SOME ASPECTS OF THE GEOCHEMISTRY OF KIMBERLITE XENOCRYSTS

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Thesis submitted in fulfilment of the requirements
for the degree of Master of Science
at the University of Cape Town

Department of Geochemistry,
University of Cape Town.
October, 1974.

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ABSTRACT

The heavy mineral concentrates of eight kimberlite pipes or dykes in Southern Africa have been examined and sorted into the mineral groups: garnet, clinopyroxene, orthopyroxene, olivine, chromite and spinel.

More than five hundred determinations of the chemical composition of these xenocrysts have been made by means of the electron microprobe analyser.

It has been shown that garnets with compositions similar to those found as inclusions in diamond are present in the heavy mineral concentrates of the Bobbejaan Diamond Mine, Kao kimberlite pipe, Koffiefontein Diamond Mine, Newlands kimberlite pipe, Premier Diamond Mine and Sekretariskop kimberlite pipe.

Chromites with compositions similar to the chromites found as diamond inclusions have been found at the Newlands kimberlite pipe.

An orthopyroxene from the Koffiefontein Diamond Mine has a composition similar to the enstatites found as inclusions in diamond.

Sub-calcic diopsides have been shown to exist in the heavy mineral concentrates of the Kao kimberlite pipe and the Premier Diamond Mine. The Precambrian age of the latter makes these diopsides important to the interpretation of the structure of the Upper Mantle beneath Lesotho as suggested by Boyd (1973a).

High-calcium, high-chromium, green garnets have been found in the concentrates of the Newlands kimberlite pipe. This is the only pipe in South Africa known to contain these garnets. A garnet from this locality, thought to have been derived from a disaggregated grospydite xenolith, has a composition similar to those of the

Zagodachnaya kimberlite pipe, Yakutia (N.V. Sobolev et al., 1968).

A niobium-bearing rutile has been found in the heavy mineral concentrates of the Rietfontein kimberlite pipe.

The compositions of these xenocrysts have been compared with the constituent minerals of peridotite-pyroxenite xenoliths, eclogite xenoliths and the discrete nodule (megacryst) association. It can be shown that most of the xenocrysts examined can be regarded as being derived from one of these xenolith types. Comparisons between the compositions of the minerals found as inclusions in diamond and the xenocrysts have been made. It has been shown that garnets with compositions similar to those garnets found as inclusions in diamond, although rare, are more plentiful than suspected.

I INTRODUCTION

The mineralogy of kimberlite and its related rocks has attracted considerable interest over the last decade, particularly the compositions of the xenocrysts and xenoliths which are thought to have been derived from the upper mantle. Evaluation of the proportion and type of these xenoliths has been regarded as the most reliable method of assessing the petrologic nature of the upper mantle beneath the Precambrian shield areas (Dawson, 1971).

There are two major types of ultramafic xenolith found in kimberlites, the peridotite group and the eclogite group. The peridotite group is more abundant and is made up of various assemblages of olivine, orthopyroxene, clinopyroxene and garnet with minor amounts of phlogopite, chromite, spinel, magnetite and sulphide-bearing minerals. The eclogite group of xenoliths consists mainly of garnet and clinopyroxene, but rutile, olivine, orthopyroxene, kyanite, corundum, spinel, quartz, phlogopite, sulphides, graphite and diamond have been found as accessory minerals (Mathias et al., 1970). Many kimberlite xenocrysts are considered to have been derived from disaggregated xenoliths of mantle-derived rocks which were themselves sampled by the kimberlite during emplacement. These xenocrysts are readily obtained from the large volumes of heavy mineral concentrates recovered during the diamond extraction process, and include the high pressure minerals garnet, clinopyroxene, orthopyroxene, olivine, spinel, ilmenite, magnetite, rutile, chromite, zircon, corundum and diamond. Most of the garnet, clinopyroxene, orthopyroxene and olivine is likely to have been derived from disaggregated xenoliths, but other minerals such as ilmenite, magnetite, rutile and zircon may be more closely connected to the formation and subsequent development of the kimberlite magmas.

Diamond is found in kimberlites, the diamond content of which varies considerably. The only other source rocks for diamonds indisputably recorded in South Africa are eclogite xenoliths and individual eclogitic minerals from kimberlite (Gurney, Siebert and Whitfield, 1969). Garnets and clinopyroxenes having similar compositions to the garnets in eclogite xenoliths have also been found as inclusions in diamonds (Meyer and Boyd, 1969, 1970, 1972; V.S. Sobolev et al., 1972; N.V. Sobolev et al., 1971a, 1971b; Meyer and Svizero, 1974; Prinz et al., 1974). Some garnets found as inclusions in diamond are closely related to garnets from peridotite xenoliths in that they are high in magnesium and chromium and low in calcium, iron and aluminium contents, with minor amounts of manganese and titanium (Meyer, 1968; Meyer and Boyd, 1969, 1970, 1972; V.S. Sobolev et al., 1969; N.V. Sobolev et al., 1969, 1970, 1971a, 1971b; Meyer and Svizero, 1974; and Prinz et al., 1974). In both cases the bulk of the iron present in these garnets is present as Fe^{2+}. As shown by Gurney and Switzer (1973), however, there are certain small differences in composition between the garnets found in the common garnet peridotites and those found as inclusions in diamond. These differences can be demonstrated by means of Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams (Figures 4 and 5), but in general the diamond inclusions have higher magnesium and lower calcium associated with high chromium contents. Olivine and orthopyroxene are also found as fairly common inclusions in diamond (Meyer and Boyd, 1970, 1972; N.V. Sobolev et al., 1970; Meyer and Svizero, 1974; Prinz et al., 1974). Using the Matsoku kimberlite pipe peridotite-pyroxenite suite as a guide (Cox et al., 1973), it appears that the olivine and orthopyroxene inclusions are probably closely related to the garnet inclusions and that all three, possibly together with the rare chromiferous clinopyroxenes reported from diamonds, are derived from a mantle peridotite not yet reported from kimberlite. Two xenoliths from the Aykhal and Excelsior kimberlite pipes have been reported to contain garnets with the characteristics of diamond inclusion garnets (V.S. Sobolev et al., 1969; Boyd and Dawson, 1972), but the other components of these rocks were completely serpentinised. One of these xenoliths contained diamond and the only other xenoliths which contained diamonds were from the same Russian source, the Aykhal pipe, Yakutia (V.S. Sobolev et al., 1969). There are no other clearly substantiated finds of diamond in peridotite. References in the early literature to such discoveries are unsubstantiated and must be considered doubtful in view of the known loose use of the term 'peridotite'.

One of the most interesting features of kimberlites is that there has not been shown to be any general relationship between the amount of heavy minerals present, their relative proportion, the overall bulk chemistry of the kimberlite and the diamond content of the pipe or dyke. Thus minerals found associated with diamonds as inclusions or concretions on diamond are of particular importance because they must be considered to have formed in equilibrium with the diamond.

This study was undertaken because it was felt that careful examination of any individual kimberlite concentrate could yield useful information on the xenolith suite and on the presence of minerals probably co-genetic with the diamond. In certain cases, for example Premier Mine, it is very difficult to find ultrabasic xenoliths in the kimberlite because they are rare. In other cases prospecting or mining operations are not currently in progress (e.g. Newlands) and may not have been sufficiently large in scale to have penetrated through the oxidised near-surface yellow ground (e.g. Sekretariskop). In such cases it is not possible to obtain a representative collection of the xenolith suite present and a study of the concentrate minerals can be especially valuable. Even in pipes where xenoliths are common (e.g. Roberts Victor) or at least readily obtainable (e.g. Kimberley Mine, Bellsbank, Bobbejaan), it appears from the results to be presented here that a study of the concentrates is still useful because it is relatively easy to determine the presence of xenocrysts of unusual composition which can be interpreted as being derived from xenoliths not hitherto reported from these localities.

This study extends the work of Gurney and Switzer (1973) on kimberlite xenocrysts from sources other than the Finsch Diamond Mine. Gurney and Switzer have reported the existence of magnesium-rich, calcium-poor, lilac-coloured garnets in the concentrates from the Finsch Diamond Mine which contained sufficient chromium to make them compositionally similar to the garnets found as inclusions in diamond. This discovery showed conclusively that N.V. Sobolev et al. (1969) were correct when they suggested that kimberlite heavy mineral concentrates had been inadequately sampled and the full compositional range of their constituent minerals was not yet known, thus providing the justification for this work.

Heavy mineral concentrates from a number of kimberlite pipes and dykes in Southern Africa were selected for study on the basis of their known xenolith and/or xenocryst content. Where possible, similar minerals from different sources have been investigated, but the range in xenocryst minerals and the compositions of these minerals was too large to make a comprehensive study feasible. Some of the minerals identified in the concentrates were not studied in any detail because an emphasis was placed on those minerals likely to yield most information.

Hence, electron microprobe determinations of the compositions of the minerals garnet, orthopyroxene, olivine, clinopyroxene, spinel and chromite from various kimberlites were carried out. Ilmenite was not examined in this study because a similar, but more comprehensive, investigation of ilmenites was being undertaken separately.

II SAMPLE LOCALITIES AND SAMPLE PREPARATION

1. SAMPLE LOCALITIES

The samples examined in this study were mostly taken from the heavy mineral concentrates of eleven kimberlite pipes or dykes intruded into various stratigraphic horizons in Southern Africa. The occurrences were geographically spread from Rietfontein in the north-west Cape to Kao in northern Lesotho. The approximate location of these kimberlites may be seen in Figure 1. Brief descriptions of their exact position, geological setting, ultramafic xenolith suite and approximate diamond content follow. The diamond grade given is only the average number of carats per 100 metric tonnes; no indication as to the value per carat is given and different intrusions within a single occurrence may have very different grades.

(a) Bobbejaan Diamond Mine

This mine is situated on the Bobbejaan fissure which is the most easterly of the two fissure systems on the farm Bellsbank, N.W.48, which is 68 km north-north-west of Barkly West, Cape Province. The western fissure system differs from the Bobbejaan fissure in that there are four small 'blows' on the kimberlite dyke, three of which have been worked for diamonds. The Bobbejaan fissure strikes N30°E and dips 85°E, having an average width of 50-80 cm over a distance of 2600 m with a maximum width of just over 1 m (Bosch, 1971). The Bellsbank fissure system was intruded into the dolomite of the Campbell Rand Series of the Transvaal system which forms a plateau and the western boundary of the Harts River Valley. A strong structural control prevails in the Barkly West area; the kimberlites and major topographical features are elongated and aligned in a NE-SW direction.

The kimberlite has been described by Bosch (1971) and Skinner (1973). Bosch termed it a phlogopite-carbonate rock containing olivine xenocrysts and thus was not peridotitic. This conclusion was not confirmed by Skinner who described olivines in the matrix of the kimberlites, thus tending to reaffirm their peridotitic nature. Olivine megacrysts are present in the kimberlite and were considered to be xenocrystic in origin. The ultramafic xenoliths found in the Bobbejaan kimberlite are listed by Rickwood, Gurney and White-Cooper (1969), and Rickwood (1969), and in the Guide for the First Field Excursion of the International Conference on Kimberlites (1973).

The diamond content of the Bobbejaan Mine is roughly 30-40 carats per 100 metric tonnes and the diamonds are of higher quality than those from most other primary deposits in South Africa.

(b) Finsch Diamond Mine

This open-cast mine lies on the farm Brits approximately 37 km east of Postmasburg and 160 km west of Kimberley. At surface the wall rock is ironstones of the Middle Griquatown Series of the Transvaal System which are 130 m thick and lie conformably on the dolomite series. The upper layers of the pipe were ironstone rubble and clays of thicknesses varying from 2 to 15 m covering 'yellow ground' which extended to a depth of greater than 100 m below surface. A crescent-shaped body of mudstone 30 m wide forms a margin between the ironstones and the pipe itself.

There is no published petrological study of the kimberlite at this stage, but the heavy mineral concentrate showed that over 90% was garnet and that ilmenite and chrome diopside were extremely rare (Gurney and Switzer, 1973). The diamond content of the pipe has been given as 86 carats per 100 metric tonnes of kimberlite mined (de Beers Consolidated

Mines Annual Report, 1970).

(c) Jagersfontein Diamond Mine

Situated in the south-western Orange Free State, the Jagersfontein Mine ceased production one hundred and one years after the kimberlite was found in 1870. Williams (1932) mentioned that two kimberlite types were present, having very different diamond contents: the 'grey ground' being very low, and the 'blue ground' being much higher. Jagersfontein had an average diamond yield of 10 carats per 100 metric tonnes of 'blue ground' for the years 1902-1913 (Wagner, 1914), and 7,09 carats per 100 metric tonnes for 1969, and 5,9 for 1970. The quality of the Jagersfontein diamonds, however, "far surpassed that of diamonds from any other mines" (Williams, 1932, p. 27), thus making it an economic proposition even at the low recovery grades. Jagersfontein was a 'blow' on a fissure which extends to the east and west of the main pipe and Williams thought it might be situated at the intersection of two or more fissures. The two kimberlites at Jagersfontein were different not only in diamond content, but also in accidental xenolith content with the 'grey ground' having so many shale and mudstone inclusions that it could hardly be classed as a kimberlite (Williams, 1932). The 'blue ground' formed a rock which ranged in hardness from 'soft' to 'hardebank', and according to Wagner (1914) was a normal basaltic kimberlite having large and small olivine crystals, with plates of phlogopite and rounded grains of garnet scattered through a groundmass of calcite and serpentine, rich in crystals of perovskite, apatite and granules of iron ore, but hardly any mica.

The ultramafic xenoliths found at Jagersfontein have been listed by Rickwood (1969), in which the non-eclogitic xenoliths are described, and by Rickwood, Gurney and White-Cooper (1969) who list and describe the eclogitic nodules.

The Jagersfontein kimberlite intruded the Beaufort shales of the Karroo System.

(d) Kao Kimberlite Pipe

The main Kao kimberlite pipe and its satellite pipes are to be found at an elevation of 2500 m in the Stormberg Volcanics at the top of the Karroo System in the Maluti Mountains of Northern Lesotho. The pipe occupies a steep corrie with small streams draining directly into the Kao stream and thence into the Maliba Matso River (Rolfe, 1973). The main pipe is one of the largest in Southern Africa, ranking after Orapa in Botswana and Premier in South Africa. The petrography of the Kao kimberlites has been described by Clement (1973) and an account of the general geology of the pipe was given by Rolfe (1973). The heavy mineral concentrates and their distribution have been described by Nixon and Hornung (1968) and the xenolith suite reviewed by Nixon and Boyd (1973a). The diamond content of the pipe varies within the different kimberlites, but never exceeds 18 carats per 100 metric tonnes.

(e) Koffiefontein Diamond Mine

This mine is located on the largest of a group of three pipes, along a northwest-southeast trending line, which were considered by both Wagner (1914) and Williams (1932) to be linked below surface by a single kimberlite dyke. They were thought to be fissure enlargements or what were described as 'blows' on the Bellsbank main fissure and Newlands dykes. The Koffiefontein pipe intruded the rocks of the Ecca Series of the Karroo System which consist mainly of flat-lying shales into which numerous dolerite sills have been concordantly and transgressively intruded. In the area the Karroo succession is approximately 320 m thick and directly overlies Precambrian granite-gneiss. The kimberlite itself is a soft blue rock, tuffaceous in character, composed of abundant fragments of kimberlite, individual kimberlitic heavy minerals and a variety of wall rock fragments and minerals derived from the break-up of wall rock material. The kimberlite contained two distinct generations of olivine, one of which is considered to be xenocrystic and the other much smaller euhedral grains which have been almost completely serpentinised. The groundmass of the kimberlite consisted essentially of serpentine with minor amounts of phlogopite. The accessory minerals were perovskite, magnetite and rare calcite (Guide for the First Field Excursion, International Conference on Kimberlites, 1973). The xenoliths in this pipe are mainly of Karroo shale, dolerite and crustal material. Ultramafic xenoliths have been found in this kimberlite, but are uncommon although the heavy mineral concentrate seemed to indicate a normal distribution of these nodules. The diamond content of this pipe is approximately 10 carats per 100 metric tonnes.

(f) Newlands Kimberlite Pipes

These particular pipes are the most northerly of five 'blows' aligned over 600 m, along a series of fissures trending northeast-southwest on the farm Newlands, N.V.42, in the Barkly West area of the Cape Province. The kimberlites intruded flat-lying to undulating shales and mudstones of the Dwyka Series of the lower Karroo System and were partially capped by the remnants of a dolerite sill. The kimberlites have a mica-rich matrix and contain well rounded olivine xenocrysts. The various 'blows' show distinct differences in wall rock inclusion types which are described in the Guide for the First Field Excursion of the International Conference on Kimberlites (1973). In this guide a list of the different ultrabasic xenoliths found at Newlands is given, but on examination of the heavy mineral concentrate, it was found that chromite was not particularly rare, but that there was less ilmenite than expected. The concentrate examined from this locality is presumed to have come from Blow No. 5 because the heavy mineral concentrate was obtained from a dump next to this blow. This may be incorrect because although the concentrating machinery was located next to this blow, there is no guarantee that the material actually originated from it. The green garnets embedded in the kimberlite matrix were found in a kimberlite dump next to Blow No. 4. Kyanite eclogite was found at one of the old concentrate tailings dumps and as far as can be ascertained, has not previously been recorded from this locality.

There are no figures available as to the number of diamonds recovered from the Newlands pipes as mining ceased there in 1889, but it is recorded that the diamonds were small, of good quality and that octahedra predominated. The diamonds have been described as similar to those of the Frank Smith Mine and it is probable that some portion at least were derived from disaggregated eclogites.

(g) Premier Diamond Mine

Situated near Cullinan 30 km east-north-east of Pretoria, the Premier Mine is one of the eleven known kimberlite occurrences in the area, but the only one which contains economic quantities of diamonds. The Premier kimberlite pipe is unique in that it is the oldest known kimberlite in Southern Africa. Age determinations on the kimberlite itself and an intrusive gabbroic sill have shown that the pipe has a minimum age of 1100 million years, but may be considerably older (Allsopp et al., 1967); thus establishing that the kimberlite was Precambrian, whereas most other Southern African kimberlites were Cretaceous in age. Eight kimberlite types have been identified at the Premier Mine and have been described briefly in the Guidebook for the First Field Excursion of the International Conference on Kimberlites (1973). The ultrabasic xenoliths found at the Premier Mine have been listed by Rickwood (1969) and Rickwood, Gurney and White-Cooper (1969). Premier Diamond Mine has a diamond content of 30-40 carats per 100 metric tonnes.

(h) Rietfontein Kimberlite Pipe

This pipe is situated in the Mier Coloured Reserve, Gordonia, northwest Cape Province, and is approximately 150 m in diameter and associated with a narrow dyke of basaltic kimberlite which can be traced for some 1300 m northeast of the pipe. The kimberlite has been described as basaltic containing abundant garnet and chrome diopside. The pipe itself is intrusive into Dwyka shales. The xenolith suite consisted of eclogite, kyanite eclogite, peridotite and pyroxenite (Gurney et al., 1971). One of the features of the heavy mineral concentrate from this pipe was the relatively large amounts of kyanite found compared with other kimberlites. The pipe has been prospected, but not mined for diamonds. Preliminary figures indicate a low grade, but the pipe is diamondiferous.

(i) Roberts Victor Diamond Mine

This mine, which has also been known as Rovic or Damplaats, is situated on the farm Damplaats some 40 km east of Boshof in the western Orange Free State. The kimberlite body consists of a number of enlargements on two parallel fissures. The No. 1 fissure strikes N28°E with a dip varying between 76° and 86° east on which three pipes and three blows are developed. The area is covered by approximately 12 m of Kalahari sand. Down to 100 m the wall rock is black carbonaceous shale belonging to the Lower Ecca Series underlain by Dwyka tillite, grits and black shales from 2 to 13 m thick. This sedimentary sequence lies on Ventersdorp lavas which rest on basement granite-gneisses and Dominion Reef formations. A 20 m thick post-Karroo dolerite sill intrudes the Ventersdorp lavas 26 m from the top of the 160 m thick volcanics.

The Roberts Victor kimberlite is micaceous, having a groundmass consisting of phlogopite, calcite and magnetite with xenocrysts of garnet, phlogopite, olivine and pyroxene. The xenoliths at Roberts Victor are numerous. The Roberts Victor Mine is famous for the variety of ultramafic inclusions, especially the eclogites which here are far more abundant than the peridotitic nodules. The different types of eclogite and peridotite found at this mine are given by Rickwood (1969) and Rickwood, Gurney and White-Cooper (1969). The spinel nodule, BD1988, was found by J.B. Dawson at this mine during 1973 and as far as is known is unique because of its size (1,5 kg) and as a similar nodule has not been previously reported (Figure 41).

The diamond content at Roberts Victor has varied considerably during the life of the mine, depending on the kimberlite worked and the efficiency of the recovery methods. Wagner (1914) recorded an average grade of 32,5 carats per 100 loads. At present the grade is 20 carats per 100 metric tonnes in a new section of the mine. The heavy mineral concentrate from Roberts Victor is almost completely lacking in chromites and ilmenites, and is predominantly derived from disaggregated eclogites.

(j) Sekretariskop Kimberlite Pipe

This occurrence lies on the boundary between the farms Uitdraai 357 and Sekretariskop 358, 10 km east of Koffiefontein in the Fauresmith district of the Orange Free State. It is not really a pipe, but a dyke enlargement on a north-south trending fissure. The kimberlite is elliptically shaped, the main axis being 350 m along the strike of the fissure. Maximum width is 90 m. The pipe is intruded into the shales of the Karroo System and is covered by 6 m of calcrete. Very little work has been done on the petrography of the kimberlites which are extremely weathered but have been regarded as basaltic rather than micaceous (J.B. Hawthorne, personal communication, 1974). Three different kimberlites have been classified on the basis of the number of wall rock inclusions: 40%, >60% and >90%. Ultramafic xenoliths are very uncommon, but this may be due to the very weathered nature of the kimberlites. This pipe has been prospected and has the very low diamond content of less than 1 carat per 100 metric tonnes.

(k) Star Diamond Mine

This mine is situated on the farm Wynandsfontein 653 in the Winburg district of the Orange Free State, some 5 km north of Theunissen. According to Allan (1961), Star is one of a number of old mines along a ten mile length, due east and west of Theron Station, O.F.S., which all apparently exploited the same dyke, or a set of closely spaced parallel dykes and/or 'pipes' which represent local enlargements corresponding to the 'blows' on the Bellsbank and Newlands fissures.

The kimberlite is described as "a serpentinised-olivine-pyroxene-phlogopite peridotite, often with a marked brecciated appearance and with accidental and cognate inclusions" (Allan, 1961, p. 310), but close to the dyke-country rock contact it becomes highly micaceous in places. The kimberlite fissure has a maximum thickness of 1 m, a nearly vertical dip and is controlled by a set of east-west joints in the country rock. In places a number of fissures occur in what Allan describes as an en echelon pattern. These fissures cut through a thick Karroo dolerite sheet dipping up to 45°E and overlying horizontally bedded shales of the Lower Beaufort Series of the Karroo System. The approximate diamond content of this fissure is 30 carats per 100 metric tonnes, but the gem stones are generally of very high quality and good colour. Most of the diamonds, however, consist of clips or blocks.

2. SAMPLE PREPARATION

(a) Preliminary Examination

Most of the concentrates examined in this study were provided by J.J. Gurney of the University of Cape Town or J.B. Hawthorne of De Beers Consolidated Mines Limited. Additional concentrates were collected on field excursions to the Kao kimberlite pipe, Roberts Victor Diamond Mine, the Newlands kimberlite pipes, and the Bobbejaan fissure. Most of the samples are monomineralic xenocrysts except the garnet-spinel nodule from Bobbejaan Diamond Mine and the spinel nodule from Roberts Victor Mine. As the heavy mineral concentrates are obtained during prospecting and/or mining operations at the different localities by processes of varying efficiency, the samples were further concentrated by means of a bromoform separation (S.G. = 2,83) after rough screening through 5, 10 and 20 mesh Tyler screens; the −5+10 and −10+20 mesh fractions being retained for examination and concentration. The concentrate was then thoroughly washed in acetone and distilled water and cleaned in a Dawe Ultrasonic cleaning tank. The samples were then dried at 110°C and a preliminary sorting into mineral groups was carried out on the basis of one or more simple mineralogical properties.

The concentrates contain garnet, clinopyroxene, orthopyroxene, olivine, chromite, spinel and occasional combinations of these minerals but seldom more than three at the size ranges being examined. Other minerals found in the concentrates were ilmenite, kyanite, zircon, rutile, phlogopite, amphibole, sulphides and magnetite. At some pipes or dykes certain minerals are absent from the heavy mineral suite, for example, ilmenite was not found in the Bobbejaan Mine concentrates and as far as is known has never been found at this fissure (Carlstein, personal communication). The relative proportions of the heavy minerals varied from kimberlite to kimberlite, but have not been determined accurately. The Rietfontein heavy mineral concentrates contained 50% garnet; ±20% clinopyroxene, orthopyroxene and olivine; ±5% ilmenite, spinel and chromite; ±1% of minerals such as kyanite and zircon; ±1% of amphibole, mica and other minerals; and the remainder was made up of rock fragments. The Newlands heavy mineral suite contained ±50% garnet; ±10% orthopyroxene; ±10% olivine; ±5% clinopyroxene; ±5% ilmenite and chromite; the rest was rock fragments. Other minerals such as rutile and magnetite were rare. Garnets made up ±70% of the Koffiefontein heavy minerals; the clinopyroxenes, orthopyroxenes and olivines ±7% each, with ilmenite and chromite accounting for ±2%. Rock fragments made up ±10% of the total. At the Kao kimberlite pipe the amounts of clinopyroxene, orthopyroxene and olivine were ±5%, ±10% and ±10% respectively. Garnet was the most prevalent mineral, making up ±65% of the total. Ilmenite and spinel proportions were ±2%, with the remainder being 0,5% odd minerals, e.g. rutile and rock fragments. The rock fragments were made up of minerals and kimberlite and/or combinations of minerals such as eclogite. The Bobbejaan, Premier and Sekretariskop specimens were received already sorted into mineral groups, thus the relative proportions of these minerals in the concentrates were not known. The Roberts Victor sample had also been through a preliminary sorting before this study was begun, but consisted predominantly of garnet, clinopyroxene and eclogite fragments. Ilmenite and spinel were rare at this locality, and olivine and orthopyroxene were uncommon.

The specimens from the Jagersfontein, Star and Finsch heavy mineral concentrates were received ready for analysis, thus the relative proportions of the constituents were not known. The major portion of all the concentrates examined was thus made up of garnet, the pyroxenes, and olivine. However, the accessory or rare minerals in certain concentrates proved to be of considerable interest. In the Rietfontein and Kao concentrates, niobium-bearing rutiles were found. These were identified by X-ray diffraction methods. One of these rutiles from Rietfontein has been analysed for niobium and zirconium by X-ray fluorescence spectrometry and contained 1,3% Nb and 0,16% Zr (H.S. Smith, personal communication, 1974). Two different types of kyanite have been found in the Rietfontein concentrate (Gurney et al., 1971) along with fairly substantial quantities of zircon, which is found in most heavy mineral concentrates, but is generally very rare. One of the most interesting discoveries made during this study was the green garnets at the Newlands kimberlite pipes. These garnets have been found co-existing with chromites and clinopyroxenes in the concentrate, in situ in a weathered micaceous kimberlite and co-existing with an olivine in a dark 'hardebank'-type olivine-rich kimberlite matrix.

It was reasonable to expect that the ultramafic xenolith suites of the respective kimberlite occurrences might bear some relation to the mineral content of the concentrates, but this was not necessarily correct. No comprehensive investigations of the distribution of ultramafic xenoliths in the particular kimberlites examined in this study have been undertaken and relative proportions of minerals in the concentrates were not known with any degree of accuracy. Thus comparisons between the ultramafic xenolith and heavy mineral suites could only be approximations. The types of xenolith found at these localities have been mentioned in a previous section. However, overall impressions were that the Newlands, Roberts Victor and Kao concentrates showed some relation to their xenolith suites. At Sekretariskop and Koffiefontein ultramafic nodules were rare, but abundant garnet and clinopyroxene, and garnet, olivine and orthopyroxene respectively were found. Little is known of the xenolith suites at the Star and Finsch diamond mines, but pyroxenite, lherzolite, eclogite and kyanite eclogite nodules have been found at Rietfontein (Gurney et al., 1971).

(b) Mineral Separation

A detailed sorting of the mineral groups was made on more stringent lines by taking into account mineralogical properties such as crystal form and habit, cleavage or lack of it, lustre, streak, fracture, hardness and particularly colour. In certain cases where mineralogical criteria for distinguishing mineral groups from one locality, differed to those used for another locality, X-ray diffraction methods were employed to characterise a representative specimen from that mineral group.

(i) Garnets and other silicate minerals

The garnets were sorted into arbitrary groups on a colour basis, for instance purple, lilac or mauve, red, pink, orange, brown, yellow or green, where applicable. There were no definite boundaries between the colour divisions and gradations between them exist. At very few localities was the complete colour range found and the amounts of the various coloured garnets varied considerably from kimberlite to kimberlite and appeared to be related to the xenolith suites at the particular occurrence. Certain of the lilac-coloured garnets at the Finsch Diamond Mine had been shown to be low-calcium, high-magnesium garnets closely related to the high-chromium diamond inclusion garnets (Gurney and Switzer, 1973) and thus lilac garnets were selected for further examination. N.V. Sobolev et al. (1973) also based their search for chrome-rich garnets on colour using violet and lilac as their criteria. They also noted that chrome-rich, calcium-poor garnets could be distinguished by means of a weak 'alexandrite effect'. The 'alexandrite effect' was a change in colour of the garnet with different illumination (Neuhaus, 1960; N.V. Sobolev, 1971).

Hence particular attention was paid to lilac-coloured garnets and especially those considered to show an 'alexandrite effect'. After the discovery of the green garnets at the Newlands kimberlite pipe, it was noted that a gradation from 'very alexandritic' to 'non-alexandritic' existed and showed that the intense lilac colour could be mis-classified as green depending on the type of lighting used while sorting. The colour basis for garnet sorting was very useful as a first approximation, but, as will be shown, was not a definitive criterion on which to base estimates of chemical composition. Thus, the garnets were divided into colour groupings which must necessarily be arbitrary, due to the nature of the examinations, but which were carried out under the same lighting conditions as far as possible.

Other silicate mineral groups, clinopyroxenes, orthopyroxenes and olivines were sorted mainly on the basis of colour and cleavage. The clinopyroxenes selected for further examination were chrome diopsides showing least alteration and optical clarity. These grains had a range in colour from an 'apple' green to a deep green. It was difficult to separate the clinopyroxenes into groups, but specimens from the complete colour range were selected for analysis. The orthopyroxenes were distinguished from the olivines by their cleavage and generally browner colouring, but in the Kao heavy mineral concentrate the distinction was so slight in some cases that a number of orthopyroxenes were misidentified as olivines. Such orthopyroxenes showed distinct compositional differences to those correctly identified, as discussed later. These two types of orthopyroxene can be divided into enstatites and bronzites (Nixon and Hornung, 1968).

The olivines were separated from some of the clinopyroxenes by their yellow-green colour and apparent lack of crystal form.

(ii) Opaque minerals and other non-silicate minerals

A magnetic separation of the opaque minerals was carried out after the preliminary sorting to separate out magnetite and any other minerals with high magnetic susceptibilities. Such minerals were removed and not used in this study. Chromites and spinels were distinguished from the other opaques by means of crystal habit because one or more well developed octahedral faces was usually present. Rutiles were separated from the remainder of the opaque minerals by their characteristic yellow-brown streak, but ilmenites, which were not usually extracted during the magnetic separation, were not collected as they were not to form a part of the study.

One of the features of the opaque minerals from the Newlands kimberlite was that some of the chromites proved to be magnetic and that four separate groupings were required, these being: euhedral, magnetic and non-magnetic; and anhedral, magnetic and non-magnetic. These divisions were later shown to be slightly misleading as the differences in composition between the groups was not large. A few grains of opaque minerals occasionally remained unidentified and were discarded for analytical purposes.

Minerals such as kyanite and zircon were not analysed in this study, but the presence of the two types of kyanite in the Rietfontein concentrates was confirmed (Gurney et al., 1971). The rare minerals found were not examined in any detail in this study, the major emphasis being placed on the minerals forming the rocks of the peridotitic and pyroxenitic suites.

(c) Specimen Mounting

The mineral grains selected for further examination were mounted on glass slides and made into thin sections. The procedure entailed placing the grains, in some predetermined pattern, in a 'mould' on a 'non-stick' surface and pouring a liquid 'Araldite' epoxy resin over them so that after the resin had set and been cured, the grains were enclosed in an 'Araldite block'. This block was then temporarily mounted with the sample grains uppermost. This face of the araldite was then milled away until all the grains were sufficiently exposed for analysis purposes. (Most grains selected were from the +5 and −5+10 mesh size fraction.) The grains were then polished using successively smaller grades of diamond paste, the sequence being 6μm, 3μm, 1μm, ½μm. The polished face was mounted on a glass slide using a similar epoxy resin. The remainder of the 'Araldite block' was removed by milling and the polishing process repeated. The section was then inspected under the petrographic microscope and the grains checked for optical clarity and any obvious inclusions or exsolution features which would render them unsuitable for electron probe analysis. The thin section was coated with a conducting surface film for analysis because silicate minerals and some of the other minerals do not conduct current and thus cannot maintain the surface of the specimens close to earth potential (Long, 1967). This film is applied by the settling of a layer of carbon on to the specimen by means of a carbon arc in a reduced atmosphere.

III ANALYTICAL PROCEDURES

1. THE ELECTRON MICROPROBE

The principles and theory of electron microprobe analysis, which combined the methods of X-ray spectroscopy and electron optics techniques, have been given by Castaing (1951), Keil (1967), and Long (1967). "The electron probe microanalyser consists of an electron optical system which focuses an electron beam into an area of about 1μm diameter on the surface of the specimen, a stage on which the specimen and standards are mounted, a microscope which allows the area of interest to be selected and positioned in the electron beam and one or more spectrometers which select and measure the intensity of the characteristic radiation of the elements to be determined." (Long, 1967) The characteristic X-ray spectra generated by the electron beam were identical to those produced in fluorescence excitation by X-ray irradiation, but the slowing down of the electrons produced a continuous spectrum which constituted a background upon which the characteristic X-ray lines are superimposed. The basic measurement was a comparison of the net intensity of a particular X-ray line generated in the specimen with that generated in the standard by the same incident current. To a first approximation, the concentrations and characteristic intensities are related by the expression:

$$C_{\text{specimen}} = C_{\text{standard}} \cdot \frac{I_{\text{specimen}}}{I_{\text{standard}}} \qquad \text{(Long, 1967)}$$

A number of correction factors must, however, be calculated to allow for the effects of differences in absorption, secondary fluorescence and atomic number of the specimen.

The analyses in this study were made by means of the Microscan 5, manufactured by Cambridge Scientific Instruments Limited. It is described as having complete electron optics operating up to 50 kV and giving 1000Å resolution; a large area servo-controlled specimen stage with facilities for light optical viewing in both reflection and transmission mode; two servo-controlled, linear, fully-focussing curved crystal spectrometers, with 75° take-off angle, 500 mm Rowland circle and capable of detecting all elements above Be in the periodic table; a double display system with integrated control panel; two nucleonic counting channels and a complete vacuum system. The instrument was semi-automatic and eight command units were used to select Bragg angles which could be pre-set manually. Each command unit had an associated pulse height analyser and an angular offset unit used for the determination of backgrounds. The required command unit was selected by push button to control the spectrometer drive servo-motor.

(a) Instrumental Conditions

The elements determined during this study were Si, Al, Ti, Cr, Fe, Mn, Mg, Ca, Na, and K, but not all these elements were determined in every analysis. Na, K, and often Ca were omitted in analyses of spinels and chromites because experience showed these elements to be below detection. In some of the orthopyroxene analyses K was not determined. Partial analyses for Ca, Mg, Cr, and Si were carried out on some of the garnets from the Koffiefontein, Premier and Sekretariskop kimberlites. Instrumental conditions were the same as used in the determination of all ten major elements.

The following tables give the conditions for a routine 10 element analysis:

TABLE A

EHT	15kV	
Current	1,5 μ amps	
Filament saturation current	±2,5 amps	
	Channel 1	Channel 2
Counter	Flow proportional	Flow proportional
Gas	97,5% Argon+ 2,5% CO_2	97,5% Argon+ 2,5% CO_2
Window	6 μm Mylar	6 μm Mylar
Counter voltage	±940 volts	±1030 volts
Dead time on counter	3,6 μseconds	3,8 μseconds
Crystal	Quartz, 2d = 6,686Å	Rubidium acid phthalate, 2d = 26,122Å
Elements analysed	Fe, Mn, Cr, Ca, Ti, K	Si, Al, Mg, Na

TABLE B

Element	X-ray line	Peak angle ($^\circ 2\theta$)	Background angle ($^\circ 2\theta$)	Pulse height analyser setting (volts)
Si	Kα	$31^\circ 40'$	$33^\circ 05'$	130-430
Ti	Kα	$48^\circ 33'$	$49^\circ 48'$	130-220
Al	Kα	$37^\circ 14'$	$38^\circ 29'$	90-320
Cr	Kα	$40^\circ 03'$	$41^\circ 18'$	90-410
Fe	Kα	$33^\circ 40'$	$34^\circ 55'$	90-410
Mn	Kα	$36^\circ 39'$	$37^\circ 54'$	90-410
Mg	Kα	$44^\circ 30'$	$45^\circ 45'$	50-300
Ca	Kα	$60^\circ 18'$	$61^\circ 31'$	90-200
Na	Kα	$54^\circ 15'$	$55^\circ 45'$	50-330
			$52^\circ 45'$	50-330
K	Kα	$68^\circ 03'$	$69^\circ 48'$	80-200
			$66^\circ 18'$	80-200

2. STANDARDS

In this study five mineral standards and two synthetically prepared standards were used. The mineral standards were Marjalahti Olivine; Kakanui Augite, Hornblende and Pyrope; and 52NL11, a chromite from the Stillwater igneous complex. The synthetic glass standards were a pure diopside prepared by F.R. Boyd at the Geophysical Laboratory of the Carnegie Institution, Washington, and a synthetic rutile. A synthetic glass of pure Cr_2O_3 became available at the end of the work and this was used to determine the correction factor for the line interference on manganese, as described in the section on data presentation. These standards were mounted at the Smithsonian Institution, Washington, for J.J. Gurney. They were selected for kimberlitic mineral analyses because (a) the correction factors for the standards were similar in magnitude to those for kimberlitic minerals, and (b) these standards cover the range of values expected from these minerals.

Different standards were used for determining the same elements in the various mineral groups; for example, when analysing for Si in a garnet, Kakanui Pyrope was used; as the standard in a clinopyroxene, Kakanui Augite was used; in an olivine, Marjalahti Olivine; etc. Combinations of standards were chosen to keep the number of standards used as low as possible, but at the same time maintaining the best instrumental conditions for each element and keeping the correction factors for the sample within the limit of 10 relative %.

The correction factors for all the elements except Cr in the silicate mineral analyses were ±4,5% relative or better. The Cr correction factors were ±10% relative or better for all the elements analysed. Table (C) indicates which standards were used for the individual elements in the different mineral groups and typical values of correction factors.

TABLE C

	Garnet	Clino-pyroxene	Ortho-pyroxene	Olivine	Chromite	Spinel
Si	KP +0,5%	KA −2,7%	KA −2,5%	MO 0,2%	KP 7,8%	KP 8,4%
Ti	KH 0,1%	KH 0,1%	KH n/a	KH n/a	KH 10,2%	KH n/a
Al	KP 0,8%	KA 0,1%	KA 4,4%	KA n/a	CHR 2,8%	CHR 3,5%
Cr	CHR 9,3%	CHR 10,0%	CHR 11,1%	CHR n/a	CHR 0,5%	CHR 3,6%
Fe	KP 0,5%	KA 0,6%	MO 1,0%	MO 0,5%	CHR-0,4%	CHR 4,0%
Mn	KP n/a	KP n/a	KP n/a	KP n/a	KP 6,0%	KP n/a
Mg	KP −1,0%	KA 0,3%	MO 3,4%	MO −2,4%	CHR 9,8%	CHR−4,0%
Ca	Di 0,6%	Di −0,5%	Di 1,0%	Di n/a	n.d.	n.d.
Na	KH n/a	KH −4,3%	KH −4,5%	KH n/a	n.d.	n.d.
K	KH n/a	KH n/a	KH n/a	KH n/a	n.d.	n.d.

where KP is Kakanui Pyrope
KA is Kakanui Augite
KH is Kakanui Hornblende
MO is Marjalahti Olivine
Di is pure Diopside
CHR is 52NL11 - Stillwater Chromite
n/a means no correction factor applied.
n.d. is not determined.

The correction factors shown in this table were calculated from actual analyses chosen at random from each mineral group. For certain elements no correction factors are given, the abbreviation n/a being used. This means that no correction factor was required in the analysis of that particular grain. More often than not the actual amount of element present was less than 0,05%.

The standard values used in this study are given in Table (D) in weight per cent of the element.

TABLE D

	Kakanui Augite	Kakanui Hornblende	Kakanui Pyrope	Marjalahti Olivine	52NL11 Chromite	Pure Diopside	Synthetic Rutile
Si	23,71	18,87	19,38	18,81	n.d.	25,93	
Ti	0,44	2,63	0,28	n.d.	0,28		59,95
Al	4,16	7,89	12,56	n.d.	10,27		
Cr	n.d.	n.d.	n.d.	n.d.	30,45		
Fe	5,26	8,49	8,30	8,70	17,18		
Mn	0,10	0,07	0,22	0,22	0,16		
Mg	10,04	7,72	11,16	29,00	7,42	11,23	
Ca	11,31	7,36	3,69	n.d.	n.d.	18,51	
K	n.d.	1,70	n.d.	n.d.	n.d.		
Na	0,94	1,93	n.d.	n.d.	n.d.		
Original Analyst	JN	JN	EJ	JN		FRB	

JN is J. Nelen, Smithsonian Institution, Washington.

EJ is E. Jarosewich, Smithsonian Institution, Washington.

FRB is F.R. Boyd, Geophysical Laboratory, Carnegie Institution, Washington.

n.d. means standard not used for that element.

3. DATA REDUCTION AND PRESENTATION

(a) Data Reduction

The data from the Microscan 5 was simultaneously printed and punched on to paper tape by an ASR33 teletype with paper tape punch. The data set produced was read into a UNIVAC 1106 computer and converted into machine code and stored by departmental programmes PRTAPE or TAPEREAD. Following the procedure of Boyd, Finger and Chayes (1969), the data reduction was done in two separate steps by two different programmes. The original data set was used to create a further data set which was an initial approximation to the composition of the unknowns based on intensity ratios between unknown and standard. In the second part of the reduction procedure the various matrix correction factors were calculated, applied and the initial composition corrected, if necessary, by iteration.

The first programme, known as PRDAT or DATFAN, took the peak and background counts, averaged them, calculated the average net peak counts and count rates for both the standards and the unknown samples, and calculated conversion factors known as 'confacs' and 'nominal concentrations'. 'Confacs' were direct ratios between net peak count rates and weight per cent standard and the 'nominal concentrations' were the ratios of net peak counts per second per weight per cent standard. The nominal concentrations were first approximations of the compositions of the unknown samples. This programme arranged the results of the above calculations into a data set which was the input for ABFAN (Boyd, Finger and Chayes, 1969). This programme calculated the matrix corrections and final corrected compositions.

ABFAN, as used in this study, was the revised version of the original programme now termed ABFAN2 (Hadidiacos, Finger and Boyd, 1971). The absorption correction of Philibert (1963) with the overvoltage modification of Duncumb and Shields (1963) was used in ABFAN. Constants for the Leonard coefficient have been suggested by Heinrich (personal communication to Geophysical Laboratory) and incorporated in the programme. Reed's (1965) modification of the Castaing equation was used to calculate the fluorescence correction. Atomic number effects were treated by the method of Duncumb and Reed (1968) and the backscatter and stopping power corrections were calculated. Heinrich's (1966) constants for the calculation of mass absorption coefficients were stored in a datablock called ABDAT along with atomic weights of elements, wavelengths of the $K\alpha$ lines and K absorption edges. The correction factors for all the standards used in this study were stored in various computer files which were accessed by PRDAT and ABFAN during the correction procedure. ABFAN may be used to correct $K\alpha$ intensities of the elements from Na to Kr and $L\alpha$ intensitites from Rb to La, i.e. atomic numbers 11 to 57.

The final printout from ABFAN gave the elements in the order in which they were analysed and the EHT in kilovolts used for each element. The absorption corrections, fluorescence corrections, backscatter corrections and stopping power corrections were listed for all the elements analysed. The initial composition before correction, the corrected composition and the composition in weight per cent of the oxide were the final parts of the first section of the table of results. The second section of this listing gave the number of iterations required to produce a composition that differed from the previous cycle by less than 0,1% relative of any of the elements present. Reed's gamma function (Reed, 1965) indicates the presence of any significant fluorescence effects and the atomic proportions of the elements based on the requisite number of oxygens. Pyroxene factors and the Ca/(Ca+Mg) ratio were calculated and listed when the atomic proportion calculation was based on six oxygens.

(b) Data Presentation

Most of the data in Tables 1 - 53 is presented as given by ABFAN, but in certain cases further data reduction was necessary. The chromites and spinels are known to contain significant amounts of Fe in the trivalent state, but the electron microprobe only measures total Fe and ABFAN calculates total Fe as FeO. Thus all the chromite and spinel analyses were recalculated by means of a programme known as FERRIC (Finger, 1972). This programme takes an analysis in weight per cent of the oxides, calculates the atomic proportions and cation proportions, then estimates the Fe^{3+} content, corrects the Fe^{2+} and prints out a recalculated analysis with both Fe_2O_3 and FeO, and various ratios such as Cr/(Cr+Al), $Mg/(Mg+Fe^{2+})$ and $Mg/(Mg+Fe_{total})$. An estimate of the error involved in the Fe^{3+} calculation is given and the Fe^{3+} content is only significant if it is greater than the actual error of the calculation.

In all cases where this programme was used, the footnote "Fe_2O_3 and Fe^{3+} are calculated from total Fe and the structural formula." will be found on the relevant tables. The analyses of the green garnets from the Newlands Kimberlite Pipe (Tables 22, 23 and 30) were also recalculated using FERRIC due to the low totals obtained in most of the analyses when Fe was represented as FeO. The calculated Fe^{3+} contents of these garnets are roughly one half to three quarters of the estimated error; thus the Fe^{3+} content is not really significant. It is, however, reported because, by including it, the balance in the structural formula is considerably better than that achieved using total Fe as Fe^{2+}. The balance is still not correct and the totals in a number of cases are still low, but it is suspected that a significant amount of NiO may be present. This possibility will be dealt with in the section on the Newlands green garnets.

A correction for a chromium interference on manganese was also necessary in a number of analyses. This was due to the $CrK\beta$ peak on the $MnK\alpha$ peak, the angles in 2θ being $36^\circ 20'$ and $36^\circ 39'$ respectively. A pure, synthetic Cr_2O_3 glass was used to calculate the correction factor by the following method. The relative count rates were determined at the CrKα and MnKα peak positions and two background positions on either side of the respective peaks using this glass. Count rates at similar positions were determined for the standard 52NL11 which was used for all Cr analyses. Because the Cr_2O_3 glass contained no Mn, any counts registered at this peak and the backgrounds must be due to the CrKβ peak. The peak counts were deadtime corrected for both the Cr_2O_3 glass and 52NL11 and net count rates determined. The ratio of the counts on the MnKα peak to those on the CrKα peak was calculated for the glass and this factor was used to determine the number of counts on the MnKα peak for 52NL11 which were due to Mn only. Thus a count rate for a known amount of Mn in 52NL11 was calculated. Hence the amount of 'apparent' manganese due to the CrKβ peak could be estimated. The correction factor was such that for 100% Cr_2O_3, 0,9624% MnO would seem to be present. Thus analyses with more than 10% Cr_2O_3 present were corrected by subtracting 0,0096% MnO for each 1% Cr_2O_3.

The data is presented as weight per cent of the oxide as given by ABFAN, except where FERRIC and/or a Cr correction have been applied, with the atomic proportions calculated on the relevant number of oxygens. Except for the clinopyroxenes, the analyses are arranged in decreasing magnitude of the $Mg/(Mg+Fe^{2+})$ ratio. The clinopyroxenes are arranged in descending order of the Ca/(Ca+Mg) ratio. The $Mg/(Mg+Fe_{total})$ ratio is given where applicable, and for the silicate minerals Ca, Mg, Fe proportions are calculated to 100% and presented. For the garnets the Ca, Mg, Cr proportions are also given. The partial analyses for Ca, Mg, Cr and Si of the garnets from Koffiefontein Diamond Mine, Premier Diamond Mine and Sekretariskop Kimberlite Pipe have Ca, Mg, Cr proportions calculated to 100% and are arranged in descending order on the basis of their Mg content.

4. ERRORS AND ACCURACY

(a) Errors

Possible sources of error in the analyses presented could be caused by inaccurate standard values, inappropriate standards, inaccurate standardisation during analysis, long term instrumental drift and/or changes in instrumental parameters during analysis, X-ray spectral line interferences and enhancements, sample effects, and the chemical state of the element sought. The standards used in these determinations have been described in a previous section and only in the case of 52NL11, when used as a standard for Al and Mg, were possible errors introduced. The Al and Mg contents of this standard were not as well known as was the Cr content because 'inter-grain' homogeneity was suspect. This source of error was minimised by using one particular grain of this standard for all analyses involving chromites and spinels. Errors caused by inaccurate standardisation were impossible to correct because the data reduction procedure was carried out after each analytical session had ended. This type of error may be detected by the comparison of the 'confacs' produced during the processing of the data. The 'confacs' from the same standard from different analytical sessions should not differ by more than 5-10 relative %, all other parameters being the same for each analytical session. One method of preventing these errors was to run the standards at the start and end of each session which indicated whether instrumental drift had to be taken into account.

Instrumental drift during an analysis was unlikely because the electron beam current was checked or re-set, if necessary, after each analysis, i.e. approximately every fifteen to thirty minutes. The manufacturer's specifications guarantee stability of all electrical supply units to ±1% over 30 minutes. Thus long term instrumental drift was unlikely to be a major source of error in these analyses.

The spectrometers on the Microscan 5 had a repeatability of 12"2θ for the Bragg angles and spectrometer resolution was better than 15% measured as half width at 60% peak height; thus random errors introduced by spectrometers not returning to the exact Bragg angle can be discounted in nearly all cases. Other changes in instrumental conditions were readily detected by a decrease in count rate during the fixed counting time and such count rates were not used in the calculation of the results. The counting time on each peak was 10 seconds and each background 10 seconds. Each peak position was counted a minimum of four times and each background a minimum of twice.

Errors in the analyses caused by X-ray spectral line interferences were few, the major error being the high MnO values caused by the CrKβ line. The method of dealing with this error at the higher Cr_2O_3 values has been described in the previous section on data reduction and presentation. The Mn content in nearly all the analyses was less than 0,5% MnO and thus Mn could be regarded as a minor or even trace element, but any analyses having less than 10% Cr_2O_3 and calculated by ABFAN will be in error by 0,0096% MnO per 1% Cr_2O_3. Thus an analysis showing 9,6% Cr_2O_3 and 0,5% MnO should actually show 0,41% MnO. The detection limit for manganese was 0,0060% Mn which was equivalent to 0,0083% MnO. Hence the error in the uncorrected MnO values was significant analytically. The conclusions reached in this study were not changed in any way by disregarding these errors. For this reason the apparent MnO values were not corrected in most of the analyses.

There were numerous other X-ray spectral lines which could cause interference errors in the analyses, but the amount of the interfering element was generally suspected to be too low, with respect to the major element, to cause any severe errors. A possible exception to this was a VKβ 1st order line very close to the CrKα, but the amounts of vanadium present in the low-chromium garnets were unlikely to materially alter these values and again not likely to have changed the overall conclusions. Another possible interference was that of BaLα, on TiKα, but because the BaLα line is on the low angle side of TiKα, there would be no interference on the background position which is $1^{o}15'2\theta$ higher than the TiKα peak.

The samples used in this study were mounted as single grains and analysed as double-polished thin sections, except for the spinel-garnet nodule PJL-13, spinel nodule BD1988 and the small Rietfontein nodule, which were analysed as rock sections. Single phase grain mounts were subject to the same possible causes of error as rock sections. These sections contain minerals of differing hardness which will be more or less resistant to the polishing process. Relief effects must be minimised and were most likely to occur at phase boundaries. These effects were possible in grain mounts, but were not as serious as in rock sections. Inadvertent tilting of the section normal to the electron beam and/or uneven cutting and polishing can cause errors, but the high take-off angle reduced these considerably (Long, 1967). 'Edge effects' are caused by the electron beam falling on a surface which is not normal to the electron beam and are prevented by positioning the beam well away from grain boundaries. Uneven or inconsistent carbon coatings of the samples are a possible source of error, but were reduced by coating all the samples on the same instrument using the same instrumental conditions.

The chemical valence states of the elements in the samples analysed cannot be determined by the electron microprobe. The amount of Fe was determined as total Fe and generally reported as FeO, so the cases where significant amounts of Fe^{3+} were present had to be dealt with separately. The apportionment of the total Fe to FeO and Fe_2O_3 must be an approximation and dependent on the accurate determination of the other elements present. The methods used to estimate Fe^{2+} and Fe^{3+} were based on satisfying the relevant structural formulae after calculating cationic proportions; thus errors in analysing other elements present could be compounded in the ferric calculation.

The possibility that Cr was present as Cr^{2+} in Lunar olivines has also been suggested for kimberlitic olivines (Meyer and Boyd, 1972). There has been little work done on the valence states of Cr in kimberlitic minerals, but no significant errors were likely to have been caused by regarding all Cr as Cr^{3+}. If Cr was present as Cr^{2+}, a similar procedure to that used for calculating Fe^{2+} and Fe^{3+} would be necessary, but the errors in the estimation of Cr^{2+} would probably make the result of doubtful value.

(b) Accuracy

Boyd (1968) considered that, at best, electron microprobe analyses had an accuracy of ±1-2% of the amount of the element present. The analyses in this study are considered to have an accuracy of ±2,5% of the amount of the element present, except for the uncorrected manganese values. No estimate of accuracy can be given on these latter values. A garnet from the Roberts Victor Diamond Mine, occasionally used as a standard, has been analysed as an unknown sample in a number of analytical sessions and the results of these analyses show that for the garnets there is a maximum error of 3% relative to the amount of element present at the 95% confidence level.

Similar levels of accuracy were achieved for the analyses of clinopyroxenes, orthopyroxenes and olivines, but the chromite and spinel analyses are considered to be less accurate. Most analyses presented have totals between 99,0% and 101,0%, but others which range from 98,0% to 102,0% are also given. A few analyses, especially of spinels, have totals which fall outside these ranges, but are presented to illustrate relative composition changes; for example, spinel nodule BD1988 seems to have different spinel compositions in different areas of the nodule (Tables 48 and 49).

IV KIMBERLITES AND THE UPPER MANTLE

Kimberlite has been described as "a very rare potassic, ultrabasic, hybrid igneous rock that occurs in small diatremes or in dykes or sills of limited extent. It has an inequigranular texture, the porphyritic aspect being due to megacrysts of olivine, enstatite, chrome diopside, pyrope, picro-ilmenite and phlogopite, set in a finer grained matrix of which serpentine, carbonates, phlogopite, magnetite and perovskite form the major part. Many of the megacrysts are derived from fragmentation of mantle-derived garnet lherzolite (blocks of which are embedded in the kimberlite) and are in various stages of reaction with the kimberlite matrix. The matrix may or may not contain diamond: even in the most diamondiferous kimberlites diamond is a very rare and widely dispersed mineral." (Dawson, 1971, p. 188).

The reasons given by Dawson for studying kimberlite are that: firstly, they are the only primary terrestrial source of diamonds; secondly, it contains xenoliths which have been derived from the upper mantle and it can be demonstrated that kimberlite has sampled the upper mantle more extensively than any other magmatic activity; and thirdly, that it contains a higher concentration of 'incompatible' elements than other ultramafic rocks (Dawson, 1971).

The kimberlite itself is often a breccia near surface, but there is evidence that it is an igneous rock and has been formed by magmatic activity (Dawson and Hawthorne, 1970; 1973). It is certain that the origin of kimberlite must lie in the upper mantle because of the numerous minerals and mineral assemblages consistently found in kimberlite which could only be formed under mantle conditions of temperature and pressure. The upper mantle origin is also indicated by Sr isotope data. Berg and

Allsopp (1972) have indicated that fresh unaltered kimberlite may have an initial Sr^{87}/Sr^{86} ratio of 0,704.

The depth of origin for kimberlite may be estimated from the data for the stability of diamond. Kennedy and Nordlie (1968) have predicted that it will not form at depths less than approximately 160 km, which is equivalent to a pressure of 55 kb. This would indicate a minimum depth of origin for kimberlite. Wyllie (1972) has suggested that a garnet peridotite consisting of garnet, clinopyroxene, orthopyroxene, olivine and traces of minor minerals is representative of the upper mantle beneath the continents.

Three separate hypotheses have been suggested for the origin of kimberlite. These have been termed: 'the residual hypothesis', 'the zone refining hypothesis' and 'the incipient melting hypothesis' (Dawson, 1971). These hypotheses have been summarised by Gurney (1974):

(1) "In a mantle of garnet peridotite with minor phlogopite, ilmenite, apatite and zircon, a partial melting event at depth gives rise to a liquid with the composition of a picritic basalt. Extended fractionation occurs at depth until the small volume of residual fluid left acquires the characteristics of kimberlite. Eclogites are seen as possible high pressure cumulates from the garnet peridotite partial melt (O'Hara and Yoder, 1967)."

(2) "In a mantle of garnet peridotite, a liquid is generated by partial melting at depth of approximately 600 km and this, being dynamically unstable in the earth's gravitational field, moves upward by a process of 'solution stoping' or 'zone refining'. During the upward movement of such a fluid, the major elements remain more or less in equilibrium with the solid phases at all depths. The elements unable to substitute readily in the minerals of ultrabasic rocks become

progressively enriched. The volatile content increases continuously and this leads to an ultimate explosive emplacement (Harris and Middlemost, 1970)."

(3) "The mantle is garnet peridotite which contains minor amounts of a phlogopite, rich in potassium and titanium. (Such mica has been found and described at Lashaine, N. Tanzania (Dawson, Powell and Reid, 1970).) In contrast to Hypothesis (1) (relatively large degree of melting plus prolonged fractionation), Hypothesis (3) suggests a small degree of melting predominantly involving the mica and the clinopyroxene and creating a fluid rich in K_2O, Na_2O, TiO_2, Al_2O_3, CaO, FeO and Cr_2O_3, but also containing considerable MgO and SiO_2. This fluid, modified by precipitation of chromite, magnesium ilmenite, knorringite garnet and calcium-poor garnet, is kimberlite (Dawson, 1972)."

None of these three hypotheses explains satisfactorily all the observed chemical mineralogical and petrological features of kimberlite (Gurney, 1974). The study of the ultramafic xenoliths found in kimberlite can help to obtain information on upper mantle compositions and processes which could give rise to the formation of kimberlite.

Garnet lherzolite has been used extensively in the study of the mantle-derived xenoliths because it is relatively common and has been found as 'granular nodules' or 'sheared nodules' (Boyd and Nixon, 1972). This rock is made up of the minerals garnet, olivine, orthopyroxene and clinopyroxene. Phase equilibrium studies on simple systems such as $MgSiO_3$-$CaMgSi_2O_6$ at 1 atm (Boyd and Schairer, 1964) and at 30 kb (Davis and Boyd, 1966) have shown that the solid solution of a clinopyroxene towards enstatite is sensitive to temperature in the range 900-1500°C and insensitive to pressure up to 30 kb. A temperature of equilibration for the assemblage diopside-enstatite may be estimated from this data using the Ca/(Ca+Mg) ratio.

The solid solution of garnet in orthopyroxene has been shown by Boyd and England (1964) and MacGregor (1974) to be sensitive to pressure in the system $MgO-Al_2O_3-SiO_2$. MacGregor has determined the alumina contents of enstatites in equilibrium with pyrope and with spinel. This data has been used to estimate pressures of equilibration of the assemblage garnet or spinel, clinopyroxene, orthopyroxene and olivine when the temperatures of equilibration have been estimated by means of the Di(en) solvus of Davis and Boyd (1966). Thus the temperature and pressure of equilibration of a garnet lherzolite can be estimated. It must be noted, however, that these temperatures and pressures are based on data for ideal compositions in simple systems. Wood and Banno (1974) have shown that corrections to both temperature and pressure estimates can be made so that these estimates are valid for natural rock systems also.

Garnet lherzolites have been found at Thaba Putsoa, Lesotho, which have been intensely sheared and Boyd (1973a) has described 'a pyroxene geotherm' which is 'perturbed' from the Clark and Ringwood (1964) 'shield geotherm'. This geothermal gradient is reconstructed using the temperatures and pressures of equilibration of the sheared lherzolites and the granular or non-sheared lherzolites. The 'geotherm' has been used to suggest that the shearing in the mantle was caused by the break-up of Gondwanaland. The 'geotherm' is, in fact, a fossil geothermal gradient which existed in Cretaceous time and has been used to indicate the depth of the low velocity zone.

Thus the upper mantle-derived rocks and minerals found in kimberlite are important in studies of kimberlite and its genesis. Lherzolite and other peridotitic nodules, however, are only part of the ultramafic nodule suite in most kimberlites; eclogites are also present as xenoliths. Eclogites are known to be a primary source of diamonds in kimberlites and a diamond found in an eclogite contained mineral inclusions similar to those making up the eclogite (V.S. Sobolev et al., 1972). Thus knowledge of the actual xenoliths, their constituent minerals, the diamond and its inclusions are all necessary to explain the genesis of kimberlite.

V INCLUSIONS IN DIAMONDS

Natural diamonds from West and South Africa, Brazil, Venezuela, Thailand and the U.S.S.R. have been shown to contain individual mineral inclusions of various compositions and certain combinations of these minerals (Sharp, 1966; Harris, 1968; Meyer, 1968; Gurney et al., 1969; Meyer and Boyd, 1969, 1970, 1972; Meyer and Svizero, 1974; Prinz et al., 1974; V.S. Sobolev et al., 1969, 1972; and N.V. Sobolev et al., 1969, 1970, 1971a, 1971b, 1972). Some of the minerals found as inclusions were garnet, olivine, orthopyroxene, clinopyroxene, chromite, kyanite, rutile, zircon, phlogopite, magnetite and pyrrohotite. These species have been regarded as crystallizing in equilibrium with the diamond (Meyer and Boyd, 1972; N.V. Sobolev et al., 1969). Some of the mineral inclusions exhibit the crystal form and habit of the diamond, which has been imposed on them (N.V. Sobolev et al., 1972).

The ultramafic xenolith suite in most kimberlites contains various eclogitic and peridotitic assemblages, but in varying proportions at the different occurrences. The phases making up the eclogites were garnet and clinopyroxene, as major components with or without kyanite, corundum, orthopyroxene, olivine, graphite, rutile and diamond as minor to very minor constituents. The peridotite rocks commonly contained olivine, orthopyroxene, clinopyroxene and garnet and occasionally accessory amounts of chromite, ilmenite, phlogopite or graphite. Thus the minerals common in the ultramafic xenoliths have been found as individual inclusions in diamond.

The following minerals, which are constituents of the peridotite rock suite, have been found co-existing as inclusions in diamond: olivine-enstatite, olivine-garnet, olivine-chromite, chromite-garnet, diopside-garnet, enstatite-garnet, olivine-garnet-clinopyroxene, garnet-enstatite-olivine, garnet-olivine,muscovite-chromite (Meyer and Boyd, 1972; Meyer and Svizero, 1974; N.V. Sobolev et al., 1970; Prinz et al., 1974). The phases which have been found in eclogitic assemblages and co-existing as inclusions in diamonds were: omphacite-garnet, diopside-garnet, pentlandite-chalcopyrite, omphacite-phlogopite-rutile, garnet-silica, garnet-silica-and an unknown phase, garnet-actinolite-altered kyanite, omphacite-and an unknown phase, garnet-magnetite, garnet-omphacite-magnetite-hornblende-silica, garnet-omphacite-muscovite, garnet-magnetite-silica, garnet-omphacite-silica, and garnet-sanidine-magnetite (Meyer and Boyd, 1972; Prinz et al., 1974; V.S. Sobolev et al., 1972; N.V. Sobolev et al., 1971a).

Thus monomineralic and polymineralic inclusions in diamond represent two distinct rock type assemblages, but there has been no proven case of a single diamond containing inclusions from both types, although Prinz et al. (1974) found one diamond (No. 30) to contain olivine, rutile, silica and what they considered to be omphacite, but was too small for quantitative analysis. The olivine was similar to those found in the garnet peridotite suite ($Fo_{92,6}$ with 0,11% Cr_2O_3) and because the rutile and omphacite suggest an eclogitic assemblage, Prinz and his co-workers suggested that it might be an olivine eclogite with possibly epigenetic silica or a mixture of portions of the two suites. This assemblage of minerals illustrated the diffculties of deciding which inclusions were syngenetic with the diamond and which were epigenetic. Harris (1968) stated that quartz is an inclusion in diamond and despite the fact that "no obvious fractures emanate from the specimen to the diamond surface", he considered the inclusion to be epigenetic; the basis of his criteria being that many of the minerals found as inclusions in diamond do not have stability fields at the conditions envisaged for diamond synthesis (Meyer and Svizero, 1974). Some minerals found as inclusions in diamonds and regarded as syngenetic appeared to have some crystals with xenohedral morphology imposed upon them by the host diamond (N.V. Sobolev et al., 1970, 1972; Prinz et al., 1974).

The criteria for deciding what were syngenetic and epigenetic or primary and secondary inclusions in diamond have not been defined and the classification of a mineral inclusion as syngenetic or epigenetic has been the personal decision of the investigator concerned. Thus considerable differences in criteria might exist and inclusion regarded as primary by one investigator might be secondary to another.

The true relative abundance of minerals occurring as primary inclusions in diamond is impossible to estimate at present. The diamonds are sorted and roughly classified at small mines and then made into 'parcels' which are sold to buyers who further sort and grade them. The diamonds recovered from all the mines of the De Beers group are sent to the Central Sorting Office in Kimberley where they are sorted and graded. The diamonds are sold to jewellers or dealers by the buyers or the main selling organisation of De Beers Consolidated Mines Limited. The diamonds containing inclusions are usually purchased from jewellers or industrial dealers by the workers concerned (Prinz et al, 1974; Meyer and Boyd, 1972). The persons interested in the inclusions usually select specific diamonds for investigation. Thus many diamonds containing inclusions may never be examined and the inclusions never identified. The true relative abundance of minerals occurring as primary inclusions in diamond is never likely to be known for all the diamondiferous kimberlites, but it may be possible to determine the relative mineral abundances for a single pipe or dyke if all the diamonds having inclusions can be examined.

Meyer and Boyd (1972) estimated the relative abundances in decreasing order to be: olivine, garnet, chromite, enstatite and diopside. Meyer and Svizero (1974) concurred with this finding for Brazilian diamonds. However, from the numerous papers of the two Sobolevs and their colleagues, it seems that garnet is the most abundant inclusion in Russian diamonds, followed by chromite and clinopyroxene (V.S. Sobolev et al., 1969, 1972; N.V. Sobolev et al., 1969, 1970, 1971a, 1971b, 1972). They have reported very few analyses of olivines and occasional ilmenites and rutiles. Prinz et al. (1974) had garnet as their most abundant inclusion, with clinopyroxene and olivine second and third respectively. These authors also reported magnetite and silica as fairly common inclusions. As far as is known, no detailed study of all the inclusions in diamonds from a specific kimberlite has been reported, thus making the true relative abundance of mineral inclusions impossible to establish.

1. GARNET

The two different types of garnet found as inclusions in diamond can be related to garnets from the peridotite or eclogite rock suites. One type which was generally orange or orange-yellow in colour was closely related to eclogite garnets. There are, however, very few recorded cases of inclusions in diamond from diamondiferous eclogites. V.S. Sobolev et al. (1972) reported a diamond, containing clinopyroxene, two rutiles and an intergrowth of garnet with clinopyroxene, in an eclogite from the Mir kimberlite pipe, Yakutia. The significance of this find was that the minerals of the eclogite and the inclusions were analysed showing that the diamond and the eclogite were undoubtedly syngenetic.

The second type of garnet found in diamonds was similar to the common xenocrysts of the Kimberley mines (Reid and Hanor, 1970) and to the garnets found in peridotitic xenoliths. There were, however, distinct compositional differences between the xenolith garnets and those found as inclusions. These garnets have more Mg and less Ca compared with the xenocrysts and the garnets from the xenoliths. The amount of Fe present is low and seemed almost entirely to be in the ferrous oxidation state (Gurney and Switzer, 1973). The Cr content was high but within the range found in knorringite garnets from kimberlite (Nixon and Hornung, 1968). Knorringite garnets, some having higher Cr contents than the diamond inclusion garnets, have been found in the U.S.S.R. (N.V. Sobolev et al., 1973), at Kao (Nixon and Hornung, 1968; Hornung and Nixon, 1973), at the Newlands pipes (this study), and at Finsch (Gurney and Switzer, 1973), but the amount of Ca present is higher than in the diamond inclusion type. Low-calcium garnets from peridotite xenoliths are very rare indeed; only two occurrences have been reported (V.S. Sobolev et al., 1969; Boyd and Dawson, 1972) and in both cases the garnets are in serpentinised ultramafic nodules. Gurney (personal communication) recently found a nodule from the Kimberley area of South Africa which contained such garnets and is relatively unserpentinised. This particular xenolith is a sheared garnet harzburgite.

Except for the "completely serpentinised diamond-bearing garnet peridotite" from the Aykhal Pipe, U.S.S.R. (V.S. Sobolev et al., 1969), there are no substantiated cases of diamonds being found in peridotite xenoliths or minerals of peridotitic origin, although many of the minerals included in diamonds are peridotitic.

For the purposes of this study, a basis for comparison between the garnets analysed and the diamond inclusions had to be constructed. All the known garnet, diamond inclusion data were plotted on two ternary diagrams; these being Ca-Mg-Cr and Ca-Mg-Fe (Figures 4 and 5 respectively). The eclogitic garnets plot close to the Ca-Mg axis on the Ca-Mg-Cr ternary because of their very low chromium content. The remaining 'diamond inclusion garnets', except for the two high-calcium, high-chromium garnets of N.V. Sobolev et al. (1970), show restricted compositions in terms of their Ca, Mg and Cr contents. The points indicating extreme compositions were used to delineate a 'field' embracing all the diamond inclusion garnets. Since Gurney and Switzer (1973) completed their study of the Finsch garnets, a number of new analyses of diamond inclusion garnets have been carried out. Some of these are outside the former compositional range and greatly increase the size of this field compared to what it was when their results were reported. This "new" 'field' showed that the garnets found in diamonds had a considerably larger range in composition than shown previously, with the major difference being that the highest Ca content was almost double the former values. Also included in Figures 4 and 5 were the data for the mineral concretions on polycrystal aggregates of diamond (N.V. Sobolev et al., 1971a) which show that these garnets were very similar to those found as diamond inclusions. However, they were more restricted in composition in that most were more magnesium-rich and poorer in Cr, while the Fe content is not markedly different. It must be noted that the garnets delineating the 'garnet diamond inclusion field' on the basis of a Ca-Mg-Cr ternary plot were not necessarily the same ones as on the Ca-Mg-Fe plot. The compositions of all these garnets are given in Table 54.

2. OLIVINE

According to Meyer and Boyd (1972), Harris (1968), and Meyer and Svizero (1974), olivines were the most common of all silicate inclusions in diamond. Their most remarkable feature was the small range in composition although they have been found in diamonds from such widely separated localities as South West Africa, Ghana, Sierra Leone, Thailand, Venezuela, Brazil and Yakutia. The olivines had a composition between 91,5 and 95,0 mole per cent forsterite and contained minor amounts of Ni, Mn, Ca, Cr, and Al, while Ti is below detection (Meyer and Boyd, 1972; Meyer and Svizero, 1974; Prinz et al., 1974). These olivines were similar to those found as xenocrysts in kimberlite and in the ultramafic xenoliths (Nixon et al., 1963; O'Hara and Mercy, 1963) with respect to their Mg/(Mg+Fe) ratios and concentrations of Mn, Ni, Ca, and Al, but the olivine inclusions in diamond contained far more Cr. The Cr_2O_3 content in the inclusions ranged from 0,02% to 0,15% and by analogy with lunar olivines which can contain up to 0,4% Cr_2O_3 (Haggerty et al., 1970), the chromium in the olivine inclusions might be present as Cr^{2+} (Meyer and Boyd, 1972).

3. ENSTATITE

This mineral was relatively uncommon as an inclusion in diamond, but a little more plentiful than diopside. There was little difference in composition between all the published analyses of enstatite inclusions, except for the analysis of the exsolved enstatites from diamonds No's. 1 and 3 of Prinz et al. (1974). The enstatite in diamond No. 1 had much more Ti, Fe and Al and less Mg, while No. 3 had extremely low Al_2O_3 (0,09%). This particular orthopyroxene was found in a polymineralic assemblage in which the garnet was of the eclogite type. An analysis of a clinopyroxene was also reported which was similar to some of the diopsides reported by N.V. Sobolev et al. (1970, 1971a, b). Prinz and his colleagues claimed that the enstatite and diopside were exsolved from a clinopyroxene which had a calculated composition similar to the 'subcalcic diopsides' of Nixon and Boyd (1973b). This particular diamond also contained a suspected omphacite and must be considered anomalous.

The enstatites found in ultramafic xenoliths have similar compositions to those found as inclusions in diamond (Meyer and Boyd, 1972). The enstatite inclusions have similar Mg/(Mg+Fe) ratios and show very little solid solution toward garnet and diopside. The Al_2O_3 and Cr_2O_3 contents were low in these inclusions, which was consistent with the high pressure of formation of diamond because, within the stability field of garnet, high pressure greatly reduces the solution of Al_2O_3 and Cr_2O_3 in enstatite (Boyd and England, 1964; Green and Ringwood, 1970). The range of Al_2O_3 values in these enstatites was not similar to those found in peridotitic xenoliths. The Al_2O_3 content of the enstatite diamond inclusions varied from 0,09% to 1,32%, diamonds No's. 1 and 3 showing these extreme values (Prinz et al., 1974). Most of the inclusions, however, have between 0,44 and 0,97% Al_2O_3 (Meyer and Boyd, 1972; Meyer and Svizero, 1974), although Prinz and his colleagues (1974) report 0,30% Al_2O_3 for an enstatite in their diamond No. 24. The range of Al_2O_3 in orthopyroxenes from peridotitic xenoliths was higher than the levels in the diamond inclusions. Enstatites from ultramafic nodules containing less than 0,7% Al_2O_3 were very rare (Cox et al., 1973; Nixon and Boyd, 1973a, 1973b).

4. CLINOPYROXENE

Two types of clinopyroxene have been found as inclusions in diamond and as crystalline aggregates with diamond (Williams, 1932; Meyer and Boyd, 1972; Meyer and Svizero, 1974; Boyd and Nixon, 1970; V.S. Sobolev et al., 1969, 1972; N.V. Sobolev et al., 1969, 1971a, 1971b; Harris, 1968; Prinz et al., 1974), but they were rare and the least common inclusion of the mineral forming the peridotite-type rocks. The separation of these clinopyroxene inclusions into the two groups, eclogitic and peridotitic, was made on the basis of the composition of the diopside and its co-existing phases. The two types of inclusion have been plotted in part of the pyroxene quadrilateral (Figure 6). The most marked difference in composition between the groups was that the Fe content of the eclogitic clinopyroxenes was considerably higher than that of the peridotitic diopsides. The eclogitic-type clinopyroxenes were more numerous than the peridotitic and this seemed to be the case for the Russian and non-Russian data. All the diopsides show a reduced solid solution towards $MgSiO_3$. The two inclusions found by Meyer and Boyd (1972) were regarded as differing from the common chrome diopsides of garnet lherzolites and from the omphacites characteristic of eclogite xenoliths. Prinz et al. (1974) reported two inclusions which they termed 'subcalcic diopside' which exsolved into diopside and enstatite in proportions of 80:20 in one case and 70:30 in the other. The enstatite and diopside analyses were used to calculate the composition of the 'homogeneous subcalcic pyroxene' before exsolution. They also reported omphacitic or near-omphacitic pyroxene inclusions from six diamonds, four of which contained co-existing garnet. Their diamond No. 33 had nine monomineralic omphacitic inclusions of the same composition, but one bimineralic omphacite and garnet inclusion. This omphacite had a composition which differed from the other nine in Mg and Fe content. It was not clear whether the garnet had exsolved from the clinopyroxene or not. The K_2O contents of three omphacite inclusions from diamonds No's. 18, 33 and 42 ranged from 0,62 to 0,87% which were considerably higher than the range of K_2O in omphacites from eclogites given by Erlank and Kushiro (1969).

Monomineralic inclusions of clinopyroxenes having high Ca/(Ca+Mg) ratios do not necessarily imply low equilibration temperatures because they may not have formed in equilibrium with primary enstatite and the estimated temperatures given by the Di(en) solvus of Davis and Boyd (1966) should not be used.

5. CHROMITE

Chromites found as inclusions in diamond or co-existing with diamond have an almost unique range of compositions for terrestrial occurrences (N.V. Sobolev et al., 1971a; Meyer and Boyd, 1972; Prinz et al., 1974; Smith and Dawson, 1974) (Table 55). They were particularly high in chromium content and two of them had exceptionally high Fe^{2+} components and significant amounts of ZnO and MnO (Meyer and Boyd, 1972). The chromite analysed by Prinz et al. (1974) was unique in that there was no Fe^{3+} component at all and no zinc, but the Fe^{2+} component was much lower than in the Sierra Leone inclusions (Table 55). The only other terrestrial examples of chromites with both high Cr and Fe^{2+} contents were from a chromite dyke cutting a diopside skarn in the Outokumpu Mine, Finland, which contained 5,4% ZnO (Thayer et al., 1964), and two chromites from podiform deposits in the Coolac District, Australia (Golding and Johnson, 1971). Chromites from meteorites, however, had similar compositions to the Sierra Leone inclusions, as do some of the silicate inclusions in iron meteorites (Bunch et al., 1970; Smith and Dawson, 1974). An interesting point made by Meyer and Boyd (1972) was that a polymineralic assemblage of chromite and either Mg or Ca pyroxene had never been found as an inclusion in diamond, although both chromite plus garnet and chromite plus olivine assemblages have been found. The chromite-olivine geothermometer of Irvine (1965, 1967) and Jackson (1969) unfortunately was not applicable because Meyer and Boyd (1972) obtained temperatures of over 4000°C for the formation of an olivine-chromite inclusion, when a pressure correction on the partition co-efficient was made. They considered these figures grossly in error because the temperatures were about 1000°C above the solidus for peridotite in the pressure range up to 100 kbar (Ito and Kennedy, 1967; Kushiro et al., 1968). Smith and Dawson (1974), using this geothermometer to estimate the temperatures of a number of spinel lherzolites, garnet-spinel lherzolites, spinel harzburgites and a spinel-amphibole harzburgite, found that the temperatures varied over a very wide range. The mean value and individual values were all so much higher than that obtained by means of the 'diopside thermometer' that no reliance could be placed on them. The thermochemical data for the Mg-Fe partitioning in chromite and olivine, on which this geothermometer was based, were probably inadequate for the Mg-rich compositional range (Boyd, 1971).

VI RESULTS

1. GARNET

The garnets were selected for chemical analysis on the basis of colour. The range of colours in a particular heavy mineral concentrate varied considerably and specimens were chosen mainly from the lilac-mauve colour range which may have shown an 'alexandrite effect'. The 'alexandrite effect' as used in this study is not quite the same as used by N.V. Sobolev et al. (1973). In this study, all sorting was done in direct sunlight and the 'alexandrite effect' here means that a slight red-green colour change was seen when the grain was removed from the direct sunlight. The edges of some grains showed this slight colour change when the orientation of the grain was changed, even in direct sunlight. The lilac-mauve and alexandritic garnets formed the bulk of the analyses, but the compositions of a number of other garnets from the various concentrates were also determined. For instance, Koffiefontein red and orange-yellow garnets were analysed so that most of the colour range was represented and, hopefully, the full range of chemical composition. Garnets of colours other than lilac or mauve from the Bobbejaan, Newlands, Kao, Roberts Victor and Sekretariskop heavy mineral concentrates were analysed to determine this range. Certain garnets from the Koffiefontein, Premier and Sekretariskop concentrates were analysed only for Ca, Mg, Cr and Si, and were plotted on Ca-Mg-Cr ternary diagrams to determine whether any of the garnets had similar Ca, Mg and Cr contents to the garnets found as inclusions in diamond. The garnets delineating the 'diamond inclusion field' were plotted on these diagrams to make this determination. The Premier garnets plotting in or close to this field were later analysed for all 10 major elements and replotted.

All the xenocryst garnet analyses have been plotted on Ca-Mg-Cr ternary diagrams, and all, except the partially analysed garnets, on Ca-Mg-Fe ternary diagrams. The 'diamond inclusion field' was shown on all these diagrams by plotting those diamond inclusion garnets which had extreme compositions.

The analyses represented in Figures 2 and 3 were those of Gurney and Switzer (1973, and unpublished data) and were plotted so that comparisons with the data of this study could be made. This data showed that there were two distinct 'trends' for the garnet analyses from kimberlite, when plotted on a Ca-Mg-Cr ternary diagram. On the Ca-Mg-Fe ternary diagram the peridotite-pyroxenite trend extends away from the Mg apex and towards the Fe apex parallel to the Mg-Fe axis. The eclogite trend extends directly away from the top of the diamond inclusion field in a direction almost parallel to the Mg-Ca axis (Gurney, 1974).

Since Gurney and Switzer (1973) completed their study of the Finsch garnets, new analyses of garnet inclusions in diamond have been reported (Meyer and Svizero, 1974; Prinz et al., 1974). Some of these new analyses have considerably enlarged the size of the diamond inclusion field from what it was when the work on the Finsch garnets was completed. More of the Finsch garnets now plot inside the 'new' diamond inclusion field, but some do not contain sufficient Cr to do so. These garnets, however, are more magnesium-rich than those plotting inside this field.

(a) Bobbejaan Diamond Mine

Purple and red garnets were analysed from the heavy mineral concentrates and the results of these analyses are presented in Tables 1 and 2 respectively.

One of the six purple garnets plots on the high-magnesium side of the diamond inclusion field because it does not contain sufficient chromium, although low in calcium content (Figure 7). The other five purple garnets have similar compositions and plot above the diamond inclusion field, although very close to it. On the Ca-Mg-Fe ternary diagram all six garnets plot inside the diamond inclusion field (Figure 8).

One of the twelve red garnets is compositionally different to the rest. It plots on the peridotite-pyroxenite trend rather than the eclogite trend which is well defined in Figure 7. These garnets show a restricted range of Ca component (Figure 8), but do not plot on the peridotite-pyroxenite trend on this diagram because they have been shown to be eclogite-type garnets as far as Ca-Mg-Cr is concerned. One, however, is very eclogitic with a high calcium component.

These two colours were chosen because no lilac garnets were found in the heavy mineral concentrate from this mine. A few alexandritic garnets have been found at this mine, but occur as discrete nodules with inclusions of bright green clinopyroxene.

(b) Kao Kimberlite Pipe

Lilac garnets showing a slight alexandrite effect, some which did not, and orange-yellow garnets were analysed from this pipe. The results of these analyses are presented in Tables 10, 11 and 12 respectively.

One of the ten slightly alexandritic garnets plotted in the diamond inclusion field on both the Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams (Figures 9 and 10). The rest of these garnets plotted above this field on Figure 9, but were almost indistinguishable from the other garnets on the Ca-Mg-Fe ternary diagram. These garnets illustrate part of the peridotite-pyroxenite trend.

One of the lilac, non-alexandritic garnets plots inside the diamond inclusion field on a Ca-Mg-Cr basis (Figure 9) and another does not have sufficient chromium. The other nine all plot on the peridotite-pyroxenite trend. On a Ca-Mg-Fe basis (Figure 10), these garnets are clearly separated from the cluster. As before, one plots in the diamond inclusion field; the other does not.

Some of the twelve orange-yellow garnets show the start of the eclogite trend and the others the peridotite-pyroxenite trend. One of these garnets is very calcium-rich relative to the others. The Ca-Mg-Fe ternary diagram (Figure 10) indicates how little variation there is between some of the garnets on this basis.

(c) Koffiefontein Diamond Mine

Mauve-lilac garnets which showed a slight alexandrite effect, some which did not, red garnets and orange garnets have been analysed from this mine. These analyses may be found in Tables 15, 16, 17 and 18 respectively. Table 16 shows partial analyses only.

Two slightly alexandritic garnets out of thirty-four plotted inside the diamond inclusion field and another two near to it, but were too low in chromium content (Figure 13). Figure 14 shows that these garnets and one other plot well inside the diamond inclusion field, although most of the others plot close to it at the calcium-rich end of the field. One of these garnets has an exceptionally low calcium content, plotting below the diamond inclusion field in both ternary diagrams. The mauve garnets from this heavy mineral concentrate are very variable in composition, one of them being the most iron-rich and another the most chromium-rich of all the Koffiefontein garnets analysed.

The mauve garnets are included with the slightly alexandritic ones in the Ca-Mg-Cr ternary diagram, but are left out of the Ca-Mg-Fe one because their iron content was not determined. None of these garnets plot inside the diamond inclusion field.

The red garnets follow the eclogite trend, with one garnet having a high calcium component. The remainder plot at the low-chromium end of the peridotite-pyroxenite trend.

The orange garnets also follow the peridotite-pyroxenite trend, but show more variation in composition. They plot in similar positions on the Ca-Mg-Fe ternary diagram to the Kimberley garnets analysed by Reid and Hanor (1970).

The colour of the garnets, to a certain extent, reflected the compositions of the garnets: the red ones were all low-chromium bearing, compared to the slightly alexandritic garnets; the orange garnets were more iron-rich than the slightly alexandritic ones. Thus colour, in the Koffiefontein garnets, seems to be a fair guide to chemical composition.

(d) Newlands Kimberlite Pipes

Mauve or lilac garnets showing a slight alexandrite effect, two mauve-green garnets which were very alexandritic, and bright green garnets were analysed from this pipe(s). No red or orange garnets were analysed from the Newlands pipe. The analyses of the mauve, slightly alexandritic garnets and the very alexandritic garnets are presented in Tables 20 and 21. The green garnet analyses are given in Table 22 for the garnets found as xenocrysts, in situ, in kimberlite; Table 23 for the xenocrysts from the concentrate; and Table 30 for the green garnets co-existing with chromites. The garnets which do not have specific sample numbers are arranged in decreasing order on the basis of the magnitude of the $Mg/(Mg+Fe^{2+})$ ratio.

The mauve garnets show a large range of compositions on the Ca-Mg-Cr ternary diagram (Figure 15), most of which follow the peridotite-pyroxenite trend. One garnet (No. 14, Table 20) in this group has an unusual composition and will be dealt with separately. Two of these garnets plot inside the diamond inclusion field on both Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams (Figures 15 and 16). There is a remarkably restricted range of composition on a Ca-Mg-Fe basis because there is very little variation of the iron component. These garnets follow neither the peridotite-pyroxenite trend nor the eclogite trend.

Mauve garnet No. 14 (Table 20) has more calcium and less chromium and magnesium than any other garnet in this group and plots well away from the others on both ternary diagrams. This garnet is considered to have been derived from a disaggregated grospydite xenolith.

One of the mauve-green garnets which was very alexandritic was not very different in composition from the slightly alexandritic garnets, but the other was the most chromium-rich in this group of garnets and almost the most calcium-rich.

The green garnets found at this mine are unique for Southern African kimberlites. The only other kimberlitic garnets with similar compositions have been found in the heavy mineral concentrates of the Mir, Udachnaya and Dalnaya kimberlite pipes in Yakutia, U.S.S.R. (N.V. Sobolev et al., 1973). The only xenoliths known to contain these green garnets were found in the Dalnaya and Sytikauskaya kimberlite pipes (ibid.). One of these nodules was composed of green garnet, olivine containing clinopyroxene and chrome-spinel grains as inclusions, chrome diopside and chromite. The other contained completely serpentinised olivine, green garnet and chromite (N.V. Sobolev et al., 1973).

The least altered Newlands green garnets were selected for analysis, but PJL-11 (Table 21) shows severe chemical alteration has taken place. The altered sections have been represented on Figures 15 and 16 by symbols differing from the one used for the unaltered green garnets. The green garnets vary considerably in composition with PJL-9 and PJL-11 (unaltered section) being extreme cases with respect to the calcium component. PJL-7 has the highest chromium component and one of the garnets co-existing with a chromite has the lowest chromium component (Figure 15). On the Ca-Mg-Fe ternary diagram (Figure 16), the remarkably restricted range of iron component, seen for the alexandritic garnets, is continued by the green garnets up to 70% calcium component, which on this 'trend' is PJL-11. This garnet also has the lowest iron component of all the Newlands garnets. PJL-11 is a garnet which must be looked at carefully because of the alteration which has taken place in certain sections of the garnet. The major portion of the garnet is homogeneous in composition, but it shows signs of severe alteration with the formation of what appeared to be secondary orthopyroxene and mica. The kelyphite rim which surrounded this garnet was not left intact after the mounting process, so it was impossible to decide exactly what happened to this grain after its formation and emplacement. A few of these green garnets had euhedral, opaque inclusions which are suspected to be chromites, but could not be analysed successfully due to polishing effects.

One of the major problems concerning the green garnets was that the totals for the analyses were generally low. These ranged from 98,06% (PJL-11c, Table 23) to 101,05% (PJL-5, Table 23) which is an extreme case, but most were well below 99%, only five out of nineteen analyses totalling more than 99%. These analyses have all been presented with the calculated FeO and Fe_2O_3 contents from FERRIC (Finger, 1972), but the ternary diagrams have been plotted with the

Fe component being total Fe as calculated by ABFAN (Boyd et al., 1969). The MnO results have been corrected for the chromium interference. There is, however, a possibility that NiO may be present in the garnet. A scan with the electron microprobe from $30^{\circ}2\theta$ to $90^{\circ}2\theta$ with a LiF(200) crystal indicated that nickel was present in grain No. 1 (Table 30) (R.S. Rickard, personal communication, 1974). It is not known exactly how much Ni there is in this garnet or if there is nickel in any of the others. An estimate of 0,5% NiO has been made for this grain (Rickard, personal communication). The structural formula balance is heavy for the trivalent atoms in these analyses and low for the divalent atoms, thus indicating that nickel could be missing from the analyses at present. The inclusion of nickel would alter the FeO, Fe_2O_3 contents as calculated by FERRIC (Finger, 1972) and improve the balance of the structural formula.

The Newlands green garnets are remarkably similar to those found in some Yakutian heavy mineral concentrates and peridotite nodules (N.V. Sobolev et al., 1973). These garnets have been plotted on Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams (Figures 17 and 18) to compare them with the Newlands data. The major difference between the Newlands data and the Russian data is the larger range of iron component from the Russian data for what are termed the "chrome pyropes with moderate and high Ca content (16-43% Ca component)" (ibid., p. 42, 1973). Newlands garnets are not as well represented in this range as the Russian ones, but the alexandritic garnets are equivalent to the lower levels of this range of composition.

It is probable that these green garnets are phases from disaggregated peridotite rocks as yet unknown from Southern African kimberlites. It is unlikely that the analyses of the green garnets presented in this study are representative of the whole range of composition of these garnets.

(e) Premier Diamond Mine

Mauve garnets, some of which show a very slight alexandrite effect, were first analysed only for Ca, Mg, Cr and Si. These results were plotted on a Ca-Mg-Cr ternary diagram and the garnets which fell inside the diamond inclusion field were analysed for the ten major elements. The full analyses are given in Table 34 and the partial analyses in Table 35.

These garnets, when plotted on a Ca-Mg-Cr ternary diagram (Figure 19), show that two of the eight garnets plotting inside the diamond inclusion field are likely to have been separate fragments of the same garnet because of their remarkably similar compositions (Table 34, No's. 3 and 4). All eight of these garnets plot inside the diamond inclusion field on the Ca-Mg-Fe ternary diagram (Figure 20). The remaining thirty-three mauve garnets follow the peridotite-pyroxenite trend and also show that high-calcium, moderately high-chromium garnets also exist at this mine. These garnets could be compared with the Russian garnets (N.V. Sobolev et al., 1973) of 'moderate to high Ca content' and to some of the Newlands garnets. Green coloured garnets have been found at Premier, but were aluminium-rich garnets rather than chromium-calcium-rich garnets.

(f) Rietfontein Kimberlite Pipe

Yellow, orange, dark orange, red, reddish purple, rose, pink and lilac coloured garnets from this pipe have been analysed by Gurney and Switzer (unpublished data).

None of these garnets plot inside the diamond inclusion field on the Ca-Mg-Cr ternary diagram (Figure 21), but two did on the Ca-Mg-Fe ternary diagram (Figure 22). If the garnets plot inside the diamond inclusion field on both diagrams, they are considered to be similar to those found as inclusions in diamond. These two are not low-calcium, high-magnesium garnets. Both the eclogite and peridotite-pyroxenite trends are well developed on the Ca-Mg-Fe ternary diagram with the variable eclogite garnet compositions well illustrated. Some of these garnets have very high calcium components and are likely to have been derived from kyanite eclogites, which have been found at this pipe (Gurney et al., 1971).

(g) Roberts Victor Diamond Mine

Yellow and orange garnets were analysed from this mine and the results of these analyses are presented in Table 43. There are very few lilac garnets in the heavy mineral concentrates, none of which were alexandritic.

The Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams (Figures 23 and 24) show the start of the peridotite-pyroxenite trend and the eclogite trend and a restricted range of calcium component on a Ca-Mg-Fe- basis. The range of $Mg/(Mg+Fe^{2+})$ ratios is the largest for the garnets examined in this study, but these are mainly eclogite garnets. This might have been expected as Roberts Victor is well known for its numerous eclogite xenoliths. This range, however, is not as large as that for Kao where a garnet, E7, from an eclogite (Nixon et al., 1963) and one analysed by Hornung and Nixon (1968) have $Mg/(Mg+Fe^{2+})$ ratios of 36,6 and 28,5 respectively. The latter garnet is also presumed to have been derived from an eclogite as it contains only 0,06% Cr_2O_3. These garnets have been plotted on Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams (Figures 12 and 13).

(h) Sekretariskop Kimberlite Pipe

Mauve garnets and red garnets were analysed from this dyke enlargement. The results of these analyses are given in Tables 51 and 50 respectively. Three mauve garnets out of thirty-four plotted inside the diamond inclsuion field on a Ca-Mg-Cr ternary diagram (Figure 25). The mauve garnets were analysed only for Ca, Mg, Cr and Si, so it is not known where they plot on a Ca-Mg-Fe ternary diagram. These garnets follow the peridotite-pyroxenite trend, but seem to be a little more restricted in their range of composition than similar garnets from other pipes.

Most of the red garnets on the Ca-Mg-Cr ternary diagram (Figure 25) plot around the start of the eclogite and peridotite-pyroxenite trends, but a few follow the latter trend. On a Ca-Mg-Fe ternary diagram, however, only the peridotite-pyroxenite trend is shown by these garnets.

The garnets from this pipe show that colour criteria can be misleading if chemical composition is to be inferred purely on a colour basis, as seen on a Ca-Mg-Cr ternary diagram. There may, however, be a clearer distinction between these two groups of garnets on a Ca-Mg-Fe basis.

2. CLINOPYROXENE

The chemical compositions of clinopyroxene xenocrysts selected from the heavy mineral concentrates of the Bobbejaan, Finsch, Kao, Newlands, Premier, Rietfontein and Sekretariskop kimberlites have been determined. The clinopyroxenes in garnet peridotite nodules are particularly important because temperatures of equilibration for the xenoliths can be estimated from the Ca/(Ca+Mg) ratio of the clinopyroxenes, if they have formed in equilibrium with enstatite (Davis and Boyd, 1966).

It can be assumed, in most cases, the clinopyroxene xenocrysts were formed in equilibrium with enstatite, olivine and an aluminous phase which might be either garnet or spinel, i.e. they have been derived from disaggregated peridotite xenoliths. It is possible, however, that the xenocrysts may have been derived from discrete nodules or megacrysts (Nixon and Boyd, 1973c). These nodules are considered by Nixon and Boyd (1973c) to have formed in equilibrium with enstatite and that the temperatures of equilibration estimated by the Di(en) solvus of Davis and Boyd (1966) are applicable. For each set of clinopyroxene analyses Ca, Mg, Fe components are calculated by ABFAN2 (Boyd, Finger and Chayes, 1969) and presented as Ca, Mg, Fe percentages. These components have been plotted in a small area of the pyroxene quadrilateral after Boyd and Nixon (1972). The temperatures, in degrees Centigrade, indicated on the clinopyroxene diagrams, are for points on the Di(en) solvus in the system $CaMgSi_2O_6$-$MgSiO_3$ at 30 kb after Davis and Boyd (1966).

(a) Bobbejaan Diamond Mine

The compositions of the clinopyroxenes from the Bobbejaan mine are given in Table 3 and have been plotted in part of the pyroxene quadrilateral (Figure 27). This figure indicates that these diopsides were likely to have equilibrated within a temperature range of 975° to $1075^{\circ}C$. The range of Ca/(Ca+Mg) ratios is 48,1 to 46,6 and $Mg/(Mg+Fe^{2+})$ ratios is 93,2 to 92,2. Thus these xenocrysts are likely to have been derived from what Nixon and Boyd (1973b) term the granular ultrabasic nodule suite. The range of Al_2O_3 content in these clinopyroxenes is from 0,23% to 1,05% which is considerably lower than that shown by the clinopyroxenes of the peridotite-pyroxenite xenoliths from the Matsoku kimberlite pipe (Cox et al., 1973). The Bobbejaan clinopyroxenes also contain less Cr_2O_3 than the Matsoku ones. They are more similar in composition to the clinopyroxenes in the granular garnet lherzolite xenoliths from the Thaba Putsoa and Mothae kimberlite pipes (Nixon and Boyd, 1973b) than to those from the Matsoku xenoliths (Cox et al., 1973).

(b) Finsch Diamond Mine

The clinopyroxenes from this mine have similar amounts of Cr_2O_3, TiO_2, Na_2O and Al_2O_3 to the clinopyroxenes from the Matsoku and Thaba Putsoa nodules (Table 6)(Cox et al., 1973; Nixon and Boyd, 1973b). The range of equilibration temperatures estimated from the Davis and Boyd (1966) data are higher for these clinopyroxenes than for the Bobbejaan diopsides (Figure 27). It is likely that the Finsch diopsides have also been derived from granular ultrabasic nodules, which equilibrated at temperatures between 1100° and 1125°C.

(c) Kao Kimberlite Pipe

The clinopyroxenes from the Kao kimberlite pipe show a large range of Ca/(Ca+Mg) ratios (Table 13). There are, however, two distinct groups of these clinopyroxenes; one has a range of Ca/(Ca+Mg) from 48,6 to 40,0 and the other from 35,8 to 30,4 (Figure 28). These ranges are generally similar to those shown by clinopyroxenes from Thaba Putsoa and Mothae xenoliths (Nixon and Boyd, 1973b) and Letseng-La-Terae nodules (Bloomer and Nixon, 1973), but there are distinct differences between the various pipes. The range of temperatures of equilibration for the first group of Kao diopsides is 925° to 1250°C, and for the second group, which are 'sub-calcic diopsides', the range is 1350° to 1450°C. The 'calcic' diopsides have a much larger range of temperatures of equilibration than do those from Thaba Putsoa and Mothae (Nixon and Boyd, 1973b). The sub-calcic diopsides fit within the estimated range of temperatures of equilibration for the sheared ultrabasic nodules at Thaba Putsoa and Mothae (ibid., 1973b).

The high Ca/(Ca+Mg) ratio Kao clinopyroxenes have amounts of Al_2O_3 ranging from 1,03 to 2,42%; Cr_2O_3 from 0,29 to 0,59%; Na_2O from 0,42 to 1,77%; TiO_2 from 0,03 to 0,39%; and $Mg/(Mg+Fe^{2+})$ ratios from 91,6 to 86,4. These figures indicate that these Kao clinopyroxenes are not significantly different from those analysed by Nixon and Boyd (1973b, 1973c) and Boyd and Nixon (1972, 1973b) from the Thaba Putsoa and Mothae granular garnet lherzolites.

The sub-calcic diopsides have similar ranges of Al_2O_3, Cr_2O_3, TiO_2 and Na_2O contents to the diopsides from the Thaba Putsoa and Mothae sheared ultrabasic nodules and to the discrete clinopyroxene nodules (Nixon and Boyd, 1973c). Thus these xenocrysts could have been derived from either type of nodule.

(d) Newlands Kimberlite Pipes

The analyses of the diopsides from the Newlands kimberlite pipe(s) are presented in Tables 24 and 32. The latter table is an analysis of a clinopyroxene formed in equilibrium with a chromite. The estimated temperatures of equilibration of these diopsides are 1000° to 1125°C (Figure 29). Thus it is likely that they were derived from granular garnet peridotite xenoliths.

There is, however, a possibility that the estimated temperature of equilibration for the diopside in equilibrium with the chromite (1100°C) may not be valid. Clinopyroxenes have been found in peridotite nodules in equilibrium with chromite (N.V. Sobolev et al., 1973; Bloomer and Nixon, 1973), but enstatite has not been reported as existing in either nodule. The estimated temperature of equilibration of the Russian nodule is 950°C and the Letseng-La-Terae nodule 1175°C. If the diopsides were not in equilibrium with enstatite when formed, then the Di(en)solvus of Davis and Boyd (1966) should not be used to estimate temperatures of equilibration.

The most remarkable factor concerning the Newlands diopsides is the very high values of Cr_2O_3 in analyses 2 and 6 (Table 24). These amounts are higher than any reported for clinopyroxenes from Thaba Putsoa, Solane, Mothae or Matsoku (Boyd and Nixon, 1972; Nixon and Boyd, 1973b, 1973c; Cox et al., 1973). The Al_2O_3 contents of the Newlands diopsides range from 0,71 to 2,20%; the Na_2O from 1,89 to 3,46%; and the TiO_2 from 0,05 to 0,32%. The $Mg/(Mg+Fe^{2+})$ ratio varies from 93,1 to 91,7 and Ca/(Ca+Mg) from 47,2 to 44,3.

(e) Premier Diamond Mine

The compositions of the twenty-three clinopyroxenes analysed from the heavy mineral concentrates are presented in Table 36. Figure 30 shows that there is a bimodal distribution of diopsides in this concentrate, indicating that both 'calcic' and sub-calcic diopsides are present in this concentrate. The Ca/(Ca+Mg) ratio ranges from 46,8 to 43,8 and 36,8 to 31,2 respectively. The 'calcic' diopsides, by analogy with the Thaba Putsoa data (Boyd and Nixon, 1972), are likely to have been derived from granular ultrabasic nodules and the sub-calcic diopsides from sheared peridotite xenoliths or discrete clinopyroxene nodules.

The 'calcic' diopsides have estimated equilibration temperatures ranging from 1050° to 1175°C, which are higher than those estimated for the Thaba Putsoa and Mothae granular nodules. The Al_2O_3, Cr_2O_3 and Na_2O contents are similar to the Thaba Putsoa diopsides, but have very different $Mg/(Mg+Fe^{2+})$ ratios. For these Lesotho diopsides, this range is 95,4 to 93,2, while the range for Premier is 90,1 to 87,9. The Premier diopsides show more similarity in composition to some of the clinopyroxenes from the peridotite-pyroxenite xenoliths from the

Matsoku pipe than to those from Thaba Putsoa and Mothae (Cox et al., 1973).

The sub-calcic diopsides do not show any marked compositional differences from the diopsides in the Thaba Putsoa and Mothae sheared nodules in terms of Al_2O_3, Cr_2O_3, Na_2O and TiO_2. The range of $Mg/(Mg+Fe^{2+})$ ratios is 91,3 to 88,6 for the Premier diopsides and 92,2 to 89,7 for the Thaba Putsoa diopsides (Nixon and Boyd, 1973b).

The sub-calcic diopsides of the Premier mine are important when considering the upper mantle model proposed by Boyd (1973a). This model is based on the temperatures and pressures of equilibration of granular and sheared garnet lherzolite nodules from Thaba Putsoa and Mothae. These values show a 'geotherm' which has been "perturbed" from the Clark and Ringwood (1964) 'steady state geotherm'. Boyd (1973a) has suggested that the shearing in the mantle which produced the very high temperatures of equilibration was caused by the break-up of Gondwanaland. The significance of the sub-calcic Premier diopsides is that the Premier kimberlite has been shown to be Precambrian in age (Allsopp et al., 1967), but the Thaba Putsoa and Mothae kimberlites are Cretaceous in age. Hence, the break-up of Gondwanaland cannot explain the existence of these sub-calcic diopsides in a Precambrian kimberlite.

(f) Rietfontein Kimberlite Pipe

The compositions of the diopsides from the Rietfontein heavy mineral concentrate are presented in Table 37. Figure 31 shows that these clinopyroxenes have temperatures of equilibration of 925° to 1025°C. The Ca/(Ca+Mg) ratio varies from 48,4 to 47,2 for eleven analyses. This is a particularly restricted range when compared to the clinopyroxene data from the other pipes in this study. The $Mg/(Mg+Fe^{2+})$ ratio ranges from 93,7 to 91,6, which is also relatively restricted. Compared to the diopside data for the granular lherzolites from Thaba Putsoa and Mothae, these diopsides are more iron-rich, but have similar amounts of Cr_2O_3, TiO_2 and Na_2O. The Al_2O_3 content of some of these grains is distinctly lower than in some of the Lesotho diopsides.

(g) Roberts Victor Diamond Mine

Eleven clinopyroxenes have been analysed from the heavy mineral concentrate of this mine. These analyses are presented in Table 44. Figure 32 indicates that one of these clinopyroxenes is markedly different from the others. This grain (No. 3, Table 44) has a markedly different $Mg/(Mg+Fe^{2+})$ ratio of 80,1 compared with the range of 94,6 to 89,4 shown by the other ten. The $Ca/(Ca+Mg)$ ratio has a value of 46,8. This grain is likely to have been derived from an eclogite and thus the Di(en) solvus of Davis and Boyd (1966) cannot be used to estimate a temperature of equilibration.

Grain No. 2 was originally considered to have been derived from an eclogite because the garnet in equilibrium with it contained virtually no chromium. Its position in Figure 32, which is on the high-iron side of the cluster of points, indicates it is more likely to have been derived from a garnet-pyroxenite. The estimated temperatures of equilibration of the remaining diopsides lie between 1000° and 1100°C. These have probably been derived from peridotitic xenoliths rather than eclogitic xenoliths. The Al_2O_3 content of these diopsides ranges from 0,23 to 3,95%; the Cr_2O_3 content from 0,75 to 3,17%; Na_2O from 0,47 to 3,34%; and TiO_2 from 0,09 to 0,24%. It is surprising that most of these clinopyroxene xenocrysts could be regarded as peridotitic rather than eclogitic considering that eclogite xenoliths are more plentiful in this kimberlite than peridotite xenoliths.

(h) Sekretariskop Kimberlite Pipe

The clinopyroxenes from this pipe have a range of $Ca/(Ca+Mg)$ ratios from 48,3 to 43,7 (Table 52) and equilibration temperatures between 1000° and 1100°C (Figure 33). One grain, however, has probably been derived from an eclogite because of its low $Mg/(Mg+Fe^{2+})$ ratio of 79,1 compared with the others which vary from 95,1 to 90,1. No equilibration temperature has been estimated for this grain as it probably did not form in equilibrium with enstatite and thus the Davis and Boyd (1966) Di(en) solvus cannot be used. The Al_2O_3 content of the rest of the xenocrysts ranges from 0,43 to 2,44%; the Cr_2O_3 content from 0,98 to 3,15%; the TiO_2 content from 0,03 to 0,29%; and the Na_2O content from 1,20 to 2,87%. These clinopyroxenes have similar compositions to those in the granular ultrabasic nodules from Thaba Putsoa and Mothae (Nixon and Boyd, 1973b) and thus can be considered to have been derived from peridotite xenoliths.

3. ORTHOPYROXENE

Orthopyroxene is one of the major constituents of the garnet peridotite suite of rocks and phase equilibrium studies in simple systems have shown that the Al_2O_3 content of an enstatite may be used to estimate the pressure of equilibration of a mineral assemblage containing the enstatite, diopside, olivine and an aluminous phase, i.e. either garnet or spinel (MacGregor, 1974). The temperature of equilibration of this assemblage must, however, first be obtained from the Di(en) solvus after Davis and Boyd (1966).

Boyd and Nixon (1972) have described an 'enstatite geothermometer' which requires that diopsides and enstatite must have formed in equilibrium and, similarly to the Di(en) solvus of Davis and Boyd (1966), the solid solution of the diopside in enstatite may be used to estimate temperatures of equilibration using the Ca/(Ca+Mg) ratio of enstatite (ibid., 1972). There is some uncertainty introduced in relating the enstatite solvus to the diopside solvus (Boyd and Nixon, 1973a). This is a relative uncertainty and an estimate of the error is ± 50°C.

Enstatite is, therefore, an important mineral in the peridotite assemblage and if it is assumed that enstatite xenocrysts have probably been derived from disaggregated peridotitic xenoliths, then these xenocrysts can be used to estimate temperatures and pressures of equilibration by the above method (Boyd and Nixon, 1973).

(a) Finsch Diamond Mine

The chemical compositions of three orthopyroxenes from this mine have been determined. The results are presented in Table 7 which shows that the $Mg/(Mg+Fe^{2+})$ ratios are low compared to enstatites derived from ultramafic nodules. The Al_2O_3 content is high compared to these nodules. It is likely that these xenocrysts were derived from crustal, probably granulite, assemblages because the orthopyroxene in granulite nodule LBM-43 from the Matsoku kimberlite pipe has a very similar composition (Cox et al., 1973).

(b) Kao Kimberlite Pipe

Some of the orthopyroxenes from Kao were originally identified as olivines due to their yellow-green colour as opposed to the normal light orange-brown colour, but when analysed, were shown to be magnesium-rich orthopyroxenes (Table 14). These orthopyroxenes were enstatites, whereas the others could more correctly be called bronzites. The range of $Mg/(Mg+Fe^{2+})$ for these orthopyroxenes is 94,1 to 83,4, which is similar to diamond inclusion enstatites which range from 94,2 to 86,8. The Al_2O_3 content of the Kao orthopyroxenes varies from 0,28 to 2,04%, and the diamond inclusions from 0,09 to 1,32%. However, most of the diamond inclusion enstatites have a range of Al_2O_3 between 0,31 and 0,97%. Two of the Kao orthopyroxenes have more than 1,75% Al_2O_3;

twelve have between 1,25 and 1,0%; and the other eleven less than 1,0%. The two highest are not, however, inconsistent with the rest of the data. The analyses for these two xenocrysts, No's. 9 and 11 (Table 14), indicate that the tetravalent structural site has not been filled completely by silica. If the balance in the structural formula is completed, i.e. by apportioning Al^{IV} to Si to add up to 2,000, it will be noticed that considerably more Al is required by the tetravalent sites in analyses 9 and 11 than in the others. The amount of aluminium remaining is then assigned to the divalent structural site. The Cr_2O_3 content of the Kao orthopyroxenes varies from 0,60% to less than 0,01% and the Cr_2O_3 content of the diamond inclusion enstatites varies between 0,11% and 0,62%. Hence it is difficult to decide which, if any, of these orthopyroxenes is similar to the enstatites found in diamond inclusions. The Kao orthopyroxenes, compared with those in the peridotite-pyroxenite xenoliths from the Matsoku kimberlite pipe, have a larger range in Al_2O_3 and Cr_2O_3 values (Cox et al., 1973).

If the "enstatite thermometer" is used to estimate temperatures and pressures of equilibration of enstatite xenocrysts by the method of Boyd and Nixon (1972), the range of temperatures indicated by the Kao orthopyroxenes is 940° to 1420°C. The range of temperature estimated using the Di(en) solvus of Davis and Boyd (1966) was 950° to 1450°C, which is remarkably good agreement. The pressures of equilibration using the enstatite temperature estimates range from 40 to 70 kb. If this method is used to estimate the temperatures and pressures of equilibration for all the Kao orthopyroxenes, most would show that they were formed at high temperatures and pressures. This result is in agreement with the diopside data which indicates the existence of sheared garnet peridotite xenoliths at Kao. No estimate of pressure may be made for grain No. 4 (Table 14) because the Al_2O_3 content of 0,28% is too low to be used. MacGregor (1974) had experimental data for the 1% Al_2O_3 isopleth, but for any Al_2O_3 contents below this value, extrapolation is necessary. However, to extrapolate for 0,28% Al_2O_3 is unwise because the result would be higher than 90 kb or more.

(c) Koffiefontein Diamond Mine

The orthopyroxene grains from this mine show a similar range in $Mg/(Mg+Fe^{2+})$ content to the Matsoku and Kao orthopyroxene data (Table 19). This range is from 94,1 to 85,8. One of the analyses is almost certainly of an orthopyroxene derived from a xenolith of crustal origin because it has an $Mg/(Mg+Fe^{2+})$ ratio of 77,3; high FeO content (14,46%); and high Al_2O_3 content (2,15%). For the rest of these orthopyroxenes the range in Al_2O_3 values is 0,66 to 1,02%, which is smaller than the range shown by the Kao orthopyroxenes, but larger than that for the Matsoku orthopyroxenes. Grain No. 2 (Table 19) has a high Al_2O_3 content (2,49%) and a high $Mg/(Mg+Fe^{2+})$ ratio of 93,8. The high Al_2O_3 is due to the tetravalent site being unfilled, as was the case for the Kao orthopyroxenes. If this site is filled with Al^{IV}, the amount of aluminium remaining is then assigned to the divalent structural site. The Cr_2O_3 content of this grain (0,93%) is higher than the amount of Cr_2O_3 present in the diamond inclusion enstatites, the Kao orthopyroxenes, the Matsoku orthopyroxenes (Cox et al., 1973) or the Thaba Putsoa orthopyroxenes (Nixon and Boyd, 1973b). The reason for this high value is unknown, but it is possible that all or some of the chromium is present as Cr^{2+}, but there is as yet no evidence to suggest that this is so.

(d) Rietfontein Kimberlite Pipe

The enstatites analysed from the heavy mineral concentrates from this pipe have higher $Mg/(Mg+Fe^{2+})$ ratios than the orthopyroxenes from the other two pipes. This ratio varies from 94,8 to 90,8 (Table 38), but this smaller range of values is probably explained by sampling effects. Only eight grains were analysed from this pipe as opposed to twenty-five and twenty-one from the other two. The Al_2O_3 content of the orthopyroxene ranges from 0,63 to 1,81%, but again the amount of Al required to fill the tetravalent structural site varies. The Cr_2O_3 content of the Rietfontein orthopyroxenes varies from 0,08 to 0,39%, which is similar to the values for diamond inclusion enstatites and for the orthopyroxenes in the Matsoku peridotite-pyroxenite xenoliths (Cox et al., 1973).

The orthopyroxenes from this pipe, however, have an estimated range of equilibration temperatures and pressures which are considerably lower than the range estimated for the Kao and Koffiefontein orthopyroxenes. The range for the Rietfontein enstatites is 900° to 1000°C and 42 to 46 kb for these temperatures and pressures respectively. These temperatures are in fair agreement with those estimated using the Di(en) solvus of Davis and Boyd (1966) which were in the range 950° to 1050°C.

4. OLIVINE

The compositions of twenty-one olivines have been determined during this study: eleven from the Newlands kimberlite pipe and ten from the Rietfontein kimberlite pipe. As xenocrysts olivines are the least informative of the minerals making up the peridotitic rock suite.

(a) Newlands Kimberlite Pipe

The analyses of the olivines from this pipe are presented in Table 25. Compared with the olivines from the Matsoku xenoliths, the Newlands olivines show a considerably smaller range of $Mg/(Mg+Fe^{2+})$ ratios.

These are 94,8 to 83,4 and 94,0 to 91,8 respectively (Cox et al., 1973). This restricted range is probably due to sampling effects because only eleven olivines were analysed from the Newlands pipe, whereas the Matsoku data is from selected rocks of different textures and modal proportions. Two of the Newlands olivines have 0,05% Cr_2O_3 present and three others contained 0,03% Cr_2O_3. Olivines found as inclusions in diamond generally contain more than 0,05% Cr_2O_3, although many of them have less (Meyer and Boyd, 1972; Meyer and Svizero, 1974; Prinz et al., 1974).

(b) Rietfontein Kimberlite Pipe

The $Mg/(Mg+Fe^{2+})$ ratios of the olivines analysed from the Rietfontein heavy mineral concentrates range in value from 92,4 to 91,8. This range is considerably smaller than that shown by the olivines in the Matsoku peridotite-pyroxenite xenoliths (Cox et al., 1973), but this may be due to sampling effects. None of the Rietfontein olivines contained more than 0,03% Cr_2O_3. Thus it is unlikely that any of these olivines are similar in composition to those found in diamond inclusions. The olivines from the Rietfontein and Newlands kimberlites can be considered as having been derived from disaggregated peridotite xenoliths.

5. CHROMITE

The chemical compositions of chromites from four heavy mineral concentrates were determined during this study. Those from the Star Diamond Mine were mounted when received, and thus no control over the selection of these was possible. The Jagersfontein and Rietfontein samples were selected purely on the basis of their good crystal form, but the Newlands chromites were divided into four groups based on crystal form and magnetic properties. After the first euhedral, magnetic chromites were analysed, it was realised that a number of them had 60% or more Cr_2O_3 present. The chromites included in diamonds had at least 61% Cr_2O_3 (Meyer and Boyd, 1972; Table 55) and it was decided to limit the number of analyses of Newlands chromites to those having ± 60% Cr_2O_3 only. This was achieved by a preliminary examination using the microprobe.

As many chromites as possible from each of the four categories were mounted as double polished thin sections and the count rates for chromium determined very rapidly. Those chromites which had approximately 60% Cr_2O_3 or more were then analysed for Si, Ti, Al, Fe, Mn and Mg. Calcium was not determined. For the anhedral chromites, the grains giving the lowest count rates for chromium were also analysed for the above elements.

The chromite data was plotted on diagrams of the system $(Fe^{2+},Mg)(Fe^{3+}Al,Cr)_2O_4$, similar to those of Smith and Dawson (1974). A 'diamond inclusion field' can be delineated by plotting the data from known chromite inclusions in diamond and the chromite concretions on aggregates of diamond (Meyer and Boyd, 1972; N.V. Sobolev et al., 1971; Prinz et al., 1974; Smith and Dawson, 1974). An exception was made for the two inclusions from Sierra Leone (Meyer and Boyd, 1972) because they have exceptionally high Fe^{2+} components and were thus excluded from the 'divalent atom fields' of Smith and Dawson (1974). The plotting and comparison of electron microprobe data on diagrams of this type was, however, fraught with difficulties. Analyses from this study had to be corrected for chromium X-ray line interferences and the Fe^{2+} and Fe^{3+} components calculated from a determination of total Fe and stoichiometry. This calculation has been made using different methods by different authors although the bases of the calculations are similar. These components were recalculated where possible using original analysis figures by one method only, thus making comparisons between the data from various sources consistent within that method. This was done for the analyses of the inclusions in diamond and the 'concretions with aggregates of diamond' given in Table 55.

When comparing chromite analyses by means of these diagrams, there was always some doubt as to the exact position of the point due to the uncertainty in the Fe^{3+}, Fe^{2+} calculation (Finger, 1972). Thus the separation of grains on the basis of their Fe^{2+}, Fe^{3+} components may not be valid because the errors in their determination were likely to be larger than the actual differences observed.

(a) Jagersfontein Diamond Mine

One of the chromites from this locality contained 62,26% Cr_2O_3 and the other four had between 59 and 60% Cr_2O_3 present, but the titanium, iron and aluminium contents varied considerably (Table 9). These chromites have been plotted along with those from the Star Diamond Mine in Figure 34, but without drawing in the diamond inclusion fields for the sake of clarity. The points on this diagram are separated by their Fe^{2+} components except for chromites 4 and 5 which are remarkably similar in composition. These two grains plot close to the diamond inclusion chromites on the divalent atom section of the diagram, but contain too much Fe^{3+} component to be similar to chromites found in diamond. Although all these grains contain approximately 60% Cr_2O_3, none of them are similar to those found as diamond inclusions.

(b) Star Diamond Mine

The chromites from this mine show a range in composition from 54 to 59% Cr_2O_3 (Table 53), but they contained too much Fe_2O_3 and FeO to be similar to the diamond inclusions. Some of these chromites show slightly restricted compositions on the trivalent section of the Smith and Dawson (1974) diagram, with two groups of four and five grains each around the point $Cr_{13}Fe^{3+}_{2}Al_{1}$ and the remainder having an Al component which did not exceed 2. The chromites in the two groups are separated by their Fe^{2+} components which are amongst the highest recorded for kimberlitic chromites. The Star chromites had, on average, more titanium present than those from Jagersfontein, and the range 0,88% to 3,3% indicated that the titanium content was very variable in these chromite structures. None of these chromites plotted in the diamond inclusion field because the chromium content was too low.

(c) Rietfontein Kimberlite Pipe

The chromites analysed from this locality were selected on crystal form, and thus a large range of compositions from 32 to 55% Cr_2O_3 was found (Table 40). On the basis of Figure 35, it seemed as though there was a bimodal distribution in contrast to the findings of Smith and Dawson (1974) who reported that kimberlites, in general, showed a complete range of compositions for chromites and that they were not bimodally distributed. This distribution for the Rietfontein chromites cannot, however, be regarded as being at variance with the Smith and Dawson (1974) finding because only thirteen of these chromites were analysed. This number of analyses was too few to be able to make any firm conclusions as to the overall compositional distribution of chromites in a pipe.

The chromites had a restricted range of Fe^{2+} and Fe^{3+} components compared with the wide range in Cr and Al, and did not show as large a range of TiO_2 values as the Jagersfontein and Star chromites. Again, no chromites were found which had compositions in the diamond inclusion field.

(d) Newlands Kimberlite Pipe

The analyses of the chromites from the Newlands heavy mineral concentrate are presented in Tables 26, 27, 28, 29, 31 and 33; the latter two being the chromites co-existing with the green garnets and clinopyroxenes respectively. The euhedral and anhedral, magnetic and non-magnetic chromites have been plotted on the Smith and Dawson (1974) diagram (Figures 36, 37 and 38).

Most of the euhedral, magnetic chromites plot close to the diamond inclusion chromites (Figure 36) with seven of them plotting very close to each other. Three of these seven are separated from the others in terms of the Fe^{2+} component, thus leaving four grains which plot in or just outside the range of diamond inclusions. Grains No's. 7 and 8 plot within the limits of the inclusion compositions and apart from a chromite in a spinel lherzolite from De Beers Mine, Kimberley (Smith and Dawson, 1974; Figure 40), no other kimberlitic chromites have been reported which plot within these compositional ranges. The chromites had low TiO_2 contents which were similar to those found in chromites included in diamond. The rest of the euhedral, magnetic chromites had compositions ranging from 53 to 64% Cr_2O_3 and 0,01 to 2,36 TiO_2 (Table 26). It must be emphasized that the full range of compositions for this group is not known due to the selective sampling procedures used.

The euhedral, non-magnetic chromites, analysed in full (Table 27; Figure 37), excepting grain No. 9, had remarkably similar compositions and were plotted as a single group of eight (Figure 37) because they were almost impossible to distinguish individually. Grain No. 9 was poorer in MgO, Al_2O_3 and Cr_2O_3, but richer in FeO and Fe_2O_3 and considerably richer in TiO_2, almost double the next highest TiO_2 %.

The anhedral chromites, magnetic and non-magnetic, chosen for analysis on the basis of their ± 60% Cr_2O_3 contents were remarkably similar in composition, except for grain No. 5 of the anhedral, magnetic group which was distinctly more iron-rich than the others (Tables 28 and 29). These xenocrysts, with the one exception (No. 5), plotted close to the diamond inclusions (Figure 38). The two grains in each group having the least Cr_2O_3 were also shown on this figure, with the lowest value being grain No. 4 of the anhedral, magnetic type, 43,42% Cr_2O_3. This chromite had low TiO_2, 0,38%, but the range of TiO_2% for both anhedral groups was smaller than that for the euhedral, magnetic chromites but similar to the euhedral, non-magnetic grains (i.e. 0,1 - 1,5% TiO_2). The chromites co-existing with the green garnets and the clinopyroxenes were very different in composition (Table 31; Figure 38; and Table 33). Those in equilibrium with the clinopyroxenes contained more than 60% Cr_2O_3, but still did not fall in the diamond inclusion field. Those in equilibrium with the green garnets (Table 31) had compositions which plotted well away from the diamond inclusion chromites (Figure 38).

6. SPINEL

Two nodules containing Al_2O_3-rich spinel have been analysed during this study: one is a garnet-spinel nodule, PJL-13, from the Bobbejaan Diamond Mine, and the other is a large spinel nodule, BD1988, from the Roberts Victor Mine. Garnet-spinel nodules have been found at the Bobbejaan fissure previously and they are not uncommon in the concentrates from this mine.

(a) Bobbejaan Diamond Mine

The composition of the garnet and spinel grains in this nodule are presented in Tables 4 and 5 respectively. Table 4 shows the compositions of six separate garnet grains from various sections of the nodule. These analyses are similar in all respects. Thus it can be said that the garnet is homogeneous throughout this nodule. Table 5 shows the compositions of the spinels which can also be said to be homogeneous. There is no difference in composition between the small (~1mm diameter) spinel inclusions in the garnets and the main body of the spinel. This nodule also contains what are thought to be primary sulphide minerals in the matrix. The sulphide-spinel contact area showed a complex intergrowth of a Cu-Fe-rich sulphide and an Mg-Al-Fe silicate phase. This was a rim to the main body of the sulphide which was an Ni-Fe-rich sulphide. Neither of these sulphides has been positively identified, but it is suspected that they may be pyrrhotite and pentlandite. A Ca-Mg-Al silicate inclusion in the Ni-Fe sulphide also had a rim of Cu-Fe sulphide intergrown with an unknown silicate phase.

(b) Roberts Victor Diamond Mine

The spinel nodule BD1988 was found at the Roberts Victor Mine by J.B. Dawson and weighs 1,5 kg. A diagram of this nodule is presented in Figure 41 with the positions of the thin sections marked. This nodule contained a number of inclusions of garnet and an inclusion of garnet completely enclosing olivine. Two analyses of the garnet inclusions in Slide 1 are presented in Table 45 and the analyses of the olivine and its surrounding garnet in Table 47 and 46 respectively. The composition of the spinel grains in the garnetiferous zone of Slide 1 and the main body of the spinel are presented in Table 48. Table 49 shows the composition of the spinel in Slide 4. The analyses presented in Table 48 leave much to be desired because the totals were high when calculated and when the Fe^{3+} correction was applied, they became higher. They are, however, presented to illustrate the marked difference in composition of the spinels in different parts of the nodule. The difference in composition between Slide 1 and Slide 4 (separated by a distance of some 10 cm) is shown best by the amounts of Al_2O_3 and Cr_2O_3. Slide 1 spinels have ± 52% Al_2O_3, while Slide 4 spinels have ± 57%, and the Cr_2O_3 content varies between ± 11% and ± 5%. The Fe content of the two areas is also very different. The differences in Al_2O_3 and Cr_2O_3 content suggest that there are areas of different composition present in this spinel. The data for these spinels are plotted with the spinel data for nodule PJL-13 in Figure 40.

7. CORUNDUM

An analysis of corundum from the Finsch Mine is presented in Table 8. This analysis was carried out to determine how much Cr_2O_3 was present. It is likely that this grain was derived from a corundum-bearing eclogite. Compared to the analyses of corundum given by Deer, Howie and Zussman (1963), it contains more Cr_2O_3 and TiO_2 than some of the metamorphic corundum, but not as much Cr_2O_3 as ruby. This grain had a pale pink colour similar to the corundum found in certain eclogites from the Bobbejaan Mine.

8. RIETFONTEIN ULTRAMAFIC NODULE

Some of the mineral compositions in this small nodule (25 mm X 15 mm), which consisted mainly of garnet and clinopyroxene, were determined because a zone of very fine grains was seen at a boundary between a large garnet and clinopyroxene. The analyses presented in Tables 41 and 42 for the garnets and clinopyroxenes of this nodule show that it is peridotitic. The clinopyroxenes are iron-poor compared to most of the diopside analyses presented in this study. The diopsides are plotted with the rest of the Rietfontein diopside data in Figure 31 and show lower temperatures of equilibration than do the diopside xenocrysts (940°C as opposed to 1000°C). The garnets are all of similar composition, except for analysis No. 1, but this has a low total compared to the others, which have high totals; thus the differences can be accounted for by analytical uncertainty.

VII DISCUSSION

This study has shown that N.V. Sobolev et al. (1969) and Gurney and Switzer (1973) were correct when they suggested that kimberlite heavy mineral concentrates had been inadequately sampled and that if studies were carried out to look for minerals of unusual compositions, they would be successful.

The examination of the heavy mineral concentrates from the Bobbejaan, Jagersfontein, Kao, Koffiefontein, Newlands, Premier, Sekretariskop, Rietfontein and Star kimberlites has shown that certain minerals have compositions which have not been reported up till now. This study cannot be regarded as comprehensive for each occurrence owing to the extreme selectivity exercised when choosing specimens for electron microprobe analysis. It is significant that although many analyses have been carried out, the actual number of grains analysed of any particular mineral species from any one kimberlite source is insufficient to represent the full range of chemical compositions present. The maximum number of analyses for any specific mineral group is for garnets from Koffiefontein, but these were divided into four separate groups of 35, 9, 11 and 14. For any one separate mineral grouping between 6 and 25 analyses were carried out.

1. GARNET

The garnet group has been divided into certain species representing theoretical end-members of an isomorphous series and many garnet analyses are recalculated with respect to these end-members. These calculations have not been made in this study because the methods of recalculation vary considerably between different authors (Rickwood, 1968; Nixon and Hornung, 1968; Boyd, 1969; N.V. Sobolev et al., 1973).

The chemistry of the garnets found in peridotitic and eclogitic xenoliths can, however, be represented on ternary diagrams. The major variations in garnet composition can be represented by means of Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams. For example, the differences in chemistry between the garnets from peridotite and eclogite nodules and the diamond inclusion garnets may be clearly seen in Figures 21 and 22.

The close comparison of data from various sources is difficult unless all the data has been similarly treated. Hence the garnet compositions represented in Figures 11, 12, 17 and 18 have, where necessary, been recalculated on a 'total Fe as FeO basis' so that direct comparison with electron microprobe data may be made.

The results of the garnet analyses presented and described in Section VI(1) show that low-calcium, high-magnesium garnets have been found in the heavy mineral concentrates from the Bobbejaan, Kao, Koffiefontein, Newlands, Premier and Sekretariskop kimberlite pipes or dykes. These kimberlites are very different in size, geographical location, diamond content and chemical composition. They carry very different xenolith and xenocryst suites. They have been developed to different extents, e.g. from prospecting operations at Sekretariskop to open cast and underground mining at Koffiefontein and Premier respectively. The garnets are important because they plot in or close to the diamond inclusion field on both Ca-Mg-Cr and Ca-Mg-Fe ternary diagrams. Thus, along with the low-calcium, high-magnesium Finsch garnets, they can be considered to have crystallized in equilibrium with the diamond in a liquid and transported to the surface rapidly on emplacement of the kimberlite with no significant re-equilibration (Gurney and Switzer, 1973).

All the kimberlites containing these garnets are diamondiferous, albeit to different grades. Sekretariskop has the lowest diamond content of 0,1 carats per 100 metric tonnes and Premier the highest at about 35 carats per 100 metric tonnes. The relative proportions of the different minerals and, in particular, the proportions of different coloured garnets in a heavy mineral concentrate need to be well known before any numerical relationship between the diamond content of the kimberlite and the number of low-calcium, high-magnesium garnets present can be formulated.

Because the pipes or mines in which low-calcium, high-magnesium garnets have been found were all diamondiferous, a logical extension of this work is to look for similar garnets in a kimberlite which is non-diamondiferous. There is, however, a problem because some of the diamonds in certain kimberlites are thought to have been "resorbed"; that is, they have been dissolved by the liquids with which they were in equilibrium. If this had occurred, it is possible that low-calcium, high-magnesium garnets might still be present in the heavy mineral concentrates. Thus the actual number of these garnets found in any particular heavy mineral concentrate in this study may not be representative of the true picture. A factor which may influence the relationship betwen the low-calcium, high-magnesium garnets and the diamond content of a kimberlite is that it is not known from which specific kimberlite types the diamonds or these garnets have been derived in certain mines. As an example, there are at least three separate intrusions of kimberlite recognised at the Premier Mine and up to eight kimberlite types have been described. It has been reported that "the three main types of kimberlite at the Premier Mine contain diamonds in economic quantities and that the diamond grade only varies when there is a distinct variation in the amount of foreign inclusions." (Guide for the First Field Excursion of the International Conference on Kimberlites, 1973). To ascertain the relative proportions of heavy minerals and different coloured garnets in a particular kimberlite type at a mine such as Premier, would require strict sampling control and might prove to be impractical at a working mine.

The low-calcium, high-magnesium garnets from the Newlands kimberlites must also be considered carefully because it is not known from which kimberlite they were derived. If, however, the kimberlites of Blows No. 4 and 5 are assumed to be similar, apart from their crustal xenolith contents, it is significant that diamondiferous eclogites, high-calcium, high-chromium green garnet and the low-calcium, high-magnesium garnets have been found in one source. The Udachnaya kimberlite pipe in Yakutia is similar in this regard because low-calcium, high-magnesium garnets, high-calcium, high-chromium garnets and diamondiferous eclogites have been found in this pipe (N.V. Sobolev et al., 1973; Ponomarenko et al., 1973). Figures 15, 16, 17 and 18 show that the garnets from the Newlands kimberlites are remarkably similar in composition to those reported by N.V. Sobolev et al. (1973). In Figure 15 there is a distinct gap in composition with respect to the Ca component between the green garnets and the 'very alexandritic' garnets, excepting grain No. 14 (Table 20). If the data for the Udachnaya kimberlite pipe only is considered, this 'compositional gap' is evident on Figure 17 because the only garnet from Udachnaya, in what N.V. Sobolev et al. (1973) call "chrome pyropes with moderate and high Ca content", has the lowest Ca component in this group. The rest of the points in this 'moderate and high Ca content group' are for garnets from the Dalnaya and Mir kimberlite pipes. The only garnets, as far as is known, from the Udachnaya pipe which would plot in this 'composition gap' on the Ca-Mg-Cr ternary diagram are the garnets found as diamond inclusions (N.V. Sobolev et al., 1970). These garnets have markedly different compositions compared with the other diamond inclusion garnets (Figure 4). A garnet from the Premier Mine, which could be described as having "moderate to high Ca content" (N.V. Sobolev et al., 1973), plots in a similar position to the Udachnaya diamond inclusions on a Ca-Mg-Cr ternary diagram (Figure 19). This is the only garnet found in this study which is similar to these diamond inclusion garnets. N.V. Sobolev et al. (1973) report garnets having similar compositions to these diamond inclusion garnets as far as the calcium component is concerned, but not as low chromium components (Figure 17).

The slightly alexandritic garnet from the Newlands pipe (No. 14, Table 20) is similar to the Udachnaya diamond inclusion garnets in CaO and MgO content, but has much less Cr_2O_3. This garnet is considered to have been derived from a grospydite xenolith because it is remarkably similar in composition to the green garnets in grospydite xenoliths from the Zagodachnaya kimberlite pipe in Yakutia (N.V. Sobolev et al., 1968). Most of these garnets were intergrown with chrome-rich kyanite of different hues of blue, and in one case a chrome-bearing clinopyroxene was found with the garnet (N.V. Sobolev et al., 1968). N.V. Sobolev et al. (1973), however, state that "the garnets of the chrome-bearing eclogites differ from those of similar composition in equilibrium with olivine. These features are: (1) the higher iron content of the eclogite garnets; (2) a rather lower chrome content; and (3) the frequent presence of inclusions of chrome-bearing kyanites. It must be stressed that xenoliths of such Cr-rich eclogites as found in the Zagodachnaya pipe are totally lacking in the Mir, Udachnaya and Dalnaya pipes." (p. 48, 1973).

Kyanite eclogite has been found in the heavy mineral concentrate of the Newlands pipe (Gurney, personal communication), but it is not known if this sample contains green garnets. The Newlands and Udachnaya pipes are thus not as similar as first thought. The paragenesis for the high-calcium, high-chromium garnets is considered by N.V. Sobolev et al. (1973) to be garnet plus clinopyroxene plus olivine without enstatite. These authors further suggest that the paragenesis for the Udachnaya diamond inclusions, which, besides the rare garnets, contains two diopsides and olivine, is a typical wehrlite paragenesis. A third paragenesis is postulated by these authors for the low-calcium, high-magnesium garnets similar in composition to the diamond inclusion garnets, in which it is suggested that the most likely paragenesis is garnet, olivine and/or enstatite without clinopyroxene. Thus three separate parageneses are required to explain the chemical composition of the garnets from the Udachnaya, Mir and Dalnaya kimberlite pipes (N.V. Sobolev et al., 1970, 1973). These parageneses can also be considered applicable to the garnets found in the Newlands kimberlite pipes. The garnets from the Premier Mine show similar characteristics to the Newlands and Udachnaya kimberlites for garnets of low and moderate to high Ca content (Figure 19), but as far as is known, no green, high-calcium, high-chromium garnets have been found in the heavy mineral concentrates from the Premier Mine.

The garnets which cannot be ascribed to either the low-calcium, high-magnesium type or to the moderate to high-calcium, high-chromium type illustrate the peridotite-pyroxenite trend and/or the eclogite trend (Gurney, 1974). The garnet compositions represented in Figures 2 and 3 can be used to illustrate these two trends. On the Ca-Mg-Fe ternary diagram the eclogite trend is shown by the increase in Ca component away from the Mg apex, while the peridotite-pyroxenite trend shows an increase in Fe with the Ca component relatively constant below 15%. This trend is well illustrated by the data of Reid and Hanor (1970) for the Kimberley garnet xenocrysts. The garnets from the Finsch Mine, when plotted on a Ca-Mg-Cr ternary diagram (Figure 2), show the eclogite trend close to the Ca-Mg axis and increasing in Ca component and the peridotite-pyroxenite trend extending above and beyond the diamond inclusion field, away from the Mg apex of the diagram. The limit to this trend in terms of chromium component seems to be close to the knorringite garnets of Nixon and Hornung (1968) and Hornung and Nixon (1973) (Figure 11). N.V. Sobolev et al. (1973) suggested that there would be a limit to garnet compositions in kimberlites which would be near 30% in terms of chromium component as plotted on a Ca-Mg-Cr ternary diagram. The garnet data from the heavy mineral concentrates of the kimberlite pipes and dykes in this study show that the eclogite trend and peridotite-pyroxenite trend are present in nearly all cases, the exceptions to this occurring where selective sampling precludes the chances of finding certain garnets or where xenoliths of either the peridotite-pyroxenite or eclogite suites are known to be rare. For example, eclogite is rare as a xenolith in the Kimberley mines. Thus the Reid and Hanor (1970) data only shows the peridotite-pyroxenite trend. The Roberts Victor kimberlite contains far more eclogites than peridotites and thus more eclogitic garnets will be found than peridotitic ones.

Nixon and Boyd (1973b) and Boyd and Nixon (1972) show that the garnets from granular lherzolite and sheared lherzolite nodules from Thaba Putsoa may be separated in terms of chemical composition by means of a Ca-Mg-Fe ternary diagram. This separation may also be shown on a

Ca-Mg-Cr ternary diagram, but when dealing with xenocrysts, it is virtually impossible to try to assign a particular garnet xenocryst to either the sheared or granular nodule suites.

2. CLINOPYROXENE

The diopsides from the Bobbejaan, Finsch, Newlands, Rietfontein, Roberts Victor and Sekretariskop kimberlites have compositions similar to those from many other kimberlite pipes, but some of the diopsides from the Kao kimberlite pipe and Premier Diamond Mine have compositions which have not been reported until now.

Sub-calcic diopsides have been found in the heavy mineral concentrates of both these kimberlite pipes. A sub-calcic diopside is one which shows a greater solid solution towards enstatite than diopsides from other plutonic rocks. Sub-calcic diopsides have compositions near a mean of $wo_{31}en_{62}fs_7$ (Boyd, 1969). These diopsides were first described by Nixon et al. (1963) from the Thaba Putsoa kimberlite pipe in Lesotho and have since been reported from Mothae, Solane and the Kao satellite pipe (Nixon and Boyd, 1973a; 1973b). These diopsides have been shown to be a phase in garnet lherzolite nodules which have been deformed by shearing (Boyd, 1973a). The data from these sheared nodules from the Thaba Putsoa, Mothae and other Lesotho pipes has been interpreted by Boyd (1973a) to reconstruct 'a pyroxene geotherm' and it is on this 'geotherm', which is a geothermal gradient, that he bases his model for the upper mantle beneath Lesotho (Boyd and Nixon, 1973b). It is suggested in this model that granular garnet lherzolites in the upper mantle represented a 'steady-state geotherm' with a slope similar to the 'shield geotherm' of Clark and Ringwood (1964). This 'geotherm' was then 'perturbed' (Boyd, 1973a) by an event which caused major heating in the upper mantle at depth of 150-200 km. This event is represented by the sheared garnet lherzolites which have equilibrated at higher temperatures and pressures as estimated by the methods of Davis and Boyd (1966) and MacGregor (1974). (The pressures have been corrected using the calculation developed by Banno and Wood (1973) and by methods removing Na components from the amount of Al_2O_3 in the enstatite which is used for the pressure estimate.) The cause of this major heating event is postulated to be the break-up and dispersal of Gondwanaland. Smith and Hallam (1970) have concluded that the initial rifting of Gondwanaland began in the late Jurassic and Early Cretaceous, but that the dispersal took place in Late Cretaceous or Tertiary times. Briden (1967) has found evidence of four episodes of continental drift from paleomagnetic data for the southern hemisphere since the Cambrian separated by quasi-static intervals. Hence Boyd and Nixon (1972, 1973a), Nixon and Boyd (1973b) and Boyd (1973a) have suggested that the severe heating of the sheared garnet lherzolites, by as much as 300°C above the ambient preshearing temperature, and the actual shearing of these xenoliths may have been caused by the lithospheric plate movements which took place during the break-up of Gondwanaland.

The diopsides from the Kao kimberlite pipe (Table 13, Figure 28) show two distinct ranges of Ca/(Ca+Mg): one from 48,6 to 40,0 and the other from 35,8 to 30,4. This bimodal distribution of clinopyroxenes is evident for all kimberlite pipes which have sub-calcic diopsides in the heavy mineral concentrates or sheared garnet lherzolites. The estimated temperatures for the equilibration of the Kao diopsides are 925° to 1250°C and 1350° to 1450°C for the two groups 'calcic' and 'sub-calcic' respectively. Boyd and Nixon (1972) indicate that there are three fields of composition for kimberlitic diopsides: 'calcic', 'sub-calcic' and more iron-rich diopsides which often occur in clinopyroxene-ilmenite intergrowths. Some of the Kao diopsides analysed in this study do not, however, fit into these composition fields. Some of the 'calcic' diopsides are no different to many others from various kimberlite pipes, but four of them have similar Ca/(Ca+Mg) ratios to the clinopyroxenes intergrown with ilmenite (Gurney et al., 1973). These four diopsides have a range in Ca/(Ca+Mg) ratios from 41,1 to 40,0, but do not have as much iron as the diopsides in the clinopyroxene-ilmenite intergrowths or ilmenite-bearing nodules, and thus do not fit into any of Boyd's (1969) composition fields. Sub-calcic diopsides, however, can be divided into two different associations: one with sheared ultrabasic nodules, and the other "the discrete nodule (megacryst) association" (Nixon and Boyd, 1973b; 1973c). The Kao sub-calcic diopside xenocrysts can be regarded as representing both these associations because one sub-calcic diopside has an $Mg/(Mg+Fe^{2+})$ ratio of 91,6 which is similar to the $Mg/(Mg+Fe^{2+})$ ratios of diopsides in sheared garnet lherzolites and the others have a range of ratios from 87,3 to 86,8 which is very similar to the range shown by the clinopyroxene discrete nodules from Thaba Putsoa and Mothae (Nixon and Boyd, 1973c).

The diopside in the sheared garnet lherzolite nodule from the Kao satellite pipe had a Ca/(Ca+Mg) ratio of 40,8 (Nixon and Boyd, 1973a) which places it close to the four anomalous 'calcic' diopsides analysed in this study. Thus it is most unlikely that the full range of composition of diopsides from the Kao pipe is known and is fully represented by the data of this study or any previous results or all the data combined. The data from the orthopyroxene xenocrysts of the Kao pipe indicates that only four out of twenty-five samples could be regarded as being derived from granular lherzolites, if the temperatures and pressures of equilibration are estimated using the 'enstatite geothermometer' and the Al_2O_3 content of the enstatite (Boyd and Nixon, 1972; MacGregor, 1974). The other twenty-one orthopyroxenes have a range of temperatures from 990° to 1400°C and pressures from 53 to 68 kb, thus placing them on the sheared lherzolite limb of the 'pyroxene geotherm' (Boyd and Nixon, 1972; 1973a).

The 'pyroxene geotherm' and the model for the upper mantle beneath Lesotho are based on data from various Lesotho kimberlite pipes and are explained by the break-up and dispersal of Gondwanaland (Boyd, 1973a), but this explanation cannot be applied to the data from the Premier Mine. It has been shown (Section VI.2(d)) that sub-calcic diopsides exist in the Premier Mine heavy mineral concentrate and by analogy with the sub-calcic diopsides from the sheared xenoliths from the Thaba Putsoa, Letseng-La-Terae and Mothae kimberlite pipes, these diopsides are likely to have been derived from similar ultramafic nodules. The temperatures of equilibration estimated from the Di(en) solvus after Davis and Boyd (1966) are 1050° to 1175°C for the calcic diopsides and 1325° to 1400°C for the sub-calcic diopsides. These temperatures are higher than those estimated for the equilibration of the granular garnet lherzolites and sheared garnet lherzolite nodules from Lesotho (Boyd and Nixon, 1973b). Unfortunately pressures of equilibration cannot be obtained from the diopside data only and no orthopyroxenes from this mine have been analysed in this study. Thus the 'enstatite geothermometer' cannot be used. If, however, it is assumed that the sub-calcic diopsides were derived from disaggregated sheared xenoliths and that pressure data was available, it may be surmised that an 'inflected or perturbed' geotherm similar to that for Lesotho could be shown to exist at the Premier Mine. This is likely because of the high temperatures indicated by the sub-calcic diopsides. If the data from the Clark and Ringwood (1964) "shield geotherm" was applied, the pressures extrapolated would be in the region of 100 kb or more, which are too high.

The break-up and dispersal of Gondwanaland could have caused the heating and shearing of the Lesotho garnet lherzolite nodules, but cannot be cited to explain the 'assumed geotherm' for the Premier Mine. The age for the emplacement of the Lesotho kimberlites and the Premier kimberlites are very different - Cretaceous compared to Precambrian respectively (Allsopp et al., 1967; Guide for the First Field Excursion of the International Conference on Kimberlites, 1973). As mentioned previously, Smith and Hallam (1970) give late Jurassic to Early Cretaceous as the time of initial rifting of Gondwanaland. Piper (1973) has concluded from paleomagnetic data that continental drift between Africa and the Canadian Shield occurred in Precambrian times. Thus it is possible that the heating event necessary to produce the sub-calcic diopsides found at Premier could have been caused by tectonic plate movements. More data on the compositions of diopsides and orthopyroxenes from the Premier Mine is, however, necessary before any conclusions on the genesis of these sub-calcic diopsides can be reached. A sheared nodule from the Premier Mine has been found to contain sub-calcic diopside (Gurney, personal communication). Thus it is likely that the sub-calcic diopsides were derived from sheared lherzolite nodules and that the assumed 'geotherm' is a distinct possibility.

3. ORTHOPYROXENE

The orthopyroxene data presented in this study complements the clinopyroxene data in that equilibration temperature and pressure estimates have been made using the 'enstatite geothermometer' (Boyd and Nixon, 1972). Similar estimates of temperature are obtained from the Di(en)solvus of Davis and Boyd (1966). The Kao orthopyroxene data indicate a range of temperature from 940° to 1420°C and pressures ranging from 43 to 68 kb. These temperatures are remarkably similar to those estimated by means of the 'diopside geothermometer', i.e. 940° to 1450°C. The orthopyroxenes from the Rietfontein heavy mineral concentrates indicate equilibration pressures and temperatures similar to the diopside temperature estimates.

The Koffiefontein orthopyroxene with the exceptionally high Cr_2O_3 content of 0,93% is possibly the only enstatite found in this study which could be described as having a composition similar to the enstatites found as inclusions in diamond.

Orthopyroxene xenocrysts could become more useful than diopside xenocrysts if the 'enstatite thermometer' of Boyd and Nixon (1972) can be shown to be valid by phase equilibrium data. Boyd and Nixon (1973a) have constructed a 'perturbed geotherm' using the data from enstatites which co-exist with ilmenite and they have described a "lherzolite-absent zone" in which many ilmenite-bearing nodules seem to plot. This zone is regarded by Boyd and Nixon (1973a) as being the top of the low-velocity zone in Cretaceous time. Considerably more data will be necessary before this hypothesis can be confirmed or rejected.

4. OLIVINE

The olivines analysed in this study from the Newlands and Rietfontein kimberlites showed considerably smaller ranges of $Mg/(Mg+Fe^{2+})$ ratios than the olivines in the Matsoku xenoliths (Cox et al., 1973; Section VI.4). This is thought to be due to sampling effects because only eleven olivines from the Newlands pipe and ten from Rietfontein were analysed. Thus it would be presumptuous to base any conclusions on these very restricted ranges. The Cr_2O_3 content of the Newlands olivines is a little higher than normal, but many other olivines contain similar amounts of Cr_2O_3. The Newlands olivines are approximately similar in composition to the olivines found as inclusions in diamond, but probably do not contain sufficient Cr_2O_3 to be equated with these olivine inclusions.

The Rietfontein olivines show very little difference in composition from the olivines found in other ultramafic rocks. Thus it is difficult to say more than that they were derived from disaggregated peridotitic xenoliths. This also applies to the Newlands olivines. Considerably more data is required before the narrow ranges of $Mg/(Mg+Fe^{2+})$ ratios can be confirmed. It is most unlikely that the full range of composition of these olivines has been found in either heavy mineral concentrate.

5. CHROMITE

The chromites from the Rietfontein heavy mineral concentrate showed that there was a large range of possible compositions for chrome-rich spinels in this kimberlite, but there was a bimodal distribution. Smith and Dawson (1974) have shown that for kimberlites in general the compositions of chromites were normally distributed. Their observations have been made after considering chromite data from numerous kimberlites from South Africa and Russia. These authors mention that chromite data from widespread localities all seem to plot in a narrow range of composition from $(Mg_2Fe_6^{2+})(Al_{14}Cr_2)$ to $(Mg_3Fe_5^{2+})(Al_1Fe_1^{3+}Cr_{14})$. Thus a trend is shown here which is world wide and from their diagrams it can be seen that no bimodal distribution exists. The bimodal distribution shown in

Figure 35 may thus be a local phenomenon or due to insufficient sampling. The Fe^{2+} and Fe^{3+} content of the Rietfontein chromites is restricted to the range given by Smith and Dawson (1974).

Some of the chromites from the other mines - Newlands, Jagersfontein and Star - are distinctly different in composition to those from Rietfontein because they all have considerably higher Cr_2O_3 contents. Chromites from the Star and Jagersfontein Diamond Mines are generally richer in Fe^{2+} and Fe^{3+} than those found as inclusions in diamond, but these are exceptions. None of the chromites from either of these mines plotted in the diamond inclusion field. The TiO_2 content (2,56%) of a chromite from Blow 144, Lesotho, was too high to permit close comparison with the diamond inclusion chromites, although it plotted very close to the diamond inclusion field (Figure 39). The chromites from Jagersfontein fit in well with the plotted data of Basu and MacGregor (in press), but they do not present the results of the analyses of these chromites, thus making direct comparison with the Jagersfontein chromites difficult.

Two of the chromites from the Newlands mine have been shown to plot in the diamond inclusion field and nine others close to it. The four groups of Newlands chromites - euhedral magnetic and non-magnetic, anhedral magnetic and non-magnetic - overlap considerably in composition, although there are certain differences. The euhedral non-magnetic chromites show a very restricted range of composition very close to the diamond inclusion field, but well within the range of composition of the euhedral magnetic grains. The anhedral non-magnetic chromites at the high Cr_2O_3 levels also plot in a similar position to the euhedral non-magnetic chromites. One of the anhedral magnetic chromites had considerably more Fe present and slightly more TiO_2, similar to the values for some of the euhedral magnetic chromites. The full range of compositions for all these groups has not been determined, but the anhedral magnetic chromites seem to have a much larger range of composition than the others. The chromites co-existing with the clinopyroxene and the green garnets should be considered separately because Smith and Dawson (1974) note that in a group of lherzolites the principal correlation with high Cr content of the spinel is the absence of Ca-rich pyroxene rather than the presence of garnet. N.V.Sobolev et al. (1973) have reported the existence of a peridotite nodule from the Dalnaya kimberlite pipe, Yakutia, containing green, high-calcium, high-chromium garnet and chrome diopside, and Boyd (1973b) has analysed a granular ultrabasic nodule from Letseng-La-Terae, Lesotho, which has moderate-calcium, high-chromium garnet, chrome diopside and chromite.

The chromites in equilibrium with the green garnets from the Newlands mine plot in very different positions compared to the Russian and Lesotho chromites just mentioned (Figures 38 and 39), but the Newlands garnets are higher in Ca and Cr component than either of the Russian or Lesotho garnets (Figures 15 and 17). The chromites in equilibrium with the clinopyroxenes, however, had very high Cr_2O_3 contents ($>60\%$). A comparison of the clinopyroxenes co-existing with these chromites shows that the chromite with the lowest Cr component (Russian) is in equilibrium with the diopside having the highest Ca component (Figure 29), but the chromite with the highest Cr component is in equilibrium with a diopside of considerably lower Ca component. This might have been expected from the Smith and Dawson (1974) correlation. It is difficult to come to any conclusions with regard to the green garnets and co-existing chromites and their relationship with the clinopyroxene and co-existing chromite without further data. It is significant that the nodule in the Dalnaya kimberlite pipe also contained partly serpentinised olivine and the other Russian nodule contained completely serpentinised olivine. The Letseng-La-Terae nodule, however, contains only garnet, diopside and chromite (Bloomer and Nixon, 1973). No nodules have been found at the Newlands pipes with the mineral phases green garnet, diopside, chromite, olivine and orthopyroxene present and if N.V.Sobolev et al. (1973) are correct in formulating the paragenesis of the green garnets, it is unlikely that this assemblage will be found. Xenoliths containing the green garnets and/or high Cr_20_3 chromites have not been found at the Newlands pipes.

Euhedral chromites are rather more plentiful in heavy mineral concentrates than previously suspected. They are not likely to have been derived from chromite-bearing lherzolites because the chromites in these nodules are generally small and anhedral. The large euhedral chromites from the Newlands mine have been found co-existing with a red-purple garnet, as well as the green garnets and a clinopyroxene, as mentioned previously. These chromites have also been found as xenocrysts in the kimberlite itself. Many kimberlites in Lesotho and South Africa have chromites in the heavy mineral concentrates and their importance cannot be overlooked. The minerals found as diamond inclusions are rich in chromium and thus the actual formation of these minerals in equilibrium with the diamond must involve chrome-rich liquids.

Considerably more data on chromites with very high Cr_20_3 content is needed, especially with regard to the association with green garnet, clinopyroxene and olivine, before any definite ideas on their paragenesis can be formulated. Unfortunately the experimental data on chromites is limited and precludes them from being used as reliable indicators of temperature and pressure (Meyer and Boyd, 1972; Smith and Dawson, 1974).

6. SPINEL

The data from the garnet-spinel nodule PJL-13 and the spinel nodule BD1988, when plotted on the Smith and Dawson (1974) diagram (Figure 40), show that these spinels are similar to those found in spinel lherzolite xenoliths which are inclusions in basalt (Basu and MacGregor, in press). The variation in composition of spinel nodule BD1988 from the Roberts Victor mine in different sections of the nodule is marked with respect to Cr, Al and Fe content. The analyses of the garnet inclusions and the 'garnet-olivine' inclusion show that these garnets are eclogitic in nature and no different in composition, although some 5 cm apart (Figures 23, 24 and 41). The 'garnet-olivine' inclusion is a central core of olivine and an outer rim of garnet completely enclosing the olivine. The whole inclusion is enclosed in the spinel matrix.

The garnet-spinel nodule PJL-13 from the Bobbejaan fissure is remarkably similar to the garnet-spinel nodules JJG294 and 295. The compositions of these two latter nodules are given in the Guide for the First Field Excursion of the International Conference on Kimberlites (1973). Neither of these nodules show any Fe^{3+} component and they are more Al-rich than PJL-13. Recalculation of these analyses using FERRIC (Finger, 1972) showed no Fe^{3+} component to be present, which is unusual but possible. The garnets JJG294 and PJL-13 differ in FeO, Al_2O_3 and CaO content, but not markedly. Garnet JJG295 is markedly different to PJL-13 and JJG294, having more CaO, less MgO and less Al_2O_3, but all these garnets are eclogitic in nature.

Both the Bobbejaan Mine and the Roberts Victor are known for the preponderance of eclogite xenoliths over peridotite nodules and from the Al_2O_3 content of the spinel it is not surprising that the garnets associated with these nodules are eclogitic as opposed to peridotitic.

In the nodule PJL-13 there are a number of sulphide minerals included in the spinel. These sulphides are thought to be primary. Electron microprobe X-[illegible] images have been produced and show in one case that complex intergrowths are present. Close to the spinel-sulphide boundary there is a Cu-Fe-rich sulphide intergrown with Mg-Al-Fe silicate. Outside this Cu-rich sulphide-silicate zone there is an Ni-Fe sulphide which makes up most of the sulphide. There is a similar intergrowth around an unidentified Ca-Mg-Al silicate inclusion in the same Ni-Fe sulphide phase with the inner Ca-Fe-rich sulphide rim. Such intergrowths are not uncommon in eclogite nodules (Bishop et al., 1974; Desborough and Czamanske, 1973).

7. RUTILE

Niobium-bearing rutiles have been found in the Rietfontein and Kao heavy mineral concentrates. These rutiles were identified by X-ray diffraction methods. The rutile from the Rietfontein kimberlite was analysed using standard X-ray fluorescence methods. This rutile contained 12,960 ppm niobium and 1600 ppm zirconium (H.S. Smith, personal communication, 1973). The rutile from the Kao kimberlite pipe has not been analysed, but the X-ray diffraction data is very similar to the Rietfontein data. Niobium-bearing rutiles have not been reported from kimberlites, as far as is known, but F.R. Boyd has found similar levels of niobium in a rutile from one of the Lesotho kimberlite pipes (personal communication to J.B. Dawson).

These rutiles are likely to have been derived from disaggregated eclogite xenoliths because eclogites are known to contain rutile as a primary phase (Rickwood et al., 1969). Little is known about the trace element contents of kimberlitic rutiles, but these rutiles may be one of the sources of niobium in the upper mantle.

8. FURTHER DISCUSSION

Cox, Gurney and Harte (1973) have reported the compositions of the minerals forming a suite of peridotite-pyroxenite xenoliths from the Matsoku kimberlite pipe, Lesotho. The minerals forming these xenoliths have a wide range of composition; for example, the $Mg/(Mg+Fe^{2+})$ ratio for the garnets varies from 85,6 to 69,8; for the clinopyroxenes from 94,7 to 84,2; for the orthopyroxenes from 93,8 to 85,6; and for the olivines from 94,8 to 83,6. It has been suggested that the Matsoku kimberlite pipe is unusual because of these wide ranges of composition and that the xenoliths, some of which are sheared, do not fall in the 'sheared lherzolite' limb of the 'perturbed geotherm' (Boyd, 1973a).

The garnets from the Matsoku xenoliths have a range of $Mg/(Mg+Fe^{2+})$ which is similar to that shown by the Koffiefontein garnets: 89,8 to 70,5 (Tables 15, 16 and 17). If a Ca-Mg-Fe ternary diagram is used as a basis for comparison, the Matsoku garnets (Figure 24 in Cox et al., 1973) and the Koffiefontein garnets show very little difference in composition (Figure 14).

The clinopyroxenes in these xenoliths have a range of Ca/(Ca+Mg) ratios from 45,3 to 44,4, which is within the ranges shown by the 'calcic' diopsides from both the Kao and Premier heavy mineral concentrates. The estimated temperature of equilibration for the Matsoku clinopyroxenes is 1050°C (Cox et al., 1973).

The orthopyroxenes from the Kao heavy mineral concentrate have a larger range of Al_2O_3 and Cr_2O_3 contents than the orthopyroxenes in the Matsoku peridotite-pyroxenite suite, as well as a larger range of $Mg/(Mg+Fe^{2+})$ ratios. The values are 94,1 to 83,4 for Kao and 93,8 to

85,6 for the Matsoku orthopyroxenes.

The only Matsoku mineral compositions which do not have equivalents in the heavy mineral concentrates are the iron-rich clinopyroxenes, garnets and olivines, e.g. the garnets from LBM18 and 11102 and the diopsides from LBM18 and 11102. The Matsoku olivine data cannot be compared with the data from this study because few olivines were analysed and they were chosen at random from the heavy mineral concentrates. The xenoliths LBM18 and 11102, however, represent extreme compositions in this xenolith suite. The garnet data from the Rietfontein kimberlite pipe indicates that the iron-rich compositions of the garnets LBM18 and 11102 may have equivalents in the Rietfontein heavy mineral concentrates (Figure 22). The absence of these iron-rich minerals at these localities is not surprising because in this study comparatively few diopsides have been analysed from any one kimberlite and most of the garnets analysed were selected as possible low-calcium, high-magnesium garnets, which have high $Mg/(Mg+Fe^{2+})$ ratios.

VIII CONCLUSIONS

This study has shown that a number of minerals of unusual composition have been found in the heavy mineral concentrates of various kimberlite pipes. The range of compositions of some of these minerals has been extended and in some cases minerals, which were unknown in Southern African kimberlites, have been found.

Low-calcium, high-magnesium garnets, which have similar compositions to the garnets found as inclusions in diamond, are present in the heavy mineral concentrates of the Bobbejaan, Kao, Koffiefontein, Newlands, Premier and Sekretariskop pipes or dykes.

Two different species of green garnet have been found in the heavy mineral concentrates from the Newlands kimberlite pipes. One of these species is a high-calcium, medium to high chromium, mauve-green, alexandritic garnet which is very similar in composition to the green garnets found in grospydite xenoliths in Yakutian kimberlites (N.V. Sobolev et al., 1968). Thus it is likely that this Newlands garnet has been derived from a similar xenolith. The second species of garnet are high-calcium, high-chromium, deep green garnets which have been found as xenocrysts, in situ, in the kimberlite; as xenocrysts in the heavy mineral concentrates; and co-existing with chromites.

Besides the garnets with compositions similar to those found as diamond inclusions, a garnet from the Premier Mine has been shown, in terms of its Ca, Mg and Cr contents only, to have a composition similar to the unusual diamond inclusion garnets from the Udachnaya kimberlite pipe, Yakutia (N.V. Sobolev et al., 1970). None of these high-calcium garnet species have been reported from Southern African kimberlites until now.

Diopsides from the Kao kimberlite pipe have been shown to have compositions as yet unreported. These diopsides have very low Ca/(Ca+Mg) ratios and can be considered as having been derived from both sheared garnet lherzolite xenoliths and clinopyroxene discrete nodules if the terminology of Nixon and Boyd (1973b) is used.

The Premier Diamond Mine has been shown to have similar diopsides to the ones just described in the Kao heavy mineral concentrate. Subcalcic diopsides have not been reported from this mine previously and these diopsides are important to the interpretation of the model for the mantle beneath Lesotho proposed by Boyd (1973a).

Two diopsides from the Newlands kimberlite pipes have more than 3,5% Cr_2O_3 present, which is higher than most kimberlitic diopsides reported previously. One of these Newlands diopsides has more than 4% Cr_2O_3, which is an exceptionally high amount.

The orthopyroxenes from the Kao kimberlite pipe may be used to estimate temperatures and pressures of equilibration if certain assumptions are made and the enstatite geothermometer is used (Boyd and Nixon, 1972). The results show that sheared garnet lherzolites must be present at Kao because most of the orthopyroxene xenocrysts analysed, equilibrated at temperatures of $\pm$ 1400°C and pressures of $\pm$ 60 kb. These estimates complement the diopside data from this pipe.

One of the orthopyroxene xenocrysts in the Koffiefontein heavy mineral concentrate has a Cr_2O_3 content of 0,93%, which is similar to the amounts of Cr_2O_3 in the enstatites found as diamond inclusions. The composition of this enstatite is very similar to those of diamond inclusion enstatites.

Chromites containing more than 60% Cr_2O_3 are more common in kimberlitic heavy mineral concentrates than suspected previously. One has been found in the Jagersfontein concentrate and twenty-six have been found in the Newlands concentrates. Two more chromites co-existing with clinopyroxenes also contained more than 60% Cr_2O_3. Of these twenty-six chromites, two plotted inside the diamond inclusion field and another nine very close to it.

Spinel nodule BD1988 has garnet inclusions, including one completely enclosing olivine, which have compositions similar to eclogite garnets. The spinel nodule itself has a variable composition over a distance of 10 cm and is similar to the composition of spinels in spinel lherzolites found as inclusions in basalt.

A rutile containing 1,3% niobium and 0,16% zirconium was found in the heavy mineral concentrate of the Rietfontein pipe. Another rutile from the Kao kimberlite pipe has been identified as a niobium-bearing rutile by X-ray diffraction methods.

The compositions of the minerals forming the peridotite-pyroxenite xenoliths of the Matsoku kimberlite pipe are similar to the compositions of xenocrysts from various kimberlites. Hence the wide range in composition for the minerals of the Matsoku peridotite-pyroxenite xenoliths is not unusually large.

This study of kimberlitic xenocrysts has proved to be very fruitful because it has been shown that minerals previously unknown in Southern African kimberlites have been found and proved to be of unusual composition. Xenocrysts are far easier to obtain than xenoliths and thus afford more scope in determining the range of composition of the various minerals present in kimberlite as xenoliths or xenocrysts. Comprehensive studies of the xenocryst suites of many kimberlites are needed so that the relative proportions of the minerals be known and the full ranges of composition of the minerals may be determined. The data presented in this study has shown that most of the xenocrysts examined can be regarded as being derived from disaggregated peridotitic or eclogitic xenoliths and others from disaggregated discrete nodules.

ACKNOWLEDGEMENTS

I am indebted to a number of people, including my colleagues in the Geochemistry Department at the University of Cape Town for their help and guidance without which this thesis could not have been completed.

In particular I would like to acknowledge the assistance of the following, with grateful thanks:

Prof. L.H. Ahrens, for permitting me to work on this project;

J.J. Gurney, for suggesting the project, for his unfailing help, encouragement, guidance, patience and supervision throughout the project and for many of the samples examined;

J.B. Hawthorne, de Beers Consolidated Mines Limited, Kimberley, for many of the samples examined, for information on numerous kimberlites, for his help and much hospitality during visits to Kimberley and for pointing out that green garnets were to be found at the Newlands kimberlite pipes;

J.B. Dawson of the University of St. Andrews, Scotland, for permitting me to work on the spinel nodule BD1988 and his guidance, wide experience and many thought-provoking suggestions during field excursions and throughout his stay in South Africa;

A.R. Duncan, for his instruction on the use of his computer programmes PRTAPE, TAPEREAD and PRDAT and for his help and suggestions in all matters pertaining to the use of the computer;

R.S. Rickard, for his instruction on the use of the electron microprobe and for proof-reading much of this thesis;

J.P. Willis, for his help and advice on the quality of the data and methods for improving it;

A.J. Erlank, for his interest and helpful suggestions which were often a source of inspiration;

H.S. Smith, for the use of his computer programme TRIPLOT which was used to plot the ternary diagrams in this thesis and the analysis of the niobium-bearing rutile;

Mrs. A. Borchers of de Beers Consolidated Mines Limited, Kimberley, for first suggesting the existence of the green garnets at the Newlands kimberlite pipes;

C.R. Clement of de Beers Consolidated Mines Limited, Kimberley, for his help and hospitality during visits to Kimberley;

O. Carlstein of the Bobbejaan Diamond Mine, for his help in the collection of unusual specimens and for his hospitality;

H.S.A. du Plessis and W.A. du Plessis, for permitting access to the Newlands kimberlite pipes;

J. Appollis, for his help in the production of the thesis;

Mrs. S.C. Davids, for drafting many of the diagrams and her help at all times;

Assoc. Prof. A.O. Fuller, for the use of darkroom facilities;

R. Mitchell, for carbon-coating many of the grain mounts;

Mrs. M.J. Reichardt, for her expert typing of this thesis and her unfailing patience, encouragement and good humour throughout a trying period, without which this thesis might never have been completed;

Miss M.K. Sher, for assistance in sorting some of the concentrates;

J. Williams, for his help in the preparation of the ternary diagrams;

D. Wilson, for preparing the polished grain mounts and thin sections;

The Council for Scientific and Industrial Research for financial support during this project.

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