50	200	40
Omphacite RV.32	10	10	15	40	100	<50	20
Omphacite RVL.5	10	<10	10	40	<50	200	20
Limit of detection	10	10	10	10	50	50	10

In all clinopyroxene specimens

B	<10
Li	<50
Be	<0.5
Ge	<10
As	<100
Y	<10
Ag	<0.1
Bi	<5
Cd	<10
Sb	<10
Ba	<100
La	<100
Pt	<50
Cu	<10
Zn	<50
Au	<5
Pb	<10

+ Analysed by Analytical Research Section, Anglo American Research Laboratory.

TABLE 39.

X-RAY DIFFRACTION DATA FOR CLINOPYROXENE FROM PERIDOTITE AND ECLOGITE XENOLITHS.

ASTM card No. 11-654 Diopside			Chrome diopside BF.1		ASTM card No. 17-522 Omphacite			Omphacite RV.32	
d(Å)	I	hkl	d(Å)	I*	d(Å)	I	hkl	d(Å)	I*
4.69	1	200	-	-	6.4	30	110	-	-
4.47	3	020	-	-	6.4	50	020	4.39	VW
4.41	3	111	4.43	W	3.8	10	-	-	-
3.66	3	111	-	-	3.33	10	021	3.311	VW
3.35	11	021	3.33	VW	3.19	50	220	3.181	S[3]
3.23	25	220	3.212[3]	S	3.12	10		3.10	VW
2.991	100	$22\bar{1}$	2.985[2]	VS	2.976	100	$22\bar{1}$	2.973	VS[1]
2.952	25	310	2.929[1]	VS	2.915	50	310	2.900	VS[2]
2.893	30	$31\bar{1}$	2.889	MS	2.880	50	$31\bar{1}$	2.878	MS
2.837	1	130	-	-	2.549	40	$13\bar{1}$	2.543	MS
2.566	20	$13\bar{1}$	2.557	MS	2.521	40	202	2.514	W
2.528	40	$002,20\bar{2}$	2.521	W	2.484	50	221	2.475	MS
2.518	30	$11\bar{2},22\bar{1}$	2.500	MS	2.268	35	311	2.260	W
2.392	3	131	2.376	VVW	2.192	30	$22\bar{2},112$	2.190	W
2.304	15	311	2.283	W	2.127	70	330	2.123	W
2.218	13	112	2.204	W	2.118	70	$33\bar{1}$	2.117	MS
2.200	11	$022,22\bar{2}$	2.194	VVW	2.088	20	421	2.089	VW
2.157	9	330	2.141	MS	-	-	-	2.041	VVW
2.134	15	$33\bar{1}$	2.125	MS	2.019	70	041	2.018	MS
2.109	7	$42\bar{1}$	2.100	W	1.987	10	240	1.980	VVW
2.077	1	420	2.061	VVW	1.958	10	$13\bar{2}$	1.959	VVW
2.043	13	041	2.031	W	1.934	10	$24\bar{1}$	1.934	VVW
2.016	9	$40\bar{2},240$	2.017	W	1.879	10	$51\bar{1}$	-	-
2.009	9	202	1.994	VVW	1.833	10	$331,42\bar{2}$	-	-
1.970	7	$13\bar{2}$	1.964	VVW	1.810	20	$510,33\bar{2}$	1.805	W
1.862	3	331	-	-	1.778	10	241	-	-
1.838	5	510,422	-	-	1.749	10	421	-	-
1.832	3	222	1.822	W	1.733	40	150	1.731	W
1.815	3	132	-	-	1.660	30	$24\bar{2},042$	1.659	VW
1.777	1	421	-	-	1.624	20	$223,44\bar{1}$	1.624	VW
1.755	11	150	1.745	MS	1.609	30	531	1.608	W
1.720	1	$51\bar{2}$	-	-	1.597	20	440	1.593	W
1.713	1	$11\bar{3},312$	-	-	1.566	10	530	1.561	VVW
1.685	1	$15\bar{1}$	-	-	1.545	10	660,113	-	-
1.674	5	$042,24\bar{2}$	1.663	VW	1.531	10	350	1.536	VW
1.659	5	$31\bar{3}$	-	-	1.523	10	$60\bar{2}$	1.528	VW
1.625	25	$22\bar{3},53\bar{1}$	1.624	VVW	1.502	20	$53\bar{2},402$	1.496	VW
1.618	5	440	1.618	MS	1.472	20	242,060	1.469	VW
1.588	3	530	1.606	W	1.441	10	$441,62\bar{2}$	1.438	VVW
1.565	3	600	1.576	VVW	1.421	10	442	-	-
1.551	3	550	1.552	VVW	1.412	10	061	-	-
1.529	1	$6\ 60\bar{2}$	1.527	VVW	1.402	80	531,260	1.397	MS
1.526	9	$402,62\bar{1}$			1.378	10	$26\bar{1}$	-	-
1.504	11	$13\bar{3}$			1.363	10	711	-	-
1.494	1	242			1.324	30	$71\bar{2}$	1.321	VW
1.488	3	060	1.480	VW	1.316	10	$261,53\bar{3}$	-	-
1.468	1	$33\bar{3}$			1.308	20	710,621	1.302	VW
1.463	1	441			1.290	10	$44\bar{3}$	1.289	VVW
1.447	3	$51\bar{3},62\bar{2}$			1.273	30	$550,26\bar{2}$	1.268	VW
1.424	13	531	1.411	W	1.262	10	$40\bar{4}$	-	-
Plus other lines					Plus other lines				

d : interplanar spacings

I : intensity of reflections

* estimated intensity, using the following scale:

VS = very strong
S = strong
MS = moderately strong
W = weak
VW = very weak
VVW = very, very weak

hkl : Miller indices

1,2,3 indicates strongest, second strongest and third strongest reflections respectively.

B. THE CLINOPYROXENE OF THE ECLOGITES (OMPHACITE).

General description.

Clinopyroxene, normally considered to be of the omphacite variety, is an essential constituent of all the eclogites xenoliths and ranges in amount from about 20 to 80 volumetric per cent. When fresh the pyroxene varies in colour from a dark bottle green to pale blue-green and is quite distinct from the chrome diopside found in the peridotite xenoliths. Unfortunately in almost every specimen the pyroxene has been extensively altered to very fine-grained, light, greyish green aggregates in which only relicts of the original material have been preserved. In thin-section the clinopyroxene varies from very pale green to almost colourless and shows no perceptible pleochroism.

The textural relationships between the clinopyroxene and garnet are illustrated in Plates 15 to 20. The clinopyroxene grains are invariably anhedral or irregular and generally have the appearance of being interstitial to the garnet. Typically the clinopyroxene grains are fractured and often show the characteristic pyroxene cleavages. Parting planes with thin zones of alteration are not uncommon.

The clinopyroxene grains, where unaltered, only rarely contain visible inclusions. Inclusions which have been detected include small rounded or elongated grains of garnet (RV.8) and minute, prismatic crystals of rutile (RVL.16). In one specimen (RVL.16) the clinopyroxene is in places myrmekitically intergrown with the garnet, as illustrated in Plate 36. Exsolution lamellae of garnet within the clinopyroxene, such as observed by the writer in an eclogite xenolith from Yakutia (G.G. Whitfield, unpublished A.A.R.L. Report), were not seen.

The clinopyroxene also shows uneven optical extinction, suggestive of tectonic deformation. However, kinking, gliding and translation features were not seen.

Alteration and melting of the clinopyroxene.

As has already been mentioned the clinopyroxene in virtually every specimen of eclogite exhibits a peculiar form of alteration. This takes the form of either large areas of pyroxene altered to ultrafine-grained material which is particularly concentrated along fractures and partings (as illustrated in Plate 37) or a distinct partial melting of the clinopyroxene as shown

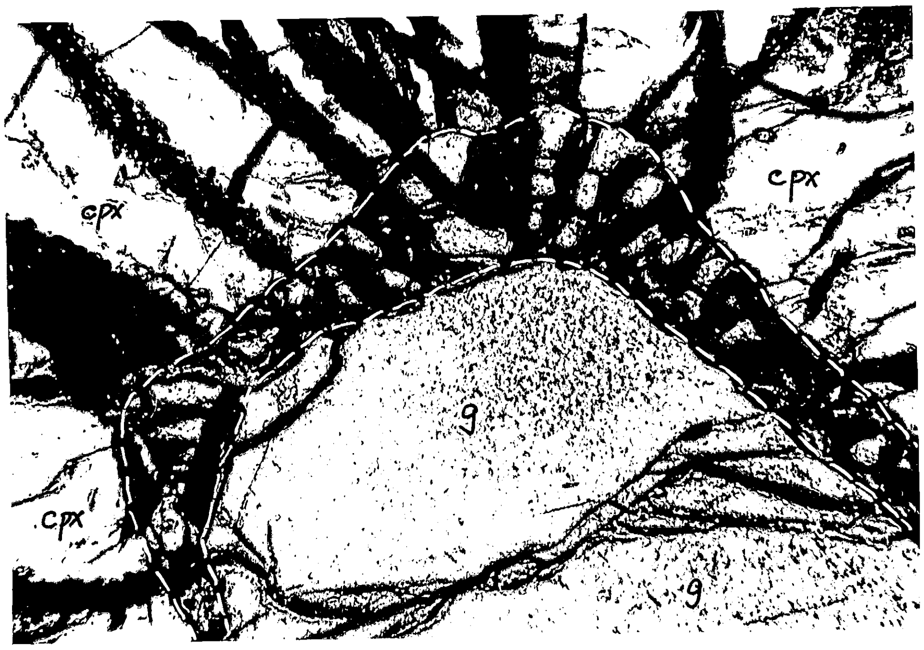


PLATE 36. A myrmekitic clinopyroxene (cpx) - garnet (g) intergrowth in eclogite RVL.16. The outlined myrmekitic zone consists of a fine intergrowth of garnet (clear) and clinopyroxene, now altered to opaque material.
Magnification X 47, ordinary light.

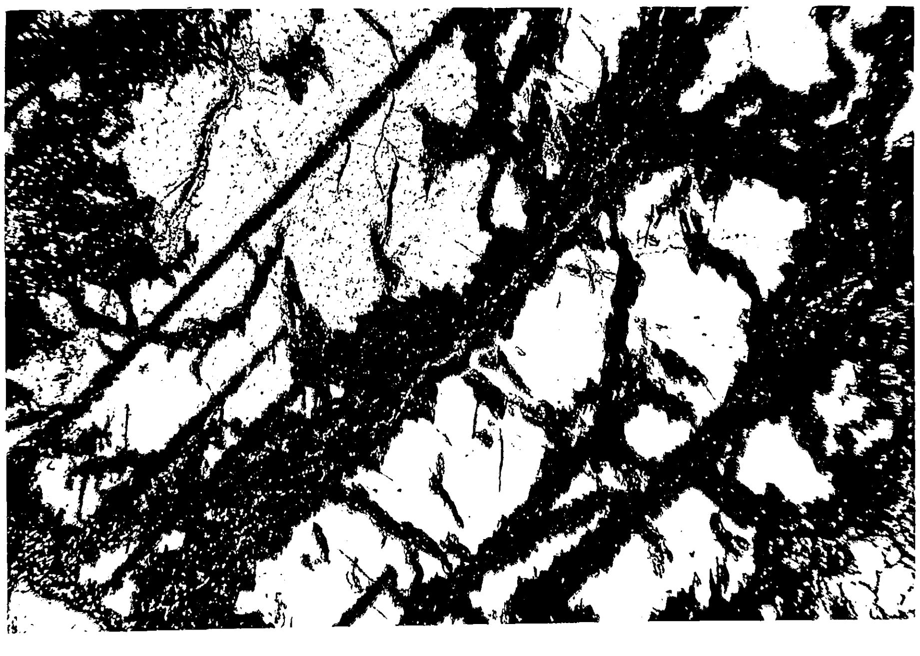


PLATE 37. Clinopyroxene from eclogite RV.33. The original material has altered along cracks and partings to an opaque, ultrafine-grained product.
Magnification X 57, ordinary light.

in Plate 38. A distinct "quench" texture is also often evident in much of the altered pyroxene (see Plate 24).

X-ray diffraction studies revealed the very fine-grained secondary material to be essentially poorly crystalline clinopyroxene plus zeolitic material and possibly a minor amount of feldspar. Berg (1968) has found an abundance of an analcime-type zeolite in the altered pyroxene of Roberts Victor eclogites. He attributes this zeolite formation to weathering of the omphacite deep within the kimberlite.

Switzer and Melson (1969) have recently studied several typical kyanite eclogites from the Roberts Victor Mine and have described in detail the fine-grained secondary assemblages in the pyroxenes. They record that the primary omphacite is altered to a very fine-grained mixture of plagioclase, clinopyroxene and possibly glass, while thin veins and patches of secondary glassy material, also containing crystals of plagioclase, augite, hornblende, spinel, calcite and analcite, are present. The observations made during the present study have shown that partial melting of the pyroxene, with the formation of secondary minerals and glassy material, is a feature common to all the Roberts Victor eclogites.

Partial melting of the omphacitic clinopyroxene, with subsequent quenching of the liquid formed, may take place by the three processes outlined below, or by some combination of them (Switzer and Melson, 1969).

1. Increase in temperature at constant pressure.
2. Rapid release of pressure at constant temperature.
3. Introduction of water into the eclogite at constant temperature and pressure.

Consideration of these three processes indicates that the most likely cause of melting will be by a sudden release of pressure at high temperatures. At atmospheric pressure omphacite from a Roberts Victor eclogite begins melting at 1030°C and is completely melted at 1260°C (Switzer and Melson, 1969). At 30 kb omphacite consisting of equal proportions of jadeite and diopside still melts incongruently over a range in temperature from 1500°C to 1600°C and at even higher temperatures for a more diopside-rich omphacite (Bell and Davis, 1969). Consequently a sudden pressure release on an eclogite at high temperatures would cause partial melting of the omphacite to take place. The presence of small amounts of water in the melt (as witnessed by the formation of hydrous minerals such as amphibole, zeolite and mica) would undoubtedly enhance the formation of a liquid by lowering the temperature at which the melting could take place.

Physical properties and composition.

Optical properties have been measured for a number of the omphacite grains, namely those from the analysed eclogites and are presented in Table 36. Deer *et al* (1962, vol. 2) record that variations in optical properties of omphacite do not show any clear relationship with chemical composition and that attempts to correlate the two are of little practical value. Mathias *et al* (1970) record small variations in the β refractive index and optic axial angle of the eclogite pyroxenes examined by them but, like Nixon *et al* (1963), mention that they are not diagnostic for compositional variation. In the light of this it was thought that a detailed study of the optical properties of the clinopyroxene would prove of little value.

The results of a chemical analysis of two pure clinopyroxene separates from eclogites RV.32 and RVL. 5 are presented in Table 37, together with calculated structural formulae (Deer *et al*, 1966), atomic ratios and specific gravities. Unfortunately the clinopyroxene from the large majority of the eclogites is so extensively altered that chemical analysis would be useless. Electron microprobe analysis of the unaltered omphacite relicts is the only technique which would be suitable for a chemical study of the pyroxenes and this unfortunately was not available to the writer. Kushiro and Aoki (1968) have shown that pyroxenes from Roberts Victor eclogites can be regarded as consisting of a variable solid solution of acmite ($NaFeSi_2O_6$), jadeite ($NaAlSi_2O_6$), diopside ($Ca,MgFeSi_2O_6$), hypersthene ($MgFeSiO_3$), $CaAl_2SiO_6$ and $CaTiAl_2O_6$; diopside, jadeite and hypersthene normally constitute some 90 per cent of the end-members.

Examination of the results of the clinopyroxene analyses from the present study indicate that diopside is the major pyroxene component, followed by jadeite and hypersthene. Assuming all lime to be present as pure diopside ($CaMgSi_2O_6$), the omphacite from RV.32 contains 54.3 per cent diopside and that from RVL.5, 54.7 per cent diopside. Sobolev (1968b) has reported that the chemistry of the eclogite clinopyroxenes from the Yakutian kimberlites is

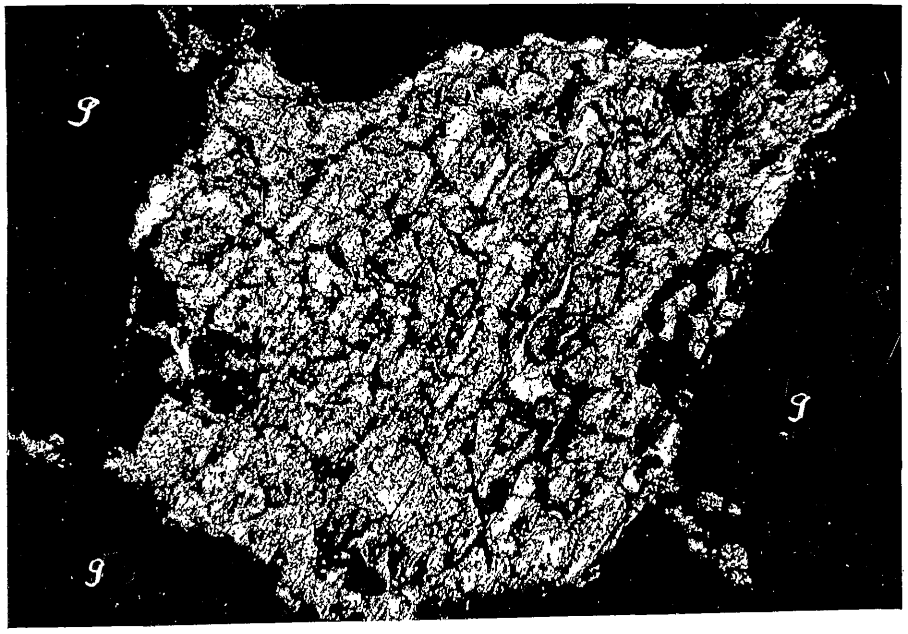


PLATE 38. A partially melted grain of omphacitic clinopyroxene surrounded by garnet (g). The clinopyroxene, originally a single grain, has melted incongruently to form a number of small, irregular grains separated by interstitial glass. Specimen RV.9.
Magnification X 135, polarised light.

distinct for different types of eclogites. A similar conclusion for the Roberts Victor eclogites will however need many more analyses.

The results of semi-quantitative trace element analysis of the two eclogitic pyroxenes is presented in Table 38. X-ray powder diffraction data of pyroxene RV.32 is given in Table 39 and can be seen to compare very well with that of an omphacite reference material (ASTM card No. 17-522).

5. Mica.

A. MICA IN THE PERIDOTITES (PHLOGOPITE).

In many of the specimens of both garnetiferous and spinel-bearing peridotites and also in the highly altered peridotite xenoliths, a small amount of phlogopite mica is present, either as a possible primary phase or as a secondary mineral formed during a period of phlogopitisation within the kimberlite.

Whether of primary or secondary origin, the phlogopite occurs as scattered, dark brown irregular flakes, normally one or two millimetres across and of lath-like outline in thin-section. In many cases their secondary nature is obvious by the fact that they follow and are closely associated with thin veins of secondary serpentine, patches of calcite and iron ore segregations. In places it is also evident that earlier silicates have been partially replaced by the mica. Normally the phlogopite is intergranular but occasionally small flakes are found completely enclosed within primary olivine crystals or simultaneously penetrating two adjacent grains of olivine. Fine-grained phlogopite, together with other materials, is also a typical reaction product of the peridotite-type garnets (in kelyphitic rims) and rarely, a result of alteration of the enstatite.

In thin-section the phlogopite is weakly to distinctly pleochroic in shades of light yellowish brown to almost colourless. Occasionally the grains exhibit a slightly darker margin. The typical phyllosilicate cleavage is well developed. The results of the measurement of the β refractive index of phlogopite from several peridotite xenoliths are recorded below. Estimation of the optic axial angle ($2V_{\alpha}$) indicates values from about 0° to 3°. Comparison with optical data in Deer _et al_ (1962, vol. 3, p.42) supports the assumption of a phlogopite composition for the mica, bordering on that of biotite.

Specimen No.	n_β
BF.1	1.597
BF.2	1.594
W.6	1.595
RV.15	1.601
RV.16	1.609

Deformation structures of varying degree are evident in the phlogopite of a number of the xenoliths. This is revealed by the presence of undulatory optical extinction, bent cleavage planes, chevron structures and kink bands, a magnificent example of which is illustrated in Plate 39. Deformation structures of idential appearance have been produced experimentally in biotite grains deformed under conditions of 5 kb confining pressure and 500°C (Borg and Handin, 1966) and they have shown that the kinking mechanism takes place by gliding parallel to (001) when the gliding plane is initially subparallel to the maximum principal compressive stress. Observation from the present study has shown that the extensively deformed phlogopite grains are always accompanied by the typical deformation structures in both the olivine and orthopyroxene.

Dawson and Powell (1969) have recently described what they regard as primary mica in several unserpentinised peridotite xenoliths derived from the Lashaine carbonate volcano in Tanzania. They regard this as clear evidence of the presence of a primary volatile-bearing phase in the upper mantle.

The presence of the deformation structures within much of the phlogopite examined during the present study may be of considerable genetic significance, possibly enabling a distinction to be made between a mica which is a primary constituent of the peridotite and that which is secondary. It is thought that in many cases a primary mica can be recognised by the presence of gross deformation features such as kink bands and chevron patterns, whilst mica of secondary origin will be relatively undisturbed. This reasoning is based on the assumption that tectonic deformation of the peridotites could only have taken place whilst they formed part of some extensive and probably deep-seated rock mass. It is highly unlikely that the peridotite xenoliths were subjected to any considerable stress after incorporation into the kimberlitic fluid and consequently the presence of grossly deformed phlogopite crystals indicates that such mica was present before incorporation, that is, when still part of a postulated peridotite mass.

If this argument is valid there is then a clear indication that a considerable amount of phlogopite in the peridotites may be primary and not of secondary origin as has been generally assumed. It is interesting to note that in their recent work Mathias <u>et al</u> (1970) whilst acknowledging that mica is commonly present in the xenoliths state (p.117) "..... the difficulty in deciding whether mica is primary or secondary is such that we have frankly evaded the issue by leaving it out altogether from the 'primary' assemblages .... although it might well be in a minority of cases". The significance of the occurrence of a primary volatile-bearing and potash-rich phase in the upper mantle is considerable. It can be used to explain the source of potassium in ultramafic potassic lavas and in addition provides a source of both radiogenic heat and volatiles (Dawson and Powell, 1969).

B. MICACEOUS MATERIAL IN THE ECLOTITES.

Almost every specimen of eclogite contains a certain amount of micaceous material, which is generally considered to be of secondary origin. The amount of micaceous material varies from merely a trace to over 40 per cent. Normally the micaceous material is closely associated with the garnet and constitutes one of the major constituents of the kelyphitic reaction rims. Small subhedral crystals of mica have also commonly formed in the thin veinlets of glassy material seen in many of the eclogites.

In the more altered eclogites (RV.18, RV.29) the micaceous material has apparently extensively replaced both garnet and clinopyroxene, the garnet more so than the pyroxene. This micaceous material forms irregular dark brown aggregates and often contains relicts of unreplaced garnet.

Seen in thin-section the mica is normally strongly pleochroic in shades of yellow to reddish brown, colours which make it distinct from the phlogopitic mica of the peridotites. The darker colour of the eclogite micas can probably be attributed to a higher ferric iron and titanium content. Features characteristic of tectonic deformation were not recognised in any of the eclogite micas, a fact which lends support to their being of secondary origin. Optical data of mica from several eclogites are recorded below. Indications are that these eclogite micas are probably biotite in composition and contain a greater amount of ferric iron and titanium than the peridotite mica.

Specimen No.	$n\beta$
RV.8	1.620
RV.18	1.607
RV.20	1.599
RV.29	1.618

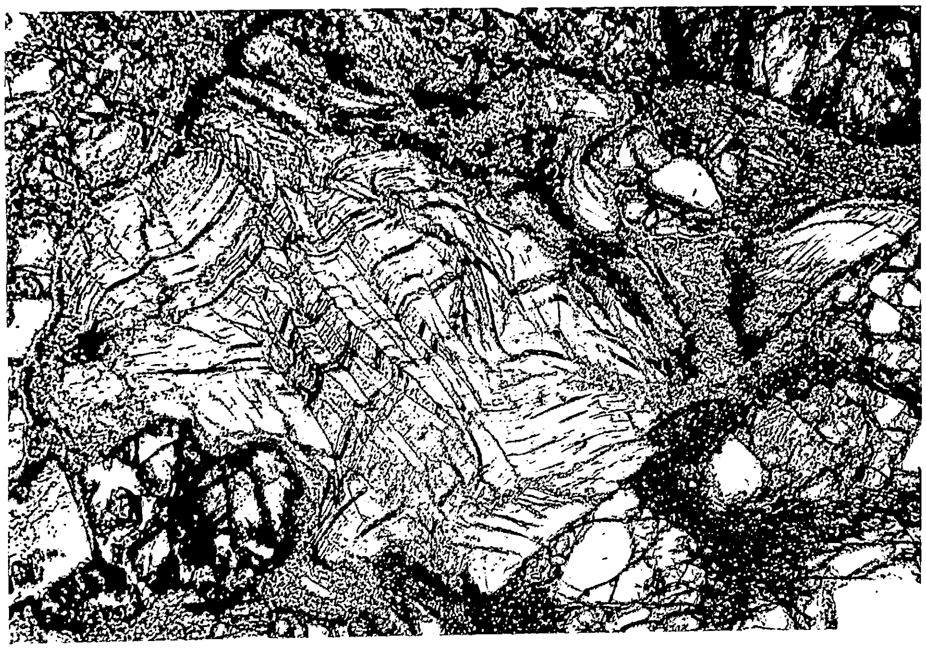


PLATE 39. A highly deformed crystal of phlogopite in peridotite BF.2. Notice in particular the chevron structure and kink bands. Magnification X 15, ordinary light.

6. Spinel.

Spinel is present as a primary constituent of the peridotite xenoliths and as a secondary mineral in many of the eclogites, typically associated with the kelyphitic reaction rims. The secondary eclogite spinels, identified only in thin-section, are normally dark green and occur in only minute amounts. No primary spinels were seen in the eclogites.

The spinel found in the peridotites occurs in two forms, firstly as idiomorphic to rounded, opaque grains, not exceeding 2 mm in diameter, and secondly, as fine symplectic intergrowths with pyroxene, as illustrated in Plate 40. X-ray diffraction examination of the spinel-pyroxene symplectites shows the pyroxene to be a monoclinic form structurally similar to diopside, while the spinel, which is a transluscent golden-brown in thin-section, is probably of the picotite-type (rich in magnesium, chromium and aluminium). In one instance a spinel-phlogopite symplectite was recognised.

The opaque, idiomorphic grains of spinel, identified as picrochromite, are normally completely free of inclusions except for rare small rounded grain of silicate seen in polished section. These grains occur scattered throughout the spinel peridotites and constitute a trace constituent in several garnet peridotites. Several X-ray fluorescence spectrographic scans of concentrates of these chrome spinels revealed, in addition to chromium and iron, traces of nickel. Measurement of the unit cell of a number of these spinel grains gave the values listed below, and together with a determination of their specific gravities indicate the picrochromite composition (Deer et al, 1962, vol. 5, Fig. 6). Facilities for refractive index determination were unfortunately not available.

Specimen No.	Unit cell (Å)	S.G.
W.1	8.30	4.46
DT.6	8.31	4.49
RV.12	8.33	4.51

From experimental grounds (MacGregor, 1964) the presence of a chrome-rich spinel would be expected in the non-garnetiferous peridotites. What has taken place essentially is that the chromium which would have formed part of a chrome-rich pyrope garnet, has at lower pressures, formed spinel.

The significance of the symplectic spinel-pyroxene grains cannot be easily explained but they possibly occur in original garnet peridotites which have been partially melted and then equilibrated again under conditions at which spinel peridotites are stable. MacGregor (1964) has shown experimentally that:

4 enstatite + spinel $\rightleftarrows$ forsterite + pyrope.

It is conceivable that in a natural peridotite system, in which both calcium and iron are present, the following reaction could take place:

2 diopside + chrome-rich spinel $\rightleftarrows$ forsterite + chrome-rich pyrope-grossularite garnet.

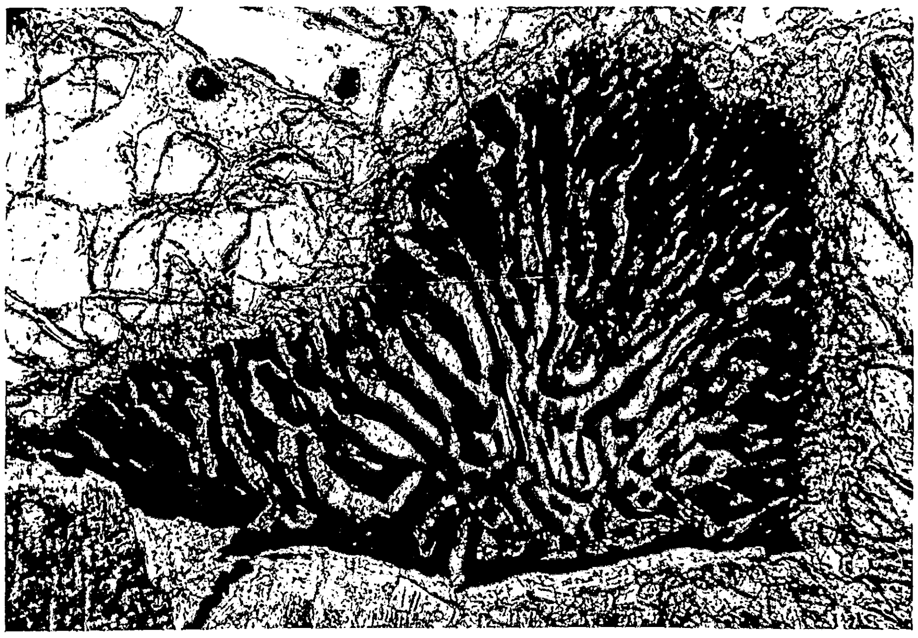


PLATE 40. A symplectic intergrowth of spinel and clinopyroxene in peridotite RV.17.
Magnification X 110, ordinary light.

7. Kyanite and Corundum.

Kyanite is present in minor amounts in the three kyanite eclogites and has been recorded as a trace constituent in several other eclogites. Corundum constitutes a trace constituent in two eclogites, and in at least one case, is considered to be a primary phase. The amount of kyanite in the kyanite eclogites varies from approximately three to nine per cent.

The kyanite is easily visible in hand specimen (see Plate 21) as bright blue, platy grains scattered throughout the rocks. Studies in thin-section (see Plate 20) show that the kyanite occurs as rounded to subhedral grains with good cleavage, set either in the highly altered pyroxene or as inclusions in the garnet. In one specimen (RV.6) the kyanite is often associated with very small tabular grains of dark blue corundum, as illustrated in Plate 41. Sobolev et al (1968) have reported similar corundum occurrences in grospydite xenoliths from Yakutia and record that its origin as a primary or secondary mineral is not always clear. Switzer and Melson (1969) regard the corundum in the kyanite eclogite xenoliths examined by them to be of secondary origin. Mathias et al (1970) has also recorded one corundum-bearing kyanite eclogite. In the absence of any distinct features indicating its secondary origin the corundum is considered by the writer to be a primary constituent.

Refractive index measurements indicate that the kyanite is in no way different to kyanite from metamorphic rocks, a value of 1.713 being obtained for the α direction. In general kyanite occurs typically as a mineral of high-grade regional metamorphism (Deer et al, 1962, vol. 1).

Kyanite eclogites are known to occur as both xenoliths in kimberlite and as lenses or bands in gneisses. Godovikov and Kennedy (1968) have shown that chemically kyanite eclogites from kimberlites are similar to metamorphic kyanite eclogites. Green (1967) has produced experimentally a kyanite eclogite assemblage from a high alumina basalt composition. In 1969 Green investigated the diopside-kyanite join at high pressures and temperatures and for an initial composition corresponding to 2 anorthite + 2 enstatite + 1 diopside produced a stable mineral assemblage consisting of clinopyroxene solid solution + garnet + minor quartz + minor kyanite at pressures of 27 kb to 36 kb and a temperature of 1200°C. There can be little doubt that kyanite eclogites could be produced naturally by the crystallisation of certain gabbroic compositions under high pressure and high temperature conditions.

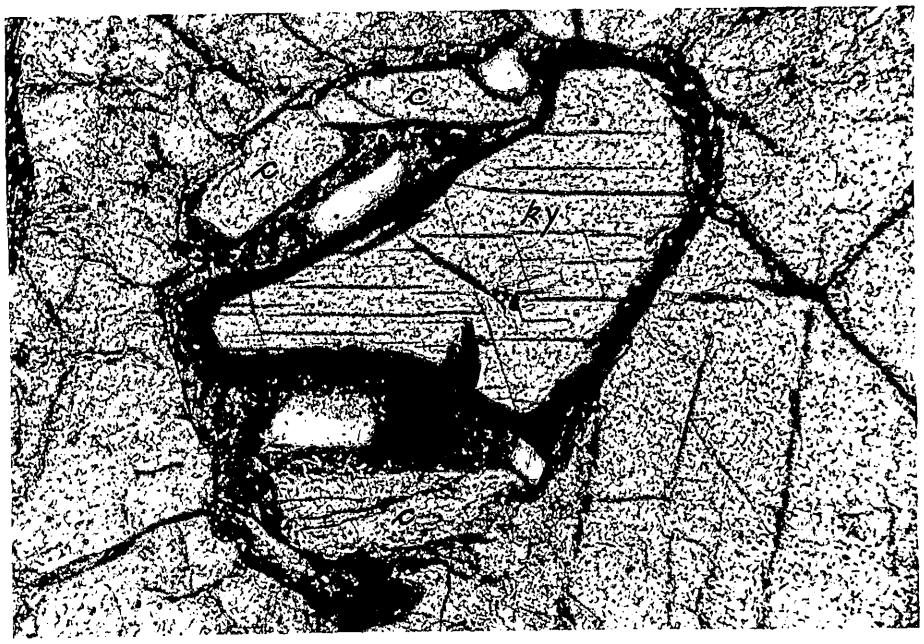


PLATE 41. A grain of kyanite (ky) [enclosed by garnet] with tabular crystals of sapphire corundum (c) in eclogite RV.6. A minor amount of glassy material occurs interstitially. Magnification X 50, ordinary light.

8. Diamond and Graphite.

Although diamond was only detected in one specimen of eclogite (RV.4) and in none of the peridotites it is of considerable importance. Two of the diamonds found in eclogite RV.4 are shown in situ in Plates 22 and 23. Broadly the diamonds in the eclogite occur in two distinct forms:

1. Clear, colourless well-formed octahedral crystals, which are occasionally twinned, or serrate clusters of clear, colourless intergrown crystals (shown in Plate 42).

2. Irregular blackish aggregates, showing only slight development of crystal faces (shown in Plate 43).

The well-formed single crystals, exclusively of octahedral habit, normally exhibit straight and sharp or only very slightly grooved crystal edges. No modification of the basic octahedral habit by rhombic dodecahedral or cube faces was seen. The octahedral faces are smooth, show virtually no curvature and appear to be made up of thin growth lamellae oriented parallel to the octahedron faces. Typical "negative" trigons were occasionally seen on the (111) faces.

The serrate intergrown crystals, scanning electron-micrographs of which are shown in Plate 44, are very similar to the single octahedral crystals but more abundant. The habit of individual crystals in these clusters is also octahedral, the clusters consisting of numerous intergrown diamonds, each of which is made up of fairly thick, irregularly developed growth sheets parallel to the (111) planes. The result is that these diamond clusters exhibit a jagged or serrated outline, suggesting that crystal growth was spontaneously initiated from a number of separate points with the eventual linking up of the crystals. Occasional "negative" trigons were recognised on the (111) faces (see Plate 44) and specks of opaque, black matter, thought to be graphite, were seen in places. Under high magnification thin cracks transect many of the diamonds (see Plate 44) and are thought to be related to the sub-parallel fractures in the co-existing garnet. As with the fractures in the garnet, these cracks are probably due to tectonic deformation of the eclogite.

The irregular, dark, diamond aggregates are less well formed than the diamonds already described and show only a limited development of crystal faces.

PLATE 42. Clear octahedral and serrate diamond intergrowths from eclogite RV.4.
Magnification X 12.

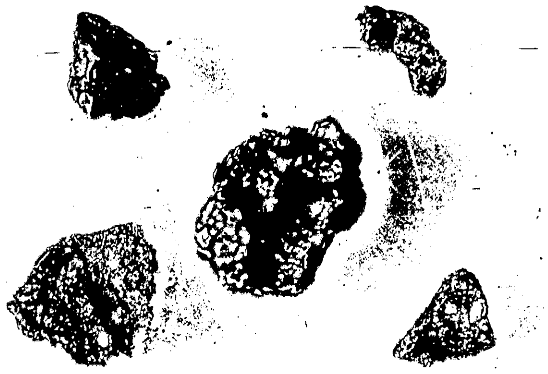


PLATE 43. Irregular diamond-graphite aggregates from eclogite RV.4.
Crystal faces are seldom seen.
Magnification X 12.

Crushing of these aggregates showed that they consist of colourless diamond finely intergrown with opaque, black material, identified by X-ray diffraction as graphite.

Several very interesting points have arisen out of the study of these diamonds and should be kept in mind when theories regarding the origin of diamond are considered.

1. The diamonds in the eclogite probably formed under conditions similar to the diamonds found in kimberlite. Consequently knowledge of the formative conditions of the host eclogite will provide a clue to the conditions under which the diamonds in kimberlite formed.

2. The detailed petrological and mineralogical studies of the eclogite xenoliths of the present study has indicated that the diamondiferous variety cannot be distinguished from the normal eclogites. Rickwood and Mathias (in press), in their study of diamond-bearing eclogites, have arrived at a similar conclusion.

3. The diamonds in eclogite have probably not suffered any corrosion or dissolution since their formation. Their octahedral habit and growth-plate structure strongly suggests that natural diamond growth is essentially on the (111) plane. The presence of "negative" trigons on the smooth (111) faces lends support to the theory of Tolansky (1955) that such trigons are growth features and not the products of etching.

The presence of two distinct modes of occurrence of diamond in a single eclogite xenolith cannot be readily explained. The presence of finely intergrown graphite in certain diamonds suggests that in places diamond formation was inhibited and that graphite formed instead. It is possible that during diamond formation the conditions fluctuated around the diamond-graphite equilibrium boundary. Alternatively one can argue that the graphite represents the result of a partial diamond ——> graphite inversion which took place after crystallisation.

Except for the graphite associated with the diamonds in eclogite RV.4 no other graphite was detected in any of the eclogites. In two peridotites (BF.4 and BF.9), however, small, rounded shiny flakes of graphite, approximately 1 mm in diameter, were found.

No diamonds were found in any of the peridotites, despite a careful search. Although diamonds have been previously reported as occurring in peridotite xenoliths from kimberlite (Wagner, 1928; Williams, 1932) the results of the present work have not substantiated these findings. Williams(1932, vol. 2, p. 417) however distinctly states: "Although most of the diamonds found in the cognate inclusions have been found in eclogites, yet diamonds have been found in the peridotites, and had a sufficient quantity been treated by Gardner Williams some diamonds would probably have been found". In spite of Williams' comments no diamonds have since been reported from any true peridotite xenoliths, despite a host of workers being active in this field.

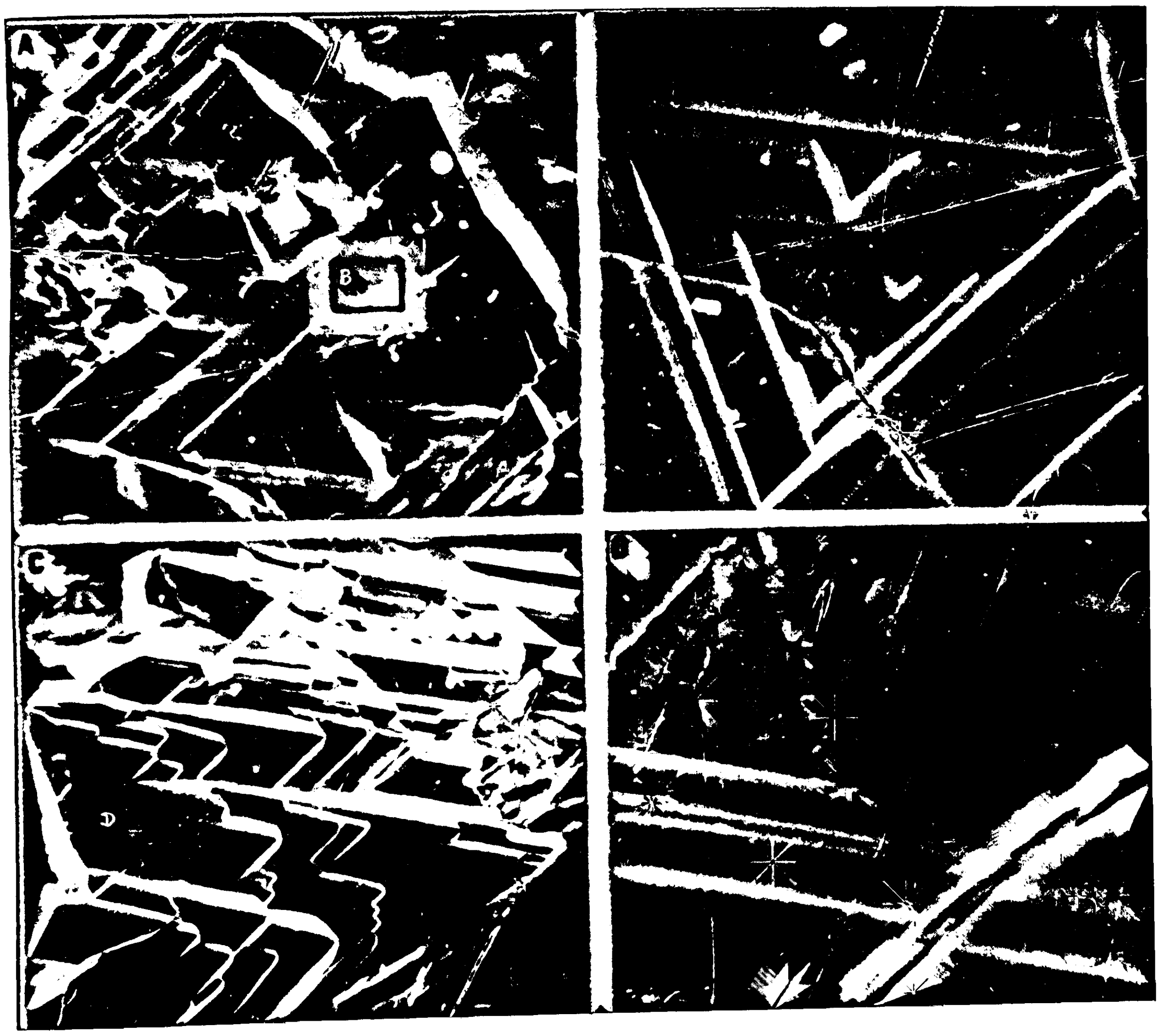


PLATE 44. Fragments of serrate diamond intergrowths, as seen with a scanning electron microscope, are shown in A and C (magnification X 50). Enlarged portions of these two fragments (as marked) are shown in B and D and both illustrate the typical "negative" trigons on the (111) faces and the cracks which transect the diamonds.

9. Other Minerals.

In the peridotites trace amounts of sulphides (pyrite, marcasite, pyrrhotite) were detected.

Ilmenite was found in one altered xenolith (DT.10) and may represent a secondary product. It is interesting to note that the crystal structure of the ilmenite from this specimen is very similar to that of the typical magnesium-rich ilmenite from kimberlite. Comparison of the two was made using X-ray diffraction powder films. A polished section examination of an ilmenite concentrate showed that a considerable amount of hematite is associated with the ilmenite, mainly as discrete bodies but occasionally as thin exsolution lamellae. The hematite in turn contains fine exsolutions of ilmenite.

Rutile is a mineral often present in the eclogites in trace amounts. It is brownish yellow and transluscent in thin section and often contains minute oriented plate-like inclusions (hematite?). No rutile was detected in the peridotites.

Secondary minerals found in the eclogites include quartz, calcite, analcite, stilbite, amphibole, spinel and mica. In the peridotites the secondary minerals are represented by serpentine, chlorite, talc, mica and calcite.

10. Summary and Discussion.

Olivine.

Examination of the olivine from the peridotite xenoliths has shown that it usually occurs as colourless, partly serpentinised, anhedral grains roughly 5 mm in size. Features characteristic of plastic deformation and recrystallisation have been recognised in many of the olivine grains and indicate that the peridotites have undergone tectonic deformation and plastic flow, probably at high temperatures and pressures. The conditions for such deformation would be found in the upper mantle where tectonic recrystallisation may constitute an important flow mechanism.

The composition of the olivine, which corresponds to that of forsterite, ranges between 91 and 94 per cent of this end-member. The exceptionally restricted compositional range of the olivine has also been borne out by chemical analysis of selected olivines, which has shown the extreme paucity of minor elements (except nickel). No significant differences between the olivine of the garnet peridotites and spinel peridotites was noticed, neither were any differences between that from the different pipes recognised.

The composition of the olivine is in agreement with that for other suggested upper mantle rocks such as the Norwegian and Swiss garnet peridotites (O'Hara and Mercy, 1963) and is also in accordance with the narrow range of olivine composition for other garnet peridotite xenoliths from kimberlite (Nixon et al 1963; Mathias et al 1970; Carswell and Dawson, 1970). It is interesting to note that the forsterite contents of the olivines are of the same order as those for chondritic meteorites (Mason, 1963), a feature which lends support for a chondritic earth model.

Finally it should be mentioned that X-ray diffraction evidence indicates that olivine formed in a high pressure environment shows no structural peculiarities compared with olivine from a relatively low pressure environment.

Orthopyroxene.

As with the olivine the orthopyroxene forms fairly large, anhedral grains usually pale greenish yellow and often exhibits features characteristic of stress and tectonic deformation. There is evidence of a possible inversion of enstatite to clinoenstatite, probably by a shear-stress mechanism. This together with the other phenomena caused by deformation supports the conclusions that the peridotites have undergone extensive tectonic deformation, probably at fairly high temperatures within the upper mantle or lower crust.

The composition of the orthopyroxene corresponds to that of enstatite and shows a narrow range of composition from 94 to 88 per cent of the enstatite end-member. The range in composition, although small, is slightly larger than that for the olivine. No consistent variations between the different pipes or between the harzburgites or lherzolites could be noticed.

Chemical analyses have shown that the enstatite from the garnet peridotites is exceptionally low in alumina (and to a lesser extent in lime and chromia) when compared with enstatite from a spinel peridotite. This clearly indicates that the garnet peridotites must have formed a higher pressures than the spinel peridotites and supports the findings of O'Hara and Mercy (1963). These results are also in keeping with the experimental work of Boyd and England (1964) and MacGregor and Ringwood (1964).

From the work of Green and Ringwood (1967b) it appears that the inversion of aluminous enstatite to low-alumina enstatite plus garnet takes place at a depth of approximately 50 km beneath the Precambrian Shields (see 72-100 km. Green and Ringwood, 1967b, Fig. 2). Consequently we can consider that spinel peridotite would not be stable below this level. There is however petrographic evidence to suggest that a transition zone between garnetiferous and spinel peridotite, possibly several kilometres thick, does exist. The number of spinel peridotite xenoliths examined suggests that, contrary to experimental investigations (Boyd and MacGregor, 1964; Ito and Kennedy, 1967), a fairly extensive zone of spinel peridotite (containing aluminous enstatite) is apparently present beneath the continental crust of southern Africa.

X-ray diffraction studies of two enstatites, one from a garnet peridotite and one from a spinel peridotite show a slight but consistent variation in interplanar spacings, a feature which can no doubt be correlated with the variation in alumina.

At this stage it is perhaps fitting to mention that O'Hara and Mercy (1963), using detailed geochemical evidence obtained by analysis of co-existing olivine and orthopyroxene from garnet peridotite xenoliths in kimberlite, concluded that these rocks (as compared with peridotite nodules in basalt) represent upper mantle material. The basis of their argument is that in the garnet peridotite xenoliths the ratio Fe/Fe+Mg for olivine is greater than the ratio Fe/Fe+Mg for orthopyroxene. According to O'Hara and Mercy this implies that the olivine and orthopyroxene in these rocks are equilibrium assemblages. A similar comparison (see below), based on analyses of co-existing olivine and orthopyroxene of the present study, gives comparable results and indicates that the rocks are probably equilibrium assemblages and hence probably derived from the upper mantle.

	Fe/Fe+Mg olivine	Fe/Fe+Mg orthopyroxene
BF.2	0.1358	0.1250
BF.5	0.1503	0.1441
BF.8	0.1416	0.1250
BF.9	0.1268	0.1181
BF.10	0.1380	0.1225

Garnets.

Garnets from the peridotite suite, which constitute only a minor or trace constituent of these rocks, are a vivid mauvish or magenta-pink and can be exactly matched with those from the kimberlite matrix. Most grains appear to have been tectonically disturbed and are generally surrounded by a thin kelyphitic reaction rim. In contrast the garnets from the eclogites, which constitute an essential phase, vary in colour from orange through pinkish browns to a fairly dark reddish brown. Generally they are not typical of the garnets found in kimberlite, their appearance being more characteristic of garnets from conventional high-grade metamorphic rocks. Alteration and partial melting of the eclogite garnet (and associated clinopyroxene) is evident in most of the eclogites.

Both physical properties and chemical analyses show that the peridotite garnets fall into a fairly narrow compositional range, rich in the pyrope end-member. The pyrope content of these peridotite garnets ranges from 65 to 80 per cent and they show a fairly constant almandine:andradite plus uvarovite ratio. The garnets contain significant amounts of almandine and minor amounts of andradite, grossularite and most notably, uvarovite. Reference to the work of Tröger (1959) shows that the peridotite-type garnets fall into his Variety X, that is, garnets characteristic of dunites and serpentinites.

The eclogite garnets on the other hand show a much wider compositional range and generally contain only about 40 to 60 per cent of the pyrope end-member plus considerable amounts of almandine, andradite and grossularite. Uvarovite is notably absent. Garnets from the kyanite-bearing eclogites are relatively poor in pyrope and rich in grossularite and appear to be similar in chemistry to an analysed calcic garnet from a Roberts Victor kyanite eclogite (O'Hara and Mercy, 1966).

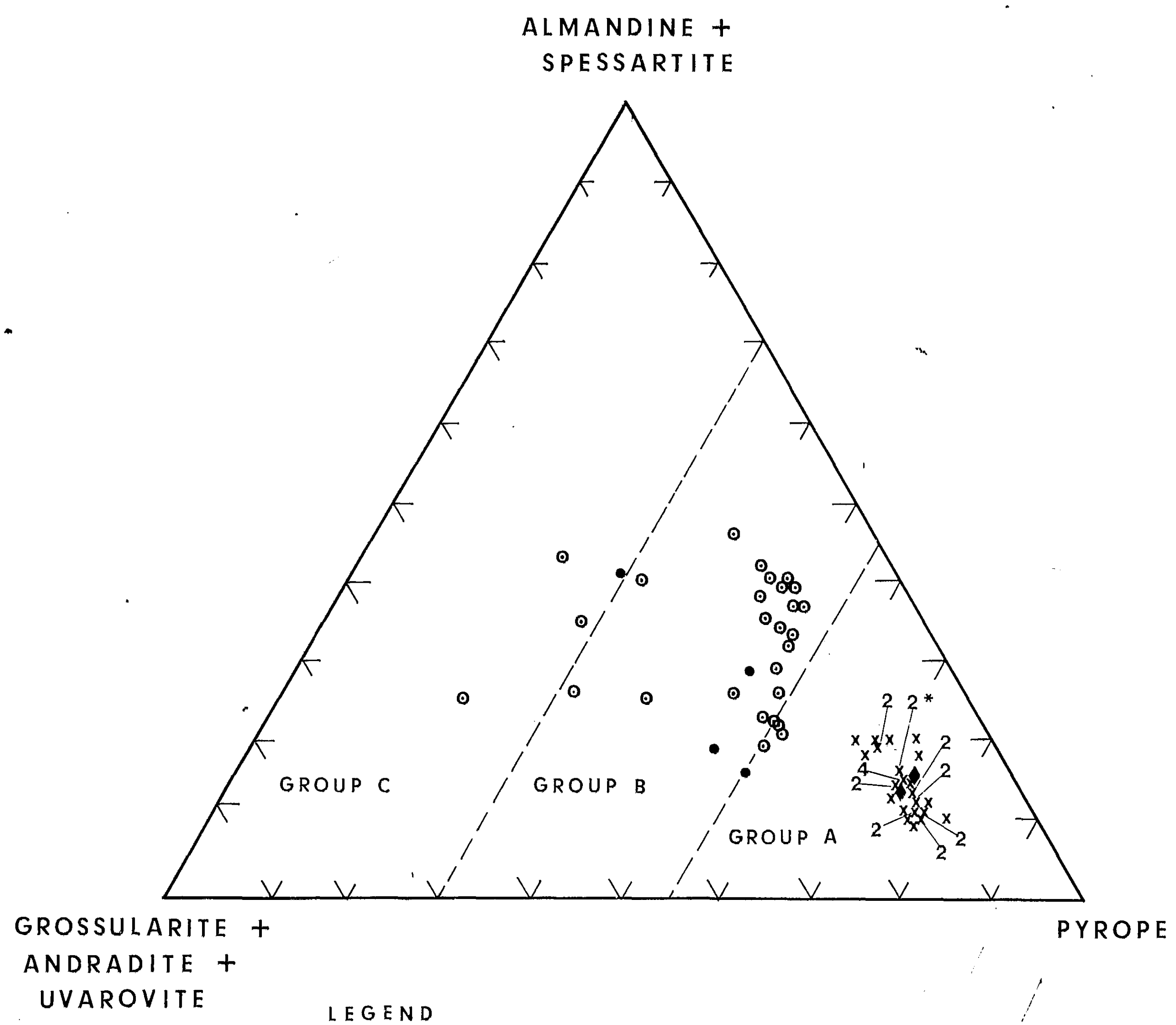
Referring to the work of Tröger (1959) it is evident that in general garnets from all types of eclogites fall into his Varieties XIV, XV and XVI, namely, garnets from the so-called griquaites and from common eclogites. It is of considerable importance to note that Tröger has seen fit to distinguish two types of griquaite garnets (Varieties XIV and XV), one type of which is (Variety XIV) very similar to typical kimberlite-type garnets. This can be interpreted as indicating that the garnet-pyroxene inclusions found in kimberlite are basically of two major types, one being the true griquaite-type which is genetically related to kimberlite and the other of a typical metamorphic type. The results of the present study suggest that the garnets from the eclogite xenoliths of the Roberts Victor pipe are essentially of the latter type, that is, garnets typical of eclogites from gneissic basement rocks.

Smulikowski (1964, 1965) and Coleman et al (1965) have both found that the pyrope content of garnets from eclogitic rocks is distinctive for each of the three main types of eclogite (see : General Nature, Classification and Origin of Eclogites, p.223, Chapter XI of this thesis).

Coleman et al have, by means of a triangular diagram with apices corresponding to pyrope, almandine plus spessartite and grossularite plus andradite attempted to group eclogitic garnets quantitatively. They record that the garnets from eclogites occurring in kimberlite pipes are of their Group A, and are characterised by pyrope-rich compositions. However the garnet compositions used by Coleman et al are only those of Tröger's Variety XIV; they have not used Tröger's Variety XV, which are also from eclogites found in kimberlite and which would most certainly fall into their Group B field.

Fig. 17 is a triangular diagram, identical with that used by Coleman et al (1965) for their eclogite garnet grouping. The estimated garnet compositions from Table 29 (peridotite-type garnets, Py-Al-An+Uv) and Table 33 (eclogite-type garnets, Py-Al-Gro) are plotted on this diagram, together with the end-member compositions of the analysed garnet specimens (Table 30 and 34). This plot, although mainly from estimated compositions, clearly shows that the peridotite garnets lie in the field of garnets characteristic of eclogite occurring in ultramafic rocks and kimberlites but that virtually all the eclogite garnets of this investigation lie in the field of garnets characteristic of common eclogite from migmatites and gneissic terrains. Possible inferences from these results are clear - either the work of Coleman et al is invalid and

FIG. 17



LEGEND

⊙ ECLOGITE GARNETS (ESTIMATED COMPOSITION, PY – AL – GRO)
x PERIDOTITE ·· (·· , PY – AL – AN + UV)
● ECLOGITE ·· (ANALYSED, TABLE 34)
♦ PERIDOTITE ·· (·· , TABLE 30)

ECLOGITE GARNET GROUPING FROM COLEMAN et al (1965) FIG. 9
GROUP A ECLOGITES – ECLOGITES IN KIMBERLITES & ULTRAMAFIC ROCKS
·· B ·· – ·· ·· GNEISSIC METAMORPHIC ROCKS
·· C ·· – ·· ·· ALPINE-TYPE METAMORPHIC ROCKS

*A number accompanying the peridotite garnets indicates more than one of same composition

Diagrammatic representation of the garnet end-member compositions of the Eclogite and Peridotite garnets

(Results are based on compositions given in Tables 29,30,33 and 34)

eclogites from kimberlite show a wide range of composition (as suggested by Rickwood et al 1968, p. 276) or the majority of eclogite xenoliths from the Roberts Victor pipe are not typical of kimberlite eclogites of the griquaite-type. The present author is inclined, at this stage, to support the latter.

On the basis of changes in garnet composition a tentative grouping of the garnets from the eclogites of the present investigation has been proposed (see p.170). This grouping of the eclogite garnets into at least three types (excluding those from the kyanite eclogites) correlates roughly with a petrographic grouping outlined earlier (p. 129). The real significance of the garnet grouping is at this stage uncertain.

The presence of pyrope-rich garnets in terrestrial rocks is of considerable petrogenic importance. Boyd and England (1959) recognised that pure pyrope is metastable at atmospheric pressure and were only able to synthesize pyrope at high pressures and temperatures, above 23 kb and 1100°C. Below these conditions the reaction involving pyrope became very sluggish. In 1964 Boyd and England demonstrated the relationship between aluminous enstatite and pyrope and at much the same time MacGregor (1964) showed experimentally that 4 enstatite + spinel $\rightleftarrows$ forsterite + pyrope. These reactions clearly indicate that garnet peridotites can be regarded as the high pressure equivalents of spinel peridotites.

MacGregor (1965), in a study of the stability fields of garnet and spinel peridotite in the synthetic system $MgO\text{-}CaO\text{-}Al_2O_3\text{-}SiO_2$, showed that at a constant temperature of 1300°C the first appearance of pyrope garnet occurs at 21 kb. The four-phase field of forsterite + diopside solid solution + enstatite solid solution + garnet (or a model garnet peridotite) was stable from 21 kb to at least 65 kb and garnets in this system showed little compositional variation.

It is important to remember that the peridotite garnets on an average contain only about 70 per cent pyrope; the appreciable substitution by other end-members, notably alamandine, which are stable at very much lower pressures (Yoder and Chiner, 1960), would undoubtedly lower the temperature and pressure conditions under which the peridotite garnets would form. Similary the conditions under which the eclogite garnets, which only contain approximately 50 per cent pyrope, formed need not necessarily be as extreme as those for the peridotite garnets and it is quite conceivable that they were able to form in the lower portions of the crust.

Clinopyroxene.

The clinopyroxene which is present in minor or trace amounts in many of the peridotites is commonly known as chrome diopside and is evident as scattered, bright green grains. It is usually closely associated with the orthopyroxene or garnet or both. In contrast to the olivine and orthopyroxene the chrome diopside is not significantly deformed; the occasional twin lamellae and indistinct parting which have developed in certain grains may reflect the effect of deformation.

The composition of the chrome diopside is mainly that of diopside but it also contains a significant amount of both the jadeite molecule and chromium, the relatively high chromium content accounting for the bright green colour. Unfortunately optical properties, which show minor variations, cannot be correlated with variations in chemical composition. It is evident however that the chrome diopside also contains an appreciable amount of enstatite in solid solution. On the basis of the chemical composition of the one chrome diopside analysed it is estimated that it equilibrated at a depth of approximately 125 km, that is, within the upper mantle. The garnet lherzolite xenoliths can therefore be regarded as originating from depths of this order.

Omphacitic clinopyroxene is an essential constituent of the eclogites. It is dark green to bluish green and is quite distinct from the chrome diopside of the peridotites. The amount of clinopyroxene in the eclogites varies considerably and ranges from about 20 to 80 volumetric per cent. While many grains show a distinct uneven extinction the most noticeable feature of the omphacitic clinopyroxenes is its alteration to ultrafine-grained aggregates consisting essentially of poorly crystalline clinopyroxene and minor amounts of analcime and plagioclase. A similar alteration was not seen in the chrome diopside.

The characteristic alteration of the eclogite clinopyroxene can be explained by the incongruent melting of omphacite. It is thought that the original eclogite was at a considerable pressure and temperature and that on a rapid release of pressure, probably at the time of intrusion of the kimberlite, partial melting of the omphacite would took place. This resulted in either the formation of ultrafine-grained aggregates or, occasionally, the production of a liquid which was quenched to form a glass. From this it can be inferred that the eclogites have come from a considerable depth, either in the lower crust or upper mantle.

Comparison of the omphacite analyses with that of the chrome diopside shows that they are considerably richer in soda, and hence in the jadeite molecule. Indications are that the omphacite also formed at high pressures, possibly within the upper mantle or lower crust. Unfortunately as the bulk of the clinopyroxene in almost every eclogite is highly altered reliable chemical analysis is impossible. Variations in the optical properties of the omphacite also show no consistent relationship to chemical composition. For a more detailed treatment of the chemistry of both the chrome diopside and omphacite electron microprobe studies should prove particularly useful.

Mica.

Small amounts of phlogopite mica have been recorded in many of the peridotites and some doubt exists as to whether it is of primary or secondary origin or both. The phlogopite occurs as small yellowish brown flakes, normally interstitial to the other silicates, and in many places is definitely a secondary product, probably formed by the action of alkalis and volatiles from the kimberlite magma. However, in a number of cases the phlogopite exhibits gross deformation structures such as kink bands and chevron patterns, suggesting that the material has undergone extensive tectonic deformation. This is also supported by the accompanying deformation features in the other silicate minerals. It appears reasonable to assume that the tectonism took place while the rocks were still part of some large, rigid mass and not while in the kimberlite. It is suggested therefore that the presence of mica with gross deformation features indicates that the mica was part of the original rock mass and hence a primary constituent.

The significance of finding a primary mica in upper mantle rocks has already been briefly mentioned. Interest in phlogopite has recently been shown by Yoder and Kushiro (1969), who have studied its stability up to 37.5 kb under gas-present and gas-absent conditions and by Kushiro et al (1967). High pressure experiments by Kushiro et al (1967) showed that phlogopite breaks down to garnet and an unidentified mineral at pressures higher than 40 kb at about 1200°C. They suggest that, in continental areas, phlogopite could be a possible potassium- and water-bearing phase in the upper mantle peridotite at depths down to 150-200 km. They also suggest that kimberlites and some potassium-rich basalts may be formed by the partial melting of such phlogopite-bearing peridotites.

Yoder and Kushiro (1969 p.558), from experimental work, note that: "The highly alkaline character and H_2O content of the liquids in equilibrium with phlogopite, the incongruent melting relationship of phlogopite to forsterite and liquid, and the high-pressure and high temperature stability of phlogopite have important bearing on the origin of kimberlite". They conclude that if liquids of kimberlite composition do in fact exist they would result from a high degree of partial melting of the parental material (phlogopite peridotite?) under hydrous conditions.

While micaceous material is also present in the eclogites it does not have the appearance of that in the peridotites and is assumed to be of secondary origin.

Other minerals.

Other primary minerals present in the peridotites include chrome spinels, graphite and sulphides. The spinels are of two types, both chrome-rich. One type of chrome spinel occur as small, generally idiomorphic grains, the other as fine spinel-clinopyroxene symplectic intergrowths. The significance of such intergrowths cannot be readily explained but it is suggested that they perhaps represent the products of incipient melting of garnet and olivine and subsequent equilibration of the liquid formed in a spinel-stable region. In general the presence of spinel in the peridotites indicates that the rocks equilibrated under lower pressure and temperature than the garnet peridotite.

In several of the eclogites kyanite is present and in one case is associated with minute amounts of corundum, which is tentatively thought to be a primary constituent. It can be argued however that the presence of secondary glass in the kyanite-corundum eclogite indicates that the corundum may possibly have formed by a melting of kyanite. The presence of kyanite, the high pressure polymorph of Al_2SiO_5, indicates a high pressure origin for the kyanites from a source rich in alumina. Recent experimental work has demonstrated that kyanite eclogites could form naturally from certain high-alumina gabbroic compositions under conditions of high pressure and high temperature.

Diamond is present in only one eclogite which shows no distinct differences from other eclogites. Its presence in this eclogite suggests that the rock formed under extreme conditions, probably at depths ranging from 190 to 555 km in the mantle. It is notable that the eclogite diamonds are of two varieties, namely colourless well-formed crystals and irregular blackish aggregates. The colourless variety appears to have formed by growth on the (111) faces. The question of diamond stability and possible formation at considerably lower pressures in natural systems has not been fully investigated so that one cannot be too confident about the conditions at which natural diamonds form. The question whether diamonds do actually occur in the peridotite xenoliths remains unanswered.

Other minerals present in the eclogites include rutile and sulphides.

X. ORIGIN OF THE PERIDOTITE XENOLITHS.

1. Suggested Origins for Peridotite Xenoliths.

As has already been mentioned (Chapters IV and V) there are basically three different theories of origin which have been seriously proposed to explain the occurrence of the well-rounded peridotite (and for that matter eclogite) xenoliths in kimberlite. Briefly these theories are:

(i) The peridotites represent fragments of high-grade crustal metamorphic rock accidentally incorporated in the kimberlite (Davidson, 1967b). Objections to this theory have been adequately dealt with by Carswell and Dawson (1970) who make it clear that there is little firm evidence in favour of a crustal metamorphic origin for the peridotite xenoliths. Carswell and Dawson state (p.179): "It would indeed be fortuitous if each kimberlite intrusion during its ascent through the crust were to intersect pods of these rock-types [i.e. peridotites] known to be rare in crustal metamorphic terrains." In the light of their very convincing arguments the theory that the peridotites represent crustal metamorphic rocks will be examined no further.

(ii) The xenoliths are cognate or co-magmatic with the kimberlite host, having formed at depth by a process of segregation, accumulation or 'ultrabasic skarn' formation (Williams, 1932; Dawson 1962, 1967b). Although often discredited this theory has considerable support, particularly with regard to the eclogite xenoliths.

(iii) The peridotites are fragments of upper mantle substance incorporated into the kimberlite magma and fortuitously brought to near-surface (O'Hara and Mercy, 1963; Harris et al, 1967; Mathias et al 1970; Carswell and Dawson, 1970). This is the view which is currently most fashionable and an impressive amount of data can be used in support of it. If the xenoliths are of mantle origin the question has to be asked whether they represent:

a) material undepleted in the more "fusible" or "volatile" constituents
b) residua left after partial melting of the mantle
c) material intermediate in composition between the a) and b) above.

2. Characteristic Features of the Peridotite Xenoliths.

Before the origin of the peridotite xenoliths can be considered it is necessary that the characteristic features of these rocks be summarised.

(i) Almost all the peridotite xenoliths from kimberlite consist essentially of a four- or three-phase mineral assemblage of olivine, orthopyroxene, pyrope-rich garnet (or chrome spinel) and clinopyroxene. Phlogopite is a possible primary accessory. This alone suggests that the peridotites originate from a relatively homogeneous source underlying the continents. A comparison of the peridotite xenoliths derived from a single kimberlite pipe, from numerous pipes of a particular kimberlite province, from different kimberlite provinces on one continent and of those from pipes on different continents clearly indicates the essential similarity between the mineral assemblages.

(ii) It has also been shown in this investigation (and similarly by Mathias et al, 1970) that garnet peridotites constitute the most abundant type of peridotite xenolith and that of the garnet peridotites, garnet lherzolite is the most abundant variety. The number of spinel lherzolites similarly exceeds the number of spinel harzburgites. It is interesting to note that a number of garnet peridotites also contain traces of primary spinel and that several of the spinel-bearing peridotites contain trace amounts of garnet. If the peridotites originate from some fairly uniform source it must be considered possible that a certain degree of zoning, both chemically and physically, will be present and that this will be reflected in significant variations in the mineralogical composition of the xenoliths. These variations will depend firstly on the pressure and temperature at which the rocks have equilibrated and secondly on whether any of the more fusible constituents have been subsequently removed.

(iii) A comparison of the modal compositions of the peridotite xenoliths also shows an essential similarity between those from different sources. The calculated average compositions and compositional ranges determined in this study are generally similar to values measured by other workers. This feature leads to the suggestion that all the peridotite xenoliths are derived from a source which is mineralogically relatively constant and also of universal extent. Although distinctions between the garnet-bearing and garnet-free peridotites and between the harzburgites and lherzolites can be made the uniformity in textural details and whole-rock chemistry clearly supports their origin from some widespread, common rock-type.

(iv) It is difficult to reconcile the relative regularity in modal composition, textural details and whole-rock chemistry with a cognate origin for the xenoliths. It is even more difficult to imagine that the multitude of original intruding kimberlite magmas, which differ considerably in composition from pipe to pipe, would be capable of universally producing, by a process of segregation or accumulation, a suite of mineralogically, texturally and chemically uniform rocks.

(v) An outstanding feature of the xenoliths is the remarkably uniform compositions of the constituent minerals. The compositions of the olivine and low-alumina enstatite from the garnet peridotites show an exceptionally small range, but the garnets exhibit a wider but nevertheless restricted range in composition. The suggestion of Rickwood *et al* (1968) that partial melting of one garnet peridotite to form a more magnesian-rich garnet peridotite in which the garnet will be more magnesian must be considered a possible mechanism for the variation in garnet composition. The spinel peridotites contain olivine of similar composition to that in the garnet peridotites but the orthopyroxene is apparently richer in alumina, a feature which indicates that the spinel peridotites formed at a lower pressures than the garnet peridotites.

(vi) The presence of pyrope-rich garnet in the majority of the peridotites provides unquestionable evidence that these rocks formed under considerable pressures and temperatures. Garnets of similar composition are only found in the associated kimberlites and in garnet peridotites of certain orogenic zones such as in Norway, Czechoslovakia and Switzerland. Garnet peridotites from such orogenic zones are generally regarded as mantle-type rocks which have been tectonically emplaced and not crustal metamorphic rocks formed *in situ* (O'Hara and Mercy, 1963; Carswell, 1968a,b). Although not impossible it is highly unlikely, from a study of the stability fields of synthetic garnet peridotite systems and natural garnet peridotites, that metamorphic conditions within the crust would be capable of forming typical garnet peridotite. Conditions for the formation of garnet peridotite, on a world-wide scale, can only be attained below the crust, that is, in the upper mantle. The presence of pyrope-rich garnets of course does not answer the question whether the xenolithic garnet peridotites are mantle segregations which formed in the kimberlite within the mantle or actually mantle rocks incorporated into the kimberlite.

(vii) O'Hara (1967) considers that the garnet peridotite xenoliths found in kimberlite have equilibrated at pressures in excess of 30 kb and between temperatures of 1000° and 1200°C. His hypothesis, based on the chemistry of clinopyroxenes from garnet lherzolite xenoliths, suggests depths of formation in excess of 100 km in the mantle. Application of the same test to one garnet peridotite xenolith examined during the present study leads to a similar conclusion,if O'Hara's hypothesis is regarded as valid.

3. Nature of the Upper Mantle and the Mohorovicic Discontinuity.

Considered as a whole, and excluding the relatively thin crust, the Earth consists of two major divisions, namely the mantle and the core. The mantle, which constitutes approximately 69 per cent of the Earth's mass, is considered to consist of solid silicate-rich material whilst the core is thought to be a liquid in part of iron-nickel composition, possibly with a substantial amount of dissolved silicon.

The most important source of physical information concerning the structure of the Earth is provided by seismology, in particular, variations in the P and S wave velocities with depth. From the variations in the time-travel relationship of seismic waves a more detailed concentric structure of the Earth is suggested and an approximate division of the Earth into seven layers can be made (Bullen, 1967). These are as follows:

Region	Approximate depth range from surface (km)	Name	Approximate density (gm/cm³)
A	0-33	Crust	3.0
		MOHO	3.3
B	33-410)	Upper mantle	
C	410-1000)		4.7
D^1	1000-2700)	Lower mantle	
D_2	2700-2900)		5.7
E	2900-4980	Outer core	9.7
F	4980-5120	Transition zone	~12.5
G	5120-6370	Inner core	~13.0

For the purposes of the present study we are only concerned with the Crust and the B Region of the upper mantle. It is generally thought that the region of basalt magma generation lies within the upper mantle (Kuno, 1967). Similar evidence points to almost all other basic and ultrabasic magmas, including kimberlites, having originated in the upper mantle (see Nixon, 1969).

The division between the A and B seismological regions is known as the Mohorovicic Discontinuity, and can be defined as a boundary where the compressional (P) wave velocity changes from about 6.4 km/sec to approximately 8.0 km/sec. Seismic evidence points to a considerable variation in the depth of this boundary but in general it lies about 35 km under continental shield areas, up to the order of 70 km under certain mountain ranges and of the order of only 5 km below the deep ocean floors.

The only silicate rocks having a mineralogy which would show a velocity of the order of 8.0 km/sec are peridotites (including dunites), eclogites and perhaps pyroxenites. Rocks with a velocity of about 6.4 km/sec include basalt, gabbro, serpentinite, amphibolite and basic granulites (Kuno, 1967).

Three main hypotheses regarding the composition of the upper mantle and the nature of the Mohorovicic discontinuity have been proposed. One is that the upper mantle is of ultrabasic composition and that the Moho represents a chemical change from essentially gabbroic to ultrabasic composition.

The second is that the Moho represents an isochemical phase change from the gabbroic composition of the lower crust to eclogite of the upper mantle (Lovering, 1958; Kennedy, 1959). The third hypothesis is that of Hess (1960) who considers the possibility of the Moho being a serpentinite-peridotite boundary.

As can be seen the composition of the upper mantle is thought to be either ultrabasic (consisting of peridotite-dunite) or eclogitic. A brief discussion regarding these two rival hypotheses can now be made.

4. Composition of the Upper Mantle (B Region).

If the Moho is considered to represent a high pressure phase change from gabbroic material to eclogite support can be gained from a number of interesting features. The origin of basaltic magmas can easily be explained by fusion of portion of the mantle, eclogite generally being regarded as a high pressure modification of gabbro (or basalt). The two reactions of typical gabbroic material (plagioclase, diopsidic clinopyroxene, orthopyroxene, olivine) to form eclogite (omphacitic clinopyroxene, garnet) are shown below (Kuno, 1967, p. 91).

(a)

$$\underbrace{Ca(Mg,Fe)Si_2O_6}_{\text{clinopyroxene}} + \underbrace{2(Mg,Fe)SiO_3}_{\text{orthopyroxene}} + \underbrace{CaAl_2Si_2O_8 + NaAlSi_3O_8}_{\text{plagioclase}} \rightleftarrows$$

$$\underbrace{Ca(Mg,Fe)Si_2O_6 + NaAlSi_2O_6}_{\text{omphacite}} + \underbrace{Ca(Mg,Fe)_2Al_2(SiO_4)_3}_{\text{garnet}} + \underbrace{SiO_2}_{\text{quartz}}$$

(b)

$$\underbrace{Ca(Mg,Fe)Si_2O_6}_{\text{clinopyroxene}} + \underbrace{(Mg,Fe)_2SiO_4}_{\text{olivine}} + \underbrace{CaAl_2Si_2O_8 + NaAlSi_3O_8}_{\text{plagioclase}} \rightleftarrows$$

$$\underbrace{Ca(Mg,Fe)Si_2O_6 + NaAlSi_2O_6}_{\text{omphacite}} + \underbrace{Ca(Mg,Fe)_2Al_2(SiO_4)_3}_{\text{garnet}}$$

The transition of gabbro (D= 3.0) to eclogite (D= 3.3 to 3.5) involves at least a 10 per cent volume decrease, a feature which can be used to explain the cause of vertical movements in the Earth's crust.

Objections to this hypothesis are many, some of which are listed below.

(i) Experimental investigations (Yoder and Tilley, 1962; Ringwood and Green, 1966) have shown that the gabbro to eclogite transition is not sudden, but transitional, the amount of garnet gradually increasing at the expense of plagioclase. Consequently the relatively sharp Moho cannot represent a transitional gabbro-eclogite change.

(ii) The formation of basaltic magmas would require complete fusion of the mantle material if it were eclogitic. This is thought to be highly unlikely as mechanisms of basaltic magma formation are generally considered to involve fractional melting. It is very interesting to note that the temperature required for the partial melting of bimineralic eclogite at 30 kb (1515° - 1565°C) is appreciably higher than that required to obtain a liquid by the partial melting of garnet peridotite (1425° - 1450°C) (O'Hara, 1963a,b).

(iii) Fragments of deep-seated rocks in basalts and volcanic pipes show that eclogites and feldspathic eclogites (garnet granulites) are extremely rare, various types of peridotites being very much more abundant. If magmas were generated in an eclogitic mantle it is only logical to assume that xenolithic inclusions would be of the eclogite and feldspathic eclogite type and not peridotite.

(iv) As discussed by Ringwood and Green (1966) an upper mantle consisting of eclogite would be gravitationally unstable when underlain by a zone of ultramafic composition as suggested by Wyllie (1963). It is highly improbable that such an unstable situation in which a dense eclogite ($D \pm 3.5$) overlies a relatively less dense peridotite ($D \pm 3.3$) could have existed throughout the Earth's history. The density of true eclogites of basaltic composition ($D = 3.55$, Ringwood, 1966a, p.299) is also appreciably greater than that used for the upper mantle in gravimetric studies ($D = 3.3$ to 3.4).

(v) With particular reference to the eclogite xenoliths from kimberlite examined during the course of the present study, chemical analysis has shown that they are not isochemical with basalts, being particularly rich in magnesia and deficient in silica and showing wide ranges of composition.

The indication is therefore that they do not originate from an upper mantle consisting of eclogite which can be regarded as the source of basaltic magmas.

The preceding discussion has clearly indicated that it is most unlikely that the upper mantle consists of eclogite. Other arguments can be quoted which lead to a similar conclusion. This leaves us with the hypothesis that the upper mantle is of ultrabasic or peridotitic composition, a theory advocated by most earth scientists at the present time. Much of the evidence in favour of this idea can only be appreciated by an intensive survey of the subject, which is beyond the scope of the present study.

Some of the evidence in favour of a peridotitic upper mantle includes the world-wide occurrence of peridotite inclusions, mainly in basalts and related rocks, the uniform mineralogy, modal compositions and bulk chemistry of these inclusions, and the occurrence of peridotites, thought to have been brought up from the mantle, in orogenic zones and island arcs. Strong support comes from the fact that fresh peridotites possess a density of about 3.3 gm/cc, a feature in accordance with the seismic velocity of the upper mantle. In addition, following the experimental work of Yoder and Tilley (1962) and O'Hara and Yoder (1967), it has been demonstrated that partial melting of garnet-bearing peridotites can yield liquids of basaltic or picritic composition, which if crystallised within the mantle (i.e. under eclogite facies conditions) would yield material of eclogitic composition. The concept of a chondrite model for the Earth, based on meteorite observations, is also in rough agreement with a peridotite mantle (Mercy, 1967).

In the light of considerable evidence accumulated by many workers over the last 10 years one can feel reasonably sure that the upper mantle is essentially of ultrabasic (peridotitic) composition (Ringwood, MacGregor and Boyd, 1964; Ringwood, 1966a,b; Harris et al, 1967). There appears to be little reason to dispute this view and in discussions concerning the peridotite and eclogite xenoliths examined during the present study it is assumed that this hypothesis is correct.

5. Mineralogy of an Ultrabasic Upper Mantle.

On the assumption that the upper mantle is of ultrabasic composition the mineralogy of such rock-types can now be discussed. It has been suggested (Rubey, 1955) that the Earth's crust has evolved over a considerable period of geologic time by the fractional melting of the upper mantle. This would have left behind a zone which for the main part would be deficient in low melting point and volatile constituents, especially beneath the continents.

This concept has been followed up to great advantage by Ringwood (1966a) who considers the upper mantle to be chemically zoned; immediately below the continents a considerable thickness of dunite (depleted peridotite) exists, with a maximum thickness of approximately 150 to 200 km beneath Precambrian Shields. Below the deep ocean floors the zone of dunite would be considerably thinner, probably only several tens of kilometres thick. In the residual dunite zone eclogite segregations would possibly form a minor and sporadically distributed constituent. Ringwood (1966b) considers that these eclogite segregations, formed during fractional melting processes leading to the production of basaltic magma, represent material which has crystallised under conditions of great pressure, high temperature and low water-vapour pressure.

Below the zone of depleted peridotite Ringwood (1966b) postulates a primitive, primary mantle material which has been arbitarily defined by the property that on fractional melting it would yield a typical basaltic magma and leave behind a refractory dunite of the alpine peridotite-type. This synthetic material, given the name "pyrolite", has somewhat arbitarily been given a composition of one part basalt and three parts alpine peridotite. Experimental work and field observations have shown that material approaching "pyrolite" in composition can occur in four distinct mineral assemblages. These are as follows. Ringwood's pyrolite equivalents are given in brackets.

Mineral assemblage	Rock type	Conditions
1. Olivine, serpentine ± amphibole	Serpentinites (amphibolite)	Low temperatures, moderate pressures, hydrous environment.
2. Olivine + alumina-poor pyroxenes + plagioclase	Feldspathic peridotites (plagioclase pyrolite)	High temperatures, low pressures.
3. Olivine + alumina-rich pyroxenes ± spinel	Peridotites or spinel peridotites (pyroxene pyrolite)	Moderate to high temperatures
4. Olivine + alumina-poor pyroxenes + garnet	Garnet peridotites (garnet pyrolite)	High pressures and temperatures. (stable to ± 400 km depth).

It therefore appears, along the lines of present-day thought, that the B region of the upper mantle probably shows both a chemical and physical zoning. An ultrabasic upper mantle will be chemically zoned on the basis of fractionation and partial melting and will exhibit physical differences as indicators of different pressure-temperature conditions of crystallisation and equilibration. It is in the light of this that the xenolithic inclusions in kimberlite can be explained.

6. Conclusions.

The preceding discussions have been, for the most part, concerned with the nature and composition of the upper mantle and not with the origin of the peridotite xenoliths as such. In the light of the evidence of upper mantle composition however it appears that the two are intimately associated and the following conclusions can be made.

(i) The peridotite xenoliths found in kimberlite represent material derived from the upper mantle and carried to near-surface by a rapidly intruding kimberlite magma. Indications are that the kimberlites have sampled the upper mantle to depths of at least 125 km. Their rounded shape can be ascribed mainly to attrition and corrosion within the gas-charged, upward moving kimberlite magma. Igneous corrosion has probably had only a minor effect.

(ii) The xenoliths probably do not represent primary, primitive upper mantle material but rather portions of the material which have undergone varying degrees of partial melting and the loss of the more volatile phases. Hence the difference between the lherzolites and harzburgites. The amount of garnet in the garnet peridotites is partially governed by the degree to which melting and fractionation has taken place, similarly so for the variation in chrome diopside content in all the peridotites. The re-crystallised and altered xenoliths, often approaching dunite in composition, represents material which has been partially fused and recrystallised in a tectonic environment. This material corresponds to a "barren" dunite in which only the refractory olivine remains.

(iii) The presence of phlogopite, considered to be a primary constituent of some xenoliths, is of great significance in that the mica is a possible source of volatiles, potassium and radiogenic heat in mantle-type rocks.

(iv) The main difference between garnet peridotites and spinel peridotites is that the garnet peridotites equilibrated at greater depths in the mantle, within the garnet-stable region. The results of the present investigation suggest that spinel peridotites are stable within the mantle below the Precambrian Shield of southern Africa but have generally been involved to a greater degree than the garnet peridotites in fractional melting processes. Those peridotites containing only a trace of garnet or a trace of spinel plus accessory garnet represent transitional types between the two major groups.

(v) There is no direct evidence to suggest that the xenoliths are cognate with the kimberlite. This does not imply that cognate segregations are not found in kimberlite. The regularity of composition, both mineralogically and chemically, suggests that the xenoliths are derived from some uniform source. Only the upper mantle fulfils all the requirements. To the writer's knowledge no diamonds have ever been found, without any doubt, in any of the true peridotite xenoliths, but graphite is occasionally found. The presence of diamonds has often been used to support a cognate origin for the xenoliths but such an argument is thought to be of dubious value.

(vi) The features of tectonic deformation and stress exhibited by many of the peridotite xenoliths conclusively indicate that the xenoliths at some stage formed part of an extensive rock mass. The advocation of an upper mantle source provides this rock mass and in addition implies that stress and possibly movement in the upper mantle are significant features of it.

(vii) The zone of kimberlite generation is within the peridotite of the upper mantle and much of the fragmentary material found in kimberlite is no doubt derived from fragmentation and comminution of the peridotite. Inclusions in diamonds similarly suggest an origin within the upper mantle. As for the origin of kimberlite itself it is tempting to speculate that the initial kimberlite magmas are formed by the partial melting of phlogopite-bearing peridotite in a garnet stable environment. In a very recent publication Dawson (1971) has outlined such a hypothesis for the evolution of kimberlite.

XI. ORIGIN OF THE ECLOGITE XENOLITHS.

1. General Nature, Classification and Origin of Eclogites.

Before the origin of the eclogite xenoliths in kimberlite is discussed it will be instructive to consider the nature and general classification of eclogites. In recent years an ever-increasing amount of attention has been paid to eclogites, rocks which are in fact very rare, and a number of very interesting features have come to light.

The name eclogite was originally introduced by Haüy (1822) for a rock composed of diallage and garnet with accessory amounts of kyanite, zoisite, amphibole, quartz and pyrrhotite. Nomenclature has changed little since then and eclogite is generally considered to be a metamorphic rock composed essentially of jadeite-bearing clinopyroxene and garnet (Church, 1968). Eclogites, as defined here, are known to occur in five petrologically distinct environments, namely:

(i) inclusions in alkali basalts
(ii) inclusions in kimberlite pipes and dikes
(iii) layers, intercalations or lenses in ultramafic (peridotite) masses
(iv) masses in high-grade metamorphic terrains, associated with gneiss or migmatite complexes
(v) bands or lenses associated with the metamorphic rocks of Alpine-type orogenic zones, and in particular, with glaucophane schists.

Smulikowski (1964, 1965, 1968), in an attempt at eclogite classification, suggests that three major groups of garnet-pyroxene rock may be distinguished. These groups differ from one another in their geological occurrence and association and also display certain distinctive mineralogical and chemical features. Smulikowski's three groups can be defined as follows:

Group 1. Ultrabasic garnet-pyroxene rocks, found in environments (i) to (iii) above, very poor in sodium, garnets are pyrope-rich, clinopyroxene rich in diopside.

Group 2. Ophiolitic eclogites, found in environment (v) above, relatively rich in sodium, of spilitic affinity, garnets almandine-rich, clinopyroxenes jadeite-rich.

Group 3. Eclogites from gneissic and migmatitic complexes, found in environment (iv) above, moderate sodium content, composition normally basaltic, garnets and pyroxenes intermediate between those of Groups 1 and 2.

Almost simultaneously with Smulikowski's classification Coleman et al (1965) presented an almost identical three-fold grouping, based similarly on mode of occurrence. As did Smulikowski they found that eclogites are divisible into three groups, which correlate with environments (i) to (iii), (iv) and (v) respectively. Coleman et al record that the pyrope content of the garnets is distinctive for each group and that there is a progressive variation in the jadeite content of the co-existing pyroxenes. Their suggestion is that the three groups of eclogite follow a compositional trend from olivine basalt to tholeiitic basalt and possibly represent highly metamorphosed basaltic material. This conflicts with Smulikowski's view as he regards his Group 1 eclogites as possibly representing primary mantle material, Group 2 eclogites as highly metamorphosed spilitic lavas and Group 3 eclogites as essentially metamorphosed gabbros and basalts.

The origin of eclogites is a problem of long-standing and numerous explanations have been used to account for them. Some explanations which are favoured include an origin as primary mantle material, as "basaltic" segregations within a peridotite mantle, as the products of Alpine-type metamorphism of basic volcanics, as an iso-chemical transformation of gabbroic or basaltic rocks in regionally metamorphosed gneiss and migmatite complexes and as a high-pressure accumulate or cognate phase of a kimberlite magma. It is clear that the rock name 'eclogite' can refer to a number of distinct garnet-pyroxene rocks, the origins of which differ considerably.

2. Characteristic Features of the Eclogite Xenoliths from the Roberts Victor Kimberlite.

(i) A considerable emphasis must be placed on the fact that all the eclogite xenoliths examined during the present study were derived from only one kimberlite diatreme, namely the Roberts Victor. This kimberlite is world-renowned for the relative abundance of eclogite xenoliths in contrast to most kimberlites. Careful examination of the old rock dumps of the Kimberley mines and reference to the literature have shown that eclogite is extremely rare in the three remaining pipes investigated. The paucity of eclogite xenoliths from the mines of the Kimberley area is well illustrated by Mathias et al (1970) who have listed 168 eclogites from numerous pipes and fissures. Of these only 10 have their source in any of the five Kimberley mines whilst 48 xenoliths are listed as originating from the very much smaller Roberts Victor pipe. In general kimberlites are, with only several exceptions, extremely poor in eclogite. With regard to eclogite xenoliths the Roberts Victor pipe cannot be considered to be typical of the vast majority of kimberlites. The inference is clear - at least the bulk of the eclogite xenoliths from Roberts Victor are most probably not related to the actual genesis of the kimberlite.

(ii) Both Mathias et al (1970) and the present study have shown that while the eclogite xenoliths are essentially a two-phase mineral assemblage of garnet and clinopyroxene, their modal, mineralogical and bulk chemical compositions vary considerably. On the basis of garnet composition they can be divided into a number of fairly distinct groups. The indication is that the xenoliths possibly originate from either a number of separate and discrete bodies in the crust or the upper mantle, or have formed by several distinct processes. The final answer may lie in a combination of both.

(iii) Many of the eclogite xenoliths from the Roberts Victor pipe are banded or layered and occasionally more than one type of eclogite constitutes a single xenolith. The inference is that the original source material was heterogeneous. This point is strongly against the concept of a primary eclogite mantle and also indicates rather that the source is geologically complex.

(iv) A transition from peridotite to eclogite has not been recorded in any of the xenoliths examined in this study and rock-types of intermediate chemistry or mineralogy are not known to the writer. Mathias et al (1970) record only two xenoliths which contain orthopyroxene, while none contain olivine. Similarly a transition between the composition of garnets from the eclogites and garnet peridotites has not been recorded, nor are the clinopyroxenes of the two types similar.

(v) As has been stressed previously the eclogite xenoliths of this study are not strictly isochemical with rocks of basaltic chemistry. The hypothesis that eclogite xenoliths simply represent transformed basaltic or gabbroic material cannot be strongly supported. It is significant to note, however, that erupted magmas are in general not primary liquids but represent liquids which have undergone continuous fractionation, at least of olivine, during ascent from the zone of magma generation (O'Hara, 1968). The concept that the eclogite xenoliths possibly represent a partially-fractionated magma trapped either in the lower crust or upper mantle must be considered a distinct possibility.

(vi) Both Smulikowski (1964, 1965) and Coleman et al (1965) consider that eclogites from kimberlite constitute part of a distinct eclogite group (Smulikowski's Group 1 and Coleman et al's Group A). Smulikowski (1964, p.29) goes as far as to say that his Group 1 eclogites ['garnet-pyroxene rocks'] "........ can be looked upon as primary Earth matter from very great depths, possibly from the Upper Mantle". He considers that the eclogites from kimberlite are quite distinct from eclogites of Alpine-type metamorphic belts and also from those found in gneiss and migmatite complexes. However evidence from the garnet compositions of the present study clearly demonstrate that the garnets from the eclogite xenoliths of the Roberts Victor pipe are very similar to the garnets from eclogites typical of gneissic terrains and migmatites (Smulikowski's Group 2 and Coleman et al's Group B). This does not rule out the likelyhood that other kimberlites may contain rare eclogite xenoliths of a different origin. O'Hara et al (1969) have emphasised that important differences appear between the chemistry of eclogites from the 'atypical' Roberts Victor diatreme and those from eclogite-poor diatremes; they stress the need to investigate more eclogites from the latter environment.

3. Suggested Origins for Eclogite Xenoliths from Kimberlite.

Over the years numerous origins have been proposed to account for the presence of eclogite xenoliths in kimberlite, but only five hypotheses need seriously be considered. These hypotheses are briefly summarised below and critically discussed in the light of present-day concepts. In addition the application of these hypotheses to the Roberts Victor eclogites examined during the present study is considered.

(i) Eclogites found in kimberlites represent primary mantle material carried up from the zone of magma generation by the kimberlite (Wyllie, 1963; Schutte, 1967). In the light of the evidence already presented on the nature and composition of the upper mantle it seems extremely unlikely that eclogites constitute an important phase. This hypothesis will consequently be considered no further.

(ii) The xenoliths represent fragments, carried up by the kimberlite, of discrete eclogite lenses or segregations within the peridotite of an ultrabasic upper mantle. Such eclogite segregations may have formed by the partial melting of garnet peridotite followed by crystallisation of the liquid formed in an eclogite-stable region.

Reay (1965) has shown that the partial fusion of an anhydrous synthetic peridotite at atmospheric pressure produces a basaltic liquid which varies in composition with fusion temperature. It is likely that a similar mechanism would prevail in the peridotite upper mantle. Variations in the composition of the eclogites and their constituent minerals can be explained by differences in the degree of partial melting of the garnet peridotite at different temperatures and pressures (O'Hara and Mercy, 1963; Kushiro and Aoki, 1968). This concept can very attractively explain the origin of eclogite xenoliths in kimberlite but has a number of serious drawbacks.

The melting of the more fusible constituents of a four-phase garnet lherzolite (assumed to be primary mantle material), such as pyrope-rich garnet and chrome diopside, will yield a liquid rich in chromium. Subsequent crystallisation of this liquid as eclogite should produce a rock relatively richer in chromium than the original garnet lherzolite. In the case of the Roberts Victor Mine the eclogites are rather poor in chromium. From experimental results and theoretical petrological deductions O'Hara et al (1969) have also pointed out that bimineralic eclogites cannot in general represent frozen liquids derived from the partial melting of peridotites.

(iii) It is also possible that eclogites are cognate with kimberlite and are formed by the accumulation, at high pressures, of garnet and clinopyroxene from a liquid formed by the partial melting of garnet peridotite (O'Hara and Yoder, 1967; O'Hara, 1968; Rickwood et al, 1968). This hypothesis, at present very popular, can also explain the existence of ultrabasic potassic magmas. It can be summarised in the words of O'Hara (1968, p.94) who states: "Protracted eclogite fractionation from an initial partial melting product of peridotite at high pressures probably leads to residual liquids so poor in silica that they do not resemble basalt, but rather alnoite, kimberlite and potassic mafic lavas". This remaining liquid is thought to contain, in addition to potash, abundant titania, phosphorous and volatile phases.

Rickwood et al (1968) and Mathias et al (1970) have elaborated on the concept of an eclogite fractionation mechanism and they suggest the possibility of two distinct fractionation trends within the upper mantle, one being from eclogite ——> kyanite eclogite ——> corundum eclogite and the other, at lower pressures, from eclogite ——> plagioclase eclogite ——> plagioclase-quartz eclogite.

This hypothesis of eclogite fractionation and kimberlite genesis is extremely elegant and also theoretically sound. While certain rare garnet-pyroxene aggregates in kimberlite may well represent high pressure crystal cumulates from a garnet peridotite partial melt the writer considers that it is very unlikely that the Roberts Victor eclogites represent such fractionation products. It is difficult to imagine that a partial melt of a garnet lherzolite would be able to produce a garnet-pyroxene assemblage so chemically distinct from the original pyrope-rich garnet and chrome diopside of the peridotite. To form a typical kimberlite magma the residual liquid would then have to be able to produce a crop of pyrope-rich garnet and chrome diopside after eclogite fractionation! In general the concept of kimberlite genesis by eclogite fractionation also infers that a fairly large volume of eclogite would be produced. In no kimberlites, except for an exceptional case such as the Roberts Victor, are eclogites of any volumetric importance.

(iv) To account for the two groups of eclogites recognised as coming from the Roberts Victor pipe, MacGregor and Carter (1969) suggest that one group represents crystals precipitated from a mafic liquid, under conditions of eclogite stability, while the other group represents the recrystallised liquids formed as the result of fractional crystallisation. The inference is that the liquids are not necessarily related to the host kimberlite and that the fractionation could have taken place in a probable basaltic liquid. This hypothesis provides a very tempting alternative.

(v) Finally it has been suggested that the eclogites xenoliths represent accidental inclusions of metamorphic eclogite picked up by the kimberlite during intrusion through the crust (Davidson, 1967b; Dawson, 1962). It has been shown that "crustal" metamorphic eclogites are distinct from true kimberlitic garnet-clinopyroxene segregations and can easily be distinguished from them. Garnet compositions of the Roberts Victor eclogites suggest that they are typical of the common eclogite-type found in gneiss and migmatite terrains and are not similar to eclogite from an ultra-basic environment. There appears to be no reason why the majority of the eclogite xenoliths from the Roberts Victor kimberlite cannot be derived from high-grade gneissic complexes within the lower crust.

4. Conclusions.

The various hypotheses that have been used to account for the eclogite xenoliths in kimberlite have been critically discussed with particular reference to those from the Roberts Victor pipe. In the light of the evidence presented in this thesis the following conclusions have been drawn.

(i) The eclogite xenoliths from Roberts Victor are not cognate with the kimberlite host and are probably not in any way related to it. The possibility of them originating as a high pressure cumulate phase of a fractioning liquid, which would also produce a residual kimberlite liquid, appears highly improbable.

(ii) Their origin as material from a primary eclogite mantle cannot, in the light of present-day mantle concepts, be supported, neither can the hypothesis that they are samples of eclogite segregations derived purely from the partial melting of a garnet lherzolite mantle.

(iii) Evidence indicates that the Roberts Victor eclogites are very similar to eclogites from regionally metamorphosed complexes of gneiss and migmatite. This suggests that the source of the eclogite may be found within some high-grade metamorphic zone beneath the sediments of the Roberts Victor area.

Smulikowksi (1968) suggests diverse origins for eclogites of this type, which he considers to fall into the granulite facies of metamorphism. The possible origins that he considers include diabase sills, basaltic lava sheets and impure dolomitic sediments. Kyanite eclogites, which can be experimentally derived from high alumia basalts and gabbroic anorthosite (Green, 1967), would possibly constitute zones in high-grade metamorphic complexes such as described by Tilley (1936).

The idea that the eclogite xenoliths are purely accidental inclusions is also supported by the relative abundance of such xenoliths in the Roberts Victor kimberlite as compared with other kimberlites. It is known that other kimberlites have produced typical high-grade metamorphic rocks, for example, the Kimberley mines produce xenoliths of amphibolite whilst in the Voorspoed Mine garnet granulites are not uncommon (G.G. Whitfield, unpublished A.A.R.L. Report).

(iv) Alternatively the source of the eclogite may be within the upper mantle or lower crust where pockets or lenses of partly fractionated basaltic magma have been halted or trapped on their path to the surface. None of the Roberts Victor eclogites can simply be regarded as chemical equivalents of extrusive basalts, their compositions being more comparable with high-alumina picritic magmas. It is thought that most magmas are continuously being fractionated during ascent and it appears quite likely that the Roberts Victor eclogite xenoliths represent such a basic magma which has solidified within an eclogite-stable region, either in the lower crust or upper mantle.

(v) The presence of diamond in one xenolith indicates that very high pressures did exist during the period of diamond formation. The diamondiferous eclogite shows no distinctive differences when compared with the other eclogite xenoliths and supports the conclusion of Rickwood and Mathias (in press) that diamondiferous and graphite-bearing eclogites are neither chemically nor mineralogically different from other kimberlite-derived eclogites. Rickwood and Mathias conclude that diamondiferous eclogites are probably formed at depth of 190 to 555 km within the mantle.

Eclogites in general, however, can form at much higher levels within the mantle or even within the lower crust; there is little doubt that eclogites can form over a wide temperature and pressure range (Smulikowski, 1968). It may be possible that at relatively high levels in the upper mantle or even in the crust abnormal pressures, perhaps high enough to allow diamond to form, would be temporarily possible. Another point to bear in mind is that although current conceptions of the temperature-pressure stability of diamond indicates an origin within the upper mantle diamond can possibly be synthesised at much lower temperature-pressure conditions. The synthesis of diamond in a natural silicate environment has not yet been accomplished.

(vi) A number of distinct eclogite types could be recognised which indicates that more than one origin may be operative. At the moment it is impossible to decide if all the eclogite-types represent the products of high-grade metamorphism or if they are partially fractionated basaltic liquids trapped in an eclogite-stable environment.

SUMMARY OF THE ENTIRE THESIS

General.

Kimberlite, several varieties of which can be defined, is essentially an altered, carbonated mica peridotite which has its origin in the Earth's upper mantle. It occurs mainly as diatremes and dikes, and it has been established that kimberlite is virtually the only primary source of terrestrial diamonds. Kimberlites are characterised by containing rare, well-rounded xenoliths of peridotite and eclogite, rock-types which have undoubtedly come from great depths. These xenoliths provide an insight to the nature and composition of the Earth's interior, particularly the upper mantle.

Early research on the peridotite and eclogite xenoliths led to a number of rival hypotheses as to their origin being postulated. Origins which have been proposed include a derivation from high-grade crustal metamorphic terrains, a cognate or co-magmatic phase of the kimberlite, samples of primary earth material or even water-worn boulders incorporated into the kimberlite.

Recently, with the impetus provided by the International Geophysical Year, research into the Earth's interior has again been stimulated and the peridotite and eclogite xenoliths found in kimberlite have received world-wide attention from earth scientists. Much controversy still exists as to the origin of these xenoliths but only three main theories need seriously be considered. These are an origin as samples of upper mantle material, as accidental inclusions of high-grade crustal metamorphic rocks or as a cognate phase intimately linked with the evolution of the kimberlite host.

The 66 xenoliths of the present investigation have been examined in detail by a wide variety of petrological and mineralogical techniques. The 42 peridotite xenoliths studied have their source in four kimberlite pipes of the Kimberley area, South Africa, namely the Bultfontein, Wesselton, Dutoitspan and Roberts Victor Mines. The 24 eclogite xenoliths were all collected from the Roberts Victor Mine, a kimberlite world-renowned for its richness in eclogite xenoliths.

Petrology.

Petrographic studies show that the peridotite xenoliths can be divided into garnet peridotites, spinel peridotites and highly altered and/or granulated peridotites. Except for the few extensively granulated specimens the peridotites are essentially phanerocrystalline medium- to coarse-grained aggregates of interlocking olivine and orthopyroxene with minor or trace amounts of one or more of dark red garnet, bright green clinopyroxene, phlogopite mica, chrome spinel (picrochromite) and rarely graphite. The average garnet peridotite, as determined from numerous modal analyses, consists of 65% olivine, 29% orthopyroxene, 0.7% clinopyroxene, 4.6% garnet and 1.0% phlogopite. The average composition of the spinel peridotites is 72% olivine, 25% orthopyroxene, 0.1% clinopyroxene, 0.4% chrome spinel and 2.2% phlogopite. Several specimens show a transition between garnet and spinel peridotite. The extensively granulated specimens consist mainly of olivine.

All peridotites show minor serpentinisation and contain small amounts of other alteration products. Many of the peridotites display features consistent with shearing and stress, thus indicating that they have been subjected to considerable tectonic deformation before incorporation into the kimberlite, probably in an upper mantle environment.

Chemical analyses of nine garnet peridotites and four spinel peridotites show that these two types are virtually identical. They are all undersaturated olivine normative rocks of tholeiitic character and typical ultrabasic composition. It essentially appears that the garnet peridotites differ from the spinel peridotites only in the pressures and temperatures at which they were equilibrated.

The eclogite xenoliths, typically ellipsoidal or discoidal in outline, are chiefly compact, medium- to coarse-grained aggregates of allotriomorphic garnet and clinopyroxene. Three specimens contain minor amounts of kyanite, at least one eclogite contains a trace of corundum and one contains numerous scattered diamonds. At least four primary eclogite mineral assemblages can be recognised, namely garnet-clinopyroxene, garnet-clinopyroxene-kyanite, garnet-clinopyroxene-kyanite-corundum and garnet-clinopyroxene-diamond. Numerous eclogite xenoliths show a rudimentary layering and on the basis of appearance and accessory mineral content at least three varieties can be recognised, the real significance of which is not known.

Detailed examination has shown that almost every eclogite displays features indicating that slight melting of the constitutent minerals has taken place. These features, illustrated by the alteration of the clinopyroxene and the formation of glassy veinlets containing crystals of feldspar, amphibole and zeolite, have apparently formed by a sudden relief of pressure on the eclogites while at great depth. This probably took place at the time of kimberlite intrusion.

Modal analyses of the eclogites show that there exists a considerable variation in the garnet: clinopyroxene ratio, the amount of garnet varying from 14% to 74% and the amount of clinopyroxene from 20% to 79%. In the kyanite eclogites kyanite constitutes between 3.3% and 9.0% while small amounts of micaceous material and other alteration products are also present in virtually every specimen.

The eclogites show a much greater chemical variation than the peridotites, and alumina, lime, iron, magnesia and soda exhibit relatively large ranges. Of the nine analysed eclogites three are nepheline normative alkalic rocks, the remainder being olivine tholeiitic. While element abundances are typically those for basic rocks complete melting of the eclogites would not produce a liquid of true extrusive basaltic composition but rather a liquid of high-alumina picritic character. The indication is that the eclogites do not simply represent transformed gabbroic material.

Mineralogy.

The olivine, found only in the peridotites, ranges in composition from Fo_{91} to Fo_{94} and invariably shows some serpentinisation. In addition to uneven optical extinction and the presence of deformation lamellae much of the olivine shows either a marginal granulation or an unusual form of recrystallisation, all these features indicating that it has undergone extensive tectonic deformation, probably in the upper mantle. Nickel is the only minor element of any significance in the olivine.

Orthopyroxene, similarly found only in the peridotites, ranges in composition from En_{88} to En_{94} and normally shows only slight alteration. Uneven optical extinction is typical, kink bands and bent crystals are common and in several specimens a possible inversion of enstatite to clinoenstatite has been recognised. As with the olivine these features indicate that much of the orthopyroxene has undergone severe tectonic stress, probably in an upper mantle environment. Chemically the orthopyroxene from the garnet peridotites contains only very minor amounts of alumina but that from the spinel peridotites shows relatively high alumina and to a lesser extent, lime. This indicates that the orthopyroxene from the garnet peridotites formed under higher pressure conditions than that in the spinel peridotites. Chromium is an important minor element in the orthopyroxene.

The garnets, present in both peridotites and eclogites, are quite distinct. The garnets in the peridotites range in colour from dark pink to magenta-pink and are estimated to contain between 65% and 80% of the pyrope end-member plus appreciable amounts of almandine, andradite and uvarovite. The peridotite-type garnets are virtually identical to those found in kimberlites and to those which are characteristic of dunites and serpentinites. The eclogite garnets, generally pinkish, orange or brownish, show a much wider compositional range and are estimated to contain between 40% and 60% pyrope plus considerable amounts of almandine, andradite and grossularite. Uvarovite is notably absent in the eclogite garnets. Generally they are characteristic of the garnets found in eclogites occurring in gneissic basement rocks and migmatites. On the basis of garnet composition at least four types of eclogite garnet can be recognised but the significance of this grouping is uncertain.

The scattered grains of bright green chrome diopside found in the peridotites consist mainly of diopside but also contain appreciable amounts of jadeite and enstatite in solid solution. On the basis of chemical composition it is estimated that the chrome diopside formed at depths of the order of 125 km, that is well within the upper mantle. The bluish-green clinopyroxene of the eclogites has an omphacitic composition and invariably exhibits considerable alteration to ultrafine-grained aggregates consisting mainly of secondary pyroxene, zeolites and feldspar. This alteration and also the formation of glassy material is thought to be due to incongruent melting of the omphacite caused by rapid release of pressure.

In certain cases phlogopite is possibly a primary constituent of the peridotites. If so its significance in rocks probably of upper mantle origin is considerable, being a potassium- and water-bearing phase which would also be able to supply radiogenic heat. The mica in the eclogites is regarded as secondary.

The results have led to the conclusion that the peridotite xenoliths are samples of a peridotite upper mantle, which is both chemically and physically zoned, and which have been brought rapidly to surface in a kimberlite magma. The xenoliths do not represent primary mantle material but rather portions of a tectonically active mantle which has undergone varying degrees of partial melting and the loss of volatile constituents. There is no evidence to suggest that they are cognate with the kimberlite and an origin as accidental inclusions of crustal metamorphic rock can be clearly disproved.

The eclogite xenoliths on the other hand probably represent either inclusions of high-grade metamorphic material intersected at depth by the Roberts Victor kimberlite or samples of eclogite lenses present in the upper mantle and which represent trapped pockets of partially fractioned basaltic magma. There is no evidence to indicate that the Roberts Victor eclogites are a cognate phase of the kimberlite or simply the products of the partial melting of a four-phase garnet lherzolite. The presence of diamond in one eclogite, which does not differ from the others, implies that great pressures existed during diamond formation.

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