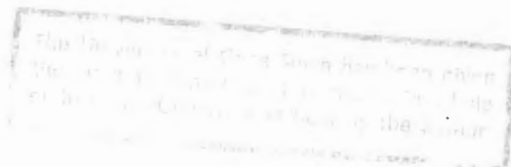


SURFACE TEXTURES AND OTHER FEATURES  
OF DIAMONDS

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A dissertation submitted to the University  
of Cape Town in part fulfilment of the  
requirements of Doctor of Philosophy.

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FOREWORD

Four papers embodying portions of the work presented here have been published in the scientific literature. These papers are:-

- i) Robinson, D.N. (1975) Abrasion features of diamond from the Lichtenburg and Wolmaranstad Diggings, Transvaal. Extended Abstracts, Diamond Conference, Cambridge, 1975.
- 2) Robinson, D.N. (1978) A review of the characteristics of natural diamond and their interpretation. Minerals Sci. Engng., 10, 55-72.
- 3) Robinson, D.N. (1979) Diamond and graphite in eclogite xenoliths from kimberlite. In: The Mantle Sample: Inclusions in Kimberlite and Other Volcanics (editors F.R. Boyd and H.O.A. Meyer), 50-58. Am. Geophys. Union, Washington.
- 4) Robinson, D.N. (1979) The development of diamond characteristics. Extended Abstracts, Kimberlite Symposium, Cambridge, 1979.

Studies of the abrasion features displayed by diamonds progressed after publication of 1) above and revised conclusions are reported here. Some of the conclusions attained in publication 3) above are also revised slightly, in the light of subsequent observations. Publication 2) above represents the culmination of the author's reading of scientific papers mostly indirectly related but, nevertheless, relevant to the subject of this dissertation.

ABSTRACT

The results of the study of more than 11 000 diamonds, from thirty kimberlite and placer deposit localities, are reported.

Forty one pristine surface textures are distinguished, including twelve which are described for the first time. Only two surface textures are ascribed to crystal growth. The others are considered to result from crystal resorption and etching although internal features, such as growth stratification and dislocation planes, are expressed in some cases. The results of etching experiments on diamond are reviewed. Oxidation is considered to be responsible for most of the resorption and etching of diamonds in nature and neither pure graphitization nor dissolution appears to be important. A high-temperature regime of oxidation can be distinguished from a lower-temperature regime. Crystal resorption and negatively-oriented etch pits result from the high-temperature oxidation. Steam and wet carbon dioxide gas, at temperatures above 950°C, are probably responsible and nearly all diamonds are affected. Resorption generally produces the tetrahexahedroid form (i.e. the rounded dodecahedron of other writers) but a much less common, approximately dodecahedral form may also result, apparently if the oxidant is depleted. Free oxygen seems to be necessary for the relatively low-temperature (down to 450°C) etching of diamond. Few diamonds display any of the positively-oriented etch features which typify low-temperature etching.

A positive correlation is demonstrated between the proportion of diamonds exhibiting octahedral or cubic surfaces and the amount of diamond in the host kimberlite. This correlation substantiates the hypothesis that the tetrahexahedroid is a resorption form of the octahedron and the cube. It is shown that the conversion, by resorption, of an octahedron to a simple tetrahexahedroid involves a minimum mass

loss of approximately 45 per cent. Even more may be lost during the conversion of a cube to a tetrahexahedroid.

A surface texture (lamination lines) which is considered to reflect the plastic deformation of diamond, was found to be common in most diamond samples. It is argued that diamonds which display this texture must be xenocrysts with respect to kimberlite. It is also argued that paired pseudohemimorphic crystals and crystals of approximately dodecahedral form (and/or displaying surface textures, such as knob-like asperities, which are associated with this form), which together constitute a few per cent of the diamonds in some kimberlites, must be xenocrysts. The mixed character of individual, kimberlitic diamond populations further favours the hypothesis that the mineral is predominantly xenocrystic. Rare type Ib diamonds are the only examples likely to be phenocrysts.

The sequence of the events which may affect diamonds is deduced. At some, possibly lengthy, interval after crystallization, some diamonds are plastically deformed. Most diamonds are then partly resorbed and etched by high-temperature oxidation within ascending kimberlite magma. Subsequently, some diamonds are slightly damaged by frictional contact with other materials and then a few are etched at a relatively low temperature. The resorption and high-temperature etching probably commences at depths shallower than about 100 km and is completed by the time kimberlite magma enters the root zones of diatremes. Most breakage of diamond crystals occurs during the final stages of high-temperature etching.

The diamonds of seventeen eclogite xenoliths were studied. The diamond content of some of the xenoliths is substantial and the disintegration of eclogitic material can account for considerable proportions of the diamonds in some kimberlites. All of the differences between the diamonds

in eclogite xenoliths and in kimberlites are consistent with the more limited access of oxidizing fluids to the diamonds in the xenoliths. A range in temperature during the crystallization of the diamond is indicated in some eclogite, while the thermodynamic "boundary" between graphite and diamond was apparently crossed during the crystallization of carbon in diamond-graphite eclogite. In some of the xenoliths there is evidence that the diamond and graphite crystallized from a liquid.

Diamonds were studied from thirteen kimberlite localities, including pipes and a dyke. Similarities in diamond characteristics indicate that diamond crystallized under a similar range of conditions and experienced a similar variety of post-genetic conditions, in most of the kimberlites. Some kimberlitic diamond populations have unique characteristics, however, while subtle differences are generally evident between populations. Comparing the characteristics of the diamonds of particular kimberlite bodies within single pipes suggests the following:-

- i. In some pipes, two or more kimberlite types may represent a single intrusion.
- ii. An individual kimberlite type may represent a pulse of magma which separated, from other magma emplaced into the same pipe, at either a shallow depth or some depth possibly as great as 100 km.
- iii. In rare cases a kimberlite type arose separately, from the earth's mantle, from other kimberlite emplaced into the same pipe.

Separate origins are indicated for the kimberlites filling spatially associated pipes at two localities.

The presence of abraded diamonds in two kimberlite pipes is noted. It is possible that some diamonds are abraded during the formation of epiclastic kimberlite at pipe vents.

Diamonds were studied from nineteen alluvial and littoral deposits. The majority of detrital diamonds are clearly derived from kimberlites while a minority are possibly derived from carbonatites. Diamond abrasion textures are described. Abrasion involves the development of percussion cracks and spall scars. These features are strongly concentrated at crystal corners, edges and asperities where ground and polished surfaces may develop. Subaqueous collisions between diamond and bedrock are considered to be responsible for most of the abrasion observed and the role of pot-holes is emphasized. Six degrees of abrasion are defined for diamonds which exhibit the tetrahexahedroid form.

Comparisons between the diamonds in some placer deposits and in some kimberlites allow the following deductions:-

- i. The Main Fissure near Swartruggens is probably not a source of any of the diamonds deposited near Boskuil and cannot be more than a minor source of the alluvial diamonds from Lichtenburg.
- ii. Most of the diamonds at Hlane, in Swaziland, are probably derived from the Dokolwayo Pipe.
- iii. In Namaqualand and adjacent areas, essentially the same diamond populations which are present in particular river valleys are also represented in littoral deposits situated near to the river mouths. Two main diamond populations are represented in the area. One of these predominates in the north and the other predominates in the extreme south. Other populations are locally important, as among the deposits in the vicinity of the Buffels River. Most of the abrasion of the diamonds occurred during their coastward transportation in westward-flowing rivers. The diamonds are derived mainly from the hinterland of the region, rather than from the

distant interior of the sub-continent. Evidence is presented which suggests that some of the diamonds are from pre-Cretaceous kimberlites.

- iv. The diamonds in the Macquarie River near Wellington, New South Wales may be derived from the same source as supplied the diamonds to deposits in the Bingara-Copeton area, 300 km north-east of Wellington.

It is considered that a deformation event is responsible for most of the brown colours of diamonds.

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## 1. INTRODUCTION

Diamond is highly valued both as a gem and for industrial use. Its value as a gem results from its optical properties (transparency, high refractive index giving a low angle of total reflection, and moderately high dispersion), its extreme physical and chemical durability and its rarity. The industrial value of diamond is a consequence of its extreme hardness and chemical inertness as well as its considerable thermal conductivity. Diamond is the hardest substance known, is chemically inert at temperatures below about 450°C and is the best known thermal conductor at room temperature (De Beers Industrial Diamond Division, 1976). The last-mentioned property minimizes damage by burning or thermal fracture (Ditchburn and Custers, 1965) and also finds direct application in industrial heat sinks.

Diamond is the tetrahedrally bonded form of carbon. Other allotropes are graphite, carbyne and a probable metallic form (Wedlake, 1974). Amorphous carbon consists of mixtures of condensed aromatic structures and is not strictly an allotrope (Wedlake, op.cit.). Since tetrahedral arrangements of carbon atoms can be linked in two ways, two polymorphs of diamond are possible. One is cubic diamond and the other is a hexagonal form, termed lonsdaleite, which is structurally similar to wurtzite. Lonsdaleite is known only in association with diamond in some meteorites (Hanneman, Strong and Bundy, 1967), at the site of a meteorite impact in graphite-bearing country rock in Russia (Vishnevsky and Paltchik, 1975) and, rarely, in placer deposits (Sokhor, Polkanov and Yeremenko, 1973). Lonsdaleite is not included in the present study.

The diamond-graphite equilibrium is the only portion of the

carbon phase diagram which need be considered here. This equilibrium (Berman, 1979) and estimates of the variation of temperature with depths beneath continental shield and oceanic regions, respectively (Harte, 1978), are depicted in Figure 1. It is apparent, from Figure 1, that the depth beneath which diamond, rather than graphite, should be the stable form of free carbon depends upon prevailing temperature, being approximately 154 km beneath shield areas and 160 km beneath ocean basins assuming the geothermal gradients shown. Should diamond crystallize out of magma, then rock solidus requirements impose a minimum depth limit for diamond genesis which may be deeper than that imposed by consideration only of the local geothermal gradient. Such a case is illustrated in Figure 1 for the possible crystallization of diamond from anhydrous eclogite magma.

Both diamond and graphite exhibit considerable metastability and each, once formed, does not readily revert to the other phase (Dickinson, 1970, p. 76). According to Evans (1976), the rapid graphitization of diamond requires temperatures in excess of 1 500°C under vacuum and higher temperatures under pressure. At 1 200°C under vacuum, graphitization should not be detectable for at least a year (Evans, *op.cit.*).

Diamond can be oxidized at temperatures above 450°C (De Beers Industrial Diamond Division, 1976). It is therefore necessary to consider the stability of diamond in the presence of oxygen. Woermann et al. (1977) have determined an expression which relates oxygen fugacity, temperature and pressure at the conditions of equilibrium between free carbon and carbon oxide gas. Rosenhauer et al. (1977) utilized this expression to plot the carbon-carbon oxide gas equilibrium at the temperature-depth conditions of a Cretaceous geothermal gradient postulated by Boyd and Finger (1975). Assuming an upper

mantle buffered at one log unit less than the fayalite-magnetite-quartz buffer, Rosenhauer et al. (op.cit.) demonstrated a maximum depth (approximately 180 km) beneath which conditions would have been too oxidizing for the formation or preservation of diamond.

Diamond is present in some meteorites (see Vdovkykin, 1967) and has been reported from rocks such as dunite (Pavlenko et al., 1974) and basalt (Kutyev and Kutyeva, 1975). The only terrestrial igneous rock known to ever contain substantial amounts of diamond, however, is kimberlite and it is generally assumed (e.g. Williams, 1932, p. 546) that the diamond in detrital deposits is derived from kimberlite. Minimum depths of origin, as estimated from the mineral characteristics of garnet peridotite and spinel peridotite xenoliths, exceed 160 km for diamond-bearing kimberlites (e.g. Boyd and Nixon, 1975; MacGregor, 1975; Danchin and Boyd, 1976). Depth estimates based on the xenoliths from some non-diamondiferous kimberlites (MacGregor, op. cit.), a carbonatite (Reid et al., 1975) and various basalts (MacGregor and Basu, 1974) are generally shallower. Diamond may therefore be virtually restricted to kimberlite, amongst igneous rocks, because only kimberlite originates at depths sufficient for diamond genesis. In addition to occurring in kimberlite matrix, diamond is also present in some eclogite xenoliths (see Robinson, 1979) and, less commonly, in some peridotite xenoliths (Dawson and Smith, 1975; McCallum and Egglar, 1976; Pokhilenko, Sobolev and Lavrentiev, 1977).

Two main types of diamond, known as type I and type II, can be distinguished by their spectral properties (Robertson, Fox and Martin, 1934). Type I diamond absorbs ultraviolet radiation of wavelength less than 330 nm and absorbs infra-red radiation of 7 to 10  $\mu$ m wavelength. Type II diamond transmits ultra-violet radiation down to about 220 nm, and transmits 7 to 10  $\mu$ m infra-red radiation. The

absorption at 7,8  $\mu\text{m}$  correlates with nitrogen content (Kaiser and Bond, 1959; Lightowers and Dean, 1964). Type I diamond contains substantial nitrogen (up to 0,3 per cent) while type II contains little. Differences in electrical and magnetic properties allow subdivisions of the type classification. Most type I diamond is designated type Ia but rare samples are paramagnetic, on account of nitrogen as single, substitutional atoms (Dyer et al., 1965) and are designated type Ib. Most type II diamond is classified as type IIa but rare examples are electrical semi-conductors, apparently on account of boron impurity (Chrenko, 1971), and are designated type IIb. Differences which are apparent between diamonds of the different types are summarized in Robinson (1978). Points worth noting are that only type Ia diamond usually occurs as well-formed crystals, type I diamond exhibits relatively poor cleavage and type II diamond deforms plastically more easily. The vast majority of natural diamonds are of type Ia (Dyer et al., op.cit.) while synthetic diamonds are usually of type Ib. It should be noted that the distinction between diamond types is not always clear-cut. Diamonds of transitional type and of mixed types also occur.

Orlov (1977, pp. 4-19) recognizes ten "varieties" of natural diamond. Each variety is supposed to be distinctive in terms of its structure (e.g. single crystal, radially-fibrous aggregate, crypto-crystalline aggregate), crystal growth form, internal stratification and impurity centres. The classification is typomorphic in that it is meant to reflect genetic features. The effects of secondary processes are therefore ignored excepting insofar as they might aid in recognizing internal features produced during crystal growth. Features considered, by Orlov, to result from secondary processes include smoky brown discolouration and a curve-faced crystal form. Ten diamond varieties are recognized by Orlov. Five of these occur as single

crystals (and occasional aggregates of a few individuals) and five occur as polycrystalline aggregates. The main characteristics of the five varieties of diamond single crystal are as follows:-

Variety I Nitrogen-containing crystals derived from colourless to yellow, plane-faced or stepped octahedra. Nearly all of the nitrogen occurs as associated atoms but a very small proportion is in the form of isolated atoms.

Variety II Nitrogen-containing crystals derived from characteristically amber-yellow to green plane-faced cubes. Most of the nitrogen occurs as associated atoms but a substantial proportion, up to a per cent, is in the form of isolated atoms.

Variety III Nitrogen-containing crystals derived from cubes and cubo-octahedra which are colourless but contain abundant, microscopic inclusions in their outer parts. The nitrogen is in the form of associated atoms.

Variety IV Variety I crystals which are coated by characteristically yellow to green diamond containing nitrogen only (?) in the form of isolated atoms.

Variety V Nitrogen-containing crystals derived from colourless octahedra rendered black in their outer parts by abundant, syngenetic inclusions of graphite. The mode(s) of occurrence of the nitrogen has not yet been firmly established.

The varieties of polycrystalline aggregate distinguished by Orlov include ballas (variety VI), a coarse-grained (4 to 5 mm) aggregate of yellow octahedra (variety VII), a fine-grained aggregate of colourless octahedra grouped about a dark, granular core (bort, variety VIII), a dark, granular aggregate of fine-grained, irregular crystals (bort, variety IX) and carbonado (variety X).

Orlov's (op.cit.) variety I diamonds are predominantly of type Ia but include occasional type Ib, type IIa and intermediate types. This variety predominates in most deposits. Variety II crystals are typically of type Ib, as is the case of variety IV crystals, while variety III crystals are of type Ia. From a geological standpoint, Orlov's typomorphic classification scheme is preferable to the "type" classification for diamond. Some revision of Orlov's scheme may, however, be necessary. For example, the distinctive, type IIa and type IIb diamonds found in some Southern African deposits probably warrant the recognition of at least another variety of diamond.

Many scientific papers have been published which deal with aspects of diamond such as its modes of occurrence, thermodynamic stability, crystal form, colour, properties in the non-visible electromagnetic spectrum, trace element impurities, mineral inclusions, isotopic composition and individual surface textures. This literature is reviewed in Orlov (1977) and in Robinson (1978). With the exception of Orlov's (op.cit.) treatise, in which a large variety of surface textures are described, diamond surface textural studies have concentrated on a few specific features and, as far as the author is aware, no comprehensive list of textures has ever been compiled.

Wagner (1914), Williams (1932), Cotty and Wilks (1971) and Grantham (1974) qualitatively distinguished between diamonds from different localities. They used criteria such as the predominating colour or crystal shape and the presence of unusual characteristics in some samples. Sutton (1928), Orlov and Prokoptchuk (1965), Polkanov (1967), Gorina (1971), Harris et al. (1975) and Harris, Hawthorne and Oosterveld (1979) have quantitatively categorised certain diamond populations. Incidences of occurrence of different crystal shapes and colours were used. Only in the investigation by Gorina (op.cit.) was



## 2. AIMS OF THE INVESTIGATION

The main aim of the present investigation is to classify diamond surface textures and to describe and explain each texture distinguished.

Subsidiary aims include the following:-

- i. To characterize the diamonds of each sample examined, according to the distributions of individual surface textures and other features such as colours, crystal forms (including subordinate forms) and degrees of crystal regularity.
- ii. To elucidate diamond crystallization and post-crystallization conditions in kimberlitic deposits.
- iii. To test whether or not the characteristics of diamond samples are related to the amounts of diamond present in kimberlites.
- iv. To determine whether or not particular kimberlites supplied diamonds to some detrital deposits.
- v. To delineate the dispersal(s) of the diamonds in some spatially-associated detrital deposits.

The basic data were gathered by documenting individual diamonds in terms of the features mentioned in i) above. Aims ii) to iv) utilize the data satisfying aim i). Aim ii) is based on observed and deduced age relationships between features and upon consideration of experimental and other evidence for the causes of certain features.

Colour and main crystal form constitute the bases of the diamond classification schemes of Harris et al. (1975) and Harris, Hawthorne and Oosterveld (1979). These investigators also studied some of the samples examined by the author. Part of the present study thus complements and expands some of the earlier work of Harris and co-workers.

### 3. SAMPLES STUDIED AND METHODS USED

More than 11 000 diamonds were studied from a total of thirty deposits. Samples are included from kimberlite pipes, from a constricted kimberlite pipe, from a kimberlite dyke and from alluvial gravels and marine terrace gravels. In some cases, separate samples were examined from different kimberlite types within a single pipe. Southern African localities predominate among the samples but small samples from the U.S.S.R., the U.S.A. and Australia are included.

In view of variations noted by Harris et al. (1975) in colour and crystal form as a function of crystal size, the decision was made to restrict the present study, wherever feasible, to diamonds of a particular size. This expedited direct comparisons between samples. The minus 11 plus 9 diamond sieve class was chosen as diamonds of this size are a major component of most deposits. They are also large enough for examination under a binocular microscope and small enough to be examined in a scanning electron microscope. Diamonds of the minus 11 plus 9 sieve class pass through a circular aperture of 3,45 mm diameter but not through one of 2,85 mm. They range between approximately 0,17 and 0,32 carat (1 carat = 0,2 g) and average about 0,23 carat in mass. In some cases only diamonds of other sieve classes were available for examination. Aperture diameters of the diamond sieves used and the mass characteristics of diamonds in the various diamond sieve classes are given in Table 1.

Sample particulars are summarized in Tables 2 and 3. In addition to the diamond samples listed in these tables, special studies were also made of other diamonds (and associated graphite) from eclogite xenoliths and of some natural and synthetic diamonds

which had been subjected to laboratory experiments.

Individual diamonds were examined under a binocular microscope, at various magnifications up to 80 times. Approximately 5 per cent of the diamonds in most kimberlitic samples and 10 per cent of those in detrital samples exhibited features which could not be adequately resolved by this technique. Wherever feasible, such examples were also examined in a JEOL JSM-35 scanning electron microscope. In addition to high magnification capability (up to 100 000 times) and high resolving power (10 nm), considerable depth of focus can be obtained in the scanning electron microscope and this capability was also utilized in photography at low magnifications. Most of the diamonds examined had already been cleaned by boiling in hydrochloric and hydrofluoric acids. Diamonds examined in the scanning electron microscope were also ultrasonically cleaned in a solution of "Decon 75" surfactant. They were then mounted on brass specimen stubs, using colloidal silver solution as adhesive, and coated with approximately 20 nm thick coatings each of carbon and gold. Coatings were applied in a JEOL JEE-4B vacuum coating unit fitted with a tilt-rotation stage. Unless otherwise stated, all photographic illustrations presented in this dissertation are scanning electron micrographs.

#### 4. DIAMOND COLOURS

Impurities may cause absorption in the visible spectrum and, hence, colour in diamond. Yellow is imparted by absorption in the violet, brown by absorption in the blue-green (Bruton, 1978, p. 413) and red or mauve by absorption in the yellow-green part of the spectrum (Custers, 1958).

Harris et al. (1975) noted that the main body colours of diamonds are colourless, yellow and brown. This was substantiated by the present study with other colours such as green, mauve, orange, grey and black being rare or absent in the samples studied. The various colours of diamond grade imperceptibly into one another and some subjectivity is unavoidable in the colour classification of samples of diamond.

##### 4.1. COLOURLESS

Diamond containing very little nitrogen impurity (i.e. type II diamond) is often colourless. Many diamonds which contain substantial nitrogen impurity are also colourless.

The nitrogen in nitrogen-bearing, colourless diamond does not occur as single, substitutional atoms. Instead, it is associated with submicroscopic platelets interstitial to the diamond lattice, resulting in absorption in the ultraviolet region which does not affect colour (Bruton, 1978, p. 411). The platelets may consist of carbon atoms, displaced by substitutional pairs of nitrogen atoms, rather than of nitrogen itself (Evans, 1973; Woods, 1976). In nitrogen-bearing diamond synthesized in the laboratory, most of the nitrogen is in the form of single, substitutional atoms, and platelets are not developed (Samoylovich et al., 1973). Such diamond

is coloured. The platelets in natural diamond have been attributed to post-crystallization diffusion of single, substitutional nitrogen atoms during millenia while diamond was held at high temperature (Dyer et al., 1965), or to the very slow growth of natural diamonds (Samoylovich et al., op.cit.). Experiments by Chrenko, Tuft and Strong (1977) support the former suggestion. These experiments indicate that at 1 300°C the diffusion of nearly all single, substitutional nitrogen atoms into other sites should occur in approximately four years.

Lack of colour in diamond is probably a consequence of crystallization conditions in some cases (colourless type IIa diamond) and of post-genetic processes in other cases (colourless type Ia diamond). According to Evans (1976), diamond held at temperatures higher than 1 200°C at atmospheric pressure will show evidence of graphitization within less than a year. Since colourless type Ia diamond displays no evidence of graphitization, any high temperature, prolonged process by which its original colour may have been modified must have occurred at high pressure.

#### 4.2. YELLOW

Yellow colour in diamond is related to nitrogen impurity and all yellow diamonds are of type I.

Canary yellow and amber are the typical colours of type Ib diamond (Harris et al., 1975). These colours are caused by nitrogen in the form of single, substitutional atoms and they fade if the mode of occurrence of the nitrogen is changed (Chrenko, Tuft and Strong, 1977). Most synthetic diamond is yellow and of type Ib and the form of nitrogen present must be incorporated during crystal growth. The survival of single, substitutional nitrogen atoms in

natural, type Ib diamond implies that such diamond did not experience prolonged residence at high temperature.

Light yellow (the "Cape" of the Diamond Trade) in diamond has been attributed, by Loubser and Wright (1973), to nitrogen occurring partly as substitutional, nearest neighbour aggregates of three or more atoms in type Ia diamond. The conditions required to produce such nitrogen are not known. It is also possible that some light yellow, predominantly type Ia diamond owes its colour, to a small amount of the nitrogen being present as single, substitutional atoms.

#### 4.3. BROWN

Brown, as used here, includes colours tinged pink or mauve. Both type I and type II diamonds may be brown.

Brown colour in diamond has been attributed to submicroscopic regions of graphite localized at epigenetic glide planes (Urusovskaya and Orlov, 1964). In support of this conclusion, it will be demonstrated in Chapter 18 that a surface texture considered to reflect internal gliding is particularly common among brown diamonds. It will also be argued (in Article 6.5.2.) that glide planes are likely to develop in diamond only at high temperature and high pressure. Since graphitization is favoured by high temperatures and low pressures (see Figure 1), the intensity of brown colouration might reflect the relationship between temperature and pressure at the time the colour is imparted.

Some brown diamonds have been shown to contain particularly high levels of trace element impurities, such as iron, aluminium and magnesium. These impurities are thought to occur as submicroscopic inclusions which were trapped during crystal growth (Bibby

et al., 1975). It is also feasible, however, that the impurities represent magma which permeated along glide planes in diamonds. Pink and mauve colours have been attributed to the presence of trivalent manganese in diamonds (Custers, 1958). Diamonds of these colours also display evidence of glide planes, however, and Orlov (1977, p. 130) refutes the conclusion of Custers (op.cit.).

#### 4.4. OTHERS

Many diamonds which appear grey or black to the unaided eye were seen, under the binocular microscope, to owe this apparent colour to countless small, black inclusions. Usually the true diamond colour could be discerned under the microscope and this colour was assigned. In cases in which a diamond appears grey to black even under the microscope, such colour is probably due to submicroscopic inclusions. Synthetic diamond grown at relatively low temperatures is usually black (Bovenkerk, 1961) and it is likely that grey or black colour also reflects relatively low temperature crystallization in the case of natural diamond. It is also conceivable that some diamonds are discoloured grey or black by epigenetic, internal graphitization.

Blue diamonds are known only as rarities from the Premier Mine, the old Kollur Mine in India (Bruton, 1978, p. 410) and the Helam Mine (Harris, Hawthorne and Oosterveld, 1979). This colour appears to be due to boron impurity (Chrenko, 1971). All blue diamond is of type IIb (Bruton, op.cit.).

Very light green diamonds, in which the colour appears to extend throughout the crystal, were rarely encountered. Orlov (1977, p. 124) notes that green diamonds have not been thoroughly studied, but mentions that green in synthetic diamonds is probably

caused by single substitutional nitrogen atoms in abundances greater than required to produce a yellow colour. Bibby et al. (1975) found that green diamonds resemble brown diamonds in containing relatively high levels of trace element impurities. Custers (1958) mentions that diamond can be coloured green by bombardment with high energy particles such as neutrons.

Green surface staining occurs either continuously, as irregular patches or as isolated spots on some diamonds (Figure 2). The colour penetrates approximately 20  $\mu\text{m}$  into diamond (Vance, Harris and Milledge, 1973). Studies by Meyer, Milledge and Nave (1965) show that the diamond lattice parameters are increased at green-stained regions, as is also the case for diamond damaged by irradiation. Orlov (1977, p. 126) considers the staining to be due to the diffusion of impurities into the surface layer of diamonds. It is possible, however, that the diffusion responsible for relatively high levels of impurities in stained regions is facilitated by diamond lattice damage caused by irradiation. Many workers (e.g. Orlov, op.cit.) have observed that heating above 500°C turns the green stain to brown. Vance, Harris and Milledge (1973) reproduced green surface staining by alpha-particle irradiation in the laboratory. They also determined that the same colour changes, to olive at 550°C and to brown at 600°C, occur in both the natural stain and the stain which they produced in the laboratory. It is therefore reasonably certain that  $\alpha$ -particle bombardment is responsible for natural, green surface staining. Harris Hawthorne and Oosterveld (1977) found that green staining is much more common among diamonds recovered from weathered, than from fresh, kimberlite at Finsch Mine. In the present investigation, green surface spots were observed on the abraded surfaces of some detrital diamonds. It is therefore evident that the staining post-dates kimberlite

emplacement and is not necessarily related to kimberlite. Brown surface staining (Figure 2) is rare. It should indicate a heating event which post-dates kimberlite emplacement.

## 5. DIAMOND CRYSTAL FORMS AND SHAPES

Diamond occurs as discrete crystals up to at least 600 g in mass (the largest recorded being the Cullinan diamond, only part of a crystal, with a mass of 3 106 carats or 621 g (Bruton, 1978, p. 446)) and as microcrystalline aggregates such as ballas, carbonado and framesite.

Controversy as to whether diamond crystallizes in the normal or tetrahedral class of the cubic system was seemingly resolved, in favour of the normal class, as a result of the Bragg's (1913) X-ray diffraction studies. Tetrahedral symmetry has since been assigned to diamond (e.g. Raman and Ramaseshan, 1947) on account of features such as the apparent absence of a centre of symmetry in some diamond crystals, with crystals exhibiting properties of the normal class being regarded as combinations of (111) and ( $\bar{1}\bar{1}\bar{1}$ ) tetrahedra. According to Williams (1932, p. 448), however, crystal symmetry that is apparently less than that of the normal class can be accounted for by the distortion of external crystal forms and classification in the normal class is entirely satisfactory for diamond.

Distortion and irregularity are common features of diamond crystals so that the form of a crystal is not always obvious. It was found that crystal surfaces could usually be identified by the surface textures which they exhibit, however, so that most of the diamonds examined could be visually identified as octahedra, cubes, tetrahedra ("dodecahedra" of most other writers), combinations of these and fragments. As previously mentioned, well-formed crystals are typical only of type Ia diamond.

### 5.1. COMMON FORMS: THE TETRAHEXAHEDROID, OCTAHEDRON AND CUBE

The octahedron is the only common, diamond crystal form generally with planar surfaces. Cubic surfaces are commonly rough and indented. Tetrahexahedroid surfaces are conspicuously curved. Examples of typical diamond crystals are illustrated in Figure 3.

The terms "rounded dodecahedron" (Moore and Lang, 1974) and "dodecahedroid" (Grantham, 1974) are improvements on the more generally used "dodecahedron" for a common form of diamond crystal. However, in addition to being characterized by curved faces, this form exhibits 24, not 12, like surfaces. The term "tetrahexahedroid" is therefore preferred in this dissertation. In the case of the tetrahexahedron ( $hk0$ ), as  $h$  increases relative to  $k$  the form approaches the cube while as  $h$  diminishes and becomes more equal to  $k$  the form approaches the dodecahedron (Dana, 1958, p. 73). Diamond tetrahexahedroids are of the latter type with " $h$ " nearly equal to " $k$ ". However, it should be noted that the curvature exhibited by diamond tetrahexahedroid surfaces prohibits their indexing in the conventional manner (Raman and Ramaseshan, 1947). The degree of curvature varies from one crystal to another, being most pronounced in examples sometimes described as "hexoctahedra" (Grantham, 1974) or "octahedroids" (Orlov, 1977, p. 79). The curvature of tetrahexahedroid surfaces is responsible for a flattening of the interfacial angle at "A" edges (terminology of Dana, op.cit., for the tetrahexahedron) away from four-fold axial corners.

Diamond crystals exhibit internal stratification that can be disclosed by etching polished sections or by X-ray topographic probing. Neighbouring layers apparently differ slightly in impurity and defect content (Seal and Wasmund, 1969) and are generally regarded as growth layers. Layers are either planar and octahedral (Seal, 1963) or

undulatory and of mean cubic orientation (Moore and Lang, 1972). Moore and Lang refer to "cuboid", rather than "cubic", surfaces in recognition of their undulatory nature. Some crystals exhibit both octahedral and cubic layering, with each type being restricted to specific growth sectors (Suzuki and Lang, 1976).

Tetrahexahedroid surfaces truncate octahedral and cubic stratification (Figure 4), indicating that the diamond tetrahexahedroid results by the partial resorption of either the octahedron or the cube. Such an origin for the tetrahexahedroid is supported by observations (Bovenkerk, 1961; Bezrukov, Butuzov and Gorokhov, 1970) that only octahedral and cubic crystals are grown in diamond synthesis experiments. Davies and Evans (1972) produced diamond "dodecahedra" by graphitizing octahedra at temperatures above 1 850°C. Frank and Puttick (1958) suggested that any process producing trigons (see Article 6.2.4.) on octahedral surfaces would tend to convert octahedra to "dodecahedra". This suggestion finds support in a report by Kanda et al. (1977). Kanda et al. produced both trigons and curved, resorption surfaces by reacting diamond octahedra with steam at high pressures. While it is firmly established that the diamond tetrahexahedroid results from resorption, the specific process responsible in nature has not been conclusively identified.

In the conversion of an octahedron to a tetrahexahedroid, a maximum of diamond is removed at the four-fold axial corners and a minimum where the six-fold axial corners of the tetrahexahedroid develop. Commencing with a cube, the tetrahexahedroid six-fold axial corners develop where a maximum is removed. Moore (1973) calculated that a minimum mass loss of 55,7 per cent is required to convert an octahedron to a rhombic dodecahedron. Slightly less needs to be removed to produce a tetrahexahedroid.

The relationship between a parental octahedron and the resorption-derived tetrahexahedroid is illustrated in Figure 5. The material loss involved in the conversion can be determined by comparing the measured volume of a tetrahexahedroid with the calculated volume of its enclosing octahedral form. A number of such determinations are plotted in Figure 6, and it is evident that attainment of the tetrahexahedroid form which has just lost all vestiges of original octahedral surfaces involves a loss of approximately 45 per cent of diamond. In view of this loss (which is a minimum in the case of pure tetrahexahedroids) being so substantial, the diamond content of any kimberlite is likely to be reflected in the relative proportions of tetrahexahedroid and octahedral forms, as previously recognised by Milashev (1965). This relationship is investigated in Chapter 15.

It is not possible to estimate accurately the relationship between the tetrahexahedroid and the parental cube. This is because most cubic surfaces are indented. Therefore, their degree of preservation is not simply related to the extent of resorption. The common indentation of cubic surfaces can be explained by recourse to some results of etching experiments by Phaal (1965), which are referred to in more detail in the next chapter. Phaal determined that at temperatures above 950°C, etchants such as wet carbon dioxide gas or steam attack diamond more rapidly at cubic surfaces than at octahedral or dodecahedral surfaces. Indentation of cubic surfaces is thus likely to have been produced under such conditions. These conditions also produce the common, trigonal etch pits demonstrated, by Frank and Puttick (1958), to develop in association with the formation of "dodecahedral" surfaces. Two manifestations of resorption therefore compete with one another. Initially, the

retreat of cubic surfaces may predominate over the "rounding" of cubic edges. With more advanced resorption the rounded (i.e. tetrahexahedroid) surfaces develop and retreat relatively rapidly so that cubic surfaces eventually disappear and an entirely tetrahexahedroid form results. The complete conversion of a cube to a tetrahexahedroid should involve a substantially greater mass loss than in the conversion of an octahedron. Stages in the resorption of a diamond cube are illustrated in Figure 7.

Bovenkerk (1961) and Bezrukov, Butuzov and Gorokhov (1970) note that in diamond synthesis experiments, cubes crystallize at lower temperatures (or much higher pressures) than octahedra. The approximate, thermodynamic fields in which the various growth forms of diamond develop in one synthesis system are shown in Figure 8. Dickinson (1970, p. 88) notes that the diamond form produced probably depends upon temperature in all diamond synthesis systems, but that the boundaries and relative sizes of the fields vary according to the carbon solvent used. By analogy with the results of diamond synthesis experiments, it is likely that natural diamond cubes crystallize at lower temperatures, or in different systems, than natural octahedra.

Combinations of the tetrahexahedroid with either the octahedron or the cube are common among natural diamond crystals. The predominant form was established in each case by comparing the average width of the tetrahexahedroid surfaces with the average edge lengths of , respectively, the octahedral and the cubic surfaces. These comparisons are illustrated in Figure 9. Since certain surface textures are restricted to particular crystallographic surfaces (see Chapter 6), subordinate crystal forms are also considered in the present investigation.

## 5.2. TWINNING AND CRYSTAL AGGREGATION

According to Slawson (1950), the statistical opportunity for twinned structures to be initiated in diamond is high and nearly all diamond crystals are twinned. Most twinning is of the mosaic type and is not readily apparent unless a crystal be sawn or polished. Gross manifestations of twinning are obvious in the contact twin (macle, see Figure 3) and interpenetrant twin. Slawson (op.cit.) considers that most aggregates are probably multiply-twinned crystals. Some aggregates also involve parallel growth.

## 5.3. BROKEN CRYSTALS, DISTORTION AND IRREGULARITY

Broken crystals are common in some diamond samples examined. In this study, crystals classed as fragments are bounded either entirely by breakage surfaces or exhibit insufficient crystal surface to enable the predominant form to be satisfactorily identified.

Some examples of breakage surfaces on diamond crystals are shown in Figure 10. Octahedral cleavage surfaces, which are usually conspicuously stepped rather than "perfectly" planar, constitute the most frequently encountered type of breakage surface but subconchoidal fracture surfaces are also common. Wilks (1958) showed that octahedral cleavage is more perfectly developed in type II, than in type I, diamond. Some breakage surfaces are unetched but in most of the diamond samples examined the majority of breakage surfaces are etched. Since etching of diamond requires temperatures in excess of at least 450°C, etched breakage surfaces are undoubtedly natural features and, in the general case, breakage has to have occurred prior to or during kimberlite emplacement. Occasionally, an octahedral depression is evident in a breakage surface. Such

depressions are likely to represent hollows vacated by inclusions and the suggestion by Sutton (1918), that much natural breakage of diamond is a consequence of stress caused by differential expansion between host and inclusion during cooling or pressure release, is difficult to refute. Wagner (1914, p. 165) noted that broken diamonds are more common in kimberlite pipes than in kimberlite dykes, however, and considered diamond crystal breakage to be largely a consequence of explosive magmatism. Tetrahexahedroid crystals are broken as frequently as are other forms so that most diamond breakage in nature must post-date crystal resorption.

Distortion is a common feature of diamond crystals (Figure 11). Even in relatively regular crystals, corners are usually represented by short edges, rather than points, and "C" edges (tetrahexahedron terminology of Dana, 1958, p. 73) of tetrahexahedroida are seldom linear. Crystal flattening or elongation may be associated with the virtual non-development of certain faces, but linearity of octahedral and tetrahexahedroid "A" edges is preserved in most cases. Complicated distortion is reflected in tetrahexahedroida with undulatory surfaces and sinuous edges. According to Gorina (1971), such distortion is a consequence of plastic deformation. Confirmatory evidence of plastic deformation is often lacking, however, and some such distortion may simply be a consequence of the undulatory nature of original cubic surfaces. Irregular crystals include forms exhibiting few, approximately tetrahexahedroid surfaces. Some of these are probably resorbed fragments, including examples which were bounded by subconchoidal surfaces. Unusual shapes may result from the resorption of imbricately-stepped octahedra and from the resorption of diamonds possessing relatively resistant, internal features. According to Orlov (1977, p. 98), solution channels which penetrate xenoliths in kimberlite magma may

extend through the diamonds in some xenoliths so as to divide them into irregular grains.

Nearly equidimensional, slightly distorted, flat, elongate and irregular crystals are distinguished in the present study. No strict criteria were adhered to in making these distinctions. Flat crystals generally have one dimension less than a third of the other two dimensions, however, while elongate crystals have two similar dimensions which are less than a third of the other dimension. Irregular crystals include examples of barely determinate form and examples with a depleted compliment of crystal surfaces and sinuous edges. Irregular crystals which are flat or elongate were included in the latter categories. Aggregates are classified according to the shape of their constituent crystals. Fragments are considered as a separate class.

#### 5.4. UNCOMMON FORMS AND SHAPES

An approximate, but conspicuously ribbed, rhombic dodecahedral form of diamond (Figure 12) was encountered in some samples examined. This form has also been described from other localities (e.g. Gorina, 1971). It is possible that the dodecahedron could result from the stacking of octahedral growth layers of regularly diminishing areal extent, as proposed by Varma (1967). Knob-like features, which are remnant, commonly occur on the ribbed surfaces of this form, however, so that it must have resulted from resorption. It will be shown in Article 6.5.8., which deals with the ribbed and knob-like surface textures, that the ribbed, approximately dodecahedral form of diamond is derived from the octahedron.

Very rare diamond crystals have the form of a rhombic dodecahedron with curved faces (Figure 13). These crystals exhibit a

peculiar texture ("rhombic serration"), which is discussed in Article 6.4.15. The form is possibly derived from a tetrahexahedroid.

Paired pseudohemimorphic crystals (see Gorina, 1971; also termed "orange peel" crystals by Mendelssohn, 1971), occur in some diamond samples. These crystals consist of two parts, with one part superficially resembling a partial overgrowth on the other part (Figure 14). The form of the relatively large portion ranges from octahedral to tetrahexahedroid while the smaller portion is generally part of a tetrahexahedroid. Both portions are of identical colour, often brown. Both portions share the same crystallographic axes and in cases which are twinned the twinning plane embraces both portions. Gorina (op.cit.) considers these crystals to be zonally structured. However, they consist of a relatively unresorbed portion and a smaller, relatively resorbed portion as would result should part of a crystal have been protected from resorption, e.g. by enclosure in another mineral.

Occasional diamond crystals exhibit tetrahexahedroid surfaces which meet concavely (i.e. at a re-entrant angle; Figure 15). Some examples also exhibit octahedral surfaces and the concavity between tetrahexahedroid surfaces is relatively pronounced when the octahedral form is relatively well developed. This variety of tetrahexahedroid is probably derived by resorption of the form referred to by Dana (1958, p. 187) as a repeated octahedral twin.

Nearly spherical shapes of diamond (Figure 16) were encountered in some of the samples examined. Rare examples of this shape are genuine ballas but most are unlike ballas in being monocrystalline (see Jaynes, 1978). The most spherical single crystals exhibit minor octahedral and major (convex) cuboid and tetrahexahedroid surfaces. They contain abundant, small black inclusions and thus appear grey or

black to the unaided eye. Close examination shows the inclusions to be strongly concentrated beneath cuboid surfaces, as in the case of crystals of mixed habit (octahedral and cubic) growth described by Suzuki and Lang (1976). Sphericity apparently results from an optimal amount of resorption of a mixed habit growth form while convexity, rather than the more frequently encountered concavity, of remnant cubic surfaces may be a consequence of the abundant inclusions in cubic growth sectors.

The trapezohedron and the trisoctahedron have also been reported for diamond crystals (Varshavsky and Bulanova, 1974). Minor trisoctahedral surfaces were noted in association with a particular surface texture (terraces; see Article 6.4.1) but the trapezohedron was not identified in the present investigation.

## 6. PRISTINE SURFACE TEXTURES

"Pristine", as used in this dissertation, refers to features developed on diamond crystals prior to their liberation or extraction from kimberlite. Crystal growth or post-genetic processes may be responsible for such features.

A total of 41 pristine surface textures are distinguished. These are listed in the Table of Contents according to the crystallographic surface(s) on which they occur. Only textures which can be recognized, but not necessarily resolved, under a conventional binocular microscope are included. Some diamond surface textures were recognized by early investigators such as Sutton (1928). Headings enclosed in parenthesis in this chapter denote textures named by the author.

It is important to note that certain textures, e.g. trigonal pits on octahedral surfaces, may exhibit either of two orientations. These orientations have been respectively designated "positive" and "negative" by Frank, Puttick and Wilks (1958). They are illustrated in Figure 17.

Prior to discussing individual textures, it is appropriate to consider experiments relating to the etching of diamond and, particularly, to the formation of positively- and negatively-oriented textures.

### 6.1. REVIEW OF EXPERIMENTAL DATA.

#### 6.1.1. Low-pressure oxidation experiments

In early experiments (e.g. Fersmann and Goldschmidt, 1911; Williams, 1932) diamond was etched in fused oxidizing salts, such as potassium nitrate and sodium carbonate, at temperatures less than 900°C. Features such as rounded trigonal pits on octahedral surfaces

were produced, but in the positive orientation only. Tolansky (1965) also produced trigonal pits by etching and noted that slow rates of attack were necessary for sharp, rectilinear, rather than rounded, pits.

The author examined diamonds which had been treated in fused sodium hydroxide at 570°C, 650°C and 720°C, respectively (M.J. Simm, personal communication). Those treated at 570°C had not been affected. Mechanical surface damage had been picked out and positively-oriented features (Figure 18) were developed on those treated at the higher temperatures.

After 1958, experimental conditions were extended by many investigators to temperatures exceeding 950°C. This resulted in negatively-oriented etch pits being produced in some experiments. Frank and Puttick (1958) first succeeded in producing negatively-oriented features by subjecting diamond to molten kimberlite at 1 450°C. They suggested oxidation by iron oxide as the specific reaction involved. Subsequently, various oxidizing gases were used in experiments by others. Using wet oxygen, Evans and Sauter (1961) produced positively-oriented textures at temperatures up to 900°C and negatively-oriented textures above 1 000°C. At between 900 and 1 000°C, hexagonal pits were produced on octahedral surfaces. Phaal (1965) produced only circular pits on diamond held in a fast-flowing stream of wet oxygen at above 1 000°C. He suggested that in Evans and Sauter's experiments, which were performed in closed systems, the reversal in etch pit orientation occurring above between 900 and 1 000°C could have been due to attack by steam in association with a reaction product, namely carbon dioxide, rather than being a function only of temperature. Phaal (op.cit.) attributed the hexagonal pits produced by Evans and Sauter (op.cit.) to the combined

effects of oxygen and wet carbon dioxide which produce, respectively, positively-oriented and negatively-oriented, trigonal pits.

Sauter (1961) and Phaal (1965) both found that oxygen readily attacks diamond above 600°C. Neither steam nor carbon dioxide is effective below 950°C and carbon monoxide is ineffective even at much higher temperatures. Phaal produced positively-oriented features below 1 000°C using oxygen, and negatively-oriented features above 950°C using either steam or wet carbon dioxide. Dry carbon dioxide was found to produce semi-polished surfaces at temperatures above 950°C.

Phaal (1965) determined etching rates at different crystallographic surfaces, under various conditions. He found that at less than 1 000°C, oxygen attacked octahedral surfaces much more rapidly than cubic surfaces. Conversely, with either steam or wet carbon dioxide at temperatures above 950°C, etching was fastest at cubic surfaces and slowest at octahedral surfaces. Phaal reconciled etch pit orientation with crystallographic variations in etch rate. Etching which is most rapid at octahedral surfaces results in positively-oriented features, while relatively rapid etching at cubic surfaces results in negatively-oriented features. The rate of etching at a particular surface depends upon the stability of the chemisorbed complexes produced there as consequences of the etchant and the type of atomic bonding of surface carbon atoms.

Sauter's (1961) and Phaal's (1965) investigations revealed that the diamond-oxygen reaction is not simply one of the oxidation of diamond to carbon-oxide gases. Instead, intermediate processes are involved. These processes include the formation of a film of black carbon (referred to as amorphous carbon by Phaal (op.cit.) but referred to as graphite by Evans and Phaal (1962)). Whether or not this film of black carbon is preserved, during the partial oxidation of

diamond, depends on the relative rates of its formation and its oxidation to gas. Relatively rapid formation and, hence, preservation of the film is favoured by relatively high temperatures and low oxygen pressures. At relatively low temperatures and high oxygen pressures, however, the film is oxidized to gas as soon as it forms.

In experiments by Phaal (1965) in which thick, black carbon films were produced (e.g. etching with oxygen gas at pressures of less than one atmosphere and temperatures higher than 1 000°C), circular etch pits were produced in the underlying diamond surface. This implies that etch rates were the same in all directions which is to be expected should diffusion of oxygen through the film be the etch-rate controlling process.

The most pertinent results of the low pressure, diamond-oxidation experiments reviewed thus far are:-

- i. Diamond oxidation involves an intermediate process whereby a film of black carbon forms at the diamond surface. At sufficient oxygen partial pressure relative to temperature, this film is removed as soon as it develops.
- ii. At temperatures of less than 950°C only oxygen gas and strong oxidizing agents attack diamond, producing positively-oriented etch pits.
- iii. At temperatures above 1 000°C, oxygen gas produces thick films of black carbon on diamond and circular etch pits form in the underlying diamond surface.
- iv. At temperatures above 950°C, steam and carbon dioxide attack diamond. Steam and wet carbon dioxide produce negatively-oriented etch pits. Dry carbon dioxide polishes diamond surfaces.
- v. For rectilinear pits to form, at least on octahedral surfaces,

the etching must not be too rapid.

#### 6.1.2. Oxidation experiments conducted at moderate and high pressures

Since all natural diamond is almost certain to have experienced very high pressures, it is important that the effect of pressure on the etch features produced during the partial oxidation of diamond should be understood. The oxygen fugacities of constant molecular proportions of oxygen gas, steam and carbon dioxide will increase with increasing pressure. Therefore, the following questions may be asked:-

- i. At temperatures above 1 000°C but with oxygen partial pressure sufficient to eliminate the accumulation of a black carbon film, will oxygen gas continue to produce positively-oriented features?
- ii. At high pressures will steam and carbon dioxide attack diamond at temperatures lower than 950°C and, if so, will negatively-oriented features continue to be produced?
- iii. At high pressure will steam and wet carbon dioxide produce negatively-oriented etch features at temperatures above 950°C, or will their effect resemble those of oxygen and strong oxidizing agents at low pressure?

The experimental results of Harris and Vance (1974) and of Harris (1975) assist in clarifying some of these questions. Harris and Vance subjected diamond to powdered, dry kimberlite, which evolved steam and carbon dioxide upon being heated, at pressures of 1 kb. At 1 050°C, positively-oriented etch pits were produced by kimberlites liberating mainly steam, while negatively-oriented pits developed in a case in which mainly carbon dioxide was liberated. At 1 300°C, negatively-oriented etch pits were produced in all cases. Harris (op.cit.) etched diamonds in steam, at 5 kb pressure, at various oxygen fugacities controlled by buffers. Harris found that at low

oxygen fugacities (nickel-nickel oxide buffer conditions) steam did not attack diamond below 950°C while negatively-oriented pits developed at higher temperatures. At relatively high oxygen fugacities (magnetite-hematite buffer and more oxidizing conditions), however, steam attacked diamond at temperatures as low as 900°C and produced positively-oriented etch pits up to at least 1 000°C. The results obtained by Harris and Vance (1974) and Harris (1975) suggest that under moderate to high pressures, and in the absence of a buffer, imposing relatively reducing conditions, the action of steam on diamond resembles that of oxygen gas at low pressures. This suggests that oxygen liberated from steam is the principal etchant at such conditions. Since steam can produce positively-oriented etch pits at temperatures as high as 1 050°C, it is likely that oxygen gas, under pressure, will also produce positively-oriented pits at temperatures substantially higher than the 1 000°C-limit observed in low pressure experiments by Phaal (1965). Wet carbon dioxide appears to produce the same surface features on diamond at moderate pressure as are produced at low pressure.

In an attempt to understand further the effects of pressure on the etching of diamond, the author collaborated with a colleague, B.A. Wyatt, in a number of experiments conducted at high pressure. Full details of these experiments are recorded in an internal, Anglo American Research Laboratory report (Wyatt and Robinson, 1975). Only a summary of relevant information is given here. In these experiments charges were loaded with finely crushed, variously modified kimberlite (Table 4) to which two diamond crystals were added, and subjected to temperatures of between 1 150 and 1 450°C at 30 kb pressure (i.e. at graphite-stable thermodynamic conditions, see Figure 1). Textural characteristics of run products suggested that partial

melting of kimberlite was attained in most runs. Yellow, cubo-octahedral, synthetic diamonds of approximately 0,5 mm diameter were used in the experiments. These were preferred to natural crystals because they exhibit planar crystal faces which are smooth excepting for shallow, dendritic patterns, known as "river markings", which do not resemble any features likely to result from etching. Although the octahedral and cubic faces of cubo-octahedral crystals have triangular and square to rectangular outlines, respectively, crystal edges are disoriented with respect to the edges of the corresponding simple forms. Edges of octahedral faces are disoriented by  $60^\circ$  and cubic edges by  $45^\circ$ , as demonstrated in Figure 19. This complication must be considered in determining etch pit orientations. Some edges of distorted crystals used are replaced by dodecahedral surfaces. Two series of experiments were performed. In one series graphite capsules sealed in platinum were used and in the other series molybdenum capsules sealed in platinum were used. The two series differed mainly in respect of the oxygen fugacities considered to have been realized. Diamond should have attained equilibrium, with respect to redox potential, with the charges in graphite capsules. In these cases, diamond could have been oxidized until equilibrium was attained. According to Biggar (1970), molybdenum capsules should impose a buffer approximating to the iron-wustite buffer. Conditions buffered by the iron-wustite reaction are less oxidizing than necessary to oxidize free carbon (e.g. see Rosenhauer et al., 1977). Diamond could have been oxidized in molybdenum capsules only prior to equilibrium being attained between the charges and the capsules. The potential for diamond-oxidation should therefore have been greater in the graphite capsules than in the molybdenum capsules.

Details of Wyatt and Robinson's (1975) experiments and of the features produced on diamond are summarized in Table 5. Some examples of the etch features produced are illustrated in Figure 20. Other features are illustrated subsequently under discussions of individual surface textures. The following results are pertinent:-

- i. In most experiments in which diamond was etched a film of graphite coated the surface.
- ii. The thickness of the graphite film produced is not closely related to the degree of etching of diamond.
- iii. Etching was relatively pronounced in the runs in which the greatest potentials for oxidation were realized.
- iv. Negatively-oriented etch features were produced down to the lowest temperature, i.e. 1150°C, employed.
- v. In cases in which diamond was strongly etched, attack was relatively pronounced at crystal edges.
- vi. Etching occurred in volatile-free kimberlite with only carbon dioxide added.

Result i) above is compatible with either graphitization or oxidation having been responsible for the etching of diamond in the 30 kb experiments. Result ii) points to graphitization not being directly responsible while result iii) substantiates that diamond was etched by oxidation. Result iv) shows that high pressure need not substantially increase the temperature necessary for the development of negatively-oriented etch pits. (The possibility of pressure reducing this temperature cannot be evaluated from the experiments performed). Result v) suggests that the diamond tetrahedroid can be produced by the oxidation of the octahedron or the cube. Result vi) suggests that water is not essential for the formation of negatively-oriented etch pits, but it must be noted that the charges concerned were

"atmosphere damp".

That diamond was oxidized in some of Wyatt and Robinson's (1975) experiments which were supposedly buffered at conditions less oxidizing than those at the carbon-carbon oxides equilibrium, demonstrates an important phenomenon. This is that the oxidation potential locally realized during an experiment may exceed that theoretically dictated by the buffer employed. During experiments at controlled oxidation potentials, special care apparently needs to be taken to ensure that the charge is always in equilibrium with the buffer.

The highest-pressure, diamond-oxidation experiments yet reported are those by Kanda et al. (1977). In these experiments diamond octahedra were etched in water, at temperatures of 1 100, 1 300, and 1 500°C, constrained at 50 kb pressure within platinum capsules. At 1 100°C, negatively-oriented trigonal pits were produced within a few minutes and tetrahexahedroid-like crystal surfaces began developing within half an hour. The same features were produced much more rapidly at the higher temperatures.

### 6.1.3. Other experiments

The reactivities of various gases and vapours, such as hydrogen, chlorine, bromine, hydrogen fluoride and hydrogen chloride, with diamond were investigated, at low pressures, by Sauter (1961). With the exception of hydrogen in the presence of a metal catalyst, none of these substances was found to attack diamond at temperatures up to 1 400°C. Instead they inhibited oxidation.

A measurable degree of uncatalysed graphitization of diamond requires temperatures of at least 1 500°C under vacuum and even higher temperatures under pressure (Evans, 1976). Davies and Evans (1972) record the formation of negatively-oriented trigonal pits in octahedral diamond surfaces during graphitization experiments. Although these

pits are trigonal in outline, in detail (Figure 21) they are more aptly described as "three bladed propellers" by Davies (1972).

Diamond can also be dissolved. Thus, Kennedy and Kennedy (1976) dissolved synthetic diamond crystals in "Invar" (nickel-iron alloy) subjected to various combinations of temperature and pressure ranging from 1 100 to 1 600°C and 45 to 60 kb. In all runs in which the "Invar" melted, diamond dissolution was complete so that, unfortunately, the features produced by dissolution-etching could not be determined (G. Kennedy, private communication). Molten kimberlite is reported to be a very poor solvent of free carbon (Wentorf, 1965).

#### 6.1.4. Inferences for natural etching

Considering the experimental evidence reviewed, the following inferences can be made concerning the origin of natural etch features on diamond:-

- i. Processes likely to etch diamond in nature include only oxidation, graphitization and dissolution. Extreme temperatures appear to be required for non-oxidative graphitization, while dissolution is unlikely to be significant in kimberlite magma.
- ii. Negatively-oriented etch features always indicate temperatures in excess of 950°C. Steam and wet carbon dioxide gas are the etchants most likely to be responsible.
- iii. Tetrahexahedroid surfaces develop on originally octahedral crystals concomitantly with the development of negatively-oriented etch pits.
- iv. At low pressures, only oxygen gas and strong oxidizing agents are capable of producing positively-oriented etch pits. Temperatures above 450°C but below 1 000°C are required.
- v. At pressures of about a kilobar and more, positively-oriented

etch features can also be produced by steam and at temperatures up to between 1 050 and 1 100°C. Sufficiently oxidizing conditions (e.g. as oxidizing as buffered by the magnetite-hematite equilibrium) are, however, necessary.

- vi. Circular etch pits are most likely to result from reaction with oxygen gas at temperatures above 1 000°C and at low pressures.
- vii. Dry carbon dioxide gas at temperatures above 950°C is likely to be responsible for chemically-polished surfaces.

Some additional, diamond etching experiments are referred to in subsequent discussions of particular surface textures to which they are relevant.

## 6.2. OCTAHEDRAL SURFACE TEXTURES

Etch pit orientations are easier to determine on octahedral than other diamond surfaces. The following pristine surface textures are restricted to octahedral diamond surfaces:-

### 6.2.1. Smooth octahedral surfaces

Where locally free of the effects of etching, smooth octahedral crystal surfaces can represent final growth surfaces. It is not always possible, however, to ascertain that entire octahedral layers have not been removed by etching. Therefore, only in the case of octahedra which lack any features which can be ascribed to resorption, can growth surfaces be positively identified.

### 6.2.2. Triangular plates (single and imbricated)

Triangular plates are developed on some octahedral crystal faces and some complex, octahedral forms consist essentially of imbricated triangular plates (see Figure 3). Williams (1932, p. 499)

referred to triangular plates on octahedral surfaces as "growth layers". Grantham (1974) preferred "plates" for the same features and noted that "terraces" has also been used. Triangular plates are octahedral in form but are seldom sharp-edged. Instead, their edges are usually rounded and they may even be completely modified to tetrahexahedroid forms (Figure 22).

In the case of synthetically grown diamonds, octahedral crystals which can be classed as imbricated apparently result under growth conditions favouring rapid nucleation, with each triangular plate being separately nucleated (Wentorf, 1965). Natural triangular plates are likely also to represent separately-nucleated octahedral overgrowths. In the present study, triangular plates were never seen to post-date resorption or etch features.

### 6.2.3. Shield-shaped laminae

Superimposed laminae of progressively diminishing areal extent commonly form terraces near to the edges of octahedral crystal faces (Figure 23). Toward four-fold axial corners, edges of laminae depart progressively from the adjacent edge of the octahedral face on which they occur. The degree of this departure increases between upwardly successive laminae. Shield-shaped laminae are generally thinner than triangular plates. They are absent from sharp-edged (i.e. unresorbed) octahedra.

Grantham (1974) considered shield-shaped laminae to be incomplete growth layers, equivalent to thin, triangular plates. Their absence from unresorbed octahedra suggests, however, that they are associated with resorption. The shield-shaped outlines of laminae and the change in outline between successive laminae are also more compatible with a resorption process. It is considered that resorption commences at the corners and edges of octahedral crystals

and truncates growth laminae. Subsequent resorption causes an inward recession, toward the centres of octahedral faces, of laminae edges. The outermost laminae are exposed soonest and therefore recede furthest, particularly from octahedral corners which are relatively susceptible to resorption. The development of shield-shaped laminae should result in octahedral crystal edges being replaced by curved, i.e. tetrahexahedroid, surfaces.

#### 6.2.4. Negatively-oriented trigonal pits (trigons)

Equilateral triangular pits in the negative orientation (Figure 24) are one of the common and most studied features of natural diamond crystals. They are generally referred to as "trigons". Pyramidal (i.e. point-bottomed), flat-bottomed and terraced varieties of trigon occur and most have edge lengths of between 0,1 and 0,2 mm. Such trigons are evident on all crystals with octahedral faces in most samples studied but are apparently absent on rare crystals, particularly sharp-edged octahedra, in some samples. It should be noted, however, that according to both Tolansky (1965) and Frank and Lang (1965), phase contrast microscopy generally discloses myriads of trigons with edge lengths of a few micrometres. Some trigons are truncated by an edge between an octahedral and a tetrahexahedroid surface. This need not indicate that trigons are older than tetrahexahedroid surfaces. Provided trigons result from etching, they should be able to expand even after one corner has met with a crystal edge.

The origin of negatively-oriented trigonal pits has been a controversial topic. Tolansky (1965 and other, previous publications) and others argued that they represent regions not filled in by surrounding growth layers. One of their main lines of evidence for a crystal growth origin was that etching experiments had only

produced positively-oriented trigonal pits. Later experiments, in which negatively-oriented trigonal pits were produced by etching, considerably weakened the growth hypothesis. Frank and Lang (1965) also convincingly refute other evidence considered to support the growth hypothesis. It is now generally accepted that both negatively- and positively-oriented trigonal pits are etch pits. Frank and Lang (op.cit.) showed that fairly large, pyramidal varieties are localized at dislocation outcrops. They also showed that in some cases trigons are not developed at dislocations which extend to the surface, and suggest that this indicates that some natural diamonds were not subjected to the necessary etch process. The form and localization of flat-bottomed trigons is not understood. They possibly bottom out at the tops of internal layers which are relatively resistant to etching. As mentioned in Section 5.1., Frank and Puttick (1958) note that etching which produces trigons should convert an octahedron to a "dodecahedron".

Rare trigons are developed on some sharp-edged octahedral crystals indicating that substantial resorption is not necessary for their development. They are usually associated with laminae, however, and probably result from the same process(es). As already noted, temperatures in excess of 950°C are probably required to produce negatively-oriented etch features. Such temperatures are unlikely to have prevailed in kimberlite magma in near-surface environments (Mitchell, 1973), so that trigons must develop at depth. Oxidation, by steam or wet carbon dioxide, is most likely responsible.

#### 6.2.5. Hexagonal pits

Hexagonal pits are invariably flat-bottomed (Figure 25) and are generally of relatively large areal extent in comparison with

trigons. As with laminae and flat-bottomed trigons, growth stratification might be an essential requirement for hexagonal pit development.

Hexagonal pits have been produced in etching experiments conducted at low pressures between 950 and 1 000°C (e.g. Evans and Sauter, 1961; Mendelssohn, 1971). According to Phaal (1965), they are to be expected at such conditions due to the combined effects of two etchants, one of which (oxygen) produces positively-oriented trigonal pits and the other of which (e.g. steam or wet carbon dioxide) produces negatively-oriented trigonal pits. It is also possible for hexagonal pits to develop at temperatures above 1 000°C. This requires an environment sufficiently oxidizing to enable the formation of the positively-oriented component of the pits.

#### 6.2.6. "Hexagonal pits containing trigonal pits"

Hexagonal pits may contain trigons or, less commonly, positively-oriented trigonal pits (Figure 26). Both types are likely to result from the combined effect of two etchants, one of which continues to react after depletion of the other etchant. For example, should oxygen involved with steam in producing hexagonal pits be depleted before the steam, continued etching by the steam would produce superimposed trigons. Alternatively, should the steam be depleted first, superimposed positively-oriented trigonal pits would result. Temperatures of between 950 and 1 000°C are most likely but higher temperatures are possible under sufficiently oxidizing conditions. It is also possible that the trigonal pits formed separately, and subsequently, to the etching event that produced the hexagonal pits.

#### 6.2.7. "Serrate laminae"

Like shield-shaped laminae, serrate laminae (Figure 27) occur as superimposed individuals of progressively diminishing areal extent. The lamina nearest the centre of an octahedral face is often the highest but isolated examples near to octahedral edges may stand relatively high. The development of serrate laminae can be likened to a coalescence of laterally-expanding, flat-bottomed trigons, mostly initiated at the edges of successively exposed, octahedral growth layers.

Serrate laminae are associated with pointed plates on cubic surfaces (Article 6.3.3.) and with knob-like asperities and dodecahedral ribbing (Article 6.5.8.). The modes of formation of all of these surface textures are discussed in Article 6.5.8. which deals mainly with knob-like asperities and dodecahedral ribbing.

#### 6.2.8. Positively-oriented trigonal pits

Positively-oriented trigonal pits (Figures 26 and 28) are much less common features than negatively-oriented trigons. As mentioned previously, they are sometimes associated with hexagonal pits. They always appear to be relatively young features.

In view of experimental evidence, there can be little doubt that positively-oriented trigonal pits result from the oxidation of diamond. They are likely to result from attack by oxygen gas, or a strong oxidizing agent, under low pressures and at temperatures of between 650 and 1 000°C. Alternatively, they may be produced by pressurized steam (or oxygen gas) in a strongly oxidizing environment, at temperatures both below and slightly above 1 000° C.

### 6.3. CUBIC SURFACE TEXTURES

Only a limited variety of textures which are restricted to cubic crystal surfaces were encountered. This may be partly due to the cubic form being relatively rare in most of the samples studied. The following cubic textures are distinguished:-

#### 6.3.1. Negatively-oriented tetragonal pits (tetragons)

Tetragonal, pyramidal pits in the negative orientation (Figure 29) are ubiquitous features of cubic surfaces of the diamonds examined. Commonly, tetragonal pits are abundant and deep.

Experiments producing negatively-oriented trigonal pits on octahedral surfaces also produce such tetragonal pits on cubic surfaces. These pits therefore share a common origin.

The relative depth of tetragonal pits, compared with trigons, and the common indentation of cubic surfaces are not surprising since the cubic surface is most easily etched under conditions producing negatively-oriented etch features (Phaal, 1965).

#### 6.3.2. Crescentic steps

Superimposed layers of crescentic to semi-circular outline (Figure 30) are sometimes associated with negatively-oriented, tetragonal pits. These layers possibly represent cubic growth layers picked out by etching, in which case they would be equivalent to the shield-shaped laminae of octahedral surfaces.

#### 6.3.3. "Pointed plates"

Pointed plates (Figure 31) are uncommon features developed on some cubic surfaces. The plate surfaces appear to be octahedral. A pointed plate may extend into a negatively-oriented tetragonal pit, in which case it resembles an octahedral crystallite which post-dates a period of etching. In passing from a cubic to a tetrahexa-

hedroid or dodecahedral surface, however, groups of pointed plates grade into ribbing (Article 6.5.8.). As discussed in Article 6.5.8., ribbing is unlikely to have been produced by crystal growth. Pointed plates are therefore likely to be remnant features which resisted the etching responsible for tetragonal pits. Pointed plates are probably also akin to the serrate laminae of octahedral surfaces. A process which could be responsible for producing pointed plates and associated surface textures is considered in Article 6.5.8.

Isolated, tiny (less than 50  $\mu\text{m}$  diameter), protruding features with symmetrical, octahedral forms (Figure 31) were noted in association with some pointed plates examined in the scanning electron microscope. These protruding features may lie astride an edge between adjacent tetragonal pits. In a previous publication (Robinson, 1979), these features were interpreted as octahedral crystallites which post-date the etching responsible for tetragonal pits. They can be regarded as variants of pointed plates, however, and the observation (made subsequently to Robinson, 1979 being in the press) that pointed plates grade into ribs on dodecahedral surfaces, places the author's previous interpretation in doubt.

#### 6.3.4. Positively-oriented tetragonal pits

Positively-oriented tetragonal pits (see Figure 45) were noted on an isolated cubic surface of only one of the diamonds examined. Imbricate wedge-forms (see Article 6.4.14.), which are also positively-oriented, are developed on the tetrahedroid surfaces of the diamond concerned.

#### 6.4. TETRAHEDROID (AND DODECAHEDRAL) SURFACE TEXTURES

The influence of octahedral structure is evident in the form

assumed by many textures developed on tetrahexahedroid surfaces. It is therefore appropriate to note the octahedral planar traces on tetrahexahedroid surfaces, as illustrated in Figure 32. Also shown in Figure 32 is the terminology used for crystal edges (that of Dana (1958, p. 73) for the tetrahexahedron), and for specific dimensions of the approximate rhomb which outlines two tetrahexahedroid surfaces sharing a "C" edge.

Since tetrahexahedroid surfaces form by resorption, the only growth features which they can exhibit are exposed, internal features and features due to re-growth subsequent to resorption. The following surface textures are restricted to tetrahexahedroid (or dodecahedral) surfaces:-

#### 6.4.1. Terraces

Concentric terraces are commonly developed about the points of emergence of six-fold, tetrahexahedroid axes (Figure 33). Regular crystals display the same number of terraces about each six-fold axial corner. Terraces are particularly prominent on some tetrahexahedroida which exhibit small, remnant octahedral surfaces. In such cases, an octahedral surface forms the innermost plateau of each set of concentric terraces. Otherwise, the innermost plateaus are defined by trisoctahedral surfaces which depart but slightly from octahedral surfaces. Successive plateau surfaces diverge progressively from (111) and converge toward (hk0). The scarps of inner terraces are steeply inclined to their plateau surfaces but successive scarp surfaces also converge progressively toward (hk0). These progressive changes, away from six-fold axial corners, in the inclinations of successive terrace surfaces result in a stepped curvature of tetrahexahedroid surfaces and also in the elimination of terraces in the vicinity of major rhombic axes. Terraces are never developed on tetrahexahedroida which appear

to have been derived from cubes.

Terrace scarps probably mark the outcrops of octahedral growth layers which were relatively resistant to resorption. This is suggested by the association with the octahedral, and not the cubic, growth form and by the tendency for the plateau surfaces of prominent terraces to approximate to octahedral surfaces. X-ray topographic studies by Moore and Lang (1974) also suggest that terraces reflect internal, octahedral layering.

The degree by which innermost terrace surfaces depart from octahedral surfaces determines the prominence of terraces. The degree of this departure can be expected to increase with increasing resorption. It should therefore be possible to qualitatively estimate the degree to which a tetrahexahedroid has been resorbed, even though it lacks vestiges of the octahedral form from which it is derived, by the prominence of its terraces. Thus, a tetrahexahedroid displaying prominent terraces is likely to have been less resorbed than one displaying insignificant, or no, terraces. Terrace prominence, however, also reflects the internal structure of a crystal. A tetrahexahedroid without terraces could therefore also result from the insubstantial resorption of an unstratified octahedron.

#### 6.4.2. Elongate hillocks

Hillocks which are elongated in the direction of the major rhombic axes are very common features of tetrahexahedroid surfaces (Figure 34). The usual form of individual hillocks varies from semi-cylindrical to semi-ellipsoidal. Semi-cylindrical hillocks may extend entirely across pairs of tetrahexahedroid surfaces joined at a "C" edge. Such hillocks can be regarded as features which are intermediate between terraces and ellipsoidal hillocks. The outlines of ellipsoidal hillocks are often slightly more blunt at the ends facing four-fold

axial corners than at the ends facing "C" edges. These outlines can be described as "boat-shaped" and it is considered likely that such hillocks have been mistaken for "boat-shaped pits" by some previous investigators (e.g. Tolansky, 1965).

Hillocks are relatively long on crystals which are partly octahedral and relatively short on crystals which are partly cubic. Therefore, the form of hillocks is related to the nature of the original growth form. Hillocks are usually long and prominent on crystals exhibiting growth form vestiges but are boat-shaped, small and subdued on more resorbed crystals. On particular tetrahexahedroid surfaces, hillocks tend to be least prominent where most resorption has occurred. The form of hillocks is therefore also related to the degree of resorption (although there are exceptions, e.g. some pure tetrahexahedroida exhibit prominent, long hillocks). In addition, some crystals exhibit only a single band of relatively prominent hillocks on each tetrahexahedroid surface. Hillock elongation parallels the strike of octahedral stratification and it is evident that the relative resistance, to resorption, of individual, octahedral growth layers also influences the form assumed by hillocks.

The relationship noted between hillock characteristics and crystal growth form should aid in identifying the growth form of tetrahexahedroida now devoid of growth form surfaces. Any tetrahexahedroid exhibiting prominent, long hillocks is likely to have been derived from a stratified, octahedral crystal. One exhibiting only subdued hillocks is likely to have originated from either a cube or a non-stratified, octahedral crystal. Prolonged resorption of a stratified octahedron could, however, also produce a tetrahexahedroid with only subdued hillocks. Similar hillocks are generally developed on all of the tetrahexahedroid surfaces of any particular crystal.

Relationships between hillock characteristics, terraces, degree of resorption and original growth form indicate that hillocks result during the resorption process which produces tetrahexahedroid surfaces. Negatively-oriented etch features are developed on associated octahedral and cubic surfaces. Some particularly wide, semi-cylindrical hillocks might represent the rounded sides of resorbed triangular plates (Article 6.2.2.).

The forms assumed by hillocks may depart substantially from those described above. Distinct textures, such as shagreen texture (see Article 6.5.2.), are thus produced. In addition, textures such as corrosion sculpture, microdisk patterns and fine striation with edge enhancement (Articles 6.4.8., 6.4.10. and 6.4.11., respectively) have very fine, elongate hillocks as component features. Modified hillocks may also be regarded as distinctive textures, as in the case described next.

#### 6.4.3. "Semi-cylindrical hillocks with hexagonal pits"

The sides of prominent semi-cylindrical hillocks may approximate to octahedral surfaces and trigons may be developed there. Much more common, however, are semi-cylindrical hillocks which exhibit hexagonal pits at their approximately octahedral sides (Figure 35). Combined forms exhibiting semi-cylindrical hillocks with hexagonal pits also exhibit hexagonal pits on their octahedral faces. As previously discussed (Article 6.2.5.), hexagonal pits can be regarded as positively-oriented in part. Etching processes which produce positively-oriented features preferentially attack octahedral surfaces (Phaal, 1965; see Section 6.1.). Therefore, octahedral sites for hexagonal pit development on hillocks are more likely to be initiated by an etchant (e.g. oxygen gas) producing positively-oriented textures than by one producing only negatively-oriented textures.

#### 6.4.4. "Low-relief surfaces"

Tetrahexahedroid surfaces seen, at low magnifications, to display only vague undulations, are designated as low-relief surfaces. In the scanning electron microscope, however, very small hillocks and other irregularities can be discerned (Figure 36). Crystals with low-relief surfaces generally lack octahedral vestiges but may display subordinate, indented cubic surfaces. Some exhibit subdued terraces about six-fold axial corners.

Most crystals with low-relief surfaces are likely to have resulted from the moderate to advanced resorption of cubic or unstratified octahedral crystals. Examples which also exhibit terracing probably represent highly resorbed, stratified octahedra.

#### 6.4.5. Shagreen texture

The Shorter Oxford English Dictionary (1968) defines "shagreened" as referring to a roughened surface of appearance like shark skin, untanned leather, etc.. The term has been used by Afanas'yev et al. (1974) to denote the appearance, at low magnification, of very fine hillocks developed in association with lamination lines on diamond tetrahexahedroid surfaces. Since shagreen texture is intimately associated with lamination lines, full discussion of shagreen texture is deferred to Article 6.5.2.

#### 6.4.6. Pyramidal hillocks

Isolated or scattered, conspicuous hillocks of rounded, triangular-pyramidal form occur on one or more tetrahexahedroid surfaces of some diamonds. Individual pyramidal hillocks are elongated in the negative orientation and present a distinctly blunt end towards four-fold axial corners (Figure 37).

Orlov (1977, p. 93) discusses pyramidal hillocks in some detail.

He considers that they result from the resorption of crystals with cubo-octahedral layering and offers geometric "proof" of their derivation. Diamonds with primary layering of the type required were not encountered, however, in the present investigation. Some pyramidal hillocks are associated with lamination lines (see Section 6.5.2.) and it is considered more likely that the pyramidal form of the hillocks results from a relative resistance to resorption at the intersections between three lamination lines. This explanation also appears to have been favoured by Urusovskaya and Orlov (1964).

#### 6.4.7. "Zigzag texture"

Zigzag patterns are sometimes observed about four-fold axial corners (Figure 38). The pattern traces the intersections between two sets of the octahedral layers not generally expressed on tetrahexahedroid surfaces. Truncated, "complex rectilinear" (Seal, 1963) octahedral growth layers are possibly represented.

#### 6.4.8. Corrosion sculpture

Fairly deep depressions of elliptical to irregular, curved outline are developed on the tetrahexahedroid surfaces of some crystals (Figure 39). Most of these depressions are between 50  $\mu\text{m}$  and 0,3 mm in maximum diameter (on minus 11 plus 9 crystals) and are separated by a surface exhibiting only minor hillocks. The bottoms of the depressions are usually striated and coalescence of depressions sometimes results in large areas, and even entire tetrahexahedroid surfaces, exhibiting only the striations. The striations resemble very fine and long, semi-cylindrical hillocks.

Wagner (1914, p. 144) and Williams (1932, p. 438, Plate 151) referred to the depressions as "pock marks". Orlov (1977, p. 93) includes them among his "etch pits". Gorina (1971) apparently first

suggested the term "corrosion sculpture" for these (and other, possibly related) features because, unlike typical etch pits, their outlines lack geometric regularity dependant on crystal structure.

Associated octahedral and cubic surfaces on corroded tetrahedroids usually exhibit only the almost ubiquitous trigons and tetragons, respectively. Only occasionally, associated octahedral surfaces are coarsely frosted (see Article 6.5.11.) and cubic surfaces exhibit small, irregular to circular micro-pits (Article 6.5.10.). Whatever causes corrosion sculpture therefore appears to preferentially affect tetrahedroid surfaces. Corrosion sculpture post-dates the resorption process which produces hillockd tetrahedroid surfaces but occasional trigons are younger. Shallow depressions (Article 6.4.9.) are relatively common on the diamonds in kimberlitic samples in which corrosion sculpturing is also common. Fine corrosion sculptures may grade into coarse frosting (Article 6.5.11.). Microdisk patterns (Article 6.4.10.) are associated or may be superimposed on corrosion sculptures.

Williams (1932, p. 438) noted the development of corrosion sculpturing beneath coatings of graphite. Gorina (1971) considers that attack by a gaseous agent, rather than a phase transformation, is the most likely cause of corrosion sculpturing. In the present investigation, black coatings were never seen to overlie corrosion sculptures, while the graphite observed by Williams (op.cit.) could have resulted from diamond oxidation at a sufficiently low oxygen fugacity. The nature of the constituent depressions suggests that corrosion sculpturing is produced by rapid, brief etching. The rare association with graphite suggests that low oxygen fugacities sometimes prevailed. This implies relatively high temperatures for the etchant concerned. Temperatures exceeding 950°C are indicated by

developments of younger trigons, unless a heating event be allowed. Steam is a possible candidate for the etchant responsible.

Wagner (1914, p. 144) observed that corroded diamonds are common among those recovered from the deeper mining levels (i.e. depths of a few hundred metres) of the Kimberley mines but that they are apparently absent from the shallow levels. This suggests that diamond was corroded after magma emplacement into the diatremes at Kimberley.

#### 6.4.9. "Shallow depressions"

Shallow depressions (Figure 40) have irregular, curved outlines. They are much shallower, but often of greater areal extent, than corrosion sculptures. The bottoms of the depressions are flat and either smooth or shagreened. Microdisk patterns (Article 6.4.10.) are sometimes associated and appear to be of the same age. As previously mentioned, diamonds with shallow depressions appear to be associated with diamonds displaying corrosion sculpture. Shallow depressions are considered to represent either an incipient, or less localized, manifestation of corrosion.

#### 6.4.10. Microdisk patterns and "patterns of micro-pits"

Circular disk patterns (Figure 41) occurring on tetrahedroid surfaces have been comprehensively described by Pandeya and Tolansky (1961). These investigators noted the circular outline of disks over crystal edges and a frequent association with patterns of etch pits. Overlap between neighbouring disks is also evident in illustrations presented by Pandeya and Tolansky (op.cit.). It can be added that fine, elongate hillocks frequently extend across disk boundaries and that large disks may have concavo-convex, rather than circular, outlines. Where micro-disk patterns are locally developed,

the summits of the uppermost disks correspond in elevation to the adjacent surfaces without disks.

In the present study, patterns of micro-pits (Figure 42) were also found to be common associates of microdisk patterns. Individual pits are circular or elliptical to rectangular in outline and only a few micrometres across. They might be allied to circular micro-pits (Article 6.5.10.). The pits are arranged in arrays which are commonly circular or oval and conceivably define the outlines of incipient disks.

According to Orlov (1977, p. 97) the opinion has been ventured that microdisk patterns result from successive accumulations of disk-shaped growth laminae. A growth origin can be refuted by the association of microdisk patterns with the patterns of micro-pits and by local areas of microdisk patterns being at lower elevations than crystal surfaces not exhibiting them. In addition, microdisk patterns have been produced experimentally by oxidation. Patel and Agarwal (1966) were responsible. They etched diamond in oxygen gas, under pressures of a few bars, at 800°C and found that very rapid etching for a short period was necessary to produce microdisks. Patel and Agarwal subscribed to the suggestion of Pandeya and Tolansky (1961), that successively superimposed disks owe their relatively high elevations to the protective action of gas bubbles of progressively diminishing size. The protective gas could have been carbon dioxide and/or carbon monoxide.

Patel and Agarwal (1966) also succeeded in producing microdisk patterns on octahedral surfaces of diamond. In the present study, microdisk patterns and patterns of micro-pits were found to be restricted to tetrahexahedroid surfaces while octahedral surfaces, where associated, displayed no unusual features. No crystal encountered with microdisk patterns exhibited cubic surfaces. Natural

microdisk patterns and patterns of micro-pits apparently result, therefore, from a process toward which octahedral surfaces are relatively resistant. Likely etchants are steam or wet carbon dioxide gas at temperatures above 950°C. Relatively high temperature and/or oxygen fugacity are/is required for the etching to be sufficiently rapid to produce microdisk patterns rather than only the common, elongate hillocks of tetrahexahedroid surfaces. In the case of steam, however, conditions need to be less oxidizing than necessary to produce positively-oriented etch features. Carbon monoxide gas is the most likely oxidation product which could have formed protective bubbles.

#### 6.4.11. "Fine striation with edge enhancement"

Some diamonds from two of the localities studied (Dokolwayo and Hlane, both in Swaziland) exhibit finely-striated to complexly sculptured tetrahexahedroid surfaces and associated, ridge-like tetrahexahedroid crystal edges (Figure 43). At the incipient stage of development of the texture, only light frosting is evident but this is absent at crystal edges. The frosting can be resolved into a system of linear to curved grooves and pits exhibiting no easily recognizable, crystallographic elements. At relatively advanced stages of development of the texture, fine, semi-cylindrical hillocks elongated parallel to the traces of octahedral growth layers are developed in the vicinity of "C" edges. Elsewhere, the hillocks assume a triangular-prismatic form produced by their truncation at one end and thinning toward the other end. As in the case of pyramidal hillocks, blunt ends are presented towards four-fold axial corners. The ends of adjacent hillocks are locally aligned so that discontinuous, wavy steps which are roughly parallel to "A" edges are apparent. The most conspicuous

feature of diamonds exhibiting this surface is that tetrahexahedroid crystal edges stand at a higher elevation than the striated surfaces of these crystal faces. Associated octahedral crystal faces exhibit no extraordinary features.

The poorly-defined crystallographic control on features constituting the texture suggest that it probably results from rapid etching. Since little diamond is removed, only short periods of etching are probably involved. Constituent hillocks are in the negative orientation. It is not understood why crystal edges should be less etched than tetrahexahedroid surfaces.

#### 6.4.12. "Ribbing" (on dodecahedral surfaces)

Ribbing is intimately associated with knob-like asperities. These two textures are therefore considered together in Article 6.5.8.

#### 6.4.13. Transverse hillocks

Rare examples of tetrahexahedroida exhibit hillocks which are elongated transversely to the common, elongate hillocks (Figure 44). Transverse hillocks are positively oriented. Such hillocks may be superimposed upon terraces and elongate hillocks, in which case a complex texture results. Positively-oriented trigonal pits are developed on any octahedral crystal surfaces present on tetrahexahedroida which display transverse hillocks. Transverse hillocks always post-date negatively-oriented textures and apparently form in association with positively-oriented trigonal pits on octahedral surfaces.

#### 6.4.14. "Imbricate wedge-forms"

Imbricate wedge-forms (Figure 45) is a rare surface texture. As in the case of transverse hillocks, positively-oriented trigonal pits are developed on any octahedral crystal faces present on tetrahexahedroida which display imbricate wedge-forms. Imbricate wedge-

forms can be regarded as a variation of transverse hillocks.

#### 6.4.15. "Rhombic serration"

Rhombic serration (see Figure 13) was noted on only two crystals, both of curve-faced dodecahedral form, among the diamonds studied. Neither of these crystals exhibits octahedral or cubic crystal surfaces and the orientation of the texture is not self-evident on dodecahedral surfaces. The development of rhombic serration appears to also result in the dodecahedral form, possibly by modification of the tetrahexahedroid. Considering that only two diamonds displaying rhombic serration were studied, speculation about the process responsible for the texture is not warranted.

### 6.5. NON-RESTRICTED SURFACE TEXTURES

Some surface textures are not restricted to any particular crystal surface of diamond. Such textures include those listed below.

#### 6.5.1. The macle line

Planes of contact twinning are characteristically expressed by a herringbone pattern (Figure 46). The "spine" marks the plane of twinning. The "ribs" are elongate hillocks in the case of tetrahexahedroida and the edges to shield-shaped laminae in the case of octahedra. Rhombic pits which lie astride the plane of twinning apparently consist of pairs of opposed trigons.

#### 6.5.2. Lamination lines (and tetrahexahedroid, shagreen texture)

Tetrahexahedroid surfaces commonly exhibit series of lineations (Figure 47) which are best seen in the vicinity of four-fold axial corners. These "lamination lines" are parallel to octahedral planar traces. One or two, transecting sets of lamination lines may be evident, with neither set being parallel to the traces of octahedral

growth layers on tetrahexahedroid surfaces. On tetrahexahedroida, lamination lines extend across the edges between adjacent surfaces. Only rarely, however, are lamination lines which might be conspicuous on tetrahexahedroid surfaces seen to extend onto associated octahedral surfaces. Then they are inconspicuous features unless marked by lines of trigons. Lamination lines are usually spaced evenly and less than 0,1 mm apart but a widely-spaced variety is also distinguished. The widely-spaced variety consists of compound lamination lines, each of a few closely-spaced individuals, which are widely separated from one another or occur in isolation. Closely-spaced lamination lines either mark steps between differently-elevated strips of tetrahexahedroid surface or mark the crests of micro-ridges. In the former case the lamination lines resemble micro-fault scarps. In the latter case there is no resemblance to faulting. Widely-spaced lamination lines on tetrahexahedroid surfaces always mark topographic ridges.

Shagreen texture (Figure 47, see also Article 6.4.5.) is generally associated with closely-spaced lamination lines on tetrahexahedroid surfaces. At low magnification, surfaces displaying shagreen texture appear rough on a very fine scale, as in the case of shark skin. At high magnification, shagreen texture is seen to consist of prolific micro-hillocks which are each approximately 10  $\mu$ m wide. Micro-hillock lengths are determined by the spacing of lamination lines. In the absence of surface irregularities, the micro-hillocks trend parallel to the traces of octahedral growth layers. At the sides of ridges which are crested by lamination lines, however, the trends of micro-hillocks deviate so that a herringbone pattern results. Widely-spaced or isolated lamination lines may, thus, easily be mistaken for macle lines.

Williams (1932, p. 461) first demonstrated that lamination lines do not express twinning. He suggested, on the advice of M.D. Mountain, that they are glide lines. More detailed X-ray diffraction analyses by Urusovskaya and Orlov (1964) substantiated William's suggestion and demonstrated that crystals exhibiting lamination lines have experienced plastic deformation by internal gliding along sets of octahedral planes.

The lack of topographic expression of lamination lines on octahedral surfaces indicates that the amount of translation involved at each glide plane cannot be more than minute. The apparent "micro-faults" on tetrahexahedroid surfaces therefore do not reflect actual amounts of translation. Instead, the "micro-faulting" is likely to be a consequence of differential resistance to resorption between strips of surface bounded by lamination lines. The manner in which lamination lines commonly define the crests of ridges on tetrahexahedroid surfaces indicates that these lines mark the traces of planes which were relatively resistant to resorption. A general, relative resistance to resorption at lamination lines is also suggested by their particularly good expression near to the four-fold axial corners of some tetrahexahedroids, since these corners are the regions where a maximum resorption of original octahedra would have occurred. Evidently, it is only in rare cases that glide planes are relatively weak planes. Lamination lines at which trigons are localized on octahedral surfaces are probably examples of structurally weak glide planes.

Lamination lines pre-date trigon formation and crystal resorption. Both lamination lines and shagreen texture are particularly common among brown diamonds but also occur on colourless and other-coloured diamonds.

According to Gane (1971), it is possible for diamond to deform plastically at room temperature. Stresses close to the theoretical strength of diamond are required, however, and only a slight tensile stress component will cause brittle fracture to occur instead (Gane, op.cit.). Evans (1976) has shown that only at temperatures above approximately 1 500°C is plastic behaviour more likely than brittle behaviour. At such high temperatures, diamond should be rapidly graphitized unless pressure is also very high. High pressure probably inhibits brittle fracturing to some extent so that Evans (op.cit.) estimates that temperatures of at least 1 300°C and pressures of approximately 50 kb probably prevailed during the natural, plastic deformation of diamond. The environment in which the plastic deformation considered responsible for initiating lamination lines on diamond probably occurred is discussed further in Section 7.2.

When lamination lines and shagreen texture are evident only near to four-fold axial corners, remaining tetrahexahedroid surfaces commonly exhibit elongate hillocks. In common with elongate hillocks, the micro-hillocks of shagreen texture probably also result from resorption. Micro-hillock forms are strongly influenced, however, by the glide planes with which they are associated.

### 6.5.3. Chemically-polished surfaces

Some tetrahexahedroid surfaces display only occasional, subdued hillocks and lack any ultrafine texture. Crystals with these polished, tetrahexahedroid surfaces display nearly perfect adamantine lustre which is usually the case only for octahedral diamond surfaces. Another notable feature of such crystals is that their edges, and edges to trigons on octahedral crystal faces, are distinctly rounded. Diamonds with polished surfaces of the type described were encountered

only among some samples from detrital deposits. Nevertheless, it is clear that the polishing is due to a chemical, rather than mechanical, process which pre-dates all abrasion features. This type of polished surface is therefore likely to be a pristine surface texture. Chemically-polished surfaces are illustrated in Figure 48.

Chemical polishing post-dates crystal resorption and the formation of trigons. A disproportionate number of the diamonds with chemically-polished surfaces also display shallow, network patterns (Article 6.5.5.). The process responsible for chemical polishing apparently also picks out the structural features which network patterns reflect.

Considering the experimental data reviewed (Section 6.1.), reaction with dry carbon dioxide gas is the most likely process by which diamond may be chemically polished. This reaction requires temperatures above 950°C (Phaal, 1965).

#### 6.5.4. Ruts

Typical ruts are illustrated in Figure 49. Most ruts trace octahedral to subconchoidal planes on tetrahexahedroid surfaces. Others radiate from inclusion cavities or are developed at seams between interpenetrantly-twinned parts of crystals. Some are sinuous. Rut sides are usually conspicuously etched while edges between such sides and crystal surfaces are typically rounded, and there can be little doubt that many ruts represent either planar zones of weakness or actual cracks widened by resorption or etching. Textures such as frosting (Article 6.5.11.) were sometimes seen to partly extend into ruts, proving that some are relatively old features. Orlov (1977, p. 98) refers to ruts as "etch channels". He (op.cit., p. 205) suggests that sinuous examples are produced by etchants which penetrated along cracks in xenolith hosts to diamond. The forms of such ruts then

reflect the forms of the cracks, rather than any planes of weakness in diamond.

#### 6.5.5. Network patterns

Patel and Agarwal (1966) imply that network patterns are common features on diamonds. In the present study they were found to be rare features noted only in some detrital diamond samples. Network patterns pre-date diamond abrasion and etching is obviously involved in their formation. Although network patterns were not observed in any kimberlitic diamond sample studied, they are therefore likely to be pristine features. Network patterns occur on cubic, octahedral and tetrahexahedroid crystal surfaces (Figure 50). In all cases the networks define the intersecting traces of octahedral planes. Tolansky (1959) and Patel and Patel (1972) report that some network patterns mark elevations on diamond surfaces. In the present study they were always seen to consist of grooves. In most cases the grooves are much less substantial features than the ruts described previously. They are sometimes difficult to distinguish from cracks.

Network patterns on cubic surfaces consist of two sets of parallel grooves intersecting at 90°. Intersections between grooves may be curved. Convex cubic surfaces (see Section 5.4) commonly exhibit network patterns. In such cases the grooves extend only partly onto adjacent tetrahexahedroid surfaces. On some cubes with indented surfaces, network patterns were found to be developed on adjacent tetrahexahedroid surfaces but to be absent within the most indented areas of the cubic surfaces.

On octahedral surfaces, network patterns consist of three, intersecting sets of parallel grooves. Each set is parallel to an octahedral crystal edge. Complex, local patterns may develop according to the variety of groove intersections involved. The network patterns

observed on octahedral crystal surfaces were seen to peter out on adjacent tetrahexahedroid surfaces.

Rhombic and crescentic network patterns develop on tetrahexahedroid surfaces. These patterns reflect two of the three directions of octahedral planar traces, the unrepresented direction being that tracing octahedral growth layering. The grooves on tetrahexahedroid surfaces may be narrow and shallow or substantially wider and deeper than those observed on other crystal surfaces. The crescentic patterns consist of particularly wide and deep, but short, grooves which resemble ruts. Crescentic patterns are considered as a variety of network pattern in which groove development is localized at intersections. They also resemble large percussion figures (see Section 8.2.). Unlike percussion figures, however, the crescentic patterns are distinct grooves, rather than mere cracks, and spall scars are not generally associated. Another variant of the network patterns developed on tetrahexahedroid surfaces consists of small, crescentic grooves arranged in series. These features are easily mistaken for chatter-mark trails (see Section 8.2.). Series of crescentic grooves also resemble scratch-like markings (Article 6.5.12.) in some respects. The depth of the grooves constituting the rhombic and arcuate patterns tends to be uniform on any tetrahexahedroid surface. Groove depth is therefore unrelated to the amount the crystal surface was lowered by resorption, which is not the case with most other network patterns.

Network patterns which consist of narrow, shallow grooves, are nearly always developed on chemically-polished diamond surfaces. Deep network patterns on tetrahexahedroid surfaces may be associated either with very fine, negatively-oriented hillocks which are superimposed on larger, elongate hillocks, or with positively-oriented surface textures. Pandeya and Tolansky (1961) record the development

of network patterns upon microdisk patterns.

Orlov (1977, p. 100) mentions experiments by Titova (1960) who produced network systems of cracks by heating diamonds in air at 700°C. Orlov suggests that cracks may be produced by heat alone and that these could be subsequently widened by etching. Air at 700°C should oxidize diamond (Phaal, 1965), however, and the features observed by Titova could have been the incipient grooves of network patterns, rather than cracks. Should Orlov's (op.cit.) suggestion, that network patterns can be initiated by heat, alone, be tenable, network patterns could be expected to be exceptionally common features of diamond.

Patel and Patel (1972) succeeded in widening the grooves of existing network patterns by etching in fused potassium nitrite at 800 to 860°C. They also found that sustained etching, which lowered the general surface of the crystals experimented on, eventually eliminated the network patterns. The latter result indicates only shallow penetration of whatever planes of weakness the grooves are localized at. Patel and Patel (op.cit.) suggest that the grooves are caused by etching which is localized at arrays of dislocations between slightly misoriented sub-grains. The sub-grains are considered to form in the vicinity of diamond surfaces during the final stages of the growth of some crystals. Patel and Patel's (op.cit.) suggestion can explain why network patterns on cubic and octahedral crystal surfaces commonly fade out on resorbed and deeply-etched surfaces. Deep extensions of sub-grain boundaries are required, however, for most of the grooves on tetrahexahedroid surfaces. Considering their resemblance to percussion figures and chattermark trails, it is also possible that some crescentic grooves are the etched sites of damage caused by impacts between diamonds and other particles. A

similar origin for scratch-like markings is discussed more fully in Article 6.5.12..

The dislocation planes presumed responsible for network patterns contrast with the glide planes causing lamination lines in generally being more easily etched than undislocated diamond. The upstanding varieties of network pattern reported by Tolansky (1959) and Patel and Patel (1972), however, possibly reflect dislocation planes which proved relatively resistant to resorption and etching.

#### 6.5.6. Inclusion cavities

Isolated cavities with octahedral sides occur in some diamond crystal and breakage surfaces (Figure 51). Cavity sides generally exhibit prolific, trigonal pits. One or two ruts commonly radiate from the cavities.

Sutton (1918, pp. 84-88) describes similar cavities and considers them to represent sites of pre-existing inclusions. This is difficult to prove but the author concurs with the opinion that inclusions were responsible for the cavities. In support of this opinion, syngenetic inclusions in diamond commonly assume an octahedral, external form (e.g. Prinz et al., 1975) and some cavities might be moulds of inclusions plucked from, or dissolved out of, their hosts. Radiating ruts reflect release of strain about the cavities. In these and possibly other cases, inclusions may have escaped from their hosts by ejecting a cleavage block of diamond. The octahedral form of some of the cavities may thus reflect the cleavage of diamond rather than the external form of an inclusion.

Strain about inclusions is most likely to result from a relative contraction of diamond, by comparison with inclusion, during cooling. That the cavities are etched indicates that they are produced during (or before) kimberlite emplacement. While diamond

crystal resorption may be important in reducing the amount and, therefore, the strength of diamond overlying an inclusion, sharp edges between cavities and crystal surfaces indicate that some inclusions must have departed after crystal resorption. Others have rounded edges and pre-date some resorption.

#### 6.5.7. "Pitted hemispherical cavities"

Hemispherical cavities (Figure 52) are conspicuous features on some diamond tetrahedra from Wellington, Australia, and from the Prairie Creek Kimberlite, U.S.A.. Most of the cavities have diameters of between 0,2 and 1,0 mm. Many are too shallow to strictly be termed hemispherical. Others actually have rectangular or hexagonal outlines. In the Wellington sample examined, most of the cavities are coated with light brown material which was not removed by ultrasonic cleaning. Cavity walls, where exposed, are marked by prolific etch pits. Cavities of circular or rectangular outline usually exhibit tetragonal pits although trigonal pits may also be associated. Cavities of hexagonal outline exhibit hexagonal pits. Tetragonal pits are diagnostic features of cubic surfaces of diamond but cavities exhibiting tetragonal pits are apparently distributed randomly on tetrahedron surfaces. It was not possible to determine the orientation of the tetragonal pits, but trigonal pits were seen to be in the negative orientation. Cavities containing hexagonal pits occur either on remnant, approximately octahedral faces or close to six-fold axial corners where octahedral surfaces would occur if preserved.

Few of the diamonds exhibiting pitted hemispherical cavities contain inclusions. Therefore, the cavities are unlikely to represent inclusion cavities. Grantham (1974) tentatively suggested that the cavities could be due to restricted growth against other mineral

grains. Such mineral grains would be required, however, to exhibit spherical, rectangular or hexagonal shapes. Also, most cavities occur on resorption, not growth, surfaces.

All of the crystals encountered with pitted hemispherical cavities are distorted tetrahedra with surfaces of low relief. As discussed in Article 6.4.4., many such crystals probably represent substantially resorbed cubes. The internal stratification of diamond cubes is undulatory (Moore and Lang, 1972). Resorption which transects the general, cubic stratification may therefore locally expose layers which are nearly parallel to a resorption surface. Etching by steam or wet carbon dioxide, at temperatures above 950°C, is relatively rapid at cubic surfaces (Phaal, 1965). Cavities may thus develop locally where cuboid layers nearly parallel to tetrahedron surfaces are exposed. In the case of pitted cavities of hexagonal outline, it is necessary that etching was relatively rapid at octahedral surfaces. The hexagonal cavities are likely to have been produced under slightly different conditions (e.g. 950 to 1 000°C with free oxygen present) than prevailed during the formation of typical hemispherical cavities.

#### 6.5.8. "Knob-like asperities" (and ribbing and other associated features)

Dodecahedral diamonds displaying ribbing (Article 6.4.12.) and knob-like asperities (Figure 53, also Figure 12) are fairly common in some samples but are absent in most samples. Such diamonds are also very common among those studied from eclogite xenoliths (see Chapter 9). Knob-like asperities occur on octahedral, as well as dodecahedral, surfaces. Serrate laminae (Article 6.2.7.) and pointed plates (Article 6.3.3.) are associated at octahedral and cubic surfaces, respectively. Coatings of very fine-grained graphite are commonly present on the surfaces of diamonds, recovered from both kimberlite and eclogite.

xenoliths, which display ribbing and knob-like asperities.

Most diamond dodecahedral surfaces display conspicuous ribs which are parallel to the major rhombic diagonal. Individual ribs are actually bounded by octahedral surfaces. The dodecahedral crystal surfaces are therefore compound and actually consist of octahedral micro-surfaces. Some ribs end in wedge-shaped terminations which generally point toward the nearest dodecahedral crystal edge. These terminated ribs grade into pointed plates as cubic surfaces are approached.

Knob-like asperities occur upon the ribbing of dodecahedral surfaces and upon serrate laminae on octahedral surfaces. The outlines to the asperities vary from nearly circular on dodecahedral surfaces, and triangular on octahedral surfaces, to grossly irregular. The asperities can be flat features, only a few micrometres in height, on some diamonds and steep-sided features, up to more than 0,1 mm in height, on other diamonds. Underlying, dodecahedral ribbing extends to the surfaces of the flat varieties of knob-like asperities. The sides of irregular asperities are finely pitted. A surface texture which is considered to be an extremely coarse variant of knob-like asperities is peculiar, among the samples studied, to rare diamonds from Pipes DK 1 and DK 2. Knob-like asperities are always of diamond identical in colour (frequently brown) to the diamond crystal on which they occur.

Knob-like asperities, ribbing, the dodecahedral form on which ribbing occurs, serrate laminae and pointed plates are all uncommon features of diamonds in general. Intimate associations between these features therefore strongly suggest that they all form together. The universal correspondence in colour between knob-like asperities and host diamond does not support any likelihood of the asperities being

overgrowths. The role of flat-bottomed trigons in the development of serrate laminae (see Article 6.2.7.) links all of the associated features to a diamond-etching process. The graphite coatings which are commonly associated with knob-like asperities and ribbing indicate that either graphitization or oxidation at a relatively low oxygen fugacity (with respect to temperature) is involved in their formation. Oxidation is the more likely process, considering the association with trigons rather than with any features resembling "three bladed propellers" (see Article 6.1.3.). Likely etchants are steam or wet carbon dioxide gas at temperatures above 950°C. One situation in which sufficiently low oxygen fugacities could be realized is within xenoliths, where kimberlitic volatiles have only limited access to any diamonds inside.

The dodecahedral form is evidently derived by resorption of the octahedron. While the formation of dodecahedral, rather than tetrahedroid, surfaces appears to be a response to a relatively low oxygen fugacity during resorption, it is not clear why this condition should alter the mechanics of the resorption process.

#### 6.5.9. "Pitted disks"

Rare diamonds from the Premier Mine appear light grey and exhibit an almost metallic lustre when viewed under the binocular microscope. Their appearance is so unusual that it was initially suspected that the specimens were of some other mineral. X-ray diffraction analysis showed this not to be the case. The surfaces of these diamonds consist of circular disks with lightly pitted surfaces, which are separated by intervening, intensely pitted areas at a lower elevation (Figure 54). Individual disks range from 10 to 70  $\mu\text{m}$  in diameter. Trigonal pits are developed on disks situated on octahedral surfaces. Pitted disks are developed on some breakage

surfaces but not on others. The texture was noted only on crystals of irregular form so that the orientations of constituent etch pits could not be determined.

The nature of areas between disks suggests that they experienced rapid etching for a short period. The circular form and less etched surfaces of disks can be explained by gas bubbles which inhibited etching. One possible sequence of events is reaction between diamond and oxygen gas liberating carbon dioxide at a temperature below 950°C. Should the carbon dioxide have adhered as bubbles for the duration of the etching, underlying surfaces would only exhibit etch features developed before bubble formation.

#### 6.5.10. Circular micro-pits

The detailed examination of low-relief, tetrahexahedroid surfaces sometimes discloses the presence of scattered, shallow pits of circular to oval outline (Figure 55). These pits commonly have diameters of between 5 and 60  $\mu\text{m}$ . Their bottoms may be flat or the pits may deepen slightly towards their margins. In most cases, only a few circular micro-pits are to be seen. Sometimes, however, they are prolific features. Then small pits occur within larger examples and neighbouring pits commonly overlap. Areas of overlap are relatively deep. Examination in the scanning electron microscope sometimes discloses the presence of associated, rectangular pits less than 5  $\mu\text{m}$  in size. These rectangular pits are possibly incipient forms of circular micro-pits. They resemble the constituent features responsible for the fine frosting of tetrahexahedroid surfaces (see Article 6.5.11.).

Circular micro-pits were also noted (rarely) on cubic crystal surfaces. They are apparently never developed on octahedral surfaces but very small pits of irregular outline may be present instead.

Where prolific, such pits can cause octahedral surfaces to be finely frosted (Article 6.5.11.).

Circular micro-pits post-date the resorption of octahedral and cubic crystals. The association with some of the constituent features of fine frosting suggests that circular micro-pits might be a variation of fine frosting. According to Phaal (1965), oxygen gas at temperatures above 1 000°C can produce a graphite film, on diamond, which is sufficiently thick to control, and equalize, the diamond etching-rates in various directions. Circular etch pits will then be produced on diamond surfaces. No graphite films were observed, however, in association with circular micro-pits. The form of and inter-relationships between circular micro-pits are also consistent with their having resulted from etching by adhering gas bubbles. Carbon dioxide bubbles, produced as a reaction product during the oxidation of diamond, could possibly be responsible.

#### 6.5.11. Frosting

Surface frosting is a common feature in some diamond samples examined but is rare or absent in other samples. It is usually only a local feature but entirely frosted crystals occur and may be confused with abraded crystals when viewed at low magnification. Frosting appears to be preferentially developed on tetrahexahedroid surfaces but commonly extends onto associated octahedral faces. It is superimposed on textures such as elongate hillocks and trigons. Relatively coarse frosting can be distinguished from relatively fine frosting under the conventional, binocular microscope. However, the one variety may grade into the other and clear distinction is not always possible.

In coarse frosting, constituent features (Figure 56) can sometimes be resolved under the conventional, binocular microscope.

On tetrahexahedroid surfaces, coarse frosting consists of a myriad of hexagonal, equidimensional to prismatic pits. Prismatic varieties are oriented in various directions but a preferred, negative orientation is evident. On octahedral surfaces the pits are flat-bottomed. Their outlines vary from irregular to trigonal (negatively-oriented) and hexagonal. Etch pit characteristics are compatible with coarse frosting having formed by rapid etching, for a limited period, by either steam or wet carbon dioxide plus subordinate free oxygen, at temperatures mostly between 950 and 1 000°C. Coarse frosting can grade into corrosion sculpture on tetrahexahedroid surfaces.

In fine frosting (Figure 57), pyramidal pits of rectangular outline are developed on tetrahexahedroid surfaces. Irregular, hexagonal and positively-oriented, trigonal pits are developed on octahedral surfaces. Rarely, fine frosting is localized in narrow, curved bands on tetrahexahedroid surfaces, thereby producing features which resemble scratches when viewed at low magnification. The characteristics of the octahedral etch features suggest that fine frosting results from rapid, brief etching, mainly by oxygen gas, at temperatures of about and below 950°C. It is common for breakage surfaces to exhibit fine frosting. This indicates that fine frosting is a very young surface texture. The fine frosting which accompanies the development of fine striation with edge enhancement (Article 6.4.11.) is distinct from that discussed here.

#### 6.5.12. "Scratch-like markings"

Linear to curved features resembling scratches (Figure 58) occur on the octahedral and tetrahexahedroid surfaces of some diamonds. Rare examples resemble percussion figures. None of these features was observed on cubic surfaces. Scratch-like markings were found to be particularly common on the diamonds of some detrital deposits

but were also noted in some samples from kimberlite. Scratch-like markings were first reported on natural diamond by the author in 1975 (Robinson, 1975).

On diamonds of the minus 11 plus 9 sieve class, individual scratch-like markings vary from a few micrometres to about 2 mm in length. The shortest are usually only a few micrometres in width while most long examples have widths up to 0,1 mm. Width is not always related to length, however, so that long examples may be narrow and short examples may be wide. Only wide examples are prominent features under the binocular microscope. Scratch-like markings are frequently, but not always, concentrated at crystal edges and on octahedral crystal faces. On tetrahedroid surfaces they are sometimes relatively abundant in the vicinity of six-fold axial corners. Parallel scratch-like markings are sometimes developed but no universal, strongly preferred orientation was noted.

At high magnification, scratch-like markings are seen to consist of evenly-spaced, crescentic to elbowed grooves arranged in series. Careful examination discloses that individual grooves trace three octahedral planes although intersections between these traces may be curved. Some wide, prominent examples of scratch-like markings exhibit one or more medial, linear grooves and linear grooves which join the elbows of crescents. Slight displacements sometimes appear to have occurred at these linear grooves. Examples of scratch-like markings which resemble percussion figures consist of a small number of relatively wide, sometimes opposed, crescentic grooves.

Similar, scratch-like features noted on detrital almandine grains were interpreted by Folk (1975) as chattermark trails accredited to glacial scouring. This was contradicted by Bull (1977) who demonstrated that light etching can produce the same features

on quartz crystal faces. The author has also observed scratch-like features on lightly-etched, breakage surfaces of kimberlitic pyrope grains. Developments of scratch-like features on kimberlitic pyrope and on diamonds recovered from kimberlite disproves any dependence on glaciation for the texture.

Scratch-like markings must reflect either mechanical surface damage or an internal, structural feature. Myriads of extremely small (edge length approximately  $1 \mu\text{m}$ ), positively-oriented, trigonal pits are frequently associated with the scratch-like markings on diamond octahedral surfaces. Such pits are otherwise very rare and it is evident that the etching which produced them also disclosed the scratch-like markings. The scratch-like markings are absent in the deepest parts of some trigons. This indicates that they are confined to the near surface. The presence of scratch-like markings on tetrahexahedroid diamond surfaces indicates that they post-date diamond resorption. Scratch-like markings are therefore likely to reflect mechanical surface damage, rather than an internal, structural feature. Mechanical spalling is seldom evident, however, at the scratch-like markings on diamonds recovered from kimberlite.

Brookes and Green (1973) observed that light etching may disclose micro-deformation, which is not otherwise evident, at the surface of a hard crystal where it has been contacted by a softer material. Contact pressures of only a hundredth of the nominal indentation hardness are required. Brookes and Green (op.cit.) consider the deformation to be by dislocation activity, i.e. plastic deformation. However, Wentorf (1959) noted that diamond is relatively weak in tension and therefore likely to fail under frictional stress by cracks resulting from the pulling apart of octahedral layers. Published photomicrographs (Brookes and Green, op.cit.; Wentorf, op.cit.

and Schlössen, 1969) of friction tracks on various materials over which indenters had been slid closely resemble natural, scratch-like markings on diamond. The natural markings are therefore considered to reflect friction between diamond and softer materials, with disclosure of the tracks requiring subsequent, light etching.

Scratch-like markings were produced on a synthetic diamond lightly etched by water-rich kimberlite at 1 080°C and 30 kb (Wyatt and Robinson, 1975). Friction was presumably a consequence of the compaction of the particulate kimberlite surrounding the diamond, as pressure was increased during the experiment.

The influence of scratch-like features on the abrasion of diamond is discussed in Section 8.5.

#### 6.5.13. Concentric patterns on ballas surfaces

Rare ballas diamonds were noted from the Premier Mine and the State Diggings. This diamond curiosity is a radial aggregate (Orlov, 1977, pp. 14-15; Jeynes, 1978). Ballas surfaces exhibit concentric, hexagonal patterns (Figure 59) which presumably represent sections through the conical constituents radiating from the ballas centres.

#### 6.5.14. Graphite coatings

A surface coating of very fine-grained, black material is common on the diamonds in eclogite xenoliths (see Chapter 9). Textures such as flat-bottomed trigons, serrate laminae and ribbing are developed beneath this coating. Black coatings are very rarely present on diamonds recovered from kimberlite. Where present, such coatings invariably overlie rare surface textures, particularly ribbing, knob-like asperities and serrate laminae. Although not strictly a diamond surface texture, it is appropriate to discuss

these black coatings in some detail.

Phaal (1965) refers to "amorphous carbon" being produced in diamond-oxidation experiments. Evans and Phaal (1962) refer to the same material as "graphite". A number of crushed samples of black material coating diamond surfaces were subjected to X-ray diffraction analysis. It was found that very poor diffraction patterns were obtained in a conventional, Debye-Scherrer X-ray camera. This suggested that the material is either poorly crystalline or predominantly amorphous. The same samples were also X-rayed in a Gandolfi camera, in which the sample is exposed through a much wider range of solid angles to the X-ray beam than in the Debye-Scherrer arrangement. Sharp diffraction patterns diagnostic of well-crystallized graphite (E. Ho-Tun, personal communication) were obtained. The poor results obtained in the Debye-Scherrer camera can be ascribed to the difficulty of producing suitable graphite samples. Well-formed graphite crystals were also imaged in the scanning electron microscope in some cases (Figure 60).

A graphite coating on diamond need not imply the purely physical transformation of diamond. As mentioned previously, graphite coatings may develop on diamonds during fairly low temperature oxidation experiments conducted at sufficiently low oxygen fugacities. Oxygen evidently catalyses graphitization. The presence of sufficient oxygen will ensure, however, that all traces of oxidation-graphitization are removed.

The common preservation of graphite coatings over certain, rare diamond surface textures indicates that the general scarcity of graphite-coated, kimberlitic diamonds is not entirely due to the coatings having been removed by magmatic attrition. This is also indicated by a general absence of graphite in deep depressions in the surfaces of some diamonds. The general scarcity of graphite coatings must be mainly due, instead, to their uncommon development.

## 7. THE SEQUENCE OF EVENTS AFFECTING DIAMONDS

In the previous chapter, relative ages were noted between some surface textures. Only in the case of trigons within hexagonal pits, is it possible that a negatively-oriented feature might post-date a feature containing a positively-oriented element. As detailed in Article 6.2.5., however, both the negatively- and positively-oriented components of this texture probably develop at about the same temperature. The relative ages between some surface textures and crystal forms were also noted in the previous chapter. Most of the surface textures and crystallographic features can therefore be arranged in a chronological sequence. The developments of the main colours in diamond can also be included in the sequence. Considering the conditions under which some diamond features were probably produced, the sequence of the events affecting diamonds can be compiled. The diamond characteristics considered are listed in the chronological order of their development in Table 6. Five main processes responsible for these characteristics are recognized. These processes are:-

- i. Crystal growth.
- ii. Plastic deformation.
- iii. Crystal resorption and high-temperature etching. The etching typically produces negatively-oriented etch features.
- iv. Damage caused by friction.
- v. Relatively low-temperature etching which typically produces positively-oriented etch features.

### 7.1. CRYSTAL GROWTH

Colours which can be attributed directly to the growth environment include the colourless of type IIa diamonds (which contain very

little nitrogen) and the amber yellow of type Ib diamonds (which contain nitrogen as single, substitutional atoms). As in diamond synthesis experiments (Giardini and Tydings, 1962), only the octahedron and cube need to be primary crystal forms. Smooth octahedral faces and triangular plates are the only growth-produced surface textures noted to ever survive. The potential for textures such as terraces, zigzag texture, some network patterns and the macle line to develop subsequently is also determined during crystal growth.

The intersection between the shield geothermal gradient and the thermodynamic boundary for diamond crystallization, which are plotted in Figure 1, indicates a minimum depth of 154 km and a minimum temperature of approximately 1 250°C for diamond crystallization. While cubes might crystallize at this temperature, octahedra probably require higher temperatures and, hence, a greater minimum depth. (It should be noted that the geothermal gradients which prevailed during periods of diamond crystallization are not known. The gradient used in Figure 1 is only one of a number of calculated or inferred examples which have been published. Depending on the example selected, any minimum temperature between 1 000 and 1 300° C can be implied for diamond growth).

The aggregation of substitutional nitrogen atoms to produce the relatively common, colourless or yellow type Ia diamonds should occur within a few years in diamond growth environments, according to the experimental results of Chrenko, Tuft and Strong (1977). This interval suggests (but does not strictly imply) that type Ia diamonds pre-date the generation of kimberlite magma, while favouring the possibility that the rare, type Ib diamonds originate in kimberlite magma.

## 7.2. PLASTIC DEFORMATION

Lamination lines are considered to reflect plastic deformation.

Most of the brown colour in diamond is considered to develop in association with plastic deformation (see Chapter 18).

The conditions estimated by Evans (1976, see Article 6.5.2) for the natural, plastic deformation of diamond places this process within the earth's upper mantle. Brown discolouration, if due to incipient graphitization (see Section 4.3 ), suggests that diamond may be taken to conditions outside of its thermodynamic stability field during the deformation event. Stress heating is likely to be responsible.

Plastic deformation requires a deviatoric stress which implies that diamonds were contained within an essentially solid medium while they were undergoing deformation. It is therefore concluded that any diamond displaying lamination lines must be a xenocryst with respect to kimberlite magma. Both Orlov (1977, p. 205) and Robinson (1978) have suggested that diamonds are plastically deformed during the shearing process which is recorded in the textures of many ultramafic xenoliths in kimberlite (e.g. Boyd and Nixon, 1975). Orlov (op.cit.) is of the opinion that the process which fractures eclogite xenoliths can also plastically deform diamonds. Boyd and Nixon (op.cit.) suggested that the shearing evident in ultramafic xenoliths could have been caused by mantle creep associated with the fragmentation of Gondwanaland. Goetze (1975) subsequently demonstrated that the deformed textures should not survive long residence at high temperature, so that they are probably caused by sheer stresses induced at the conduit walls of ascending kimberlite magma. Goetze's conclusion has been substantiated and elaborated on by Mercier (1979). According to Mercier, stresses of 0,4 to 1,2 kb are involved in the deformation of the ultramafic rocks.

### 7.3. RESORPTION AND HIGH-TEMPERATURE ETCHING

The etching which produces negatively-oriented surface textures requires temperatures higher than 950°C. Frank and Puttick (1958) suggested that etching which produces negatively-oriented etch pits would preferentially resorb octahedral corners and edges to produce rounded "dodecahedral" (i.e. tetrahexahedroid in the general case) surfaces. This suggestion has been experimentally verified by Kanda et al. (1977). Negatively-oriented surface textures were always found to be associated with tetrahexahedroid (or dodecahedral) surfaces. Crystal resorption and high-temperature etching are therefore considered to be manifestations of the same process. Oxidation, by steam or wet carbon dioxide gas, is the process most likely to be responsible.

Diamond crystal resorption is necessary to disclose the effects of plastic deformation. Resorption therefore post-dates plastic deformation. High temperature etching must pre-date kimberlite ground-mass crystallization which, according to Mitchell (1973), takes place at about 600°C. Crystal resorption and high-temperature etching therefore occur in kimberlite magma. Experimental studies by Wyllie and others (Wyllie, 1979) indicate that ascending kimberlite magma should evolve carbon dioxide gas and water vapour at between 100 and 80 km from the surface. Resorption and high temperature etching is likely to commence then. Since graphite films are rarely preserved on diamonds, conditions substantially more oxidizing than those for equilibrium between carbon and carbon oxides are suggested. That diamond is not entirely destroyed must be due to the rapid emplacement and cooling of kimberlite magma. In this regard, the kimberlite emplacement model considered by McGetchin and Ullrich (1973) allows only one hour for kimberlite magma to ascend from 100 km depth to the surface and to cool to low temperatures.

Textures such as hexagonal pits, corrosion sculpture, chemically-polished surfaces and coarse frosting are also considered to require temperatures in excess of 950°C for their development. All of these textures are younger than tetrahexahedroid surfaces although minor, negatively-oriented etch pits (i.e. trigons) were seen to be even younger in some cases. An imperfect, two-fold division of the features produced by high-temperature etching is therefore possible.

Diamond breakage surfaces commonly display trigons, hexagonal pits or coarse frosting. Much diamond crystal breakage therefore occurs before the termination of high-temperature etching.

Any diamond exhibiting resorption surfaces or high-temperature etch features must have crystallized at above 950°C, unless subsequent heating occurred.

#### 7.4. FRictionAL DAMAGE

Scratch-like markings are considered to reflect frictional damage. These markings post-date crystal resorption and high-temperature etching and are disclosed by light, low-temperature etching. Frictional damage which is disclosed is likely to be produced at temperatures between 950°C and not much below 600°C, in kimberlite which is largely particulate but still in motion. Considering that few diamonds are evidently subjected to low-temperature etching, more diamonds than those exhibiting scratch-like markings are probably frictionally-damaged at temperatures above about 600°C. Frictional damage which occurred at temperatures too low for disclosure by natural etching may be very common among the diamonds of tuffaceous kimberlite.

#### 7.5. LOW-TEMPERATURE ETCHING

The effect of low-temperature etching is epitomized by positively-

oriented surface textures. Such textures are likely to be produced only at temperatures of between slightly above 1 000°C and 450°C. Oxygen gas and pressurized steam are the likely etchants. In the case of steam, it is necessary that the environment is not buffered at too low a level of oxygen fugacity.

Textures such as coarse frosting, hexagonal pits and fine frosting can be regarded as intermediate between those due to high-temperature etching and those due to low-temperature etching. Generally, however, positively-oriented surface textures are clearly younger than any negatively-oriented features so that most low-temperature etching probably occurs below 950°C. At least some post-dates frictional damage.

A preferential loss of hydrogen from dissociating steam might increase the oxygen fugacity of kimberlite magma near to the earth's surface (Wedepohl and Muramatsu, 1979). It is possible that conditions sufficiently oxidizing to etch diamond at low temperatures could thereby result. The general scarcity of diamonds displaying positively-oriented etch features suggests, however, that sufficiently oxidizing conditions are only realized locally. This is more compatible with the contamination of kimberlite magma by atmospheric gas or ground water being responsible.

McGetchin and Ullrich (1973) stress the very rapid, adiabatic cooling of kimberlite magma which should accompany the increasing decompressibility of volatiles as depths shallower than about 10 km are attained. According to their model, low-temperature etching might be possible for only a few minutes during the formation of kimberlite pipes.

## 8. DIAMOND ABRASION FEATURES

Since diamond is by far the hardest mineral known, perhaps it is surprising that it can be abraded in nature. Although hard, diamond is also brittle and exhibits easy cleavage along octahedral planes. Furthermore, experiments by Dietrich (1977) in which soft particles were impacted against hard materials demonstrate that damage to the impacted material is largely a function of the kinetic energy, rather than the relative hardness, of the impacting particles.

Possible manifestations of the abrasion of diamond include the development of cracks, breakage surfaces and surface textures such as percussion figures, spall scars, ground surfaces and polished surfaces.

### 8.1. CRACKS AND BREAKAGE SURFACES

A severe blow to a diamond crystal will cause it to split. Experiments by Levitt (1965) showed that for a small, circular area of contact, splitting is initiated at an annular or crescentic percussion crack which develops about the area of contact made by the impinging particle. With sufficiently severe impact, this crack propagates in depth as a diverging cone which, however, soon passes into cleavage surfaces. Sutton (1928) mentions that diamonds which are severely cracked before being released from kimberlite will disaggregate under gentle treatment.

Orlov (1977, p. 167) believes that broken diamonds are more scarce in placer deposits than in kimberlites because cracked diamonds disintegrate into small fragments during transportation. This might explain scarcities of diamond fragments, but not of broken crystals, in placers. In the present study, breakage surfaces on detrital diamonds were often seen to be etched, indicating that many are pristine

features. Only rarely were percussion cracks observed which penetrate substantially into underlying diamond. It is therefore considered likely that while sedimentary transportation may winnow out intricately cracked diamonds, few diamonds not previously cracked will be broken.

## 8.2. PERCUSSION FIGURES AND SPALL SCARS

Some detrital diamonds display shallow, surface cracks of characteristic crescentic to annular-hexagonal outline (Figure 61). Tolansky (1965) reported small (10 to 50  $\mu\text{m}$  diameter) percussion figures which were disclosed, by light etching, on diamonds recovered from kimberlite. Etching was not employed to highlight surface damage in the present investigation and genuine percussion figures were observed only on detrital diamonds.

The crescentic to annular outline of percussion figures is influenced by the octahedral cleavage of diamond. On octahedral and tetrahexahedroid surfaces, at which traces of three octahedral planar directions are expressed, they tend to exhibit a hexagonal form. Percussion crack figures were not observed on cubic surfaces but square pressure crack figures with rounded corners were experimentally-produced on a polished cubic surface by Tolansky (1955, p. 57). At crystal edges, percussion figures are represented mainly by short, straight to curved cracks. These tend to cross edges between octahedral surfaces at  $60^\circ$ , "A" tetrahexahedroid edges either at  $90^\circ$  or a small angle and "C" tetrahexahedroid edges at  $30^\circ$  or  $90^\circ$ . Most percussion figures on minus 11 plus 9 sieve size diamonds are between 10 and 100  $\mu\text{m}$  in diameter. Much larger figures are few in number but are conspicuous features on some detrital diamonds.

Intersections between the constituent cracks of percussion figures

less than 100  $\mu\text{m}$  in diameter are generally angular. All gradations from crescentic (i.e. open) to hexagonal forms occur among these small percussion figures and crescentic varieties can be regarded as incompletely developed. Hexagonal outlines are developed only on locally flat surfaces. This indicates very shallow extensions of the cracks. Compound figures consisting of concentric cracks are common. In some cases the diamond between two concentric cracks has spalled off, thereby producing moat-like features about flat-topped, conical interiors. Associated, trigonal spall scars of edge length 0,5 to 5  $\mu\text{m}$  are characteristic features of small percussion figures. Spall scars are also illustrated in Figure 61. One edge to each spall scar is defined by the percussion crack and each scar marks the site of a tiny, octahedrally-bounded fragment removed from the diamond surface. Very small (edge length  $< 1 \mu\text{m}$ ) spall scars also occur which are not in contact with a crack. Spall scars resemble very small trigonal etch pits but are less regular in outline and are rough-bottomed. Subconchoidal spall scars may also occur on diamond crystals. These are most common at crystal corners and very sharp edges, particularly those representing distorted four-fold axial corners of tetrahedra, and are not necessarily associated with percussion cracks.

Closed forms are rare among percussion figures which exceed 250  $\mu\text{m}$  in diameter. In these large examples, one octahedral direction is typically poorly developed and is represented by a strongly curved crack. This continues, at each end, as a relatively long, straight crack following the other octahedral cleavage traces so that a widely open form results. In some cases a crescentic arm traverses a crystal edge, indicating considerable penetration of the crack unless its base undulates in accordance with the crystal surface. Internal reflection of light from the crack also discloses a

considerable penetration by some large percussion figures and it is conceivable that diamond crystals could thus be broken. Trigonal spall scars are much less common, per unit length of percussion crack, than with small percussion figures.

Howes and Tolansky (1955) produced surface markings on diamond very similar to the small percussion figures described. This they achieved by pressing a ball-ended diamond indenter against a diamond surface. Subsequently, Tolansky and Howes (1957) succeeded in producing hexagonal, pressure crack figures on diamond using relatively soft indenters, such as sapphire and tungsten carbide. In experiments producing pressure crack figures, the surface crack is localized just outside the area of contact of the indenter. Howes (1965) showed, by optical interferometry, that in both experimentally-produced pressure crack figures and natural percussion figures the surface inside of the crack is undisturbed. The crack marks an abrupt elevation increase of a few tens of nanometers and this elevation tapers off outside of the crack. No ductile behaviour is evident. Therefore, the stresses developed in the contact area can be calculated for experimentally-produced pressure crack figures using the Hertzian equation for elastic deformation. Bowden and Tabor (1965) detail the calculation involved. Such calculations indicate that pressure crack figures are most easily produced on octahedral surfaces of diamond. For equivalent-sized figures, slightly higher stress is required at dodecahedral surfaces and three times as much stress is required at cubic surfaces (Howes, 1959). The different effects of hard and soft indenters of like radius of curvature are expressed by the sizes of pressure crack figures produced and by the forces required to produce them. A relatively soft indenter will deform more on impact so will contact a larger area of diamond. A relatively

large pressure crack figure will therefore tend to result. However, a relatively large force is required to produce a relatively large crack figure. Stresses of approximately  $10^{11}$  dyne.cm<sup>-2</sup> are required to produce a small pressure crack figure on an octahedral diamond surface (Howes, 1959). In practice it is found that the tensile stress (but not the force) requirement diminishes with increasing size of the crack figure (Howes, 1965). Concentric crack figures develop in experiments in which the load is increased after the indenter has already produced a crack figure (Howes, 1965). Crack figures have also been produced in dynamic experiments. Cooper (1960, in Bowden and Tabor, 1965) found that a large number of impacts will produce a ring crack at a quarter the tensile stress required in static loading experiments. Although the experimental production of pressure crack figures suggests that the cracks could form by compaction in nature, all natural examples must have formed by percussion. Otherwise crack figures would be very common features of buried detrital grains of other minerals.

Two differences are apparent between experimentally-produced pressure crack figures and natural and experimentally-produced percussion figures. The first difference is that spall scars are not reported in association with pressure crack figures. Davids (1960) considers that spalling is caused by compressional stress waves being reflected at the edge of a medium and converted to tensile stress waves, which brittle materials withstand poorly. Presumably, this phenomenon is more likely with dynamically-applied, than statically-applied stresses. The second difference is that only closed forms are mentioned in reports of experimentally-produced pressure crack figures. Open (crescentic) forms of many natural crack figures are adequately explained by their being caused by angled impact trajectories.

Chattermark trails of crescentic percussion figures have been reported on diamonds (Tolansky, 1965; Howes, 1965). In most cases of apparent chattermark trails observed under the binocular microscope, in the present study, examination in the scanning electron microscope showed them to consist of pristine, arcuate features allied to network patterns (see Article 6.5.5.). Genuine chattermark trails consisting of only two, associated percussion cracks are, however, fairly common.

As short, straight to curved cracks, small percussion figures are usually strongly concentrated at crystal edges. Such a concentration would not be anticipated should most of the cracks be caused by small particles, or large but sharp-pointed particles, impacting against diamond. Preferential development of percussion figures at crystal edges is to be expected, however, should they be caused by diamond striking a relatively flat surface, such as in rolling or saltation over smooth bedrock. It is also compatible with their being caused by flat-surfaced particles striking diamond. Another reason for concentrations of small percussion markings at crystal edges is that only very small areas of contact can be made at sharp edges. Particularly small percussion figures may therefore form at such sites during collisions involving relatively little transfer of kinetic energy.

There is no report in the scientific literature of any attempt to calculate the particle size-velocity relationships necessary for natural percussion figures to form on diamond. It nevertheless seems apparent that impacting sand grains would require unrealistic velocities for them to produce percussion cracks. It also seems that for large percussion figures to result from impacts between diamond and stationary targets, excessive velocities are required for diamonds

of the sizes studied. Large percussion figures are therefore more likely to result from impacting rock pebbles or boulders.

### 8.3. GROUND SURFACES

Ground surfaces are developed at the rounded corners and edges and protuberances of some detrital diamonds. At (initially) sharp crystal corners, ground surfaces are due mainly to subconchoidal, micro-fracture surfaces. Elsewhere, ground surfaces usually consist almost entirely of closely-spaced percussion cracks and trigonal spall scars (Figure 62). Grinding at scratch-like markings (Article 6.5.12.) produces a unique, ground surface attributable to a spalling of plates of diamond bounded by neighbouring grooves of the markings (Figure 63). Scratch-like markings are often ground on detrital diamonds without any percussion markings and it is apparent that the surfaces at scratch-like markings are relatively easily abraded.

### 8.4. POLISHED SURFACES

Mechanical, smooth-polishing appears to involve a cutting (planing) action or a smearing of surface asperities (buffing). The first-mentioned process is probably restricted to the action of a hard material on a softer material. Buffing implies ductile behaviour by the material being polished. Neither of these polishing processes is known in diamond. In the commercial polishing of diamond surfaces with fine diamond powder, the surface produced (see Wilks and Wilks, 1972) resembles an extremely finely ground surface. Local relief is only about 5 nm (Thornton and Wilks, 1974), which is not resolvable even in the scanning electron microscope.

Rare detrital diamonds exhibit surfaces, between percussion

cracks and spall scars, with local relief down to less than 0,5  $\mu\text{m}$  (Figure 64). This local relief is due to extremely small, trigonal spall scars. Such surfaces can be described either as finely-ground or as polished. Surfaces qualifying to be described as mechanically polished are developed only on the most rounded diamonds encountered. Evidently, grinding of previously ground surfaces produces progressively smaller spall scars. This is to be expected since very small areas will be contacted during impacts at the asperities on ground surfaces. Minor impacts may therefore cause minor spalling and it is not easy to eliminate even sand-blasting as a possible cause of polishing. Percussion cracks which should be associated with trigonal spall scars may be too weakly developed to be evident or may truncate thin asperities so that they are seen as planar surfaces, rather than as cracks.

#### 8.5. TYPE AND DEGREE OF ABRASION

Figure 65 illustrates a diamond which was well rounded by treatment with other diamonds in an air-circuit attrition mill (C.M. Levitt, personal communication). In addition to percussion cracks and spall scars, upturned plates which resemble those developed on wind-abraded quartz grains (see Krinsley and Doornkamp, 1973) are also present. Upturned plates were not observed on any naturally-abraded diamonds. Consideration of the likely kinetic energies of particles of the sizes moved by wind also does not favour wind-action being responsible for any significant natural abrasion of diamond (excepting to possibly smooth ground surfaces). The constituent features of naturally-ground surfaces on diamond closely resemble the curved grooves and V-shaped impact pits occurring on the surfaces of subaqueously-abraded quartz grains (see Krinsley and Doornkamp,

op.cit.). In general, ground surfaces on diamonds are distributed according to the (initial) sharpness of the intersections between crystal surfaces. In exceptional cases in which grinding is localized elsewhere, this is at sites weakened by scratch-like markings. The general distribution of ground surfaces on diamonds is more consistent with subaqueous, than glacial, abrasion. It is therefore concluded that the ground diamonds examined in the present investigation were subaqueously abraded.

In some fluvial and littoral diamond deposits, diamonds are strongly concentrated in bedrock pot-holes (Wagner, 1914, p. 272; Keyser, 1972). Diamonds may travel many times around such pot-holes before either being deposited therein or escaping therefrom. In addition, considerably more diamond-bedrock collisions, per unit distance of travel, should occur within pot-holes than in wide stream channels. This is because side-wall collisions are also possible and are even likely to strongly predominate over floor collisions. For diamonds to be concentrated in pot-holes, by comparison with overlying gravel, requires a winnowing of the large rock particles also entrapped with diamonds. Such winnowing must be by comminution, which suggests that considerable abrasion may occur in pot-holes containing diamonds. While diamond-diamond collisions are unlikely events in wide stream channels, they might be frequent in pot-holes in which diamond is concentrated. As previously discussed, however, concentrations of percussion features at crystal edges probably indicate that particle-particle collisions are not responsible for much of the abrasion of diamond.

Excepting for diamonds with pristine, scratch-like markings where abrasion can be localized, the (initially) sharper surfaces of abraded diamonds are always more abraded than blunter surfaces. In all of the detrital diamond samples examined, tetrahexahedroid crystals predominate

and nearly all of the diamonds exhibit the tetrahexahedroid form. Similarly sharp edges are therefore developed on most of the diamonds. The relative degree of abrasion displayed by individual diamonds could be gauged by considering the extent of development of ground surfaces. This was done under the binocular microscope. The following categories are recognized:-

- i. Unground crystals.
- ii. Crystals ground at points of emergence of four-fold axes.
- iii. Crystals ground at sharp crystal edges (i.e. "A" tetrahexahedroid edges close to points of emergence of four-fold axes).
- iv. Crystals ground at all "A" tetrahexahedroid edges.
- v. Crystals ground at "C" tetrahexahedroid edges.
- vi. Conspicuously rounded crystals.

Examples of the categories distinguished are illustrated in Figure 66.

Some crystals classed as unground exhibit occasional percussion cracks and spall scars, mainly at crystal edges. Grinding at protruding surface features, such as hillock summits, depends on their prominence. Otherwise, no diamond assigned to a particular category ever lacks the features diagnostic of a subordinate category. The ranking scheme employed is therefore meaningful. It can be applied, up to category iii) above, to octahedra and cubes with only minor tetrahexahedroid surfaces. Between five and ten per cent of the diamonds in most of the samples studied, however, had to be excluded from consideration. Excluded diamonds include:-

- i. Sharp-edged octahedra.
- ii. Fragments.
- iii. Frosted and other finely-etched crystals on which ground surfaces are not readily distinguished from the pristine surface.

iv. Crystals displaying scratch-like markings.

Crystals with scratch-like markings (Article 6.5.11.) were excluded for two reasons. Firstly, prominent scratch-like markings at crystal edges are often difficult to distinguish, under the binocular microscope, from ground surfaces. Secondly, crystals with scratch-like markings were very often found to be genuinely more abraded than other diamonds in the same samples. It is therefore considered that scratch-like markings considerably reduce the resistance of diamond to abrasion.

9. THE DIAMOND AND GRAPHITE IN SOME ECLOGITE XENOLITHS FROM KIMBERLITE

Strontium isotope studies (Barrett, 1975) and lead isotope studies (Kramers, 1979) demonstrate that eclogite xenoliths are non-cognate with respect to the kimberlites in which they occur. At least 69 diamond-bearing eclogite xenoliths, some of which also contain graphite, and 20 containing graphite but no diamond had been reported in the literature by 1977 (see Robinson, 1979). Two additional diamond-bearing xenoliths (Shee, 1978) are included in the present study.

Eleven diamond eclogite xenoliths, one diamond alkremite xenolith, five diamond-graphite eclogite xenoliths and ten graphite eclogite xenoliths were examined. In some cases, diamond and graphite crystals were extracted for study by dissolving the xenolith silicate minerals by the method of Neuerburg (1975). Diamonds were recovered down to the 400 Tyler Mesh sieve size. In other cases, only the portions of diamond and graphite crystals exposed at xenolith surfaces were examined. Most of the xenoliths which were only superficially examined are museum specimens which could not be damaged in any way.

Xenolith particulars are summarized in Table 7. Details of the occurrences of native carbon in the xenoliths are summarized in Table 8. The petrography and mineral chemistry of the AK 1-labelled specimens have been documented by Shee (1978). Previous work done on other xenoliths is referred to where appropriate.

The diamond content of exploitable deposits is commonly referred to as the "grade" and is expressed in carats per metric tonne (cpmt). To facilitate comparisons between eclogite xenoliths and kimberlites, diamond "grades" were calculated for some of the xenoliths (Table 9).

## 9.1. DIAMOND ECLOGITE XENOLITHS

### 9.1.1. AK 1/9

Eleven diamonds and three moulds of diamond crystals are fairly evenly distributed at the surface of the 7,4 g xenolith. Some of the diamonds are illustrated in Figure 67. Most are surrounded by clinopyroxene or its alteration products but some protrude into garnet grains or kelyphitic material. The average diameters of the diamonds range from 0,3 to 2,0 mm. This corresponds to a range of 0,0002 to 0,07 carat in crystal masses calculated for assumed octahedral shapes. The total mass of diamonds (including moulds) exposed is approximately 0,135 carat. At least 0,35 per cent of the xenolith therefore consists of diamond. This corresponds to a diamond grade of at least 18 000 cpmt.

The diamonds are colourless and without graphite coatings. Most are octahedra with subordinate tetrahexahedroid or dodecahedral surfaces, but the tetrahexahedroid form predominates in some cases. Serrate laminae are developed near to the apices of octahedral faces. The apices of many of these laminae are rounded to forms resembling the pointed plates of cubic surfaces. Tetrahexahedroid surfaces display elongate hillocks. Dodecahedral surfaces are ribbed. Tetrahexahedroid and dodecahedral surfaces of diamond are in contact with the alteration products of clinopyroxene and garnet, suggesting that diamond crystal resorption occurred before the alteration of the rock.

### 9.1.2. AK 1/10

Two diamonds of approximately 0,02 and 0,2 carat, respectively, are exposed in close proximity to one another (Figure 68). Both are surrounded by clinopyroxene but they might join in depth to form an aggregate. At least approximately 0,3 per cent of the xenolith consists of diamond.

The diamonds are colourless octahedra with ribbed dodecahedral surfaces. Serrate laminae are developed on the octahedral crystal surfaces. Both diamonds are freshly broken at their exposed surfaces.

#### 9.1.3. AK 1/111

Upon the xenolith being broken in two, a diamond was disclosed in its interior (S.R. Shee, personal communication). The diamond also broke so that the breakage surface of each half of the xenolith then displayed a mould partly occupied by pieces of the diamond (Figure 69). More than one per cent of the xenolith consists of diamond.

The diamond is a colourless octahedron of mean length 4,8 mm (i.e. of mass approximately 0,95 carat). Octahedral edges are almost sharp. Thin, serrate laminae and occasional trigons are the only octahedral surface textures represented. Breakage surfaces radiate from a large, now altered, inclusion in the diamond and appear not to be etched.

#### 9.1.4. DB 1

Freshly broken surfaces of diamond are exposed at the surface of the xenolith to form a nearly closed, oblate ring of about 9 x 8 mm external diameter (Figure 70). Fine-grained micaceous material forms a narrow rim around the ring of diamond and also fills the interior of the ring. No crystallographic surfaces of diamond are exposed. It is possible that the outcropping fragments of diamond join within the specimen, thereby forming a crystal which must have originally exceeded 5 carats in mass. Diamond crystal breakage, although represented by fresh surfaces, must have preceded the introduction of micaceous material. It is also possible that the micaceous material surrounding diamond is kimberlite, in which case the association of diamond with eclogite might be fortuitous.

9.1.5. DB 2

A colourless, octahedral diamond of mass approximately 1,8 carats protrudes from garnet. The diamond constitutes approximately three per cent of the xenolith.

Crudely dodecahedral surfaces which are coarsely ribbed replace the octahedral crystal edges of the diamond. Octahedral surfaces exhibit flat-bottomed trigons and serrate laminae. An interesting feature is the development of tetrahexahedroid surfaces about the four-fold axial corner which protrudes furthest from the xenolith surface (Figure 71). These tetrahexahedroid surfaces are topographically lower than adjacent dodecahedral surfaces. Maximum exposure, maximum resorption and the development of tetrahexahedroid, instead of dodecahedral, surfaces therefore appear to all coincide.

9.1.6. DB 3

A complex aggregate of irregular, diamond tetrahexahedroida protrudes from micaceous material and altered clinopyroxene at the xenolith surface (Figure 72). A mass of approximately 0,15 carat of diamond is indicated, so that diamond constitutes approximately one per cent of the specimen. Diamond tetrahexahedroid surfaces exhibit coarse, cylindrical hillocks on which are superimposed fine, elongate hillocks. Possible lamination lines are locally just discernible. Minor cubic surfaces are also evident and these exhibit shallow, tetragonal pits. Fresh breakage surfaces are also present.

It appears that crystal resorption to produce the tetrahexahedroid form pre-dates the development of micaceous material in the xenolith. It also appears that plastic deformation of diamond may occur within eclogite but it must be noted that the identification of lamination lines is tentative.

9.1.7. DB 4

A freshly broken colourless diamond protrudes from micaceous material surrounding garnet. Little of the exposed diamond surface is crystallographic. That which is present suggests that the diamond is an octahedron with slightly rounded edges (Figure 73). As far as can be judged from the available exposure, the length of the diamond crystal is at least 5 mm, indicating a mass in excess of a carat.

9.1.8. DB 5

A group of five broken diamond crystals and fragments are exposed in altered clinopyroxene (Figure 74). It is possible that a section through a crystal aggregate is represented. The largest crystal exposed probably has a mass of about 0,01 carat and diamond is likely to constitute at least one per cent of the xenolith.

As far as can be judged from the limited exposure of crystal surfaces, the diamond crystals are octahedra with substantial tetrahexahedroid surfaces. Hexagonal pits and trigons are present on octahedral crystal faces and cylindrical, elongate hillocks are present on tetrahexahedroid surfaces. Breakage surfaces are not etched excepting for one example on the largest diamond exposed.

9.1.9. DB 6

A diamond of mass at least one carat is largely surrounded by clinopyroxene but also truncates a garnet crystal. Approximately one per cent of the xenolith consists of diamond. The diamond is a sharp-edged, sharp-pointed octahedron (Figure 75). The surface is thinly coated by opaque black material, presumably graphite. Shallow, flat-bottomed pits of irregular, hexagonal and trigonal (negatively-oriented) outline are developed in profusion on the exposed crystal surfaces and have coalesced to form flat areas without relief. It

is uncertain, however, whether the pits impress diamond or whether they are developed only within the graphitic coat. Minor breakage surfaces are the youngest features evident.

9.1.10. DB 7

A diamond of approximately 4 carats is largely surrounded by clinopyroxene but impinges against a garnet crystal. The diamond constitutes approximately 8 per cent of the xenolith. The diamond is a sharp-edged, sharp-pointed octahedron (Figure 76) which is colourless. Most of the surface consists of thin laminae with serrated to irregular outlines, which are raised above smooth, planar surfaces. Shallow, flat-bottomed pits of irregular, hexagonal and trigonal (negatively-oriented) outline are developed within laminae and on the lower, planar surfaces. Most of one exposed octahedral face appears to have not been etched to the same degree as the other exposed surfaces. On this face smooth-surfaced, oval laminae are evident. Minor, unetched breakage surfaces are developed on the diamond. The diamond is very similar to that of DB 6 excepting that no black surface coating is present.

9.1.11. DB 8

This small xenolith consists only of diamond and garnet. The garnet is the typical orange colour of eclogitic garnet and the specimen is regarded as a fragment of diamond eclogite. Two groups of diamond crystals, each of four or five interpenetrating individuals, protrude from the garnet (Figure 77). Diamond constitutes roughly one per cent of the specimen.

Individual diamond crystals are sharp-edged, sharp-pointed octahedra. Triangular plates produce steps on some surfaces. Occasional laminae which are thinner than obvious triangular plates have serrated

edges. This serration probably reflects the incomplete development of thin triangular plates (i.e. growth layers), rather than the coalescence of flat-bottomed trigons, since no obvious trigons or etch-induced laminae were observed. The crystals therefore display no clear evidence of having been modified by resorption or etching. Some crystals are modified by minor, fresh breakage surfaces.

9.1.12. PJL 18

A diamond was observed when the xenolith was broken (P.J. Lawless, personal communication). 260,7 g of the xenolith was digested in acids. Ten more diamond crystals, 42 small fragments of diamond and a few very small (up to 70  $\mu\text{m}$  diameter) flakes of graphite were recovered. Diamond (excluding the example noted by Lawless) totalled 0,0045 carat, giving a diamond grade of 17 cpmt for the portion of the xenolith treated.

The diamonds recovered are colourless, excepting for one which is very light brown. All have partial veneers of graphite. They range from nearly pure octahedra to examples in which the ribbed, grossly dodecahedral form predominates (Figure 78). Flat-bottomed trigons and serrate laminae are developed on octahedral crystal faces. Depressions which approximate cubic surfaces contain pointed plates. Ribbing is very prominent on dodecahedral surfaces. Ribs often have wedge-shaped terminations and small, knob-like asperities are developed on some of them.

Euhedral graphite crystallites with basal diameters greater than 25  $\mu\text{m}$  were observed in veneers on diamond. It is likely that the small graphite flakes recovered with diamond are also from veneers. Since all of the graphite is likely to be secondary, the xenolith is classified as a diamond eclogite and not a diamond-graphite eclogite as in Robinson (1979).

## 9.2. DIAMOND ALKREMITITE XENOLITH AK 1/110

The xenolith measures 15 x 12 x 4 mm and has a mass of 4,5 g. According to Shee (1978), medium-grained ( $\pm 2$  mm), flesh-coloured garnet is the principle constituent. The garnet is a grossular (17,1 per cent)- almandine (22,4 per cent)- pyrope (60,7 per cent) containing little of either chromium or titanium. No clinopyroxene was observed.

Under the binocular microscope, 43 diamonds can be seen exposed at the xenolith surface. Clusters of three or four diamonds occur but they are otherwise fairly evenly distributed (Figure 79). The largest diamond exposed is an aggregate of length nearly 2 mm and single crystals down to 0,2 mm diameter were discerned.

1,60 g of the specimen was subjected to dissolution. This portion was sawn from the specimen and not broken. 644 diamond crystals and a few, small, brown octahedra of spinel ( $\text{Al}_2\text{O}_3$  61,6%,  $\text{MgO}$  21,6%,  $\text{Fe}$  as  $\text{FeO}$  14,9% and  $\text{Cr}_2\text{O}_3$  1,3%) were recovered from the residue. Some of the diamond crystals were recovered broken and only fragments considered to represent more than half of a crystal were counted. Some crystals recovered intact broke upon gentle prodding. A total mass of 0,05956 carat of diamond was recovered. This gives a diamond content of 0,75 per cent or a "grade" of approximately 37 000 cpmt for the xenolith.

The crystal size frequency distribution of recovered diamonds is illustrated in Figure 80. The 75 to 150  $\mu\text{m}$  size range is the modal class in terms of the number of crystals recovered. The smallest crystal recovered has a medial octahedral length of 42  $\mu\text{m}$  and only 10 crystals measure less than 60  $\mu\text{m}$ . Since the diamonds were collected in a screen of aperture size not much smaller (37  $\mu\text{m}$  square) it is possible that the apparent scarcity of 37 to 75  $\mu\text{m}$  crystals is due to poor recovery in this size range. Therefore, minus-37  $\mu\text{m}$  crystals could be the most abundant. Diamonds less than 300  $\mu\text{m}$  in size

constitute more than 87 per cent by number but only 24 per cent by mass. The 300 to 600  $\mu\text{m}$  size range contains the best compromise between frequency of occurrence and individual crystal mass.

The diamonds are probably colourless but all exhibit locally-preserved to continuous coatings of graphite. Graphite also penetrates along cracks in some crystals. Graphite coatings are relatively poorly preserved on the diamonds exposed at the xenolith surface. A selection of diamond crystals is shown in Figure 79. All are octahedra. Parallel growth phenomenae are common, sometimes resulting in complex shapes. Most octahedra are sharp-edged and sharp-pointed but some also have compound, approximately dodecahedral surfaces. These can possibly be ascribed to the superimposition of triangular plates of diminishing areal extent but could also have been caused by resorption. The presence of incipient, knob-like asperities supports the latter alternative in some cases. Interpenetrantly-twinned crystals, but no macles, were noted. Beneath their graphite coatings, diamond surfaces display flat-bottomed etch pits of irregular to trigonal (negatively-oriented) outline. Such pits are generally abundant but less so on sharp-pointed octahedra. Most breakage surfaces are also etched or display graphite coatings.

That diamond crystals recovered whole broke upon gentle prodding suggests that cracked crystals, rather than isolated fragments, occur within the xenolith. The graphitization and concomitant etching of the diamonds post-dates most diamond breakage.

### 9.3. DIAMOND-GRAPHITE ECLOGITE XENOLITHS

#### 9.3.1. HRV 247

This 3,3 kg xenolith was discovered by C.J. Hatton who studied

its petrography and mineral chemistry (Hatton, 1978; also Hatton and Gurney, 1979). Before being broken into six fragments, the xenolith was an oblate spheroid with axial dimensions of approximately 23 x 14 x 7 cm.

Two diamonds are exposed at the xenolith surface and a further five were revealed upon the xenolith being broken. Well-formed moulds developed in breakage surfaces opposite to those in which some of the diamonds were embedded. The surface of a mould of a dodecahedral diamond surface appears to consist of clinopyroxene, suggesting that diamond resorption pre-dated the crystallization of the pyroxene. Graphite crystals were also revealed at breakage surfaces. Examination of the xenolith fragments indicated that diamond is concentrated in one portion of the xenolith and graphite in the remainder, and a rough boundary between these portions could be drawn on the reassembled xenolith. Hatton and Gurney (1979) subsequently defined a petrographic discontinuity which appears to coincide with that demarcating diamond-rich and graphite-rich portions. The re-assembled xenolith is illustrated in Figure 81.

Diamond and graphite (and rutile, etc.) were recovered from three portions of the xenolith (A, F2 and G of Figure 81). Each portion was first broken into manageable fragments using a hammer. Table 10 lists the amounts of rock treated and the number and mass of diamonds and the mass of graphite recovered from each portion. Portion A yielded 47 diamond crystals and many fragments and had a diamond content of 0,157 per cent. It contained the least graphite of the portions treated. Portions F2 and G yielded only fragments of diamond. Hatton and Gurney (1979) note, however, that they removed three diamond crystals, with a total mass of 0,1 carat, from portion G. Portion G therefore contained approximately 200 ppm of diamond.

Portion F2 contained less than 5 ppm of diamond. The average diamond grade of the portions treated is 3 610 cpmt. Portions F2 and G yielded substantially more graphite than portion A. The total free carbon content of each portion is between 0,1 and 0,2 per cent.

The smallest diamond crystal recovered (excluding possible inclusions and overgrowths) measures 0,00015 carat. The largest single crystal measures 0,1675 carat and the largest aggregate 0,2030 carat. The size distribution of the diamonds from portion A is illustrated in Figure 82. Most crystals are between 0,5 and 3,0 mm in medial length. The size distribution appears to be unimodal which is consistent with a single population of diamonds being represented. The incorporation of possible overgrowths in the data, however, would introduce an additional mode in the 37 to 75  $\mu$ m class.

Most diamonds recovered are colourless but one very light brown crystal and two very light green diamonds are represented. The light green examples might be stained at their surfaces, rather than body-coloured. Six other diamonds exhibit light green surface stainings.

Some typical features of the diamonds in the xenolith are illustrated in Figure 83. Crystallographic data for recovered diamonds are summarized in Table 11. Most diamond crystals are classified as octahedra but all are combined forms. All exhibit either grossly dodecahedral or tetrahexahedroid modifications which range from slight truncation or rounding of octahedral edges to examples in which either of the forms predominates. The dodecahedral form is much more common than the tetrahexahedroid form. Indented cubic surfaces are also represented on most crystals. However, no crystals were seen to have all six possible cubic surfaces. Crystal aggregates are fairly common and macles also occur. Macles are also present as constituents of aggregates. Some relatively large crystals can be regarded as parallel

growth forms. The approximately cubic surface of one diamond exhibits a number of features which resemble protruding, epitaxial inclusions of smaller diamonds. These features have octahedral-dodecahedral forms and display trigons on their octahedral surfaces.

More than half of the diamond crystals recovered and nearly all of those smaller than 1 mm are fragments. A substantial proportion of breakage surfaces are conchoidal to undulatory and display either fine scales of graphite or etch pits. Other breakage surfaces are "fresh". These are mainly stepped, octahedral cleavage surfaces but include splintery, subconchoidal fracture surfaces. Some "fresh" breakage surfaces could have been produced when the xenolith was broken by hammering.

Some of the diamonds have locally-developed, thin veneers of extremely fine-grained graphite. Serrate laminae are the most conspicuous features of octahedral crystal surfaces. Trigons are also common. These are flat-bottomed excepting for some small examples which are pyramidal. Ribbing is developed on dodecahedral surfaces while tetrahexahedroid surfaces exhibit elongate hillocks which may resemble ribs with rounded edges. Some dodecahedral ribs have wedge-shaped terminations. Negatively-oriented tetragonal pits and pointed plates are developed on cubic surfaces. Tiny features which resemble octahedral crystallites, including parallel growth forms, are also present on some cubic surfaces and often straddle a ridge between adjacent tetragonal pits. These crystallite-like features were noted on diamonds examined in eclogite and on diamonds recovered by acid treatment. They are colourless and apparently have the same refractive index as the diamond crystal on which they occur. Energy-dispersive micro-analysis of the features in the scanning electron microscope did not disclose the presence of any elements detectable by this method (i.e. elements

of atomic number eleven and greater). They therefore probably consist of diamond. The octahedral, crystallite-like features were previously interpreted (Robinson, 1979) as diamond overgrowths which are younger than the etching event responsible for the tetragonal pits. As noted in Article 6.3.3., however, similar features were subsequently observed which closely resemble pointed plates. The crystallite-like features might therefore be no more than a variety of pointed plates. Some of the diamond crystals in the xenolith exhibit ruts.

Graphite occurs as discrete crystals with basal diameters of 0,5 to 2,0 mm. These range from thin plates to barrel-shaped individuals exceeding a millimetre in length (Figure 83). Graphite crystals are subhedral or euhedral with slightly rounded crystal edges. Pyramidal crystal faces are evident, in addition to pinacoidal and prismatic faces, on barrel-shaped crystals. Pitting of the prismatic and pyramidal surfaces of some crystal suggests that they have been lightly etched.

There is no suggestion of any pseudomorphic relationship between diamond and discrete graphite crystals. Both minerals therefore appear to be primary. The euhedral forms of graphite crystals suggests crystallization from a fluid. The spatial relationship between diamond and primary graphite in the rock is best explained by gravimetric separation within a liquid as a consequence of the contrasting densities of the two minerals.

#### 9.3.2. XRV 22

The mineral chemistry of this specimen has been documented by Reid et al. (1976). It should be noted that before the xenolith was broken it was observed that diamond occurred mainly in one portion and graphite mainly in the remainder (J.J. Gurney, personal communication). A cursory examination of a coarsely-crushed sample of approximately 250 g of the eclogite did not disclose any more diamond or

graphite. Upon acid-digestion of the sample, however, 119 diamond crystals, 510 diamond fragments and a number of graphite crystals and cleavage flakes were recovered. Diamond totals 0,1620 carat, giving a diamond content of approximately 0,013 per cent or a "grade" of 650 cpmt, for the eclogite treated.

The size frequency distribution of diamond crystals is illustrated in Figure 84. These range from 70  $\mu$ m to 0,9 mm in mean length, with the majority between 0,25 and 0,70 mm. Most fragments are relatively small but some which display portions of tetrahexahedroid crystal surfaces were recovered up to sizes which exceed 1 mm.

Most diamonds are nearly colourless but very light brown colour becomes increasingly apparent with increasing particle size. Examples of the diamonds present are illustrated in Figure 85. Most crystals are combined forms ranging from octahedra with slightly modified edges to predominantly tetrahexahedroid or dodecahedral forms. Crystals smaller than 0,2 mm are predominantly octahedra while some of the larger are tetrahexahedroida without octahedral vestiges. Three crystals are cubes with slightly modified corners and edges. Aggregate crystals and macles are also present. Included among the tetrahexahedroida are some hopper crystals and horn-shaped crystals. These probably reflect crystallization of diamond about pre-existing mineral grains. Most breakage surfaces are not etched. Some are etched only near one of their margins and probably resulted from breakage along extensions of ruts. Much diamond breakage could have been caused by the crushing of the xenolith sample.

Octahedral crystal faces exhibit flat-bottomed and point-bottomed trigons and shield-shaped to serrate laminae. Some laminae are relatively thick and possibly represent modified triangular plates. Tetrahexahedroid surfaces exhibit cylindrical to elliptical hillocks. Dodecahedral

surfaces are ribbed. Small, negatively-oriented, tetragonal pits are developed on cubic surfaces which are not noticeably indented.

Some graphite crystals recovered are also depicted in Figure 85. Basal diameters range from about 70  $\mu\text{m}$  to 1,2 mm. All are euhedral or subhedral crystals of tabular habit, usually with slightly rounded crystal edges. There is no evidence to suggest that graphite crystals were derived from diamond.

### 9.3.3. JJG 531

Three diamonds and many graphite crystals were exposed at the xenolith surface. Features of these minerals are illustrated in Figure 86.

Six colourless diamonds were recovered from the xenolith. The smallest has a diameter of approximately 0,2 mm and the largest a diameter of 5 mm. Diamond constitutes one per cent of the xenolith, with the largest diamond accounting for more than 70 per cent of the 0,718 carat of diamond recovered. Even if the relatively large diamond is excluded, the diamond grade of the xenolith exceeds 15 000 cpmt. The diamonds are octahedra. Those from within the xenolith are almost sharp-edged but substantial, ribbed dodecahedral surfaces are developed on two of the exposed crystals. Veneers of very fine-grained graphite are present on all of the diamonds, particularly on dodecahedral surfaces. Most of the diamonds exhibit only rare trigons and locally-developed, serrate laminae on octahedral surfaces. Thin, triangular laminae are developed, however, on one of the exposed crystals. Dodechaedral surfaces are ribbed. Knob-like asperities are also developed in one case.

Discrete graphite crystals are tabular and have basal diameters ranging from less than 0,1 mm to 0,5 mm. They are euhedral to subhedral but nearly always distinctly rounded. Embayed examples are

also common. While the graphite coating diamonds is obviously secondary, that occurring as discrete crystals appears to be primary.

#### 9.3.4. AK 1/25

This xenolith was initially classified as a graphite eclogite but yielded a colourless diamond upon dissolution of the silicate minerals. The diamond and some of the graphite crystals recovered are illustrated in Figure 87.

The diamond is a flat, sharp-edged and sharp-pointed octahedron of maximum length 1,3 mm. Its mass is 0,0055 carat so that diamond constitutes approximately 0,01 per cent of the xenolith. Crystal surfaces are partly smooth. Graphite veneers are locally present, however, and beneath these serrate laminae and shallow trigons are developed.

Three graphite crystals were exposed at the xenolith surface and 16 were recovered altogether. Most graphite crystals are euhedral tabular prisms. Some are slightly rounded and others have irregular outlines. There is no reason to suspect a direct link between graphite veneers on the diamond and the discrete graphite crystals in the xenolith.

#### 9.4. GRAPHITE ECLOGITE XENOLITHS

Ten graphite eclogite xenoliths were examined. All are from the Orapa Mine. Seven xenoliths classified as graphite eclogite after superficial examination were subjected to laboratory dissolution. As mentioned previously, one of these (AK 1/25) yielded diamond and had to be re-classified as a diamond-graphite eclogite xenolith.

Details of the graphite which the xenoliths contain are summarized in Table 8. Typical graphite crystals are illustrated in Figure 88. The most important features and their relevance to diamond-bearing eclogite xenoliths are as follows:-

- i. Most graphite crystals have basal diameters of 0,2 to 4 mm

and graphite commonly constitutes between 0,1 and 0,2 per cent, by mass, of a xenolith. In these regards, the occurrence of graphite is similar to that of free carbon phases in diamond eclogite and diamond-graphite eclogite xenoliths. The three varieties of eclogite are therefore likely to have similar origins.

- ii. In a number of the xenoliths, the graphite crystals are euhedral. This suggests that the graphite crystallized in a fluid medium. Some subhedral examples can be accounted for by relatively late crystallization within volumes confined by silicate grains.
- iii. Euhedral graphite crystals are commonly slightly rounded. Associations between rounded and sharp-edged crystals are explained best by etching which occurred after solidification of the eclogite. Sharp-edged crystals could then have been protected from the etchant.
- iv. In some xenoliths, most of the graphite crystals are markedly rounded or embayed. These crystals could have been strongly etched. Alternatively, they could have been partly dissolved while diamond was being precipitated.
- v. In no instance is there any evidence to suggest that the graphite is derived from diamond. Instead, graphite appears to be a primary mineral.

10. GENERAL FEATURES OF THE DIAMOND AND GRAPHITE  
IN ECLOGITE XENOLITHS

The most striking feature of the diamond-bearing eclogite xenoliths described is that, by comparison with kimberlites, they are extremely rich in diamond. This feature of diamond-bearing eclogite xenoliths was first noted by Bonney (1899). Small xenoliths containing one large diamond or few diamonds (e.g. DB 1, DB 2, DB 3, DB 4, DB 6, DB 7, DB 8, AK 1/111 and AK 1/25) might not accurately reflect the diamond content of possibly large bodies of eclogite. Better indications of the diamond content of large bodies should come from large xenoliths and from xenoliths containing many diamonds. The best indications should come from large xenoliths displaying a unimodal diamond size frequency distribution because a significant sample of the diamond population of the parent rock is likely to be present in such xenoliths. Specimens XRV 22 and HRV 247 best meet the requirements for being representative samples. Specimens AK 1/9, PJL 18, AK 1/110 and JJG 531 meet these requirements less stringently.

Specimen FJL 18 contains approximately 40 times as much diamond as the kimberlite which transported it. XRV 22 contains approximately 1 600 times as much, HRV 247 contains 8 500 times as much and AK 1/9 AK 1/110 and JJG 531 all contain at least 15 000 times as much diamond as their host kimberlites. Only a few hundred parts of disaggregated diamond eclogite, per million parts of kimberlite, might therefore account for all of the diamond in some kimberlite. This is not to say that all, or even most, diamond in many kimberlites is derived from eclogite. Studies of inclusions in diamond indicate that eclogite-derived diamonds are usually subordinate to diamonds of peridotitic paragenesis (e.g. Sobolev, 1977). At Orapa, however, eclogitic inclusions

strongly predominate (J.J. Gurney, personal communication) and most of the diamonds in the Orapa kimberlite could have been derived from eclogite.

Orapa is the only locality from which diamonds from both kimberlite (see Section 12.5.) and eclogite xenoliths were studied. Nevertheless, it is reasonably certain that diamonds of the same colours as in the eclogite xenoliths are also common in the kimberlites in which all of the xenoliths were found. Much of the size range of the diamonds in kimberlites is represented among the xenoliths.

Significant differences were also observed between the diamonds from Orapa xenoliths and the diamonds from Orapa kimberlite, and there are good reasons for anticipating the same differences at other xenolith localities. Differences between the diamonds in the eclogite xenoliths and the diamonds in nearly all of the kimberlitic samples studied (Chapter 12) are as follows:-

- i. The octahedral form is much more common in the xenoliths.
- ii. The dodecahedral form is much more common, relative to the tetrahexahedroid form, in the xenoliths.
- iii. Serrate laminae, pointed plates, ribbing and knob-like asperities are relatively common surface textures of the xenolith diamonds.
- iv. Graphite veneers are much more frequently observed on the diamonds of the xenoliths.

All of the differences outlined above are as to be anticipated, should oxidizing, kimberlitic fluid be the main agent responsible for diamond resorption and etching. Diamond enclosed in impermeable material would not be modified by such fluid. The limited access, along grain boundaries and cracks in xenoliths, of kimberlitic fluid to diamonds in xenoliths would result in these diamonds being less modified than

any which are unprotected. Growth forms would therefore tend to survive, as is the case for most of the diamonds examined from eclogite xenoliths. Within the semi-closed systems inside xenoliths, reactions between infused fluid and diamond would approach equilibrium. Once the oxidation potential of the fluid is sufficiently diminished, graphite films would build up on diamond surfaces. This would favour the limited development of dodecahedral, rather than tetrahexahedroid, resorption surfaces and the development of the surface textures associated with graphite coatings. The external features of the diamond exposed in xenolith DB 2 and the diamonds in xenolith JJG 531 are particularly informative. Tetrahexahedroid surfaces are developed only at the most exposed part of the diamond in DB 2. The diamonds presently exposed in JJG 531 appear to have been oxidized more than those from within the xenolith.

Considering both the similarities and differences between the xenolith diamonds and diamonds more typical of kimberlites, it is unnecessary to regard the xenolith diamonds as unique. Furthermore, diamonds which are liberated from xenoliths before the cessation of diamond resorption and etching should lose the external features by which they might be recognized.

Should the crystallite-like features occurring on some of the etched surfaces of diamonds in specimen HRV 247 be diamond overgrowths, diamond resorption can pre-date diamond crystallization. This would suggest the likelihood of diamonds being partially dissolved by the liquid from which they crystallized. In HRV 247 there is also evidence that diamond resorption occurred before clinopyroxene crystallization. In none of the other specimens, is there any suggestion that diamond resorption pre-dates solidification of the eclogite. In specimens AK 1/9 and DB 3, diamond resorption is seen to pre-date the phlogopitization

of eclogite.

Only in one case (DB 3) was tentative, direct evidence obtained for the plastic deformation of a diamond in eclogite. Occurrences of brown diamonds (e.g. XRV 22), particularly when associated with colourless diamonds (e.g. PJI 18, HRV 247), also suggest, however, that diamond may be plastically deformed in eclogite. Orlov (1977, p. 205) mentions that the diamonds in fragmented, diamond-bearing xenoliths are often plastically deformed. Although Orlov is not specific, he is probably referring to eclogitic, not peridotitic, xenoliths.

Apart from the possibility of minor, diamond inclusions and overgrowths in specimen HRV 247, none of the xenoliths studied appears to contain more than one population of diamonds. Associations between single crystals, macles and aggregates (e.g. HRV 247 and XRV 22) and between octahedra and cubes therefore mean that similar associations in kimberlites do not necessarily attest to the presence of more than one generation of diamonds. The occurrence of cubes with octahedra in specimen XRV 22 probably indicates that the temperature changed during crystallization of the diamonds.

The fairly common association of diamond and primary graphite in eclogite xenoliths is interesting. This suggests that diamond in eclogite may crystallize close to its thermodynamic stability limit. A change in either temperature or pressure during the crystallization of free carbon is also indicated. At 1200°C and 47 kb, which are realistic conditions for the crystallization of diamond-bearing eclogite, the densities of both diamond and graphite are similar to their densities at normal temperature and pressure (i.e. 3,5 and 2,2 g/cm<sup>3</sup>; after Berman, 1965). Considering the difference in their densities, a gravitational separation is likely between diamond and graphite crystallizing from the same liquid. Such differentiation is probably evident in specimens HRV 247

and XRV 22. For a boundary between diamond-rich and graphite-rich portions of eclogite to be observed in at least two mantle-derived rock samples suggests that carbon-bearing eclogite occurs as abundant, very small bodies in the earth's mantle. Large bodies of igneous, predominantly carbon-free eclogite might contain diamond in their lowermost portions and graphite in their uppermost portions. Crystallization of both graphite and diamond from a liquid is more readily explained by cooling than by a change in confining pressure. Diamond crystallization should then follow graphite crystallization. Considering an analogy with the process occurring during diamond synthesis experiments (Wentorf, 1965), primary graphite crystals should be partly resorbed when associated with diamond. Specimen HRV 247 might be unique in that a period of heating possibly occurred during crystallization of the rock (see Robinson, 1979). Such an interpretation for HRV 247 depends upon the crystallite-like features, which occur on the cubic surfaces of some diamonds in the xenolith, being diamond overgrowths.

11. THE DATA REPORTED FOR KIMBERLITIC AND PLACER DEPOSIT SAMPLES

The data for samples from kimberlitic and placer deposits, which are reported in Chapters 12 and 16 respectively, refer to the distributions of particular features of diamonds. These data are tabulated as percentages of the (total or particular) diamonds which exhibit the individual features. Since it was not always possible to examine any of a sample in a scanning electron microscope, the results quoted refer to observations made under the binocular microscope.

The distributions of particular colours, crystal forms, and crystal shapes are quoted as percentages of the total of diamonds in each sample. The distributions of pristine surface textures which are not restricted to particular crystal surfaces are quoted as the percentages of the totals of diamonds, less fragments, which exhibit the particular textures. The distributions of surface textures which are restricted to particular crystal surfaces are quoted as the percentages of the diamonds, displaying the requisite crystal surface as either the predominant or a subordinate form, which exhibit the particular textures. (Less meaningful figures would have been obtained for restricted surface textures had their distributions been determined with reference to the totals of diamonds. For example, in some samples from Letseng-le-terai (Section 12.4.), it is the scarcity of crystals displaying octahedral surfaces, rather than a scarcity of trigons, which is an outstanding feature, for trigons are as commonly developed on octahedral surfaces as in other samples). As detailed in Section 8.5., up to ten per cent of the diamonds in individual samples were excluded from the totals on which the degree-of-abrasion determinations were based. The data for diamonds displaying percussion markings are percentages of the totals of diamonds in the samples. A single

percussion marking was sufficient for a diamond to be counted. Examples were not counted in which small percussion markings (generally very few) were disclosed only during examination in the scanning electron microscope.

As previously noted, some diamond colours and surface textures grade into others. Certain determinations, for example the relative proportions of light brown and brown diamonds and of coarsely-frosted and finely-frosted diamonds, may therefore not be strictly reproducible in any sample. Subjectivity is most pronounced, however, in some of the classification of diamonds according to crystal shapes. No strict criteria were adhered to in distinguishing between equidimensional, distorted and irregular crystals. These data must therefore be regarded as only semi-quantitative.

The numbers of diamonds constituting the individual samples are listed in Tables 2 and 3. Totals range from less than 50 to 500 diamonds per sample. In most cases in which less than 200 diamonds were examined, the sample size was determined by the availability of material. Exceptions are the Mir and Urals samples which were examined during a brief visit to the United Kingdom. The time at the author's disposal limited the sizes of these two samples. The inclusion of diamonds not of the minus 11 plus 9 diamond sieve class was determined partly by the nature of the material available and partly to allow comparisons between diamonds of different sizes.

With regard to samples of 200 or more diamonds, much more material was generally available than was examined. Whenever possible, large diamond parcels were sampled in their unsorted state. A reasonably random sample of the selected sieve class was obtained as follows: the approximate number of diamonds available was determined by weighing; the diamonds were spread to a circular layer on a table top; a

spatula edge was used to cut the circular layer into segments containing a fraction (usually one third) of approximately the required number of diamonds; geometrically-spaced segments were taken out to obtain approximately the required number of diamonds; final adjustment to the exact number required was affected by subtracting or adding a few diamonds without viewing them. (It was found necessary not to view the diamonds while making the final adjustment because of a strong inclination to select deeply-coloured diamonds which attract the eye). Some diamond parcels had previously been sorted, according to commercial considerations, into as many as twenty categories per sieve class. To obtain a representative sample of a sorted diamond parcel, each category of the selected sieve class was weighed and a proportionate number of diamonds was extracted for examination. It is assumed, for statistical purposes, that most of the diamond parcels sampled are representative of their localities. The Mir and Urals parcels are not considered to have been representative, since each consisted of only one commercial assortment of diamonds.

Ninety five per cent confidence limits for the determinations reported in Chapters 12 and 16 can be got by referring to Figure 89. In order to use Figure 89, the number of diamonds involved in the particular determination must be known. For data involving all of the diamonds in a sample (colours, crystal forms, crystal shapes, percussion markings), this number can be obtained from Table 2 or Table 3. For data involving most diamonds (unrestricted and tetrahexahedroid surface textures, degrees of abrasion) little error will generally be introduced by assuming numbers of 90 per cent of those in Table 2 and 95 per cent of those in Table 3. Some samples, however, are exceptional. For example, in the De Beers Mine samples only approximately 60 per cent of the diamonds are involved in the unrestricted and tetrahexahedroid,

surface texture determinations, on account of the high proportions of fragments in these samples. The numbers of diamonds involved in the octahedral and cubic, surface texture determinations are given in the relevant data tables.

Some examples of 95 per cent confidence limits (to the nearest integers) are given in Table 12. The following points are worth noting:-

- i. Wide confidence limits apply to data based on less than, about 50 diamonds.
- ii. Confidence limits are not substantially reduced by increasing the number of diamonds examined from 200 to 500.

For data involving all or most of the diamonds, 300 diamonds is therefore considered to be an optimum sample size. Samples with as few as 100 diamonds should also give meaningful results.

In most of the samples studied, only about 30 per cent of the diamonds exhibit octahedral crystal faces and only about 10 per cent exhibit cubic surfaces. The confidence limits for octahedral and, particularly, for cubic surface texture determinations are therefore much wider than for data involving all or most diamonds. For this reason, little significance is placed upon the distributions of octahedral and cubic surface textures in most samples. The data on crystal shapes are de-emphasized on account of the subjective manner in which some shapes were distinguished from others.

In order to test whether different distributions of a feature between two samples are significant (with respect to the populations from which the samples were drawn), use was made of the statistic (Dixon and Massey, 1969, p. 249):

$$z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\bar{p}(1-\bar{p})(1/N_1 + 1/N_2)}}$$

$$\text{where } \bar{p} = (N_1\bar{X}_1 + N_2\bar{X}_2) / (N_1 + N_2)$$

and it was concluded, with 95 per cent confidence, that the populations from which the samples are drawn are significantly different with respect to the feature considered, when:

$$z < -1,96 \text{ or } > 1,96$$

(In the above formulae,  $\bar{X}_1$  and  $\bar{X}_2$  are the proportions (i.e. percentages /100) of diamonds displaying the feature in the two samples and  $N_1$  and  $N_2$  are the numbers of diamonds involved in the determinations).

The percentages of the diamonds displaying lamination lines are listed in the tables (17 and 25) dealing with tetrahexahedroid surface textures. This contradicts the fact that lamination lines are not entirely restricted to tetrahexahedroid surfaces. Lamination lines, however, are developed preferentially on tetrahexahedroid surfaces. A better indication of the percentage of diamonds displaying lamination lines is therefore obtained by regarding the texture as specifically tetrahexahedroid. This results in a slight complication in the case of the Mir Mine sample, in which some diamonds without tetrahexahedroid surfaces display lamination lines.

## 12. THE CHARACTERISTICS OF THE DIAMONDS FROM SOME KIMBERLITES

Comparisons between the diamonds from associated kimberlites should contribute toward an understanding of kimberlite magmatism. In order to determine whether, or not, a particular kimberlite contributed diamonds to a placer deposit, it is essential that samples of the kimberlitic and placer diamonds be compared. The characterization of kimberlitic diamond samples is therefore a useful exercise.

The Southern African kimberlite localities from which diamond samples were studied are plotted in Figure 90. A Russian sample and a North American sample were also studied. Sample particulars can be obtained from Table 2. The data determined for each sample are presented in tables, as follows:-

Table 13: The percentages of the diamond colours distinguished.

Table 14: The percentages of the main crystal forms and of the diamonds with particular crystal surfaces.

Table 15: The percentages of the crystal shapes distinguished.

Table 16: The percentages of the diamonds (excluding fragments) which display particular, unrestricted surface textures.

Table 17: The percentages of the diamonds with tetrahedroid (or dodecahedral) crystal surfaces, which display particular surface textures which are restricted to these surfaces.

Table 18: The percentages of the diamonds with octahedral crystal surfaces, which display particular, octahedral surface textures.

Table 19: The percentages of the diamonds with cubic crystal surfaces, which display particular, cubic surface textures.

The data involving all or nearly all of the diamonds (Tables 13 to 15 and Tables 16 and 17, respectively) in most of the samples are emphasized, in the ensuing discussion, because of statistical considerations (Chapter 11). The data in Table 15 are de-emphasized, however, on account of subjectivity in distinguishing between some diamond shapes.

#### 12.1. THE 595 m, 720 m AND 785 m LEVELS OF THE DE BEERS MINE

Three varieties of kimberlite are distinguished at the De Beers Mine, Kimberley. The Breccia Kimberlite contains abundant wall-rock xenoliths, while a central core of kimberlite is distinguished from a peripheral variety mainly by its substantially greater content of diamond (C.R. Clement, personal communication). In addition to a dependance upon kimberlite variety, the concentration of diamond also varies according to the depth of mining, as illustrated in Figure 91. It was hoped that a study of diamond samples from each of the kimberlite varieties, and from different levels in the mine, would contribute toward elucidating the reasons for the variations in diamond concentration.

The De Beers Mine samples were the first to be examined and, unfortunately, diamond colour was not considered. The largest sample studied for each kimberlite is that from the 595 m level. The 595 m samples are therefore regarded as the type samples for the kimberlite varieties. Diamonds of various sizes were examined. Only the minus 11 plus 9 sieve class of the Central Core samples is considered in the ensuing discussion, unless otherwise stated. The smallness of the Peripheral and Breccia Kimberlite samples necessitates that they be considered in their entireties.

A notable feature of all of the samples is the very high

proportion of fragments which they contain (Table 14). No distinction was made between etched and unetched breakage surfaces in the data recorded. It was noted, however, that the majority of breakage surfaces are etched. Most diamond breakage in the samples can therefore be ascribed to natural causes.

12.1.1. Comparisons between the Central Core, Peripheral and Breccia Kimberlites of the 595 m Level

Both the octahedron and the cube occur largely as subordinate crystal forms among the diamonds of the De Beers Mine. Table 14 shows that the octahedral form has a similar abundance, relative to the cubic form, in all of the 595 m level samples. A similar predominance of the relatively high temperature growth form of diamond is therefore represented in all of the kimberlites. Twinned crystals are similarly scarce in all of the kimberlites. These similarities are compatible with the same, mantle-derived population of diamonds predominating in each of the kimberlite varieties. Table 14 shows that the tetrahexahedroid form is similarly predominant in all of the samples. This is compatible with the diamonds in all of the kimberlites having experienced the same conditions during which diamonds were resorbed.

Tables 16 to 19 demonstrate that, in most cases, individual surface textures are displayed by similar proportions of the diamonds in all of the kimberlites. This is the case even for textures, such as corrosion sculpturing, which are not represented in many kimberlitic diamond samples. Surface textural similarities indicate that the diamonds in all of the kimberlite varieties experienced similar, post-resorption conditions during which etching occurred. This is also indicated by the similar, particularly large proportions of fragments and broken crystals in all of the samples (Table 14).

The comparison between the three diamond samples strongly suggests that only one, primary kimberlite magma is represented in the De Beers Mine diatreme. The relative paucity of diamond in the Breccia Kimberlite can be attributed to dilution of the magma by a large volume of wall-rock xenoliths. The different concentrations of diamond in the Peripheral and Central Core Kimberlites are more difficult to explain. It is possible that the Central Core was emplaced separately from a shallow reservoir as a portion of the magma within which diamond had become concentrated. The possibility of a separate intrusion, into the diatreme, of the Central Core Kimberlite requires that the diamonds in the reservoir were not appreciably modified between successive magma surges and also that very little etching or breakage of diamonds occurred within the diatreme. Alternatively, it is possible that only a single magmatic event is represented in the diatreme. Should this be the case, it is necessary to call upon some mechanical process whereby diamonds were concentrated into the central portion of the magma column.

#### 12.1.2. Comparisons between the 595 m, 720 m and 785 m Levels

Most of the variations in crystallographic and surface textural characteristics (Tables 14 and 16 to 19, respectively) between the samples from different mining levels are insignificant, considering the small sizes of most of the samples. The diminishing diamond concentration, with depth, in each of the kimberlite bodies therefore cannot be correlated with the increasing effects of any process of diamond-resorption or diamond-destruction.

## 12.2. THE FINSCH MINE

The Finsch Mine diatreme north of Postmasburg is occupied by a single intrusion of xenolith-bearing kimberlite. The kimberlite contains abundant nucleated autoliths and is demonstrably of magmatic origin (Clement, 1975). Three hundred minus 11 plus 9 sieve class diamonds were examined from a mine-production parcel. One reason for including Finsch Mine diamonds in the present study was to test the hypothesis of Gurney, Harris and Rickard (1979) that most Finsch Mine diamonds are phenocrysts, rather than xenocrysts, in the kimberlite. Gurney, Harris and Rickard based their hypothesis on the chemical compositions of peridotite-type, mineral inclusions in Finsch Mine diamonds.

Approximately 60 per cent of the diamonds examined are brown or light brown (Table 13). Most of the remainder are colourless but a few per cent of the total are yellow.

Most of the diamonds are tetrahexahedroida and slightly more than 10 per cent are octahedra (Table 14). Cubes and fragments are also represented but neither is common. Approximately 10 per cent of the crystals are macles and slightly fewer are aggregates. Table 14 also shows that nearly all of the non-fragmental diamonds exhibit tetrahexahedroid surfaces. Octahedral crystal faces are preserved on approximately 30 per cent of the diamonds and cubic surfaces on approximately 10 per cent. Half of the diamonds are broken. The etched appearance of most breakage surfaces attests to their natural origin.

Ruts are commonly developed and rare Finsch Mine diamonds display scratch-like markings (Table 16). As many as 50 per cent of the diamonds with tetrahexahedroid surfaces display lamination lines (Table 17). Shagreen texture is associated with the lamination lines in most cases. Terraces are also commonly developed on tetrahexahedroida.

No positively-oriented surface textures were observed in the sample.

A remarkable feature of the sample, which is not shown in the tables, is that 3 per cent of the diamonds display the effects of abrasion (Figure 92). Ground surfaces post-date all etch features and are indistinguishable from some surfaces commonly developed on detrital diamonds. In most cases, only sharp crystal corners or corners and particularly sharp crystal edges are ground, but examples were noted of crystals displaying ground tetrahexahedroid "A" edges. Nearly all of the diamonds which display scratch-like markings are ground but some ground crystals are without these markings.

The most noteworthy features of the Finsch Mine sample are the preponderance of brown diamonds, the very common occurrence of diamonds displaying lamination lines and the presence of diamonds with ground surfaces.

It is considered that diamonds displaying lamination lines must be xenocrysts with respect to the kimberlite in which they occur. That so many Finsch Mine diamonds display lamination lines is therefore contrary to the hypothesis, of Gurney, Harris and Rickard (1979), that most Finsch Mine diamonds are phenocrysts.

The presence of abraded diamonds in the sample must be due to one of the following causes:-

- i. Attrition during a late stage of kimberlite emplacement.
- ii. The incorporation of diamond-bearing, sedimentary xenoliths into the kimberlite.
- iii. Attrition in the recovery plant at Finsch Mine.
- iv. Contamination of the sample with detrital diamonds from another locality.

Possibility i) above is considered most unlikely in view of the magmatic nature of the Finsch Mine kimberlite. Large xenoliths of

older, sedimentary kimberlite do occur within the magmatic kimberlite (L. Kleinjan, personal communication) so that ii) above is not impossible. Possibilities iii) and iv), however, are also difficult to disprove.

### 12.3. THE PREMIER MINE

The Premier Mine diatreme at Cullinan contains three main bodies of kimberlite (Figure 93). These have been considered to represent separate intrusions (Gerryts, 1951). They are designated, in order of apparently diminishing age, the Brown Kimberlite, the Grey Kimberlite and the Black Kimberlite. Brown Kimberlite occurs as xenoliths in Grey Kimberlite and is cut by the latter (Clement et al., 1973). It should be noted, however, that the Grey and Black Kimberlites are separated by a gradational zone of Green Kimberlite which obscures the relationship between them (Clement et al., op.cit.). The diatreme is cut by a 75 m thick gabbro sheet which dips at about 15 degrees. The gabbro, and hence the kimberlite pipe, is Precambrian in age (Allsopp, Burger and Van Zyl, 1967).

Five hundred minus 11 plus 9 sieve class diamonds were examined from each of the three main kimberlites. Green Kimberlite was included with Black Kimberlite in the sampling procedure. All of these diamonds are from the 538 m sampling level. Another, smaller sample recovered from distinctly metamorphosed kimberlite at the 370 m level of the mine was also studied. The main results of this separate study are summarized in Table 20. No features considered to have resulted from metamorphism were noted on any of these diamonds. Since the gabbro sheet does not even transect the 538 m level, the possibility that thermal metamorphism appreciably modified diamonds from the 538 m level can be discounted.

12.3.1. Comparisons between the Brown, Grey and Black Kimberlites of the 538 m Level

The distribution of diamond colours is very similar in the Grey and Black Kimberlites (Table 13). In both cases brown diamonds predominate. The Brown Kimberlite sample is strikingly dissimilar in its strong preponderance of colourless diamonds.

In all of the samples, tetrahexahedroids are much more common than octahedra, and cubes are rare (Table 14). The predominance of tetrahexahedroids is particularly marked in the case of the Brown Kimberlite sample. The abundances of crystals exhibiting octahedral or cubic surfaces (mainly as subordinate forms) are similar in the Grey and Black Kimberlite samples but are lesser in the Brown Kimberlite sample. Approximately dodecahedral crystals were noted mainly in the Grey and Black Kimberlite samples. Significantly more crystals are broken in the Brown Kimberlite sample than in the other two samples. Paired, pseudohemimorphic crystals and nearly spherical crystals are both rare constituents of both the Grey and Black Kimberlite samples, but were not noted in the Brown Kimberlite sample (Table 15). One spherical diamond in the Grey Kimberlite sample was identified as a ballas.

Diamonds displaying knob-like asperities constitute 3 or 4 per cent of the Grey and Black Kimberlite samples but are rare in the Brown Kimberlite sample (Table 16). Coarsely frosted diamonds occur in all of the samples but are particularly common in the Grey Kimberlite sample. Fine frosting is a relatively common feature of the diamonds in the Brown Kimberlite sample. Table 16 shows that diamonds displaying scratch-like markings are particularly common in the Brown Kimberlite sample. Table 17 demonstrates that coarse hillocks, hillocks with hexagonal pits, corrosion sculpture, shallow depressions and microdisk patterns

are all surface textures which are fairly common in both the Grey and Black Kimberlite samples but which are significantly less common in the Brown Kimberlite sample. Lamination lines are evident on more than 40 per cent of the diamonds in all of the samples. Serrate laminae and hexagonal pits containing trigons are both common octahedral surface textures in the Grey and Black Kimberlite samples but are either rare or absent in the Brown Kimberlite sample (Table 18).

A noteworthy feature of all of the samples is the scarcity of yellow diamonds which they contain. The substantial proportion of diamonds displaying scratch-like markings is an outstanding feature of the Brown Kimberlite sample. Other noteworthy features of both the Grey and Black Kimberlite samples include the fairly common occurrences of ribbed, dodecahedral crystals with knob-like asperities, crystals displaying hillocks with hexagonal pits and crystals displaying hexagonal pits containing trigons. The occurrences of nearly spherical crystals and of paired pseudohemimorphic crystals in these two kimberlites are also worth noting.

It is likely that the same genetic assortment of diamonds is present in all of the Premier Mine kimberlites. This is suggested by close similarities, between the samples, in the characteristics which are determined by crystal growth (and immediately subsequent) conditions. These characteristics include the proportion of yellow diamonds, the ratio between the diamonds with octahedral crystal surfaces and those with cubic surfaces, the incidence of macles and the incidence of crystal aggregates.

The similar distributions of diamond colours in the Grey and Black Kimberlite samples strongly suggest that these two kimberlites were represented by a single magma at the time that the diamonds were discoloured brown. The different distribution of colours in the Brown

Kimberlite sample indicates that the Brown Kimberlite diamonds experienced different conditions during the brown-colouring event. The individuality of the Brown Kimberlite was therefore established while this rock was a magma at mantle depths.

The Grey and Black Kimberlites must have been represented by a single magma during practically all of the resorption and most of the etching and crystal breakage which affected the diamonds in these kimberlite bodies. This is indicated by similarities in the proportions of, for example, crystals which exhibit remnant, growth form (i.e. octahedral or cubic) surfaces, ribbed dodecahedra with knob-like asperities, crystals displaying hillocks with hexagonal pits, crystals displaying corrosion sculpture and broken crystals. The Grey and Black Kimberlite magmas need to have separated, however, by the time that diamonds, and particularly those in the Grey Kimberlite, were being coarsely frosted. The different surface textural characteristics of the Brown Kimberlite sample substantiate that this kimberlite was emplaced separately from mantle depths.

#### 12.4. LETSENG-LE-TERAI

The kimberlite occurrences at Letseng-le-terai, Lesotho, have been described by Bloomer and Nixon (1973). A relatively large pipe is associated with a smaller pipe situated a few hundred metres away. A number of kimberlite types can be distinguished in each of the pipes. Included among these is the K6 Kimberlite which forms a relatively young, core-like body within the larger pipe. The small pipe is known as the Satellite Pipe. Only the K6 body is currently being exploited.

Diamond samples recovered from the K6 body, the undifferentiated "Remainder" of the main pipe and the undifferentiated Satellite Pipe were available for examination. A variety of diamond sizes were examined.

One hundred minus 11 plus 9 diamonds are included among those examined in the K6 and Satellite Pipe samples, but only 50 of those examined in the Remainder sample are of this size.

12.4.1. Comparisons between the K6, Remainder and Satellite Pipe Kimberlites

Diamond colours (Table 13) are fairly similarly distributed in the K6 and Remainder samples. Slight, but statistically significant, differences are evident. These differences are not consistent in all of the diamond sizes, however, so that their true significance is not easy to evaluate. The Satellite Pipe sample contains substantially more colourless diamonds, mainly at the expense of light brown and brown diamonds but possibly also at the expense of yellow diamonds. Diamonds containing abundant microscopic to submicroscopic, black inclusions are fairly common in the Satellite Pipe sample. Such diamonds constitute most of those classified as of "other" body colour in Table 13. They are rare in the Remainder sample and were not seen in the K6 sample.

Among the crystal forms represented (Table 14), the tetrahedroid predominates strongly. This is particularly the case in the Satellite Pipe sample, in which only about 5 per cent of the minus 11 plus 9 diamonds display octahedral surfaces, but is also notably the case in the Remainder sample. In the K6 and Remainder samples, the octahedral form is much more common than the cubic form. In the Satellite Pipe sample, however, the cubic form is about as common as the octahedral form. This is largely due to the relatively common presence of cubic surfaces on the inclusion-rich diamonds which occur mainly in the Satellite Pipe sample. Fragments are common and more than half of the diamonds in all of the samples are broken. Most of the plus 11 tetrahedroida in the K6 and Remainder samples are

classed as irregular crystals, but equidimensional crystals are fairly common in the Satellite Pipe sample (Table 15).

Ruts are very common among the unrestricted surface textures developed, particularly in the K6 sample (Table 16). Fine frosting is the only other, unrestricted surface texture noted and is displayed by a few per cent of the diamonds in all of the samples. Most tetrahedra in all of the samples display low-relief surfaces (Table 17). Lamination lines are evident on more than 40 per cent of the diamonds with tetrahedral surfaces in the K6 and Remainder samples, but are a significantly less common feature in the Satellite Pipe sample.

The K6 and Remainder samples are similar in all of the characteristics considered to be determined at mantle depths. These characteristics include crystal growth forms, colour and lamination lines. This similarity suggests that both kimberlite bodies are representative of the same primary magma. The substantially greater proportion of K6 diamonds which exhibit vestiges of growth form surfaces indicates that fewer K6 than Remainder diamonds were substantially resorbed during kimberlite emplacement. Since the surface textural characteristics of the K6 and Remainder samples are similar, it is unlikely that two magmas with different physico-chemical properties were involved. Instead, the same magma probably produced both kimberlite bodies, with more diamonds in the K6 magma pulse having been partly protected from resorption. Such protection is presumed to have been afforded by enclosure within xenoliths which were disaggregated relatively late within the magma which produced the K6 body.

Most of the Satellite Pipe diamonds may also represent the same, genetic assortment that is present in the kimberlites of the main pipe. It appears, however, that an additional population is substantially represented in the Satellite Pipe. This additional population consists

of inclusion-rich diamonds which commonly exhibit cubic crystal surfaces. (This population might also be represented in the Remainder body, but only as a very minor constituent). Notwithstanding the likelihood of a common source for most of the diamonds in the main pipe and Satellite Pipe kimberlites, the Satellite Pipe kimberlite is likely to have been separately emplaced from the earth's mantle. This is indicated by substantial differences, between the Satellite Pipe and main pipe diamond samples, in the proportions of diamonds displaying features (brown colours, lamination lines) which are considered to develop in association with the movement of kimberlite magma within diamond source regions.

#### 12.5. THE ORAPA MINE

The Orapa Mine is situated a few kilometres south of the Madgakigadi Pan Complex in Botswana. The ore-body is a pipe in which approximately 90 m of epiclastic kimberlite (i.e. sedimentary rock derived mainly from kimberlite) overlies tuffaceous kimberlite (Hawthorne, 1975).

Two hundred minus 11 plus 9 diamonds were examined from each of two parcels. One parcel (here termed the "Trenches Parcel") represents the diamonds recovered from 3 m deep surface trenches. The other parcel (here termed the "± 35 m Parcel") represents the diamonds recovered from a cut at an average depth, from surface, of approximately 35 m. In both cases the diamond host rock is epiclastic kimberlite. As is to be expected, the two samples are practically identical in nearly all respects. They are therefore described as one sample, but with significant differences between them being pointed out.

Colourless and light brown to brown are the main diamond body colours (Table 13) and are about equally important. Yellow colour is

also fairly common, as is grey colour caused by microscopic to sub-microscopic, black inclusions. Rare diamonds with green-stained surfaces are present in both samples.

Among crystal forms (Table 14), the tetrahexahedroid predominates strongly. Crystals exhibiting remnant, growth form surfaces are common, however, and cubes are represented among them. An outstanding characteristic is that more than 35 per cent of the diamonds studied are crystal aggregates. Most aggregates consist of between two and about half a dozen individual crystals (Figure 94) but microcrystalline examples (framesite) are also represented. Approximately 5 per cent of the features counted as tetrahexahedroid in Table 14 are actually of the ribbed, approximately dodecahedral form.

Diamonds displaying scratch-like markings were noted only in the Trenches sample, while inclusion cavities are significantly less common in that sample than in the  $\pm$  35 m sample (Table 16). Only a limited variety of tetrahexahedroid surface textures is represented (Table 17), and most tetrahexahedroid surfaces display only fine- or medium-textured, elongate hillocks (not included in Table 17). Few tetrahexahedroids display terraces and lamination lines are developed on fewer diamonds than in any other sample studied. Notwithstanding the general scarcity of lamination lines, diamonds displaying a few, widely-spaced lamination lines are fairly common. Triangular plates include some unusual examples which appear to have retained an octahedral, plateau surface even though most of the host crystal may have been converted to a tetrahexahedroid (Figure 94). No positively-oriented surface textures were observed in the samples examined.

A remarkable feature, not recorded in the tables, is the presence of diamonds displaying abraded surfaces (Figure 94) resembling those developed on some detrital diamonds. Ground diamonds account for

10 per cent of the Trenches sample but are rare (two examples noted) the  $\pm$  35 m sample. In approximately half of the cases, grinding is evident only at sharp crystal corners. In most other cases, only the sharpest portions of tetrahexahedroid "A" edges are ground but more abraded examples, including one distinctly rounded crystal, are also present. Most, but not all, of the relatively abraded crystals also display ground scratch-like markings. Nearly 30 per cent of the ground diamonds are aggregate crystals. Since such crystals are generally rare in Southern African placer deposits (see Chapter 16), it is most unlikely that the ground diamonds in the Orapa samples are contaminants from a placer deposit. Milling during diamond recovery cannot easily be eliminated as a possible cause of diamond abrasion. The more common occurrence of ground diamonds in the shallower, Trenches sample is compatible, however, with the diamonds having been abraded during the reworking of epiclastic kimberlite. In this regard, the possibility that the Orapa diatreme could have been situated within the confines of a once extensive, Makgadikgadi Lake (Grove, 1969), should be noted.

## 12.6. LETLHAKANE

Two kimberlite pipes are present at Letlhakane, Botswana. These are a relatively large pipe, known as DK 1, and a smaller pipe, known as DK 2, which is situated a few hundred metres away. Both pipes contain tuffaceous kimberlite. Three hundred minus 11 plus 9 diamonds were examined from each of the pipes.

### 12.6.1. Comparison between the DK 1 and DK 2 Pipes

Colourless diamonds predominate, and light brown to brown diamonds constitute most of the remainder, in both samples (Table 13). Brown diamonds are significantly more common, mainly at the expense of colourless diamonds, however, in the DK 1 sample. Yellow and grey

colours are represented, but are not particularly common, in both samples. Green surface staining is a fairly common feature, particularly among the DK 1 diamonds. In the DK 1 sample, most of the green staining is continuous on diamond surfaces but isolated green spots are more common in the DK 2 sample.

The tetrahexahedroid form predominates in both samples (Table 14). This is particularly the case in the DK 2 sample, in which tetrahexahedroids are significantly more common and the octahedral form is significantly less common than in the DK 1 sample. Although appreciably more resorption is indicated for the diamonds of the DK 2 sample than the DK 1 sample, the cubic growth form is actually better preserved in the DK 2 sample. This suggests that, prior to resorption, the DK 2 diamond population contained substantially more cubes, relative to octahedra, than did the DK 1 population. Crystal aggregates are fairly common in both samples, particularly the DK 1 sample.

All of the surface textures noted in the DK 1 sample are also present in the DK 2 sample. This includes much coarser knob-like asperities than noted from elsewhere. Frosting and corrosion sculpture (Tables 16 and 17, respectively), however, are fairly common textures at DK 2 but were not noted in the DK 1 sample. The distributions of most other surface textures vary slightly, but significantly, between the samples. The DK 1 and DK 2 diamonds are therefore likely to have been subjected to similar, but not identical, conditions. No positively-oriented textures were noted.

Differences, between the DK 1 and DK 2 samples, in characteristics which are considered to be determined at mantle depths, indicate separate derivations of a DK 1 and a DK 2 kimberlite magma from the earth's mantle. Differences between, for example, the proportions of diamonds displaying cubic surfaces and the proportions of crystal

aggregates, may attest to differences in the diamond source regions sampled by the DK 1 and DK 2 kimberlite magmas. The different proportions of brown-coloured diamonds in the two samples reflect differences associated with the movement of the kimberlite magmas in the diamond source regions. Diamond resorption was a more important process in the DK 2 magma than in the DK 1 magma, as shown by the greater proportion of tetrahedra in the DK 2 sample. That the DK 2 magma was relatively corrosive toward diamond is also suggested by the presence of diamonds displaying surface textures which are not represented in the DK 1 sample.

#### 12.7. PIPE BK 9

The generalized geology of Pipe BK 9, Botswana, is shown in Figure 95. A saucer-shaped body of kimberlite breccia occupies most of the surface area of the pipe. This rock (the "Kimberlite Breccia") consists of country-rock basalt and sandstone fragments and interstitial, magmatic kimberlite. Magmatic kimberlite which contains few country rock xenoliths is exposed at the north-western and south-eastern extremities of the pipe and underlies the Kimberlite Breccia. Preliminary field and petrographic investigations have not clarified the possible relationships between the magmatic kimberlite bodies at the north-western and south-eastern extremities of the pipe and the igneous component of the Kimberlite Breccia (C.R. Clement, personal communication).

Three hundred, minus 11 plus 9 sieve class diamonds were examined from each of two magmatic kimberlite diamond samples from the north-western and south-eastern outcrop areas, respectively. Eighty diamonds of like size were examined from the Kimberlite Breccia.

12.7.1. Comparisons between the North-western and South-eastern Bodies of Magmatic Kimberlite and the Kimberlite Breccia.

The distributions of diamond colours are similar in the south-eastern magmatic kimberlite sample and in the Kimberlite Breccia sample (Table 13). In these samples, approximately 60 per cent of the diamonds are colourless and most of the remainder are brown or light brown. The north-western magmatic kimberlite sample appears to be anomalously rich in light brown diamonds at the expense of colourless diamonds. In view of difficulties in distinguishing between very light brown and colourless diamonds, however, the true significance of this anomaly is uncertain. The consideration, below, of other characteristics of the samples helps to resolve this uncertainty. If the anomalous result obtained for the north-western magmatic kimberlite sample is discounted, then the distributions of colours within the samples are compatible with the hypothesis that the same mantle-derived assortment of diamonds is represented in all three kimberlite bodies.

The crystallographic characteristics which are considered to reflect diamond growth conditions are similar in all of the samples. Thus, crystal aggregates constitute nearly 20 per cent of the diamonds and crystals with octahedral surfaces are about twice as common as crystals with cubic surfaces (Table 14). These similarities are compatible with the hypothesis that the same genetic assortment of diamonds is present in both bodies of magmatic kimberlite and in the Kimberlite Breccia.

The proportion of diamonds exhibiting remnant, growth-form surfaces is similar in both of the magmatic kimberlite samples (Table 14). This similarity suggests that the diamonds in both bodies of magmatic kimberlite were transported from the mantle by the same magma, and tends to discount the significance of the colour difference noted between the samples. In the Kimberlite Breccia sample, however, approximately

twice as many diamonds as in the magmatic kimberlite samples exhibit octahedral or cubic crystal surfaces. The relative scarcity of substantially resorbed diamonds in the Kimberlite Breccia suggests either that the magma which resorbed these diamonds was less reactive, toward diamond, than the magmatic kimberlite magmas, or that relatively many Kimberlite Breccia diamonds were protected from resorption.

The distributions of unrestricted textures are similar in all of the samples (Table 16). Tetrahexahedroid surface textures (Table 17) are also similarly distributed in both magmatic kimberlite samples, suggesting that the same kimberlite is present in both bodies. The Kimberlite Breccia sample is markedly different, however, in the distributions of some tetrahexahedroid surface textures. Of particular importance is the exceptionally common development of corrosion sculpture on diamonds in the magmatic kimberlite samples and the absence of diamonds displaying this texture in the Kimberlite Breccia sample. The corrosion sculpture developed on most of the magmatic kimberlite diamonds is unusually fine and often passes into coarse frosting. The texture is commonly developed on cleavage surfaces. The diamonds in the magmatic kimberlite bodies, but not in the Kimberlite Breccia, were evidently subjected to unusual conditions late during their ascent toward the surface.

Comparison between the characteristics of diamond samples from Pipe BK 9 suggest that only one, primary kimberlite magma is represented. This primary magma appears to have been emplaced, however, as two separate intrusions. One intrusion resulted in the Kimberlite Breccia and the other produced the two magmatic kimberlite bodies. The postulated primary magma apparently divided during its ascent but before diamond resorption was far-advanced, i.e. at a minimum depth not much shallower than about 100 km.

## 12:8. DOKOLWAYO

The events leading to the discovery of the Dokolwayo kimberlite pipe in Swaziland are documented by Hawthorne et al. (1979), who also describe the occurrence. The kimberlite contains Ecca coal fragments so post-dates the Lower Permian. One reason for studying Dokolwayo diamonds was so that they could be compared with the diamonds of the Hlane placer deposit (Section 16.2.) considered, by Hawthorne et al., to be derived from Dokolwayo. Two hundred minus 11 plus 9 diamonds and 100 minus 7 plus 5 diamonds were examined. The smaller diamonds match most Hlane diamonds in size.

### 12.8.1. The minus 11 plus 9 Diamonds

Approximately 75 per cent of the diamonds are colourless and most of the remainder are either light brown or brown (Table 13). Rare, dark green diamonds are an unusual feature of the sample. A few diamonds exhibit green surface staining.

The tetrahexahedroid form is strongly predominant (Table 14). Crystal aggregates are fairly common. Diamonds exhibiting octahedral crystal surfaces are about three times as common as diamonds exhibiting cubic surfaces. Most crystals are irregular in shape and equidimensional crystals are scarce (Table 15).

Ruts are particularly common features (Table 16). Terraces and lamination lines are common tetrahexahedroid surface textures (Table 17). Ten per cent of the diamonds with tetrahexahedroid surfaces display fine striation with edge enhancement, a surface texture which was not encountered in any other kimberlitic diamond sample studied. The fairly common occurrence of diamonds which display fine striation with edge enhancement is probably the most noteworthy feature of the sample.

### 12.8.2. The minus 7 plus 5 Diamonds

In most respects, the minus 7 plus 5 sample studied is practically identical to the minus 11 plus 9 sample described previously. Significant differences include a higher proportion of brown diamonds, at the expense of colourless diamonds, in the minus 7 plus 5 sample (Table 13), more broken crystals in the minus 7 plus 5 sample (Table 14) and fewer tetrahedra displaying terraces and substantially more displaying lamination lines in the minus 7 plus 5 sample (Table 17). It is significant that diamonds displaying fine striation with edge enhancement are also fairly common in the minus 7 plus 5 sample (Table 17).

### 12.9. THE MIR MINE

The Mir kimberlite pipe in Yakutia, U.S.S.R., has been described by Bobrievich et al. (1959). A total sample of 25 minus 11 plus 9 diamonds, 50 larger diamonds and 25 smaller diamonds was examined. The sample is entirely from the "sawable and makeable" commercial assortment, so cannot be regarded as representative of the Mir diamond population. Because certain colours and crystal shapes are excluded from the "sawable and makeable" assortment, neither of these characteristics was determined for the sample. Crystallographic and surface textural characteristics, however, should not depart radically from those of a random sample.

The most notable feature of the sample is the marked predominance of the octahedral form (Table 14). Approximately 50 per cent of the diamonds studied are plane-faced octahedra, approximately 25 per cent are octahedra with surfaces built of imbricate triangular plates and another 13 per cent are octahedral macles. Tetrahedra comprise only approximately 10 per cent of the sample and practically all of the diamonds exhibit octahedral crystal surfaces. More than half of the

plane-faced octahedra and octahedral macles are largely sharp-edged, with the tetrahexahedroid form developed only in the vicinity of crystal corners. (These incipient developments of the tetrahexahedroid form were ignored in determining the percentages, listed in Table 14, of diamonds with tetrahexahedroid surfaces). The cubic crystal form is poorly represented in the sample. Approximately half of the diamonds are broken. Most breakage surfaces are etched and, therefore, are natural features.

Only a limited variety of surface textures were noted in the sample (Tables 16 to 19). Lamination lines are displayed by approximately 10 per cent of the diamonds (Table 17). The Mir sample is the only sample studied in which lamination lines are frequently evident on octahedral crystal surfaces, where they are marked by lines of small trigons. Triangular plates are particularly common features of octahedral crystal surfaces (Table 18). Although trigons are evident on nearly all octahedral crystal faces, they are usually few in number, small and shallow.

By comparison with the other diamond samples studied, very few of the Mir diamonds show evidence of having been substantially resorbed. Surface textures which are caused by light etching are also scarce or absent.

#### 12.10. PRAIRIE CREEK

The Prairie Creek kimberlite pipe near Murfreesboro, Arkansas, U.S.A., has been described by Meyer et al. (1977). This is the only North American locality to have produced diamonds on a commercial scale. Thirty two diamonds were examined. These are within the minus 15 plus 5 sieve size range.

More than half of the diamonds are light brown or brown (Table 13).

Most of the remainder are yellow and less than 10 per cent are colourless.

All of the diamonds are tetrahedra and few of these exhibit growth-form vestiges (Table 14). Most are severely distorted or irregular crystals (Table 15). Half of the diamonds are broken.

Ruts and inclusion cavities are common, unrestricted surface textures (Table 16). Pitted hemispherical cavities, which were encountered in only one other sample studied (from Wellington, New South Wales, see Section 16.7.), are also fairly common, unrestricted features. Low-relief surfaces predominate among tetrahedron surface textures (Table 17) and diamonds displaying terraces are conspicuously absent. Lamination lines and, to a lesser extent, triangular pyramids, are the only other common, tetrahedron surface textures.

The abundance of coloured, at the expense of colourless, diamonds is a notable feature of the Prairie Creek sample. Other notable features are the lack of conspicuous relief features on most tetrahedron surfaces and the fairly common occurrence of diamonds displaying pitted hemispherical cavities.

#### 12.11. THE LOXTONDAL MINE

The kimberlite body at Loxtondal has been described by Clement et al. (1973). The body is pipe-like but is unusual in that it swells in depth (over the vertical interval exposed by mining operations). The unusual form of the body is apparently the result of constriction where the kimberlite magma pierced a dolerite sill situated near the present-day surface. It is possible that the kimberlite magma did not attain the palaeo-surface (Clement et al., op.cit.). Should this be the case, the physico-chemical environment within the magma should have

been intermediate between that in a dyke and that in an open diatreme.

A hundred and seventy five Loxtondal diamonds were examined. The characteristics of the 100 minus 11 plus 9 diamonds included in the sample are emphasized in the ensuing discussion.

Colourless diamonds predominate markedly in the sample (Table 13). Thus, approximately 90 per cent of the minus 11 plus 9 diamonds are colourless. Most of the remainder are either light brown or yellow. Green surface staining is common. In the case of the minus 11 plus 9 and smaller diamonds, the staining is usually spread over entire surfaces. Isolated spots are more common, however, among the relatively large, stained diamonds studied.

Approximately 50 per cent of the minus 11 plus 9 diamonds are classed as octahedra (Table 14). These include rare examples completely devoid of modification by the tetrahexahedroid form. Such octahedra also lack trigons (Table 18). According to Table 14, approximately 70 per cent of the minus 11 plus 9 diamonds exhibit octahedral surfaces. Few exhibit cubic crystal surfaces. Fragments are fairly common and approximately half of the diamonds in the sample are broken. Most breakage surfaces display some etch pits, indicating that they are natural features.

Ruts are common, unrestricted surface features (Table 16). Considering that octahedral crystal surfaces are preserved on many of the diamonds, the predominance of low-relief surfaces and scarcity of terraces among tetrahexahedroid surface textures (Table 17) suggest that few of the diamonds are stratified internally. While lamination lines are commonly displayed by the small diamonds in the sample, this texture appears to be rare among the minus 11 plus 9 and larger diamonds. Corrosion sculpture (which is not differentiated from shallow depressions in Table 17) is a common, tetrahexahedroid

surface texture.

The marked predominance of colourless diamonds, the high incidence of diamonds displaying green, surface staining, the predominance of the octahedral form and the high incidence of crystals with octahedral surfaces are all notable features of the Loxtondal diamond sample.

#### 12.12. THE HELAM MINE

The Helam Mine exploits the Main Fissure, which is one of up to five, spatially associated dykes situated near Swartruggens (Fourie, 1958). At least one of the dykes (the non-diamondiferous, Male Fissure) is a lamprophyre and not a kimberlite (Skinner and Scott, 1979). Six hundred and eighteen Helam Mine diamonds were examined. Two hundred and forty six of these are of the minus 11 plus 9 size, while the others are larger. The characteristics of the minus 11 plus 9 diamonds are emphasized in the ensuing discussion.

Most of the diamonds are colourless (Table 13). Brown is also a common colour. An interesting feature of the diamonds classed as yellow is that approximately half of them are amber. These amber-coloured diamonds are probably of type Ib (Orlov's (1977) variety II). Crystals with their entire surfaces stained very light green are fairly common.

Approximately half of the diamonds are tetrahexahedroida and most crystals exhibit tetrahexahedroid surfaces (Table 14). The next most common form is the cube. Approximately 20 per cent of the diamonds are classed as cubes and more than 50 per cent exhibit cubic surfaces. Most of the cubes are colourless and without abundant inclusions. They are not properly catered for in Orlov's (1977) classification scheme. The octahedral form is also represented (Table 14). While a few crystal

aggregates are present, macles are conspicuously scarce. Fragments are fairly common and nearly half of the crystals are broken. Octahedra with negative edges and tetrahexahedroida with surfaces that are concavely kinked at major rhombic axes are fairly common in the sample (Table 15).

Ruts are the only common, unrestricted surface texture (Table 16). Tetrahexahedroid surfaces generally display short hillocks, while terraces are a rare texture (Table 17). These two features are consistent with most tetrahexahedroida having been derived from cubes. Lamination lines are a common, tetrahexahedroid surface texture. Triangular plates are a common feature of octahedral crystal faces (Table 18). Tetragons are almost universal, cubic surface textures while crescentic steps are fairly common and pointed plates were also noted (Table 19).

The presence of amber-coloured diamonds, the high proportion of cubes and of diamonds exhibiting the cubic form, the extreme scarcity of macles and the fairly common occurrence of crystals with surfaces intersecting concavely are all notable characteristics of the sample.

### 12.13. THE ANGLO WESTERN TRANSVAAL MINE

The Anglo Western Transvaal Mine, now incorporated in the Helam Mine property, also exploits the Main Fissure near Swartruggens. A hundred minus 15 plus 11 diamonds were examined. As was expected, the sample characteristics are very similar to those of the Helam Mine sample. Notable features are, thus, the presence of amber-coloured diamonds, the common occurrence of the cubic crystal form, a lack of macles and the fairly common occurrence of crystals with surfaces intersecting concavely. Substantially fewer diamonds are broken and slightly more of the diamonds with tetrahexahedroid surfaces display shallow depressions than in the Helam Mine sample (Table 17).

13. COMPARISON BETWEEN THE DIAMONDS OF KIMBERLITE

DYKES AND PIPES

It is widely accepted (e.g. Dawson, 1971), that the kimberlite in dykes was emplaced as a high-temperature liquid whereas most of the kimberlite in pipes was a gas-charged, particle-rich fluid which was rapidly cooled by adiabatic expansion. According to both Dawson (1971) and Hawthorne (1975), kimberlite pipes taper in depth and are rooted in dykes at depths of a few thousand metres below the palaeo-surface. The kimberlite in pipes therefore experienced both dyke-forming and pipe-forming conditions before solidifying. A comparison between characteristics of the diamonds in kimberlite dykes and pipes should disclose which features, if any, are only imparted to diamonds within the near-surface, pipe-forming environment. Conversely, any features displayed by the diamonds from both pipes and dykes can be ascribed to processes which operated within hypabyssal or deeper environments.

While samples were studied from twelve typical pipes (Table 2), only two samples from a single kimberlite dyke are included. The dyke samples are the Helam Mine and the Anglo Western Transvaal Mine samples from the Main Fissure, near Swartuggens. The Loxtondal Mine sample can possibly be regarded as from a body intermediate between a dyke and a pipe.

All of the most outstanding features of the Main Fissure samples, namely the presence of amber-coloured diamonds, the common occurrence of the cubic crystal form, the scarcity of macles and the presence of crystals with concavely-intersecting surfaces, undoubtedly reflect peculiarities of the diamond crystal growth (and immediately subsequent) conditions which are represented. This is also the case

regarding the notably common occurrences of colourless and octahedral diamonds in the Loxtondal Mine sample. These notable features of the dyke and constricted pipe samples were determined at mantle depths, so are irrelevant in any comparison between the diamonds in dykes and pipes.

None of the Main Fissure samples or the Loxtondal Mine sample is unique, with respect to the samples studied from pipes, in its proportion of diamonds displaying lamination lines (Table 17). This is as to be expected, considering that kimberlite dykes and pipes are similarly connected to diamond source regions.

The tetrahexahedroid form is nearly as common in the Main Fissure and Loxtondal Mine samples as in most of the samples from kimberlite pipes, and is more common than in the Mir Mine sample (Table 14). Similarly, negatively-oriented surface textures, such as trigons and tetragons, which are considered to develop during diamond crystal resorption are as well represented in the dyke and constricted pipe samples as in some of the pipe samples (e.g. Tables 18 and 19). It is therefore evident that most, possibly all, diamond crystal resorption can be completed before kimberlite magma is emplaced into diatremes. This is consistent with temperatures of less than 950°C (the minimum temperature considered to be necessary for the formation of negatively-oriented etch features) generally prevailing during kimberlite diatreme formation.

Developments of shallow depressions and corrosion sculpture among the Main Fissure and Loxtondal Mine diamonds indicate that these textures, which post-date the development of the tetrahexahedroid form, can be produced before kimberlite magma is emplaced into diatremes. Wagner's (1914, p. 144) observation that corroded diamonds are present in the deep, but not the shallow mining levels at the De Beers Mine

suggests that magma hotter than 950°C may enter the deeper portions of kimberlite pipes. Shallow depressions and corrosion sculpture post-date many of the breakage surfaces examined in the Main Fissure and Loxtondal Mine samples. Diamond crystal breakage is therefore not necessarily associated with kimberlite diatreme formation. In fact, broken diamonds are as common in the Helam Mine and Loxtondal Mine samples as in most of the samples from kimberlite pipes (Table 14). This is at variance with Wagner's (1914, p. 165) assertion that broken diamonds are more common in kimberlite pipes than in dykes and suggests that most, possibly all, diamond breakage occurs before kimberlite magma is emplaced into diatremes.

None of the relatively young surface textures, such as scratch-like markings and positively-oriented etch pits, were noted among the Main Fissure and Loxtondal Mine samples. This might indicate that these surface textures are only developed within diatreme-forming environments, were it not that they are also absent in most of the samples studied from kimberlite pipes. Considering the probable mode of formation of scratch-like markings (Article 6.5.12.), however, it is likely that this texture is developed only on the diamonds in some kimberlite pipes.

#### 14. THE MIXED CHARACTER OF KIMBERLITIC DIAMOND POPULATIONS

A striking feature of every one of the kimberlitic diamond samples studied is its mixed character. This is manifested in the varieties of colours, crystal forms and surface textures which are represented.

The presence of both octahedra and cubes, or crystals which were probably derived from cubes, in individual samples suggests that ranges in diamond crystallization temperatures are represented. Various conditions for the crystallization of the diamonds present in individual kimberlites are also suggested by associations between single crystals, macles and aggregates.

Mixtures between colourless, yellow and brown diamonds in every sample imply mainly that different post-genetic conditions for diamond are always represented. In most of the samples, nearly all of the diamonds are probably of type Ia. It is considered that these diamonds (and associated type IIa diamonds which are possibly present in some samples) were held at high temperatures (and high pressures) for long periods. The cause of the difference between colourless and yellow, type Ia diamonds has not been established. It is possible, however, that the colourless examples experienced either longer periods at high temperatures, or higher temperatures. The post-genetic history of the amber-yellow diamonds of the Main Fissure samples might differ radically from that of associated diamonds because the amber-yellow examples are likely to have been brought to the near-surface soon after crystallizing. It seems that only some of the diamonds in any kimberlite were subjected to the plastic deformation at high temperature which is considered responsible for most of the brown colour in diamonds. Brown diamonds are likely to be derived largely from the disaggregation

of sheared mantle xenoliths. Associations between brown and colourless diamonds, both displaying lamination lines, suggest that the plastic deformation of the diamonds in individual kimberlites occurred over a range of temperatures.

Studies of the inclusions in diamonds clearly demonstrate that at least two parageneses of diamond, the one eclogitic and the other peridotitic, are generally represented in individual kimberlites (e.g. Prinz et al., 1975; Meyer and Tsai, 1976; Sobolev, 1977; Harris and Gurney, 1979). Consideration of the mixtures of diamond crystal growth forms and colours in individual kimberlites, as discussed above, suggests that many genetic populations of diamond might often be represented. That this is not definitely the case, however, is indicated by the mixed character of the diamonds, presumably representing only one genetic population, in some eclogite xenoliths (see Chapter 10). Orlov (1977) has also commented upon the mixed character of the diamonds in kimberlites. He notes (p. 208) that many of his "varieties" of diamond can occur within a single kimberlite and considers this to indicate a polygenetic origin for the mineral. Orlov's conclusion is based on the presumption that each "variety" of diamond originates uniquely.

Very few diamonds in any of the samples studied do not exhibit the effects of resorption. In many of the samples, crystals ranging from very slightly resorbed, sharp-edged octahedra to substantially resorbed tetrahedra which lack vestiges of growth form surfaces, are present. As outlined in Section 7.3., diamond crystal resorption is considered to occur during the emplacement of kimberlite magma. Local inhomogeneities in the diamond-resorbing potential of magmas are unlikely to account for much of the considerable variation observed in the degree to which diamonds in individual kimberlites are resorbed.

It is more likely, instead, that variations in the degree of resorption between associated diamonds are a function of the degree to which individual diamonds were protected from the kimberlite magma. Such protection could be afforded by host xenoliths or by the enclosure of diamond in phenocrysts of abyssal origin. In the absence of any known, sufficiently common, abyssal phenocrysts in kimberlites, xenoliths must be considered responsible. Diamonds liberated early, during kimberlite magma emplacement, from their host xenoliths should be resorbed more than diamonds liberated later. Variations in the amount by which diamonds in the same kimberlite were resorbed therefore suggest that many of the diamonds are xenocrysts (assuming a non-cognate origin for the xenoliths).

Post-resorption surface textures (e.g. corrosion sculpture, micro-disk patterns, frosting, scratch-like markings, positively-oriented etch features) are developed on some diamonds but not on others, in all of the samples in which they are represented. This might be partly a consequence of some diamonds having been protected, by their xenolith hosts, from the agencies responsible for the textures. Substantially resorbed diamonds can lack textures which are developed on less resorbed diamonds, however, so that other factors must also be involved in determining whether or not a particular surface texture is developed upon a particular diamond. It appears necessary that physical and chemical inhomogeneities often develop within kimberlite magmas. Such inhomogeneities are likely to be caused by influxes of meteoric water and/or atmospheric gas at shallow levels (i.e. after most resorption of diamond is completed).

15. DIAMOND RESORPTION AND THE AMOUNT OF DIAMOND IN KIMBERLITES

The following factors are among those determining the amount of diamond present in bodies of diamondiferous kimberlite:-

- i. The amount of diamond incorporated or generated by the kimberlite magma while at diamond-stable conditions.
- ii. The degree of destruction of diamond during the emplacement of the magma to a shallow level.
- iii. The local result (i.e. diamond concentration or dilution) of differentiation processes which operated during emplacement.
- iv. The degree of contamination of the kimberlite by non-diamondiferous, conduit-wall fragments.

Factors i), iii) and iv) above are beyond the scope of the present investigation. Diamond crystal resorption is by far the most important process to consider under factor i). As first recognized by Milashev (1965), the importance of diamond resorption in a kimberlite can be gauged by the relative importance of crystal growth forms (i.e. octahedra and cubes) and resorption forms (essentially the tetrahedroid). In Figure 96, the percentages of minus 11 plus 9 diamonds exhibiting growth form vestiges, in samples, are plotted against the diamond contents of host kimberlites. Figure 97 is a similar plot using the percentages of diamonds that are dominated by a growth form. Only samples containing at least fifty, minus 11 plus 9 diamonds (excluding fragments) are plotted. Diamond contents refer to the diamonds recovered commercially and are very rough approximations in many cases. In Figure 96, particularly, a trend is evident which relates the percentage of the diamonds with preserved, growth form surfaces to the diamond content of the kimberlite. The data points are widely scattered, however, which presumably reflects variations in factors i), iii) and iv) above.

16. THE CHARACTERISTICS OF THE DIAMONDS FROM SOME  
PLACER DEPOSITS

The characterization of the diamonds in placer deposits allows valuable deductions to be made concerning their origins. In order to determine whether, or not, particular kimberlites supplied diamonds to particular placer deposits, it is necessary that the pristine characteristics of the placer diamonds and the kimberlitic diamonds be known. Related or unrelated origins for the diamonds in associated placer deposits can also be unequivocally demonstrated only by consideration of the characteristics of the diamonds concerned.

Samples from 19 placer deposits were studied. Sample particulars are given in Table 3. The data determined for each sample are presented in tables, as follows:-

Table 21 = The percentages of the diamond colours distinguished.

Table 22 = The percentages of the main crystal forms and of the diamonds with particular crystal surfaces.

Table 23 = The percentages of the crystal shapes distinguished.

Table 24 = The percentages of the diamonds (excluding fragments) which display particular, unrestricted surface textures.

Table 25 = The percentages of the diamonds with tetrahexahedroid (or dodecahedral) crystal surfaces, which display particular surface textures which are restricted to these surfaces.

Table 26 = The percentages of the diamonds with octahedral crystal faces, which display particular, octahedral surface textures.

Table 27 = The percentages of the diamonds with cubic crystal surfaces, which display particular, cubic surface

textures.

Table 28 = The percentages of the diamonds exhibiting particular degrees of abrasion and the percentages displaying percussion markings.

As in Chapter 12, the data involving all or nearly all of the diamonds in the samples are emphasized in the ensuing discussion. The diamond-shape determinations (Table 23) are de-emphasized, for the same reason as given in Chapter 12, and most attention is directed toward the distributions of colours (Table 21), crystal forms (Table 22), unrestricted and tetrahexahedroid surface textures (Tables 24 and 25, respectively) and abrasional features (Table 28).

#### 16.1. THE WESTERN TRANSVAAL

Some features of the Western Transvaal alluvial diamond field are shown in Figure 98. Between 1926 and 1947, the diggings in the Lichtenburg area produced more than 7 000 000 carats of diamond (Du Toit, 1951). Current production from the field is on a much smaller scale.

Wagner (1914), Williams (1930 and 1932) and Du Toit (1951) investigated and described the deposits in detail. These are fluviatile gravels of presumed Late Tertiary and Pleistocene age. A general fall in the elevation of the gravels to the south and south-west, plus other features such as concentrations of diamonds at the northern sides of some sink-hole deposits, led early investigators (Wagner; Williams; Du Toit; all op.cit.) to infer a southward and south-westward flow for the palaeo-drainage system responsible for the gravels. Sedimentological studies by Stratten (1979) confirm these transport directions. The early investigators cited above all commented on the distinct differences evident between the diamonds from different parts

of the field and even from neighbouring "runs" of gravel. Both Du Toit and Stratten suggest that the kimberlite dykes situated north of Swartruggens are likely sources of the diamonds found near Lichtenburg.

#### 16.1.1. The Lichtenburg and Boskuil Areas

It was possible to procure samples from only the Lichtenburg and Boskuil areas of the diamond field. Both samples are composite in that they include the diamonds from a number of operations exploiting separate properties. Diamonds of the minus 11 plus 9 sieve class were concentrated upon but other sizes were also examined. The ensuing discussion refers only to the minus 11 plus 9 diamonds examined, unless otherwise stated.

Most of the diamonds are colourless and slightly more than 10 per cent are yellow, at both localities (Table 21). Dark brown diamonds are significantly more common, at the expense of colourless diamonds, however, in the Lichtenburg sample. Rare, amber-yellow diamonds were noted only in the larger, Lichtenburg sample. A few per cent of the diamonds at both localities display green surface staining.

In both samples, tetrahexahedroid crystals predominate while octahedra are also fairly common (Table 22). Macles and aggregates are represented in both samples, with macles being particularly common among the large (minus 19 plus 17) Boskuil diamonds. A large proportion of the minus 21 plus 17 diamonds in the Lichtenburg sample exhibits cubic surfaces. Fragments and broken crystals are relatively common in the Lichtenburg sample.

Some pristine surface textures (e.g. scratch-like markings (Table 24), corrosion sculpture and microdisk patterns (Table 25)) are similarly distributed in both samples. Other pristine textures

(e.g. chemically-polished surfaces, network patterns, ruts, fine frosting (all Table 24), terraces and lamination lines (Table 25)) have significantly different distributions in the two samples. Positively-oriented features (e.g. imbricate wedge markings and transverse hillocks, see Table 25) were noted only in the Lichtenburg sample.

Considering diamonds of the same size, the distributions of diamonds which are abraded to various degrees are similar at both Lichtenburg and Boskuil. Nearly half of the minus 11 plus 9 diamonds, fewer larger diamonds and more smaller diamonds in the samples are unabraded, while percussion markings are rare features.

Differences in pristine characteristics between the samples outweigh similarities. It is therefore likely that the deposits have separate sources. Close similarities in abrasional characteristics between the samples suggest that the Lichtenburg and Boskuil diamonds were transported similar distances under similar conditions.

#### 16.1.2. Comparison with the Main Fissure, Swartruggens

The Main Fissure diamonds are described in Sections 12.12 and 12.13. These diamonds differ radically from those in both the Lichtenburg and Boskuil deposits. More than 20 per cent of the Main Fissure diamonds are cubes while as many as 60 per cent exhibit cubic surfaces. Since cubes are scarce and cubic surfaces are developed on less than 10 per cent of the (minus 11 plus 9) Lichtenburg and Boskuil diamonds, the Main Fissure cannot have supplied more than a few per cent of the diamonds in the placer deposits. A similar conclusion can also be independently attained by considering, for example, the rarity of macles in the Main Fissure and their fairly common occurrence in the placer deposits. There is no compelling reason to link any of the

Boskuil diamonds to the Main Fissure. The presence of amber-yellow diamonds and the large proportion of large diamonds which exhibit cubic surfaces in the Lichtenburg sample suggest, however, that the Main Fissure might be a minor source of the diamonds at Lichtenburg.

#### 16.2. Hlane

Diamonds occur within fluvialite grits and conglomerates of the Red Beds Formation (Triassic), which outcrop in the Hlane Game Sanctuary, Swaziland (Hawthorne et al., 1979). According to Hawthorne et al., palaeocurrent measurements indicate that the diamond-bearing strata were derived from the west-northwest and prospecting in this direction led to the discovery of the Dokolwayo Kimberlite Pipe, 30 km away from the Hlane deposits. The location of the Dokolwayo Kimberlite, the apparent absence of any other major kimberlite bodies in the area and close similarities in the compositional ranges of garnet and spinel grains in the Hlane deposits and in the Dokolwayo kimberlite, satisfied Hawthorne et al. (op.cit) that the diamonds and other kimberlitic minerals at Hlane are derived from the Dokolwayo kimberlite. The conclusion reached by Hawthorne et al. implies that the Dokolwayo kimberlite pre-dates the Jurassic. No other Southern African kimberlites are known to have been emplaced during the interval between the Lower Permian (the maximum, possible age of the Dokolwayo kimberlite, see Section 12.8.) and the Jurassic. A tentative age determination performed by Allsopp and Kramers (1977), subsequently to Hawthorne et al. having submitted their manuscript for presentation at the Second International Kimberlite Conference, confirms an unusual age (300 ± 20 my, i.e. possibly Lower Permian) for the Dokolwayo kimberlite. Only subsequently to the presentation of the paper by Hawthorne et al., were sufficient diamonds recovered from the Hlane deposits to allow a

meaningful comparison with the Dokolwayo diamonds.

#### 16.2.1. Comparison with Dokolwayo

A sample of diamonds from Dokolwayo is described in Section 12.8. While a large range of diamond sizes is represented at Dokolwayo, only small diamonds (nearly all minus 7 diamond sieve size) are present at Hlane. The comparison made here is between 100-diamond samples of the minus 7 plus 5 sieve class which were studied from both deposits. The most pertinent features of this comparison are as follows:-

- i. The distributions of diamond colours are practically identical in both of the samples (Tables 13 and 21). Thus, colourless diamonds constitute nearly 60 per cent and most of the remainder are light brown or brown. Green-stained diamonds occur at both localities.
- ii. Similar proportions of the various diamond crystal forms are represented in both samples (Tables 14 and 22). Tetrahedra predominate, approximately 5 per cent of the diamonds are octahedra and aggregate crystals are common at both places. Aggregate tetrahedra are slightly more common, and octahedra and broken crystals are slightly less common, in the Dokolwayo sample than in the Hlane sample, but these differences are not necessarily significant.
- iii. All of the pristine surface textures noted are represented in both samples (Tables 16 to 19 and 24 to 27). This is the case even for the relatively rare, widely-spaced lamination lines (Tables 17 and 25) and for fine striation with edge enhancement (Tables 17 and 25) which was not encountered in any other diamond sample studied. While some textures are more common in one sample than in the other, in no case is

this difference statistically significant.

The very close similarity between the Hlane and Dokolwayo diamond samples confirms the conclusion of Hawthorne et al. (1979) that practically all of the Hlane diamonds are derived from Dokolwayo. It is interesting that about as many Hlane diamonds as Dokolwayo diamonds are broken (Tables 14 and 22) and also that none of the Hlane diamonds examined displays any signs of abrasion (Table 28). These observations indicate that diamonds of the minus 7 plus 5 sieve size need not be affected by approximately 30 km of fluvial transport.

### 16.3. MARINE DEPOSITS OF THE SOUTHERN AFRICAN WEST COAST

Diamond-bearing marine deposits are at present being mined intermittently along the West Coast of Southern Africa from approximately 90 km north of the Orange River Mouth, southwards to beyond the mouth of the Olifants River (Figure 99). Detailed accounts of many of the deposits are given by Wagner and Merensky (1928), Williams (1930 and 1932), Stocken (1962), Keyser (1972) and by the Geological Department of De Beers Consolidated Mines Limited (1976). These authors also briefly describe the diamonds from some areas.

According to the authors quoted above, marine deposits occur only seaward of the 100 m contour and extend inland a maximum of 7 km. These deposits are beach gravels resting on wave-cut platforms which are commonly backed by fossil cliffs. Between the mouth of the Orange River and Port Nolloth, for example, four such deposits are developed at and above the present mean sea level. These are known as, in order of decreasing elevation and age, the Grobler Terrace, the Upper Terrace, the Middle Terrace (which coincides with Merensky's (1927) "Oyster Line", considered by Wagner and Merensky (1928) to be Miocene-Pliocene

in age) and the Lower Terrace (Keyser, 1972). Local names are used elsewhere and no regional correlation between individual terraces has yet been established. Detailed investigations between the Orange River estuary and Port Nolloth by Keyser (1972), show that diamonds are concentrated in the immediate vicinity of present-day and buried river mouths. This suggests that the diamonds were brought to the coast by rivers draining the hinterland. Diamonds in relatively young terraces could also have been derived from eroded, older terraces.

16.3.1. The "C" Beach and the "F" Beach of the Consolidated Diamond Mines (C.D.M.)

The C Beach sample is from approximately 12 km north of the mouth of the Orange River. The F Beach sample is from a more-elevated, older terrace deposit 10 km north of the Orange River. The F Beach deposit contains a much greater proportion of large diamonds than the C Beach deposit (M.M. Oosterveld, personal communication). Approximately 300 minus 11 plus 9 diamonds and 50 plus 21 sieve size diamonds were examined from each deposit. Unless otherwise stated, the ensuing discussion concerns only the minus 11 plus 9 diamonds.

Both samples contain more than 60 per cent of colourless diamonds and nearly as many yellow as light brown diamonds (Table 21). Colourless diamonds are significantly more common, mainly at the expense of light brown to brown diamonds, in the C Beach sample than in the F Beach sample. Among the large (plus 21 sieve size) diamonds studied, however, no such difference is apparent.

Tetrahexahedroid diamonds are strongly predominant in both deposits (Table 22). Octahedra constitute approximately 5 per cent of the diamonds while cubes and fragments are rare and aggregates are very rare. A relatively large proportion of the minus 11 plus 9

diamonds, but not of the plus 21 diamonds, in the F Beach sample are broken. Macles are particularly common among the plus 21 sieve size diamonds in the F Beach sample. In both samples, the octahedral and cubic forms are developed much more frequently among the plus 21 than the minus 11 plus 9 diamonds.

Both deposits contain large proportions of crystals classed as equidimensional (Table 23). Flat crystals are also common in the F Beach sample, in which they are about three times as common as in the C Beach sample. Flat crystals tend to be coloured brown more often than less distorted crystals, while most of the large macles in the F Beach sample are flat. Much of the differences in colour and crystal form which were noted between the samples can therefore be correlated with a difference in the distribution of crystal shapes.

Pristine surface textures are similarly distributed among the diamonds of both samples. This is even the case for textures which were not encountered in some samples, such as chemically-polished surfaces, network patterns, frosting, scratch-like markings (all Table 24), microdisk patterns and corrosion sculpture (both Table 25).

The different diamond size frequency distributions noted, by Oosterveld (personal communication), between the C and F Beach deposits are likely to reflect sedimentary sorting. Assuming that flat crystals will tend to be deposited with larger, more equidimensional crystals, the different distributions of crystal shapes in the samples can also be ascribed to sedimentary sorting. It follows that the only other significant differences (i.e. in the proportions of coloured diamonds and large macles) between the samples can also be linked to a sedimentary process. In view of the notable similarities between the samples, it is therefore very likely that the same primary assortment of diamonds is represented at both of the beaches.

Nearly half of the (minus 11 plus 9) F Beach diamonds and approximately 30 per cent of the C Beach diamonds are unabraded (Table 28). This difference is significantly large and suggests that the C Beach diamonds experienced substantially more abrasion than the F Beach diamonds. Only examples which are abraded solely at crystal corners are more common in the C Beach sample, however, so that the amount of additional abrasion is minor. In addition, it was noted that flat crystals, which are relatively common in the F Beach sample, are less often abraded than the more equidimensional crystals. Some of the difference in abrasional characteristics can therefore probably be linked to sedimentary sorting. Percussion markings are developed on slightly more of the minus 11 plus 9 diamonds of the F Beach sample than the C Beach sample. This is surprising, considering that more C Beach diamonds are abraded. Table 28 shows that the large (i.e. plus 21) diamonds in the samples tend to be substantially more abraded, and display percussion markings more often, than the minus 11 plus 9 diamonds.

The characteristics of the two samples are compatible with the C Beach diamonds representing a further-dispersed fraction of the diamond population present at the F Beach. The relatively common development of percussion markings on the F Beach diamonds requires, however, that some of these markings were produced after effective transportation had ceased.

### 16.3.2. The State Diggings

The State recovers diamonds from an approximately 8 km-wide stretch of the coast extending approximately 100 km south of the Orange River. Four marine terrace deposits occur in the area. These are described in detail by Keyser (1972). Three hundred minus 11 plus

9 diamonds were studied from a routine production parcel. The precise location from which the diamonds were won is not known to the author.

Seventy per cent of the diamonds are colourless, while yellow diamonds and light brown to brown diamonds each constitute about half of the remainder (Table 21). Green surface staining is very common and is mainly in the form of isolated spots. Brown surface spots were also noted.

Tetrahexahedroid crystals predominate strongly (Table 22). Octahedra constitute 5 per cent of the diamonds while no cubes or fragments were noted. Macles are fairly common but aggregate crystals are rare. Approximately 25 per cent of the crystals are equidimensional and very few tetrahexahedroida are irregular (Table 23).

Some surface textures which are absent or rare in the kimberlitic diamond samples studied (Chapter 12) are fairly well represented. Such textures include chemically-polished surfaces, network patterns and scratch-like markings (all Table 24). Other surface textural characteristics worth noting are that, among the crystals exhibiting the tetrahexahedroid form, terraces are a common feature, slightly more than 20 per cent display lamination lines and small percentages display microdisk patterns, corrosion sculpture or shallow depressions (all Table 25).

Approximately 15 per cent of the diamonds are unabraded and the same percentage are abraded only at their sharp points (Table 28). Nearly 50 per cent are abraded to the extent that at least their tetrahexahedroid "A" edges are frosted. Large percussion cracks are developed on more than 40 per cent of the diamonds, while small percussion figures are present on approximately 20 per cent of them.

### 16.3.3. Dreyers Pan and Annexe Kleinzee

The farm Annexe Kleinzee is situated immediately north of the Buffels River mouth. Dreyers Pan adjoins Annexe Kleinzee to the north. Three hundred minus 11 plus 9 diamonds were examined from each locality. Three marine terraces are represented in the area and both samples are from the middle terrace.

Both the Annexe Kleinzee and Dreyers Pan samples contain approximately 65 per cent of colourless diamonds and approximately half as many yellow as light brown to brown diamonds (Table 21). Ten per cent of the diamonds exhibit green surface spots and rare diamonds at both localities are spotted brown.

Tetrahexahedroida are strongly predominant in both samples while octahedra constitute approximately 5 per cent (Table 22). No cubes or fragments were observed and aggregates are very rare. Less than 10 per cent of the diamonds in each sample are broken. Approximately 25 per cent of the crystals in both samples are classed as equidimensional and most of the others are only slightly distorted (Table 23).

Pristine surface textures are similarly distributed among the diamonds in both samples. This is true even for textures which are absent in many samples, such as chemically-polished surfaces, network patterns, coarse frosting, fine frosting and scratch-like markings (all Table 24), corrosion sculpture, shallow depressions (both Table 25) and positively-oriented features such as transverse hillocks (Table 25).

Considering that the Annexe Kleinzee and Dreyers Pan samples are very similar with respect to practically all pristine characteristics, there is not reason to doubt that the same diamond population is present at both localities.

Practically all of the diamonds at both localities are abraded

(Table 28). Nearly half are abraded to the extent that tetrahedroid "A" edges are frosted while a further 25 per cent also display frosted tetrahedroid "C" edges. Conspicuously rounded, mechanically-polished diamonds also occur at both localities. Large percussion cracks are developed on approximately 45 per cent of the diamonds and similar proportions exhibit small percussion figures. There is practically no difference between the abrasional characteristics of the two samples. The Annexe Kleinsee and Dreyers Pan diamonds therefore appear to have undergone the same transportation history and the effect of any long-shore transportation between the two localities is negligible.

16.3.4. The "Uplifted Terrace" and the "Recent Emergence Terrace"  
of Koningnaas

Two marine terrace deposits are present at Koningnaas. The deposit known locally as the Uplifted Terrace is older than that referred to as the Recent Emergence Terrace. Two hundred minus 11 plus 9 diamonds were studied from each of the deposits. The data given for these samples in Tables 21 to 23 and Table 28 are rounded upwards where a half of a percentage was included in the determination.

Approximately 60 per cent of the diamonds in both samples are colourless (Table 21). Yellow diamonds are significantly more common, and brown diamonds are significantly less common, in the Recent Emergence Terrace sample than in the Uplifted Terrace sample. No green or brown surface staining was observed.

The tetrahedroid crystal form predominates strongly in both samples (Table 22). Octahedra constitute slightly more than 10 per cent of the diamonds, while cubes are rare. Broken diamonds are scarce in the Recent Emergence Terrace sample but are fairly common in the Uplifted Terrace sample. Equidimensional crystals are common in both

samples (Tables 23).

Most pristine surface textures are similarly distributed in both of the samples. For example, a few per cent of the diamonds display chemically-polished surfaces and/or network patterns, approximately 15 per cent are finely frosted, approximately 7 per cent display scratch-like markings (all Table 24) and rare examples display positively-oriented features (e.g. positively-oriented trigonal pits, see Table 26), in both samples. Significantly fewer Recent Emergence Terrace diamonds, however, display lamination lines (Table 25).

The samples differ mainly with respect to yellow, brown and broken diamonds and diamonds displaying lamination lines. In Chapter 18 it is shown that lamination lines are more commonly developed on brown (including light brown) than other diamonds. The significant differences between the samples can therefore be reduced to a relative abundance of yellow diamonds and relative scarcities of brown diamonds and broken diamonds in the Recent Emergence Terrace sample. The many similarities between the samples are compatible with the Uplifted Terrace diamond population also predominating in the Recent Emergence Terrace deposit. An additional diamond population, rich in yellow diamonds and poor in brown diamonds and broken diamonds, however, appears to have also contributed to the Recent Emergence Terrace deposit.

Only about 5 per cent of the diamonds in both samples are unabraded (Table 28). Most are abraded at their tetrahexahedroid "A" edges and more than 30 per cent are also abraded at their "C" edges. The only significant difference in the abrasional characteristics between the samples is that large percussion markings are more frequently displayed by the diamonds in the Recent Emergence Terrace sample. The diamonds in both deposits therefore appear to have under-

gone very similar transportational histories. Additional large percussion markings could have been produced during the transportation of some diamonds from an eroded part of the Uplifted Terrace to the Recent Emergence Terrace. Broken diamonds may have been winnowed out during such an episode.

#### 16.3.5. De Punt

The winning of diamonds from the surf zone at De Punt, immediately north of the mouth of the Olifants River, is described by Gurney (1979). Thirty seven minus 11 plus 9 diamonds from this locality were examined.

Approximately half of the diamonds are colourless, while light brown to brown diamonds predominate over yellow diamonds among the remainder (Table 21). Three of the diamonds examined display green surface staining and one has brown surface spots.

Tetrahexahedroid crystals predominate strongly (Table 22). Two of the diamonds are octahedra and one is a cube. One diamond is very irregular and is probably a resorbed fragment. Only three of the diamonds exhibit octahedral crystal faces and the same number exhibit cubic surfaces. Approximately 15 per cent of the crystals are broken (Table 22). Equidimensional crystals are common (Table 23).

Diamonds with chemically-polished surfaces, network patterns, patches of fine frosting (all Table 24) or corrosion sculpture (Table 25) were noted. None displays scratch-like markings (Table 24). About 30 per cent of the diamonds display lamination lines (Table 25).

Two thirds of the diamonds are unabraded (Table 28). A few are abraded to the extent that all tetrahexahedroid "A" edges are frosted and another has abraded "C" edges as well. A few of the diamonds display percussion markings, including both small and large examples.

#### 16.4. FLUVIATILE DEPOSITS IN NAMAQUALAND AND COMPARISONS WITH THE COASTAL DEPOSITS AT RIVER MOUTHS

Diamond-bearing river-terrace deposits occur up to at least 75 km upstream in the valley of the Orange River. Other drainage systems in Namaqualand and the Vanrhynsdorp District are also known to contain diamond-bearing deposits. In the valleys of the Buffels, Spoeg, Horees, Groen and Swart-Doorn river systems, only one of a series of ancient terraces usually contains substantial quantities of diamonds (Keyser, 1976). The localities from which samples were studied are shown in Figure 99.

##### 16.4.1. Daberas

The Daberas deposit is situated on the south bank of the Orange River approximately 70 km from its mouth. The deposit is uneconomic. The sample examined consists of 64 diamonds of the minus 13 plus 7 sieve size range.

More than half of the diamonds are colourless, while yellow diamonds are more common than light brown to brown diamonds among the remainder (Table 21). Green surface staining is rare.

Tetrahexahedroid crystals are strongly predominant while octahedra constitute 5 per cent of the sample (Table 22). Aggregates and fragments are rare. Ten per cent of the diamonds are broken. Equidimensional crystals are common, as are flat crystals and irregular tetrahexahedroida (Table 23).

All common pristine surface textures are represented. Rarer textures, such as chemically-polished surfaces, frosting, scratch-like markings (all Table 24), microdisk patterns and corrosion sculpture (both Table 25), are also developed.

Approximately 70 per cent of the diamonds are unabraded (Table 28).

Others are abraded only at their corners or sharpest edges, while 5 per cent are abraded at least at their tetrahexahedroid "A" edges. Large and/or small percussion figures are also developed on a few of the diamonds.

16.4.2. Comparison between Daberas and the C and F Beaches of the Consolidated Diamond Mines (C.D.M.)

The Daberas diamond sample resembles those studied from the Consolidated Diamond Mines in consisting of more than 60 per cent of colourless diamonds and in containing a substantial proportion of yellow diamonds. Brown diamonds are also similarly distributed in the alluvial and littoral deposits.

The distribution of crystal forms is very similar in the alluvial and littoral deposits. In both cases, tetrahexahedroids are strongly predominant, approximately 5 per cent of the diamonds are octahedra and cubes and fragments are rare. Equidimensional crystals might be significantly more common in the C and F Beach samples than in the Daberas sample. In its high proportion of flat crystals, the Daberas sample more closely resembles the F Beach sample than the C Beach sample.

Practically all of the pristine textures noted in the Consolidated Diamond Mines samples were also observed in the smaller Daberas sample. No surface texture represented at Daberas is not also represented in the littoral deposits. Furthermore, the distributions of most surface textures are very similar in the samples from the alluvial and littoral deposits. The only exceptions are terraces and microdisk patterns, both of which are more common in the samples from the littoral deposits.

Considering the many similarities between the samples from the alluvial and littoral deposits and the lack of any striking differences

between them, it is likely that essentially the same diamond population is present at Daberas as in the C Beach and F Beach deposits. The diamonds in the Consolidated Diamond Mines deposits could therefore have been transported by the Orange River from beyond Daberas.

It is assumed that the abrasional characteristics of the minus 13 plus 7, Daberas diamonds can be directly compared with those of the minus 11 plus 9 Consolidated Diamond Mines diamonds. This assumption is considered to be reasonable because the minus 11 plus 9 sieve class constitutes approximately the central portion of the minus 13 plus 7 sieve class. The less pronounced development of abrasional features in the Daberas sample, than in the samples from the Consolidated Diamond Mines, is consistent with the hypothesis that the diamonds in the littoral deposits were transported from upstream of Daberas. The additional, postulated transportation of diamonds from Daberas to the F Beach did not drastically modify the minus 11 plus 9 portion of the population. The main effects appear to be the abrasion of the corners of approximately 50 per cent of the diamonds, and the production of large percussion markings on approximately 25 per cent of the diamonds and of small percussion markings on approximately 5 per cent of the diamonds.

#### 16.4.3. Buffelsbank and Langhoogte

The deposit mined at Buffelsbank is on the south bank of the Buffels River. The Langhoogte deposit is situated approximately 8 km downstream of the Buffelsbank deposit in an old river bed to the north of the present Buffels River course. Three hundred minus 11 plus 9 Buffelsbank diamonds and 245 Langhoogte diamonds of the same size range were examined.

Approximately 65 per cent of the diamonds are colourless,

nearly 15 per cent are yellow and approximately 20 per cent are light brown or brown, in both deposits (Table 21). Green surface staining, which is mainly in the form of isolated spots, is a common feature at both localities, particularly Buffelsbank. Brown-spotted diamonds are also represented.

Table 22 shows that tetrahexahedroid crystals predominate strongly in both samples. Approximately 5 per cent of the diamonds are octahedra while cubes are rare. Fragments are absent and broken crystals constitute less than 10 per cent of both samples. Crystal aggregates are rare or absent, while macles are relatively common in the Langhoogte sample. Octahedral surfaces are more often preserved about the re-entrant angles on macles than on single crystals, so that the proportion of crystals with octahedral surfaces is larger in the Langhoogte sample than in the Buffelsbank sample. Equidimensional crystals are fairly common, particularly in the Buffelsbank sample, while approximately 10 per cent of the crystals in both samples are classed as flat (Table 23). Macles are seldom equidimensional, hence the smaller proportion of equidimensional crystals in the Langhoogte sample.

Most pristine surface textures are similarly distributed in both samples. Examples include chemically-polished surfaces, network patterns, coarse frosting (all Table 24), terraces, lamination lines, corrosion sculpture and microdisk patterns (all Table 25). Fine frosting and scratch-like markings (both Table 24) are both developed on significantly different proportions of the diamonds in the two samples. Fine frosting is a relatively common texture in the Buffelsbank sample while diamonds displaying scratch-like markings are relatively common in the Langhoogte sample.

The many similarities and few differences noted between the samples are consistent with the Langhoogte diamond assortment consisting

predominantly of the Buffelsbank population plus another, subordinate population. The postulated, subordinate population is rich in macles and diamonds displaying scratch-like markings but poor in finely frosted diamonds.

The Langhoogte sample contains far fewer unabraded diamonds than the Buffelsbank sample (Table 28). Similar proportions of diamonds are abraded solely at their sharp corners or also at the sharpest parts of crystal edges, in both samples. More-abraded diamonds are slightly, but significantly, more common in the Langhoogte sample. The Langhoogte macles are about as abraded as the other diamonds in the sample. It is clear that the Langhoogte diamonds are appreciably more abraded than the Buffelsbank diamonds. This is consistent with most of the Langhoogte diamonds having been transported from upstream of Buffelsbank. While more diamonds in the Langhoogte sample display large percussion markings than in the Buffelsbank sample, small percussion markings are a more common feature of the Buffelsbank sample (Table 28). Some small percussion markings were presumably developed in situ, e.g. within pot-holes, at Buffelsbank.

#### 16.4.4. Comparison of Buffelsbank and Langhoogte with Dreyers Pan and Annexe Kleinzee

Most of the pristine characteristics of the Buffels River alluvial samples are closely similar to those of the littoral samples studied from near to the river mouth. For example:-

- i. Practically identical proportions of the main colours of diamond are represented in all of the samples.
- ii. The same relative proportions of tetrahedra, octahedra and cubes are present in all of the samples. The only significant anomaly with respect to crystallographic characteristics

is the relatively common occurrence of macles in the Langhoogte sample.

iii. The various crystal shapes distinguished are similarly distributed in all of the samples, excepting for the relative scarcity of equidimensional crystals in the Langhoogte sample (which is partly a consequence of the abundance of macles in that sample).

iv. Most pristine surface textures, including fairly rare varieties such as chemically-polished surfaces, network patterns, scratch-like markings, corrosion sculpture, micro-disk patterns and transverse hillocks, are similarly distributed in all of the samples. Coarse frosting is recorded to be much more common in the samples from the littoral deposits. It must be noted, however, that fine frosting grades into coarse frosting so that the distinction is frequently subjective. If coarse frosting and fine frosting are considered together, only the Langhoogte sample is anomalous in containing a lower proportion of frosted diamonds than the other samples.

It must be concluded that the same population of diamonds predominates in all of the deposits. Although Langhoogte is downstream of Buffelsbank, the Buffelsbank sample more closely resembles the littoral deposit samples. The subordinate diamond population considered to be present at Langhoogte is evidently not represented at Dreyers Pan and Annexe Kleinzee. The more-abraded state of the littoral deposit diamonds is consistent with their derivation from upstream of Buffelsbank. Most of the additional abrasion considered to have taken place between Langhoogte and Dreyers Pan can probably be ascribed to approximately 40 km of fluvial transportation, since

little abrasion occurred between Annexe Kleinzee and Dreyers Pan. Nearly all of the minus 11 plus 9 diamonds appear to have been affected by this transportation, with most having at least their tetrahexahedroid "A" edges abraded. There is no evidence to suggest that diamond crystals were broken during their transportation to the coast.

#### 16.4.5. Quaggaskop

The Quaggaskop deposit is situated in the valley of the Zout River, a tributary of the Olifants. Thirty six diamonds from the deposit were examined. The ensuing discussion concerns only 23 of the diamonds which are within the minus 13 plus 7 size range, unless otherwise stated.

Approximately 40 per cent of the diamonds are colourless, while light brown to brown diamonds are slightly more common than yellow diamonds among the remainder (Table 21). One diamond displays green and brown surface spots and four others display only brown spots.

Most of the diamonds are tetrahexahedroida but octahedra are also represented (Table 22). Macles are fairly common. Thirty per cent of the diamonds exhibit octahedral crystal surfaces and about 10 per cent exhibit cubic surfaces. Only three crystals are broken. Equidimensional crystals are common and irregular crystals are scarce (Table 23).

None of the diamonds examined displays coarse frosting, fine frosting or scratch-like markings (Table 24). Approximately 40 per cent of the diamonds display lamination lines (Table 25), while hexagonal pits are a common, octahedral surface texture (Table 26).

Approximately half of the minus 13 plus 7 diamonds are unabraded (Table 28). Very lightly abraded to lightly abraded diamonds are also represented, while four diamonds are abraded at their tetrahexahedroid

"C" edges. One plus 13 diamond is distinctly rounded and polished. Three abraded diamonds exhibit small percussion markings.

#### 16.4.6. Comparison between Quaggaskop and De Punt

Owing to the small sizes of both samples, differences between compared data need to be substantial to be significant at the 95 per cent level of confidence. None of the differences in the data obtained for the two samples is sufficiently striking to necessarily be significant.

#### 16.5. GENERAL DISCUSSION OF THE DIAMONDS FROM NAMAQUALAND AND NEIGHBOURING AREAS

Many pristine features are distributed similarly among the minus 11 plus 9 (or minus 13 plus 7) diamond samples studied from Namaqualand and adjacent areas. For example, most of the samples contain the following:-

- i. More than 60 per cent of colourless diamonds.
- ii. More or nearly as many yellow as light brown to brown diamonds.
- iii. A small proportion of diamonds displaying brown surface staining.
- iv. A marked preponderance of tetrahexahedroid crystals.
- v. Very few aggregate crystals.
- vi. Very few diamond fragments and less than 15 per cent of broken crystals.
- vii. Approximately 20 per cent of crystals with octahedral crystal surfaces but only about 5 per cent with cubic crystal surfaces.
- viii. Substantial proportions (more than 20 per cent) of equidimensional crystals and few (approximately 5 per cent) of irregular crystals.

- ix. A few per cent of diamonds displaying surface textures, such as chemically-polished surfaces, network patterns, coarse frosting, fine frosting, scratch-like markings and corrosion sculpture, which do not occur in many of the other samples studied.
- x. A small number of diamonds displaying positively-oriented etch features (e.g. imbricate wedge markings and transverse hillocks on tetrahexahedroid surfaces and positively-oriented trigonal pits on octahedral surfaces) which are developed in very few of the kimberlitic diamond samples studied (see Chapter 12).
- xi. Common (i.e. at least 20 per cent of) tetrahexahedroida which display terraces and/or lamination lines.

Most samples do differ, in fact, in one or a few aspects from the others. In an attempt to delineate regional similarities and differences among the deposits studied, areal plots of some sample characteristics were made. These plots are shown in Figures 100 to 102. The paucity of data stations and the wide confidence limits for data based on less than 100 diamonds (see Table 13) necessitate cautious interpretations of these plots. While some characteristics (e.g. yellow to brown diamonds, and lamination lines) vary in an apparently haphazard manner, the following patterns emerge:-

- i. The deposits in the extreme south (Quaggaskop and De Punt) differ from the others in a number of respects (e.g. regarding colourless diamonds, brown staining, frosting, scratch-like markings and tetrahexahedroida displaying terraces).
- ii. Many characteristics are uniformly distributed among the deposits situated north of the Olifants drainage basin (e.g. chemical polishing, scratch-like markings and positively-oriented

textures.

- iii. Some of the features of the two deposits in the extreme south are progressively less noticeable features of the deposits further to the north. For example: the percentage of colourless diamonds generally increases northwards; the cubic form is relatively common in the deposits near Hondeklip Bay as well as in the two deposits in the extreme south; the incidences of occurrence of tetrahexahedroids displaying terraces in the samples from near Hondeklip Bay are intermediate between those in samples from further north and the extreme south.
- iv. Frosted diamonds are particularly common in most of the deposits which are spatially associated with the Buffels River.
- v. The regional distribution of green-stained diamonds is dissimilar to that of any other sample characteristic.

The patterns outlined above are consistent with the presence of two main populations of diamond in the area under consideration. One postulated population predominates in the north and the other is dominant in the extreme south. Both populations may be well represented in the central part of the area, such as in the vicinity of Hondeklip Bay. An additional population, similar to that predominating in the north excepting for containing a particularly large proportion of diamonds displaying frosting, is probably also well represented in most of the deposits associated with the Buffels River. The unique distribution of green-stained diamonds suggests that the staining is a post-depositional feature.

None of the populations distinguished closely resembles any combination of the Southern African, kimberlitic diamond populations studied (Chapter 12). The detrital populations generally contain more

yellow diamonds, far fewer fragments and broken crystals, fewer aggregates, more equidimensional crystals and more diamonds displaying chemically-polished surfaces and network patterns, than the kimberlitic populations. The northern, detrital populations also contain substantially larger proportions of diamonds displaying scratch-like markings or tetrahexahedroid terraces, than most of the kimberlitic populations.

Characteristics which reflect the state of abrasion of the diamond samples are plotted in Figure 103. Notwithstanding the paucity of data stations, a general, coastward increase in abrasion is clearly evident in the northern part of the area. This substantiates the suggestion, made previously, that fluvial transportation, rather than longshore drift, is responsible for most of the abrasion of diamonds in the north. Tentative contouring of the data also suggests a southward increase in abrasion in the northern part of the area, while a northward increase is possible in the southern part. This interpretation of the abrasional data is consistent with the south-westward transportation of a northern population of diamonds and the north-westward transportation of a southern population. Extrapolation of the contours drawn in Figure 103 would indicate that both the postulated, northern and southern populations of diamond are derived from fairly near to the coast. Such a conclusion would not contradict the view, expressed by Keyser (1972 and 1976), that the diamonds were flushed from a deflation surface situated within 65 km of the present coast.

The presence of brown-spotted diamonds in many of the samples (Figure 100 D) is interesting. This is because such diamonds must have been heated to above 600°C subsequently to their having been stained green. The Triassic-Jurassic, Karroo vulcanism is probably the most recent, Southern African thermal event during which a

substantial number of diamonds could have been sufficiently heated. The proportions of brown-stained diamonds in the samples therefore represent a minimum estimate of the diamonds likely to be derived from pre-Cretaceous kimberlites.

#### 16.6. THE WITWATERSRAND BANKET

Prior to the advent of fine-crushing processes on Witwatersrand gold mines, diamonds were recovered from mines in the East Rand, Central Rand and West Rand. The largest producer of diamonds appears to have been the Modderfontein "B" Gold Mine, which recovered 194 carats during 1923 (Lawn, 1924). Ten diamonds were examined from the Randfontein Estates Gold Mine. Nine of the diamonds are within the minus 13 plus 9 size range and one is slightly smaller.

Seven of the diamonds appear to be colourless and three are yellow, but all exhibit green-stained surfaces (Table 21). This staining is light and continuous in some cases but mostly occurs as intense dark green to black, diffuse blotches and spots. Detrital uraninite grains are the obvious, likely source of the radiation responsible. Diamond surfaces appear to be very finely frosted at the most intensely stained areas. Eight of the diamonds also display brown surface spots or blotches.

Seven of the diamonds are simple tetrahedra while two also display subordinate octahedral faces (Table 22). The other diamond is an octahedron with subordinate tetrahedral surfaces. None are either twinned or broken. Two crystals are equidimensional (Table 23).

One diamond has a chemically-polished surface and associated network patterns (Table 24). Another displays pitted hemispherical cavities observed among the diamonds from only two of the other localities included in this study (Prairie Creek and Wellington. See

Sections 12.10. and 16.7., respectively). Two of the diamonds display lamination lines.

Five of the diamonds are unabraded and the others are slightly damaged at four-fold axial corners (Table 28).

The sample examined is not markedly different from a sample of thirty eight other Witwatersrand diamonds described and illustrated by Raal (1969) and Grantham (1974), excepting that brown surface staining may be more common and the octahedral form less common. Most of the features displayed by the Witwatersrand diamonds are identical to features commonly developed on kimberlitic diamonds. A kimberlitic source is therefore reasonably certain, and pre-Upper Witwatersrand kimberlite bodies must have been present in the provenance area of the Witwatersrand Basin. It follows that a geothermal gradient sufficiently cool for diamond to be stable at depths accessible to kimberlite magma must have prevailed, in this region, at least 2 500 m.y. ago. Upper mantle temperatures beneath the Kaapvaal Craton are therefore unlikely to have greatly exceeded those which prevailed during the Cretaceous Period.

Should the heating responsible for converting green staining to brown staining have been regionally extensive, the diamonds which are only stained green would need to have been irradiated entirely after the heating event. Such restricted irradiation is unlikely (unless caused by authigenic material), so regional temperatures within Upper Witwatersrand Group strata probably never attained 600°C. The heating to above 600°C was likely to have been localized as would be the case if igneous intrusions were responsible.

#### 16.7. WELLINGTON AND AIRLY MOUNTAIN

In New South Wales, diamonds have been won from gravel-filled

channels ("deep leads") which underlie Tertiary basalts and from present-day alluvium. Eighty nine diamonds were examined from Wellington and nine from Airly Mountain. These localities are shown in Figure 104. The Wellington diamonds were dredged from the Macquarie River. The Airly Mountain diamonds are from a deep lead deposit. Nearly all of the diamonds in both samples are within the minus 13 plus 9 size range.

In both samples, approximately 40 per cent of the diamonds are colourless, while yellow diamonds are more common than browns (Table 21). Two of the Wellington diamonds display green surface spots. Two others, and three from Airly Mountain, display brown surface spots.

Tetrahexahedroida predominate very strongly, but an octahedron and a cube are included in the Wellington sample (Table 22). Octahedral surfaces are developed on approximately 10 per cent of the diamonds in the samples while examples with cubic surfaces are rare. Broken crystals are fairly common in the Wellington sample. A conspicuous feature of the Wellington sample, but not of the Airly Mountain sample, is the high proportion of tetrahexahedroida which are irregular (Table 23). Since flat crystals are also nearly all irregular in the Wellington sample, the total of irregular diamonds exceeds 70 per cent in that sample. The Wellington sample also exhibits a number of unusual surface textural characteristics, as follows:-

- i. Pitted hemispherical cavities, which were encountered in few of the other diamond samples studied, are developed on half of the diamonds (Table 24).
- ii. Terraces are conspicuously absent among the tetrahexahedroid surface textures represented (Table 25).
- iii. Only very fine hillocks are developed on any of the tetrahexahedroida and most display undulating, low-relief surfaces

instead (Table 25). Circular micro-pits, which are a rare feature elsewhere, are commonly developed (Table 24) upon these low-relief surfaces.

- iv. More than half of the diamonds display widely-spaced lamination lines (Table 25). In some cases, only one lamination line is evident so that the feature resembles a macle line. In most cases, two sets of lamination lines, each consisting of two or three individuals, intersect to produce a pattern easily mistaken for the truncated (by resorption) seams of interpenetrant twinning.

Low-relief surfaces are also a common feature of the Airly Mountain tetrahedroïda (Table 25). Both samples contain diamonds displaying positively-oriented surface textures (Tables 25 and 26). The Airly Mountain diamond population may be represented in the Wellington sample. The population which predominates at Wellington, however, is not represented in the Airly Mountain sample.

Eighteen diamonds from deep leads near Copeton and Bingara are described and illustrated by Grantham (1974). These diamonds are all irregular tetrahedroïda displaying low-relief surfaces, pitted hemispherical cavities and, in at least one case, isolated lamination lines. They therefore closely resemble most of the unusual diamonds studied from Wellington and it is possible that they are derived from the same source.

Excepting for the diamonds which display scratch-like markings, few in the Wellington sample are abraded (Table 28). Grantham (1974) also noted that only one of the eighteen Copeton-Bingara diamonds which he examined showed signs of mechanical wear. Should the Wellington and Copeton-Bingara diamonds share the same source, one of the samples must have been transported at least 170 km. The scarcity of

abraded diamonds at both localities would then be surprising.

Tertiary vulcanism could have heated some diamonds to above 500° C. The Wellington and Airly Mountain examples which display brown surface stains are therefore not necessarily derived from particularly old primary deposits.

#### 16.8. THE URALS REGION

Seventy minus 15 plus 11 diamonds were examined. All are of two commercial assortments based upon very light colour. The sample therefore cannot be regarded as representative and it was not classified further according to colour. One of the diamonds was seen to display green surface spots.

Tetrahexahedroida are strongly predominant although octahedra are represented (Table 22). All of the crystals exhibit tetrahexahedroid surfaces and approximately 10 per cent have octahedral faces. The cubic form was not observed. The absence of macles and aggregates and the scarcity of broken diamonds are likely to be consequences of the bias in the sample selection.

The distributions of many pristine surface textures are similar to those in the placer deposits of Namaqualand and neighbouring areas, described in Sections 16.3 and 16.4 (Tables 24 to 26). The Urals sample differs from those of Namaqualand, however, in the more common occurrence of low-relief surfaces on tetrahexahedroida and a lack of diamonds displaying scratch-like markings.

Approximately 75 per cent of the diamonds are unabraded. Approximately 20 per cent are slightly abraded while a few are markedly abraded.

## 17. GENERAL DISCUSSION OF THE DIAMONDS OF PLACER DEPOSITS

In all of the placer samples studied, the bulk of the diamonds display features which are no different from those displayed by the diamonds described from kimberlites. This substantiates the generally-accepted view that detrital diamonds are derived from kimberlites. In many placer samples, however, a small proportion of the diamonds display chemically-polished surfaces which were not encountered in any of the kimberlitic samples examined. Chemically-polished surfaces are considered to probably be produced on diamonds by the action of dry (i.e. steam-free) carbon dioxide gas at temperatures above 950°C (see Section 6.5.3.). While kimberlite magma might sometimes be sufficiently dry for the required conditions to be realized, carbonatite magma is a feasible alternative. Virtually all of the detrital diamonds examined exhibit features considered to require temperatures which make an igneous history mandatory. No single diamond examined displays any features suggestive of either a meteoritic or metamorphic paragenesis.

Most placer samples contain a greater variety of pristine surface textures than kimberlitic diamond samples of the same size. This suggests that more than a single kimberlitic population of diamonds is represented in most of the placer deposits.

Examination of Table 28 shows that, in the few cases in which diamonds of different sizes were examined from single localities, the large diamonds tend to be appreciably more abraded than the small diamonds. These data highlight the necessity of comparing only diamonds of the same size, in attempts to relate degrees of abrasion to relative conditions or distances of transportation. The observation, made for the F Beach sample, that flat diamonds tend to be less abraded

than more equidimensional diamonds of the same sieve class, might be largely a consequence of the lower mass of the flat diamonds. A slight advantage would therefore probably be gained by comparing diamonds similar in mass, rather than sieve size.

A striking feature of placer diamond samples is the range in the degree of abrasion between individual diamonds, of similar size, in individual samples. In most of the deposits, unabraded diamonds are associated with appreciably-abraded diamonds. This might imply that each placer deposit contains diamonds transported over widely varying distances, were it not that pristine features are not seen to vary markedly between the unabraded and variously-abraded diamonds. Local variations within single transportational systems are necessary, instead, to account for the various degrees of abrasion displayed by diamonds in individual deposits. The time spent within pot-holes may be the most important, single factor determining the extent to which a diamond is abraded during its transportation by water. In the fluvial environment, this factor is strongly dependant on stream gradient and stream bed lithology and only indirectly on the distance of transport. The proportions of unabraded and variously-abraded diamonds in a placer deposit need therefore give only a very poor indication of the distance of transport. Thus, the scarcities of abraded diamonds at the Hlane, Wellington and the Urals Region are compatible with these diamonds having been transported considerable distances, provided transportation was by streams with shallowly-inclined gradients. State-of-abrasion determinations are most valuable in comparisons between samples which can be assumed to have been transported under similar conditions.

Fragments and broken crystals are much less common in most of the placer diamond samples studied than in the kimberlitic samples.

According to Orlov (1977, p. 167), broken diamonds are progressively eliminated during transportation because they are cracked and tend to disintegrate to small particles. Most of the placer samples studied contain less than 20 per cent of broken, minus 11 plus 9 diamonds whereas virtually all of the kimberlitic samples contain more than 30 per cent. The Lichtenburg and Hlane samples are exceptional placer deposits, however, in also containing very high proportions of broken diamonds. The Hlane deposit contains a slightly, but significantly, greater proportion of broken minus 7 plus 5 diamonds than its probable source, Dokolwayo. Some small Dokolwayo diamonds were evidently broken during their transportation to Hlane, but few could have been drastically reduced in size. Considering the small size of the Hlane diamonds, it is likely that at least cracked, minus 11 plus 9 diamonds are easily broken during transportation. Intricately cracked diamonds can be expected to be winnowed out as very small particles. In both cases studied in which the diamonds in a terrace deposit could be derived from a re-worked, older terrace (the C Beach and the Recent Emergence Terrace which may have obtained their diamonds from the F Beach and the Uplifted Terrace, respectively) the relatively young deposit contains fewer broken, minus 11 plus 9 diamonds (but can contain more broken, larger diamonds, as in the C Beach sample). This is consistent with small pieces being broken from large diamonds and smaller diamonds being appreciably reduced in size, during re-working. Comparing deposits which are situated downstream or alongshore from one another (e.g. Buffelsbank - Langhoogte - Annexe Kleinzee - Dreyers Pan), however, does not disclose any consistent variation in the proportion of broken diamonds with relative distance of transport. There is therefore no unequivocal evidence for a progressive elimination of broken diamond crystals during transportation. It appears that while intricately

cracked diamonds may be winnowed out, diamonds with few cracks should survive as broken crystals. The scarcity of broken diamonds in most of the placer deposits studied therefore appears to be predominantly an inherent (i.e. pristine) characteristic of their source populations. Considering Wagner's (1914, p. 165) observation that broken diamonds are more common in kimberlite pipes than in kimberlite dykes, it could be suggested that most of the detrital diamonds studied are derived from dykes. Wagner's observation could not, however, be substantiated in the present study (see Chapter 13).

18. RELATIONSHIPS BETWEEN SOME DIAMOND CHARACTERISTICS

Harris et al (1975) and Harris, Hawthorne and Oosterveld (1979) noted that with increasing diamond size, the proportions of colourless diamonds decrease while the proportions of yellow diamonds increase, in most of the samples which they studied. The meagre data obtained for diamonds other than of the minus 11 plus 9 sieve class, in the present investigation, tend to substantiate these findings. In most cases, the proportions of yellow diamonds were found to increase with increasing diamond size, while the proportions of light brown and brown diamonds decreased. Colourless diamonds were either more or less common among the larger sizes, depending upon the relative changes in the proportions of yellow and brown diamonds.

The ratios of octahedra to tetrahedra were found to increase, with increasing diamond size, in most of the samples examined by Harris et al. (op.cit.) and Harris, Hawthorne and Oosterveld (op.cit.). The same trend was noted in most of the samples containing different sizes of diamonds which were examined in the present investigation. This trend is more clearly evident if the proportions of diamonds exhibiting octahedral surfaces, rather than only the main forms, are considered and is exemplified in the Lichtenburg and Consolidated Diamond Mines samples. It was also found that the proportion of diamonds exhibiting cubic surfaces tends to increase with increasing diamond size. The more common occurrence of growth form surfaces among relatively large diamonds is compatible with the hypothesis that some diamonds are larger than others because they were not resorbed as much. In some samples (e.g. Dokolwayo and Helam Mine), however, similar proportions of diamonds exhibiting growth forms are present within the various size fractions. In such cases, resorption was evidently not important

in the formation of the relatively small diamonds.

The percentages of broken diamonds and of tetrahexahedroids displaying lamination lines were sometimes determined separately for brown (including light brown) and other diamonds. These data are given in Table 29. In some samples (e.g. from the Premier and Orapa Mines), brown diamonds are much less commonly broken than other diamonds. In other samples, however, brown diamonds are either about as commonly broken as other diamonds or (e.g. Finsch Mine and the minus 11 plus 9 size of Dokolwayo) are significantly more commonly broken. In virtually all samples in which the relationship between diamond colour and presence of lamination lines was tested, a substantially greater proportion of brown diamonds was found to display lamination lines. A strong correlation between a brown colour and the development of lamination lines is therefore demonstrated. It is concluded that the process responsible for lamination lines (i.e. shearing stress, see Article 6.5.2 and Section 7.2) is also responsible for the colour of a large proportion of brown diamonds. The alternative, that lamination lines develop more readily on brown than other diamonds, is not supported by any of the observations made. It is possible that the dislocation planes produced by shear stresses tend to strengthen the diamonds in some populations. In populations in which brown diamonds are more commonly broken than others, the diamonds with dislocation planes may be relatively weak. It is also possible that some brown diamonds in these populations were stressed to the extent that brittle fracture occurred, but this possibility is not supported by a general lack of resorption at the edges of the breakage surfaces concerned.

No attempt was made to determine the proportions of the diamond "types" or "varieties" which are present in the samples studied. In most of the samples, however, the colour and crystallographic

characteristics indicate that type Ia or variety I crystals predominate strongly. For plastically deformed diamonds to be common in many of the samples, it is necessary that not only the relatively easily deformed but rare, type II diamonds may be deformed in nature.

Trigonal pits, serrate laminae, printed plates, semi-cylindrical hillocks with hexagonal pits, zigzag texture, fine striation with edge enhancement, ribbing, lamellar-like structures, rhombic striation, chemically-polished surfaces, fish-like separations and pitted disks) are reported for the first time. Another feature (coral-like markings) was reported for the first time early during the present investigation (Robinson, 1975).

The recognition, by means of these features, of plastically deformed diamonds and restricted to particular crystallographic surfaces (e.g. trigonal pits on octahedral surfaces, zigzag texture on cubic surfaces) was intended to include instances such as hillocks, low-angle surfaces and printed plates. To facilitate the easy identification of the nature of such diamonds in irregular diamond systems.

Only one of the primary surface features characteristic of plastically deformed diamonds is described in detail. The growth of the diamond is described by analogy to existing crystal growth processes. However, in the future, a study of the relationship between, for example, internal striations and hillocks, will be of great distinction between terraces. The growth of the diamond surface on tetrahedral surfaces. Subsequent to the initial feature commonly described in literature.

Several diamond surface textures have been identified in laboratory during etching experiments by a number of investigators.

## 19. SUMMARY OF CONCLUSIONS

As a consequence of this study, 41 pristine diamond surface textures can be distinguished. Twelve of these (hexagonal pits containing trigonal pits, serrate laminae, pointed plates, semi-cylindrical hillocks with hexagonal pits, zigzag texture, fine striation with edge enhancement, ribbing, imbricate wedge-forms, rhombic serration, chemically-polished surfaces, knob-like asperities and pitted disks) are reported for the first time. Another texture (scratch-like markings) was reported for the first time early during the present investigation (Robinson, 1975).

The recognition, by various other workers, that certain etch features are restricted to particular crystallographic surfaces of diamond (e.g. trigonal pits to octahedral surfaces, tetragonal pits to cubic surfaces) was extended to include textures such as elongate hillocks, low-relief surfaces and corrosion sculpture. This enabled the easy identification of the form(s) of many highly distorted or irregular diamond crystals.

Only two of the pristine surface textures distinguished (smooth octahedral crystal surfaces and triangular plates) can be directly ascribed to crystal growth. All of the others are produced by resorption or etching. Crystal growth processes are manifested, however, in the forms assumed by some etch-induced features. For example, internal stratification is largely responsible for the distinctions between terraces, elongate hillocks and low-relief surfaces on tetrahexahedroid surfaces. Dislocation planes are another internal feature commonly disclosed by resorption.

Several diamond surface textures have been duplicated in the laboratory during etching experiments by a number of investigators.

All of these experiments involve oxidation and neither pure graphitization nor dissolution appears to be an important process affecting diamonds in nature. Thin graphite coatings are consistently associated, however, with some uncommon surface textures (knob-like asperities, ribbing, serrate laminae and pointed plates) which appear to be produced when the oxidizing agent is used up during its reaction with diamond.

As in Robinson (1978), "tetrahexahedroid" is preferred to terms such as "rounded dodecahedron" for one of the common forms of diamond crystal. No evidence was obtained for questioning the view that this form is derived by resorption of the octahedron or the cube. Lamination lines and tetrahexahedroid surface textures such as terraces, elongate hillocks and shagreen texture are difficult to reconcile with a non-resorption origin for the form. The suggestion by Frank and Puttick (1958), that the etching which produces trigons on octahedral diamond surfaces also produces the resorption form is substantiated by the observation that most of the rare octahedra without any trigons also lack any tetrahexahedroid surfaces. Rare diamond crystal forms occur which more closely resemble the rhombic dodecahedron than does the common tetrahexahedroid.

More diamond-oxidation experiments are required, particularly at high pressures, to elucidate some of the details of the oxidation process. A sufficient body of experimental data is available, however, to enable two main episodes of diamond oxidation to be distinguished. One of these episodes probably always requires temperatures greater than 950°C and is responsible for resorption and for producing negatively-oriented etch pits. Steam and wet carbon dioxide gas are the most likely etchants responsible in nature. The other episode of etching may occur at temperatures down to about 450°C and appears to require the presence of free oxygen. The effects of this type of

etching are rarely observed but are typified by positively-oriented etch pits which usually form at temperatures below 1 000°C.

Lamination lines constitute a surface texture with particularly important implications. This texture is considered to result from the differential resorption of diamond crystals with internal, dislocation planes caused by plastic deformation at mantle depths. Plastic deformation implies a deviatoric stress which requires that the diamonds were encased within an essentially solid medium when the stress was applied. Diamonds displaying lamination lines are therefore likely to be derived from deformed mantle rocks and are unlikely to have crystallized from kimberlite magma. Knob-like asperities, dodecahedral ribbing and other associated, graphite-veneered surface textures are also important insofar as the relationship between diamonds and kimberlite magma is concerned. Considering the peculiar circumstances which are apparently involved in the formation of these surface textures, and their common development among the diamonds in some eclogite xenoliths, any kimberlitic diamonds displaying them are likely to have been liberated from xenoliths. Furthermore, only diamonds liberated after the completion of most reactions between diamond and magma are likely to retain these textures, implying that more diamonds once displayed them. Paired pseudohemimorphic crystals are considered to have been partly armoured while undergoing resorption by kimberlite magma. Eclogitic and peridotitic xenoliths and their minerals are the most common bodies of abyssal origin which are known to armour diamonds. Assuming a non-cognate origin for such xenoliths, paired pseudohemimorphic crystals are also likely to be xenocrysts in kimberlite.

Particular attention was paid to the relative ages of the diamond features studied. This enabled the sequence of the events

which can affect natural diamonds to be established, for the first time. At some time after initial crystallization, some diamonds are plastically deformed. (The duration of the interval between crystallization and plastic deformation is not known but is probably at least a few years in the case of the most common, type Ia diamonds). Most diamonds are then resorbed and etched by high-temperature oxidation in the kimberlite magma within which they are entrained. Subsequently, an unknown proportion of the diamonds in at least some kimberlite pipes are slightly damaged by frictional contact with other particles. This is followed by the low-temperature etching of a small proportion of diamonds. Most diamond crystal breakage occurs during, and after, the final stages of high-temperature etching.

The diamond content of some eclogite xenoliths is substantial and the disintegration of eclogitic material may account for considerable proportions of the diamonds in some kimberlites. Differences between the diamonds in eclogite xenoliths and those in kimberlites are consistent with a more limited access of oxidizing, kimberlitic fluids to the diamonds in the xenoliths. Among the diamonds in eclogite xenoliths, growth forms are much better preserved, a ribbed dodecahedral form tends to be developed in place of the tetrahexahedroid and graphite-veneered surface textures, such as knob-like asperities, serrate laminae and pointed plates, are relatively commonly developed.

A single eclogite xenolith may contain both diamond octahedra and cubes, which suggests a range in temperature during the crystallization of diamond. The association of primary graphite and diamond in many eclogite xenoliths also suggests changing conditions during the crystallization of free carbon, with the thermodynamic "boundary" between graphite and diamond being crossed. In these cases, the crystallization conditions for diamond must have been near to the lower

stability-limit for the mineral. The segregation of diamond and graphite in some eclogite xenoliths is consistent with a gravimetric separation which is to be expected should these minerals have crystallized within a liquid phase. For boundaries between graphite-rich and diamond-rich eclogite to be commonly sampled would then imply that very small pockets of igneous, diamond-graphite eclogite are common within the earth's mantle.

Similarities among the diamonds from most of the kimberlites included in this study are more striking than differences between them. Most localities are characterized by a preponderance of tetrahedroid crystals, mostly derived from octahedra, and there are substantially more brown-coloured than yellow diamonds and few, if any, unusual surface textures. The Swartruggens Main Fissure and the Mir Pipe, however, are exceptional localities in that they produce, respectively, an exceptionally high proportion of diamonds exhibiting the cubic form and an exceptional preponderance of octahedra. The similarities between the diamonds in most kimberlitic samples imply that most of the diamonds crystallized under similar conditions and experienced similar, post-genetic histories. These similarities tend to frustrate attempts to correlate the diamonds of placer deposits, either with possible, kimberlitic sources or with other placer deposits. Subtle differences are apparent, however, between most kimberlitic diamond populations. For example:-

- i. Brown-coloured diamonds are much more common in some kimberlites (e.g. the Finsch Mine, the Grey and Black Kimberlites of the Premier Mine, the K6 and Remainder Kimberlites of Letseng-le-terai and the Orapa Mine) than in others (e.g. the Brown Kimberlite of the Premier Mine, the Satellite Pipe at Letseng-le-terai and the Loxtondal Mine).

- ii. Aggregate crystals are common in some kimberlites (e.g. those of North-eastern Botswana, notably the Orapa Mine, and at Dokolwayo) but scarce in others (e.g. the kimberlites at Letseng-le-terai and Loxtondal).
- iii. Certain surface textures which are either rare or absent in most kimberlitic diamond populations are fairly common in specific populations (e.g. knob-like asperities in the Grey and Black Kimberlites of the Premier Mine, Orapa Mine and Pipes DK 1 and DK 2, scratch-like markings in the Brown Kimberlite of the Premier Mine and fine striation with edge enhancement in the Dokolwayo Pipe).

The characteristics of the diamonds from different kimberlite types within single pipes may be essentially the same. This is so for the Central Core, Peripheral and Breccia Kimberlites of the De Beers Mine and for the Grey and Black (but not the Brown) Kimberlites of the Premier Mine. Such associated kimberlites may represent single intrusions, with differences between them resulting from processes which operated during diatreme-filling. At the Premier Mine it is possible that the Grey Kimberlite represents Black Kimberlite magma which was severely contaminated by Waterberg Quartzite xenoliths. This possibility requires, however, that the relatively common frosting of Grey Kimberlite diamonds occurred within the diatreme, perhaps as a consequence of water being released from the quartzite xenoliths. A single magma may also have been responsible for the K6 Kimberlite and most of the Remainder Kimberlite at Letseng-le-terai. The K6 body, however, was probably emplaced as a separate pulse of magma within which xenoliths (including diamond-bearing varieties) had survived disaggregation for longer than in the magma emplaced previously.

In the magmatic kimberlite bodies and the Kimberlite Breccia of Pipe BK 9, the mantle-derived characteristics of the diamonds (i.e. those characteristics concerning crystal growth forms, colours and lamination lines) are the same but the subsequently-produced characteristics (i.e. those produced during resorption, high-temperature etching and low-temperature etching) are different. Two magmas which separated from a single, mantle-derived magma at some depth not much shallower than about 100 km are therefore probably represented in Pipe BK 9.

At the Premier Mine, the Brown Kimberlite diamond population is dissimilar, in many respects, to the population which is present in the Grey and Black Kimberlites. The causes of the dissimilarity can be traced back to the time at which diamonds were discoloured brown. Separate identities for the two magmas which produced the Brown Kimberlite and the other main kimberlites at the Premier Mine therefore appear to have been established within the earth's mantle. Similarities in the diamond characteristics which pre-date the brown-colouring event suggest, however, that both of these mantle-derived magmas contained the same initial population of diamonds.

Dissimilarities between the characteristics of the diamonds in the Satellite Pipe and the main pipe at Letseng-le-terai indicate separate mantle origins for the kimberlites in the two pipes. The Satellite Pipe kimberlite magma appears to have sampled the same initial population as is represented in the main pipe, plus another population. The minor presence, in the Remainder Kimberlite, of diamonds apparently belonging to the "other" initial population represented in the Satellite Pipe is compatible with the Satellite Pipe magma also being represented in the Remainder Kimberlite.

Considering the dissimilar characteristics of the diamonds in the DK 1 and DK 2 Pipes, these two spatially associated kimberlite

bodies do not appear to be directly related in origin.

Rare diamonds from the Finsch Mine and at least the shallowest levels of the Orapa Pipe display abrasional textures resembling those developed on many detrital diamonds. Since the Orapa Pipe contains epiclastic kimberlite and may have been inundated by a once extensive Makgadikgadi Lake, the presence of abraded diamonds is, perhaps, not surprising. In the case of the Finsch Mine, however, it may be necessary to postulate the abrasion of diamonds within a maar-type lake which developed at the pipe vent, and the incorporation of epiclastic kimberlite into subsequently-emplaced, igneous kimberlite.

Only one kimberlite dyke locality (the Swartruggens Main Fissure) is represented in the present study. Features which are ascribed to crystal resorption and high-temperature etching are displayed by diamonds from the dyke, indicating that high-temperature etching and all previous processes which affect diamonds operate at sub-diatreme levels within kimberlite magma. Neither frictionally-induced nor low-temperature etch features were observed among the diamonds from the Main Fissure. This does not definitely imply that these features develop only within diatreme-forming environments, however, for they are also absent in many samples from kimberlite pipes. Diamond crystal breakage is not any less common among the Main Fissure diamonds than in many samples from kimberlite pipes. Wagner's (1914, p. 165) assertion that diamond crystals are broken mainly during the formation of kimberlite diatremes was therefore not substantiated.

Every kimberlitic diamond population studied contains a mixture of colours, crystal forms and surface textures. The individual diamonds in any of the kimberlites therefore did not all experience identical crystallization and post-genetic conditions. Associations between diamonds exhibiting different growth forms and diamonds of different

colours raises the possibility that many more than the two, genetic populations generally indicated by studies of inclusions in diamonds may be represented in individual kimberlites. This would favour the hypothesis that diamonds are xenocrysts with respect to kimberlite. Considering the mixed nature of the diamonds in some eclogite xenoliths, however, the mixed character of the diamonds in individual kimberlites does not conclusively prove a polygenetic origin for the mineral.

Nearly all of the diamonds in all of the kimberlitic samples display evidence of having been partly resorbed, usually to a substantial degree. Diamonds which are less resorbed than others in the same kimberlite are likely to have enjoyed more protection from the kimberlite magma. The relative resorption of the diamonds in any kimberlite is therefore likely to reflect how soon, during intrusion, particular diamonds were liberated from armouring bodies. The only mantle-derived bodies known to ever armour diamonds are eclogitic and peridotitic xenoliths. Assuming a non-cognate origin for such xenoliths, variations in the degree to which the diamonds in individual kimberlites were resorbed favour a non-cognate origin for the diamonds as well. Local variations in the diamond-resorbing potential of kimberlite magmas, however, may also be responsible for some diamonds being more resorbed than others. Such variations appear necessary to account for the development of post-resorption surface textures which are present on some diamonds while being absent on other, more resorbed diamonds in the same kimberlite.

It was found that lamination lines are displayed by between approximately 10 and 60 per cent, and commonly more than 30 per cent, of the diamonds in kimberlites. These then are minimum estimates of the diamonds which are likely to be xenocrysts with respect to their kimberlite hosts. Another few per cent of the diamonds in the Grey

and Black Kimberlites of the Premier Mine and in the Orapa, DK 1 and DK 2 Pipes show other evidence of a xenocrystic origin. These are the paired pseudohemimorphic crystals and diamonds displaying knob-like asperities or related surface textures which are present in those kimberlites.

The conversion, by resorption, of a diamond octahedron to a simple tetrahexahedroid involves a minimum mass loss of approximately 45 per cent. An even greater loss is necessary to convert a cube to a simple tetrahexahedroid. It is shown that the proportion of diamonds exhibiting octahedral and/or cubic crystal surfaces is directly related to the amount of diamond in the host kimberlite. This substantiates the view that the tetrahexahedroid is a resorption form of the octahedron and the cube.

The natural abrasion of diamond involves mainly the development of percussion cracks and spall scars. This produces ground surfaces at crystal corners, edges and asperities. Surfaces that are ground to a considerable degree pass into surfaces of relatively low relief (less than 0,5  $\mu\text{m}$ ) which can be classed as polished. Such polishing appears to result from the grinding of asperities on previously ground surfaces, without any buffing action. The ground and polished surfaces on diamonds resemble the subaqueously-abraded surfaces of quartz grains and were probably also produced during subaqueous transportation. Diamond surfaces which display scratch-like markings disintegrate relatively easily during transportation, producing a unique type of ground surface. The large-scale breakage of diamond crystals is considered to be unimportant during transportation, excepting in the case of previously cracked examples.

Natural percussion cracks are similar to the pressure crack figures produced in static experiments with indenters that can be

softer than diamond, excepting that angled, dynamically-applied stresses are indicated. The pronounced localization of percussion cracks and spall scars at crystal corners and edges suggests that most abrasion is caused by collisions between diamond and bedrock, rather than between diamond and particulate materials. The number of diamond-bedrock collisions per unit distance of travel should be much greater within pot-holes than in wide channels, while considerable travel can occur within pot-holes without any effective transportation. Much of the abrasion of diamonds is therefore likely to occur within pot-holes. Five categories, each defining a particular degree of abrasion, are distinguished for diamonds which exhibit the tetrahexahedroid form.

Nearly all of the diamonds in the placer deposits studied are clearly derived from kimberlites. A minority which display chemically-polished surfaces are possibly derived from carbonatites.

The characterization of the diamonds in particular placer deposits proved to be a useful exercise. Comparisons with the diamonds of either possible source kimberlites or geographically associated placers allowed important deductions concerning the origins of the placer deposits. For example:-

- i. The Lichtenburg and Boskuil deposits are derived mainly from separate sources. The distance between main source and detrital deposit is likely to be similar in each case. The Main Fissure near Swartruggens is not a major source of the diamonds at either Lichtenburg or Boskuil.
- ii. Most of the diamonds at Hlane are probably derived from the Dokolwayo Pipe.
- iii. In the diamond placers of Namaqualand and adjacent areas, the diamond populations represented in littoral deposits near to particular river mouths are essentially the same populations

as are present in the alluvial deposits of these rivers. Two main populations appear to dominate the entire region. One of these predominates in the north of the area and the other predominates in the extreme south. An additional population is also important in deposits which are associated with the Buffels River and the littoral near to the river mouth. Most of the abrasion of the Namaqualand diamonds occurred during their coastward transportation in westward-flowing rivers. The diamonds appear to be derived from the hinterland of the region, rather than from the interior of the Southern African sub-continent, and some are probably from pre-Cretaceous kimberlites.

- iv. Most of the diamonds in the Macquarie River near Wellington, New South Wales may have been derived from the same source as other unusual diamonds described by Grantham (1974) from placers 300 km to the north-east of Wellington.

An implied presence of diamond-bearing kimberlite in the catchment area of the Upper Witwatersrand basin suggests a geothermal gradient, 2 500 m.y. ago, which was not radically steeper than the gradient which prevailed beneath the Kaapvaal Craton during the Cretaceous Period. Consideration of the surface staining displayed by diamonds from the Witwatersrand Banket suggests that while some diamonds were heated to above 600°C, regionally-attained temperatures within the Upper Witwatersrand rocks never exceeded this figure.

A strong, positive correlation between a brown colour and the presence of lamination lines supports the contention that both diamond features reflect the same phenomenon, namely a deformation event. It appears that the relatively resistant, type Ia diamonds are among those that commonly undergo plastic deformation.

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