A CLASSIFICATION SCHEME FOR DIAMOND AND A COMPARATIVE STUDY OF SOUTH AFRICAN DIAMOND CHARACTERISTICS

By J. W. HARRIS,* J. B. HAWTHORNE,† M. M. OOSTERVELD,† and E. WEHMEYER,§

ABSTRACT

A diamond classification system based on the physical features of diamond as a function of size is described. Crystal form, crystal angularity, crystal regularity determine the major morphological divisions of the classification, but transparency or opacity, colour, the number of inclusions and surface features allow further subdivision.

The system has been used to define uniquely samples of diamonds from three kimberlite diatremes, Premier, Finsch, and Koffyfontein, and an alluvial source, Dreyers Pan.

In the cases of the diatreme occurrences variations in diamond crystal shape versus size are explained in terms of a primary crystal population of octahedra and twinned crystals (macles) subsequently altered by secondary processes in the kimberlite magma. Variations in colour are discussed in terms of aggregation of nitrogen into platelets in the diamond crystal lattice as the diamond grew.

Characteristic features of alluvial diamonds from Dreyers Pan allow some conclusions to be drawn relating to the nature of the original kimberlite(s) from which the diamonds are derived.

The usefulness of the classification scheme as a framework into which other quantitative diamond studies can be fitted, is outlined.

INTRODUCTION

In the past several authors have observed that parcels of diamonds derived from different sources show distinctive features with respect to such physical properties as size, colour, morphology, crystal perfection and hardness (WAGNER, 1914; SUTTON, 1928; WILLIAMS, 1932). In order to fully differentiate diamond sources, however, quantitative investigations are required. Studies of this type have been undertaken by BOBRIEVICH (1959), MILASHEV (1965), and GORINA (1971) into some Russian diamond sources; by GRANTHAM and ALLEN (1960) on diamonds from Sierra Leone; and by WHITELOCK (1973) on Lesotho diamonds. In the first four cases, emphasis was placed on the relationships between morphology and surface features of the diamonds and, in the latter instance, diamond morphology was examined as a function of size. In addition to the work of these authors a qualitative evaluation of the incidence of certain physical features of diamonds from several parts of the world has been completed by COTTY and WILKS (1971).

In 1970 a detailed study of the physical characteristics of diamonds was initiated by two

* De Beers Industrial Diamond Division Ltd., P O. Box 916, Johannesburg, S.A.
† Geology Department, De Beers Consolidated Mines Ltd., P.O. Box 616, Kimberley, S.A.
† Computer Services Department, De Beers Consolidated Mines Ltd., P.O. Box 616, Kimberley, S.A.
§ De Beers Sorting Office, Kimberley, S.A

of the authors (J. W. H. and J. B. H.). The project was undertaken to establish whether or not the diamonds from individual sources could be quantitatively separated by observations of physical parameters. Pilot studies using diamonds from several countries showed that diamond characteristics for a particular source varied with the size of the diamond and, therefore, the physical parameters were determined against this function and detailed surface features were not included as part of the classification scheme.

After formulating a classification scheme, the diamonds from three kimberlite mines, Premier, Koffyfontein and Finsch, and one alluvial mine, Dreyers Pan in Namaqualand, were specifically studied. Two parcels of diamonds from Premier (1971/72, 1973 production) and Finsch (1971 and 1973 production) have been examined and one each from Koffyfontein (1973) and Dreyers Pan (1971). The numbers of diamonds examined from these four mines, to the nearest hundred are: Premier 24,400; Finsch 29,900; Koffyfontein 10,000; Dreyers Pan 3,600.

The results of this work indicate that the diamonds from these four mines can now be uniquely defined in terms of physical parameters. The results also indicate that for the three diatreme sources, the diamonds exhibit distinct relationships with respect to crystal form and colour against diamond size. An attempt is made to evaluate these trends in terms of the initial environment of the diamond and the possible subsequent environmental history.

THE CLASSIFICATION SCHEME

As diamond crystallizes in a number of distinct cubic habits, an obvious starting point for these investigations was an evaluation of the morphological forms of diamond.

Diamond parcels from several parts of the world were therefore examined, and by using the additional information on diamond morphologies recorded by several authors (FERSMANN and GOLDSCHMIDT, 1911; WAGNER, 1914; SUTTON, 1928; WILLIAMS, 1932), nine distinct crystal forms were chosen as the basis of this scheme (see Table 1).

As the classification was, however, intended to cover the total population of any sample of diamonds, further primary divisions were assigned to account for spherical, broken or irregular, and aggregated diamonds (Table 1). Also, a further division was allocated to the twinned diamond (the so-called macle), so that in all thirteen divisions were established.

In assigning a diamond to a particular primary division, a number of simple rules were applied.

(i) If the stone showed more than 50% of a specific shape it was placed in the relevant primary division of the classification.

(ii) If a crystal exhibited less than 50% shape it was designated an irregular (or broken) crystal.

(iii) Twinned crystals were assigned to the twin category irrespective of whether the diamond possessed a crystal form or was irregular.

THE CRYSTAL FORMS

As the crystal forms of diamond are adequately described in several texts, FERSMANN and GOLDSCHMIDT (1911), WAGNER (1914), POLINARD (1929), SUTTON (1929), WILLIAMS

TABLE 1. DIAMOND CHARACTERISTICS CLASSIFICATION

Primary Divisions

Crystal forms	*Others*
Octahedra:* dodecahedra*	Macles
Flattened dodecahedra * cubes	Spheres
Tetrahedra: cubo octahedra	Irregular forms*
Octa dodecahedra: cubo dodecahedra	Crystal aggregates
Cubo-octa-dodecahedra	

Secondary Divisions

(i)	*Transparency*	Transparent
		Opaque
	(No exceptions)	
(ii)	*Crystal angularity*	Planar
		Rounded
	(Exceptions: flattened dodecahedra cubo-octahedra, octa-dodecahedra, cubo-dodecahedra, cubo-octa-dodecahedra, spheres, crystal aggregates)	
(iii)	*Crystal regularity*	Regular
		Distorted
	(Exceptions: macles, spheres, irregular forms, crystal aggregates)	
(iv)	*Inclusion content*	None
		Few (1 3)
		Many (> 3)
	(Exception. opaque crystals)	
(v)	Colour	Colourless
		Yellow
		Brown
		Green
		Orange and amber
		Pink and mauve
		Blue
		Black
		Multiple colours
		Grey
		Smokey
	(No exceptions)	
(vi)	*Surface feature*	Transparent coats
		Opaque coats
		Graphite coats
		Frosting
	(No exceptions)	

* Macle shape divisions. In addition, "triangular macle" accounts for commonly depicted form (see text).

(1932), BOBRIEVICH (1959), BRUTON (1970), they are not discussed here, except for those cases where some description is needed to show how the assignment of a diamond to a specific division of the classification scheme, is made.

1. *The Octahedron/Dodecahedron Transition*

Observations on large parcels of diamonds of varying sizes showed that a complete transition in crystal form existed between octahedrons and the dodecahedrons. Starting with the octahedron the series began with rounding of the four-fold coigns until each of the octahedral faces became triple-faceted and the dodecahedron was developed. A point in the series, therefore, had to be determined whereby a transitional crystal could be placed in one of these two classes, and it was found that in most cases no difficulty existed if the 50% rule was applied.

Another type of octahedron/dodecahedron transition that was occasionally encountered during classification was a single crystal with one side made up of octahedral facets whilst the other side exhibited a dodecahedral form (ORLOV and PROPKOPCHUK, 1965; MENDELSSOHN, 1971; WHITELOCK, 1973). Usually, one of the forms dominated and so these crystals were assigned to the dominant crystal form.

2. *The Dodecahedron/Flattened Dodecahedron Transition*

A division for the flattened dodecahedrons was established after it was observed that such crystals constituted a noticeable proportion of the production from some sources (e.g. South West Africa, Namaqualand Coast, S.A.) Again, however, a transition series existed between the dodecahedron and its flattened counterpart.

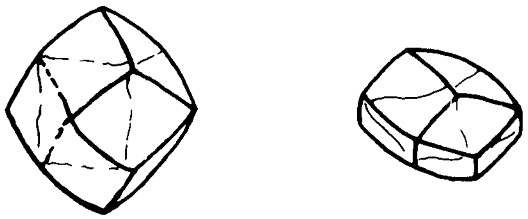

FIG. 1. The dodecahedron transition to flattened dedecahedron.

A dodecahedron when viewed approximately at right angles to one of its (110) faces exhibits five facets, four in perspective (Fig. 1). In the case of a flattened dodecahedron three of these five facets become dominant, so that a triplet of (110) faces centred around a (111) axis is observed, and there is a noticeable six-faceted girdle to the stone (Fig. 1). It was found that transition crystals of this type could again be satisfactorily classified by the use of the 50% rule.

3. *The Dodecahedron Transition to Spherical or Tetrahedral Forms*

Most dodecahedrons have a meandering shallow ridge across the short diagonal of the (110) face (see Fig. 1) and, if this suture becomes developed, crystals with twenty-four facets are produced, and in some cases forty-eight faceted crystals have been noted (GRANTHAM, 1964). The presence of multiple facets gives the crystal a high degree of sphericity and the occasional diamonds of this type encountered during classification were assigned either to the dodecahedral or spherical categories according to the first of the three rules outlined earlier.

Sometimes these multi-faceted diamonds appeared as rounded tetrahedrons. Essentially these crystals had shapes corresponding to a four-sided figure, but with each side showing multiple facets. Such crystals were assigned to the dodecahedra or tetrahedra categories depending on the degree of shape.

4. *The Macle or Twinned Diamond*

This stone is usually described as a tabular triangular crystal consisting of two prominent (111) faces divided by a twin plane parallel to these faces, the seam of the twin plane giving a herring-bone pattern to the crystal lattice, the side facets being either proud or re-entrant.

Several other forms of twinned diamond commonly occur and it was felt that the proportion of macles in a parcel might be indicative of the source. For classification, macles or twinned crystals, therefore (until recently), required only the presence of a twin plane, or more usually the surface expression of this plane—the macle line—and no cognizance of crystal shape was taken. Currently the macles are retained as a primary crystal division of the classification but are subdivided according to the shape categories asterisked in Table 1, as it was found that certain shape relationships were useful in defining a source. The twinned diamond described above was therefore classed as a triangular macle.

The macle line running across the surface of a diamond must be distinguished from lamination or striation lines. According to WILLIAMS (1932) the latter represent glide planes in diamond. More recently, MOKIEVSKY *et al.* (1962) also concluded that these features were the result of plastic deformation along slip planes in diamond.

Macles were distinguished from crystal aggregates by the fact that the former, although twinned, were contained in unit crystals, whereas aggregates were composed of two or more crystals of any shape joined together along a common edge or face, or in some other way, to form a collection of crystals.

5. *The Crystal Aggregates*

Into this division were placed two or more diamonds in some form of conjunction. A diamond may be entirely enclosed within another or may be embedded in the surface of another, or many stones may be unconformably aggregated together. As the aggregates can have distinct crystal forms they were subdivided according to the other twelve primary divisions of the classification, giving, for example, categories such as octahedral aggregates and dodecahedral aggregates (see Table 1). Macle aggregates were originally classified as a single group irrespective of crystal shape but now the same rule is adopted as for the non-aggregated macle crystals (see before).

OTHER SECTIONS OF THE CLASSIFICATION

After allocation into primary divisions the crystals were examined for a number of features, both surface and internal, that might further characterize individual sources. In general these observations were completed in a fixed sequence, but not all the features applied to all the primary divisions. The sequence, and the exceptions to it, are shown in Table 1. Where the exceptions are not obvious they are briefly discussed below.

Transparency/Opacity

This first division in the sequence was based simply on whether any part of the diamond under examination was transparent.

Crystal Angularity

For a crystal to be classified as planar, the diamond edges had to be sharp and in no way rounded. Curvature of sides or edges placed the crystal in the second category. The flattened dodecahedrons and the various combined forms (e.g. cubo-octahedrons) were always naturally rounded and for this reason were not included in this division. In the case of crystal aggregates it was difficult to assess angularity of individual stones when aggregated together and they were therefore not included. In the case of broken or irregular diamonds the division into angular and rounded was based on the 50% rule, as here the object was to roughly assess the proportions of broken crystals which were predominantly rounded compared with angular chipped diamonds.

Crystal Regularity

This feature was determined by placing the crystal in a number of different orientations and visually assessing the degree to which the crystal was misshapen. If the crystal showed no degree of elongation it was termed regular, otherwise it was designated distorted.

The macles were not divided into this category because of the manner in which this division was established originally (see previous discussion), and it was also not considered feasible to determine the regularity of aggregated crystals.

Inclusion Content

The inclusion content of the diamonds was determined by using a X5 or X10 eyepiece and recording the number of inclusions observed (see Table 1). The number three, used to separate two of the inclusion categories (Table 1), was chosen because the inclusion content could then be visually assessed without actually counting impurities. No account was taken of the type, size, colour, or position of the impurity within the diamond.

Colour

Table 1 also shows the eleven colours used in the classification. The diamonds were always examined against a white background and the colour determined visually. No distinction was made between the various intensities of particular colours, and body colours were distinguished from surface colours in a later division of the scheme (see below).

Surface Features

The principal features taken into account were the various surface coatings found on diamond and the matt surfaced or "frosted" diamond (see Table 1). Division into transparent or opaque (Table 1) was necessary as the thickness of the surface feature varied.

The smaller features readily observed on many diamond surfaces such as trigons and other etch features, or the various growth lineaments, were not considered in the classification scheme, because an evaluation of these features required much more detailed study. A complementary research programme is currently in progress to classify and characterize these finer details.

CLASSIFICATION PROCEDURE

On arrival at a diamond sorting office a diamond consignment from a specific source is size screened into various sieve classes and, in the present work, samples of diamonds from the sieve classes +7 to +21 were examined. In Table 2 these sieve classes are explained. This range of diamond sizes was chosen principally because it covered a major part of a total production—from fairly small diamonds to the largest stones (see Table 2)—but also because the diamonds could be examined with the standard X5 or X10 headloop or eyepiece used by diamond sorters.

TABLE 2. DIAMOND SIEVE INFORMATION

Sieve class*		Diameter in mm of aperture (lower screen)	Approximate average weight in carats per stone
−23	+21	8.08	5.00
−21	+19	6.55	2.72
−19	+17	5.89	1 70
−17	+15	5.41	1.30
−15	+13	4.55	0.88
−13	+12	3.90	0.57
−12	+11	3.53	0.39
−11	+ 9	2.85	0.23
− 9	+ 7	2.56	0.14

* Diamond sieves with circular apertures.

Once sieved, diamonds of a particular size were thoroughly mixed and a sample taken. The number of stones to be examined in order to obtain a representative sample was determined by trial and error in the following way. The numbers of diamonds in two samples of the same sieve class were varied until better than 10% numerical agreement was obtained in the major primary shape divisions of the classification previously described. It was found that in general, a minimum sample of 500 stones of a particular sieve size satisfied the above condition.

For the detailed analyses a minimum of 1000 stones were taken from each sieve size (although in some cases this number exceeded 4000 stones) and subdivided into more manageable batches of 500 diamonds. In those cases where the number of stones in a particular size range was less than 1000 (for example with the +19 to +21 size ranges of some sources) the total fraction was taken for evaluation.

Once the diamond samples over the range +7 to +21 had been classified, the data were computed. In the computation, the results for each diamond of a particular size were considered individually so that there was no need initially for a specific sample to be taken from a population. However, some degree of reproducibility could be monitored by using a fixed sample size, and for this purpose an initial display sheet was devised from which the information was transferred to the computer.

The computer programme determined the relationships between the divisions of the classification although this was limited by the numbers of diamonds in certain categories. The percentages recorded were for the total number of stones, and as certain secondary groupings were not determined for all the primary divisions (see Table 1), this then accounts for the percentage discrepancies that can be seen in certain instances in the Tables (e.g. crystal regularity, Table 3). The computer programme also rounded the percentages to the nearest whole number so that characteristics with an incidence of less than $\frac{1}{2}$% are not recorded in the present tables.

In all the tables, the macles are considered as being independent of crystal shape, for although a revised macle classification is now in operation, insufficient data had been collected to determine the influence of this revision on the present results.

RESULTS

Although numerous relationships were determined, discussion of results will be confined to two of the more important relationships which could be used to illustrate certain aspects of the evolution of diamond in its initial environment.

The Results of the Classification Expressed as a Function of Size

Table 3 gives the percentages of this relationship for the four mines.

Crystal Form

In general the percentage of macles increased and the percentage of dodecahedra decreased with increasing diamond size for each of the mines. Except at Premier, the percentage of octahedra increased over the same size range. Percentages of irregular stones and crystal aggregates remained fairly constant except at Koffyfontein where the irregulars decreased with increasing diamond size (Table 3). Spherical diamonds were relatively abundant at Premier Mine (Fig. 2).

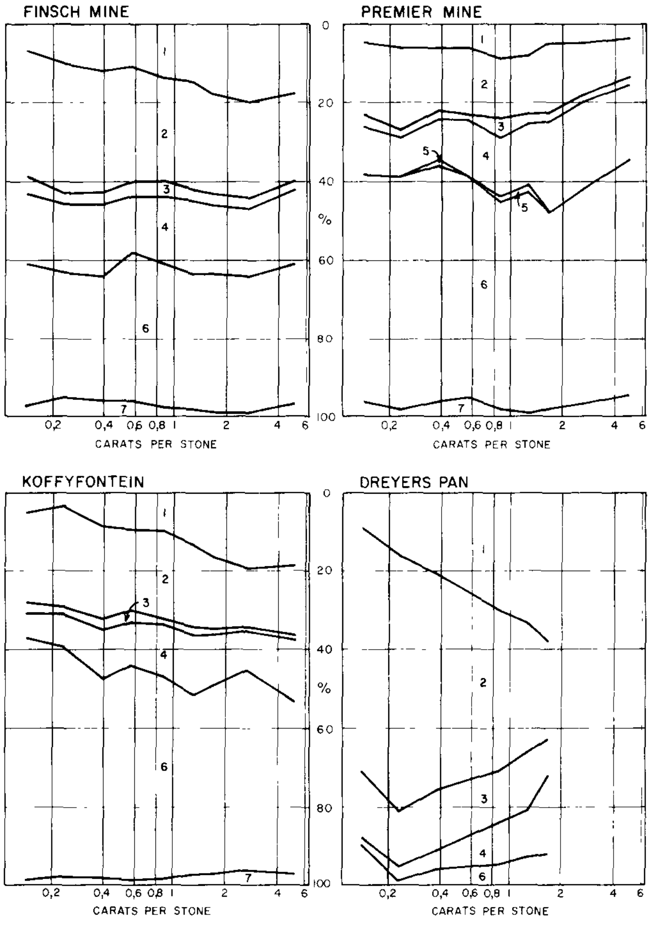

FIG. 2. Crystal form as function of size. 1 = Octahedra. 2 = Dodecahedra. 3 = Flattened dodecahedra. 4 = Macles. 5 = Spheres. 6 = Irregular forms. 7 = Polycrystalline aggregates.

TABLE 3. THE CLASSIFICATION AS A FUNCTION OF SIZE

Koffyfontein Mine — Size

	+21	+19	+17	+15	+13	+12	+11	+9	+7
Form									
Octahedra	18	19	16	13	9	9	8	3	5
Dodecs	18	15	19	21	23	21	24	26	23
Flattened dodecs	1	1	1	2	1	3	3	2	3
Cubo-octa	0	0	0	0	0	0	0	0	0
Cubo-dodec	0	0	0	0	0	0	0	0	0
Cubes	0	0	0	0	0	0	0	0	0
Macles	16	10	13	15	14	11	12	8	6
Spheres	0	0	0	0	0	0	0	0	0
Irregular	45	51	46	47	51	55	51	60	62
Cubo-octa-dodec	0	0	0	0	0	0	0	0	0
Octa-dodec	0	0	0	0	0	0	0	0	0
Tetrahedra	0	0	0	0	0	0	0	0	0
Cryst. agg	3	4	3	3	2	1	2	1	1
Transparency									
Translucent	90	94	94	94	98	89	88	95	94
Opaque	10	6	5	6	2	11	12	6	6
Angularity									
Planar	1	1	1	1	0	3	1	0	1
Rounded	81	88	75	88	33	96	97	100	99
Regularity									
Regular	9	8	14	8	7	13	5	11	10
Distorted	28	27	23	52	26	20	30	20	21
Inclusions									
None	16	18	19	20	19	31	30	30	38
Few	20	21	23	31	28	24	22	31	24
Many	54	55	52	44	50	34	36	33	31
Colour									
Colourless	67	79	78	77	83	76	69	67	61
Yellow	14	7	8	8	5	9	8	9	10
Brown	5	5	4	6	6	7	10	13	17
Green	0	0	0	0	0	1	0	0	1
Orange & amber	0	0	0	0	0	0	0	0	0
Pink & mauve	0	0	0	0	0	0	0	0	0
Blue	0	0	0	0	0	0	0	0	0
Black	1	0	0	0	0	0	0	0	1
Multiple	0	0	0	0	0	0	0	0	0
Grey	12	8	9	9	6	7	12	11	11
Smokey	0	0	0	0	0	0	0	0	0
Frosting	0	0	0	2	0	0	0	0	0
Coats									
Transparent	0	0	0	0	0	0	0	0	0
Opaque	1	0	0	0	0	0	0	0	0
Graphite	1	0	0	0	0	0	0	0	0

Finsch Mine — Size

	+21	+19	+17	+15	+13	+12	+11	+9	+7
Form									
Octahedra	18	20	18	15	14	11	12	10	7
Dodecs	22	24	25	27	26	29	31	33	32
Flattened dodecs	2	3	3	3	4	3	3	3	4
Cubo-octa	0	0	0	0	0	0	0	0	0
Cubo-dodec	0	0	0	0	0	0	0	0	0
Cubes	0	0	0	0	0	0	0	0	0
Macles	19	17	17	18	17	15	18	17	18
Spheres	0	0	0	0	0	0	0	0	0
Irregular	36	34	35	34	37	39	32	33	36
Cubo-octa-dodec	0	0	0	0	0	0	0	0	0
Octa-dodec	0	0	0	0	0	0	0	0	0
Tetrahedra	0	0	0	0	0	0	0	0	0
Cryst. agg	3	1	1	2	2	4	4	5	3
Transparency									
Translucent	76	77	85	85	92	92	98	96	97
Opaque	24	23	15	14	8	8	2	4	3
Angularity									
Planar	2	4	4	5	6	2	3	2	4
Rounded	94	91	93	94	91	95	89	93	94
Regularity									
Regular	9	15	16	20	16	11	8	5	7
Distorted	33	32	30	25	28	32	44	41	38
Inclusions									
None	9	14	19	22	26	23	27	22	25
Few	21	21	27	23	27	30	27	29	29
Many	46	43	39	41	39	39	44	45	43
Colour									
Colourless	27	26	29	28	33	37	36	34	35
Yellow	23	18	20	18	15	15	9	9	8
Brown	15	24	26	27	33	32	40	44	49
Green	17	17	15	16	12	10	9	8	5
Orange & amber	0	0	0	0	0	0	0	0	0
Pink & mauve	0	0	0	0	0	0	0	0	0
Blue	0	0	0	0	0	0	0	0	0
Black	2	2	1	1	1	0	1	0	0
Multiple	0	0	0	0	0	0	0	0	0
Grey	16	13	9	9	6	5	5	5	4
Smokey	0	0	0	0	0	0	0	0	0
Frosting	1	0	1	1	0	0	0	0	0
Coats									
Transparent	16	15	13	14	8	9	4	8	4
Opaque	0	0	0	0	0	0	0	0	0
Graphite	4	2	2	1	0	0	0	0	0

Premier Mine — Size

	+21	+19	+17	+15	+13	+12	+11	+9	+7
Form									
Octahedra	4	5	5	8	9	6	6	6	5
Dodecs	10	13	18	15	15	17	16	21	18
Flattened dodecs	2	2	2	2	5	2	2	2	3
Cubo-octa	0	0	0	0	0	0	0	0	0
Cubo-dodec	0	0	0	0	0	0	0	0	0
Cubes	0	0	0	0	0	0	0	0	0
Macles	19	22	23	16	15	14	11	10	12
Spheres	0	0	0	1	1	0	1	0	0
Irregular	60	55	50	56	53	55	60	59	59
Cubo-octa-dodec	0	0	0	0	0	0	0	0	0
Octa-dodec	0	0	0	0	0	0	0	0	0
Tetrahedra	0	0	0	0	0	0	0	0	0
Cryst. agg	5	3	2	1	2	5	4	2	4
Transparency									
Translucent	74	82	89	87	94	95	95	95	97
Opaque	26	18	11	13	5	5	5	5	3
Angularity									
Planar	4	2	3	7	13	5	6	8	8
Rounded	95	98	97	91	81	92	92	89	91
Regularity									
Regular	1	2	3	8	12	2	3	4	3
Distorted	14	18	23	18	17	24	31	25	23
Inclusions									
None	8	7	10	11	16	15	20	26	25
Few	13	16	18	25	31	30	29	30	30
Many	52	59	61	50	47	49	46	38	42
Colour									
Colourless	32	42	42	36	45	46	40	41	41
Yellow	17	8	10	13	6	5	3	4	2
Brown	19	24	30	31	37	41	46	48	47
Green	2	7	2	6	5	3	2	1	1
Orange & amber	0	0	0	0	0	0	0	0	0
Pink & mauve	0	0	0	0	0	0	0	0	0
Blue	0	2	0	0	0	0	0	0	0
Black	5	3	4	3	1	1	1	1	1
Multiple	0	0	0	0	0	0	0	0	0
Grey	24	13	12	11	6	4	7	5	7
Smokey	0	0	0	0	0	0	0	0	0
Frosting	4	0	1	4	5	0	1	3	1
Coats									
Transparent	2	7	1	3	1	2	2	2	1
Opaque	0	0	0	0	0	0	0	0	0
Graphite	4	3	11	5	1	1	1	1	4

Dreyers Pan Mine — Size

	+21	+19	+17	+15	+13	+12	+11	+9	+7
Form									
Octahedra	—	—	38	34	30	—	21	16	9
Dodecs	—	—	25	34	41	—	55	65	62
Flattened dodecs	—	—	10	15	13	—	15	14	17
Cubo-octa	—	—	0	0	0	—	0	0	0
Cubo-dodec	—	—	0	0	0	—	0	0	0
Cubes	—	—	0	0	0	—	0	0	0
Macles	—	—	19	12	11	—	5	4	2
Spheres	—	—	0	0	0	—	0	0	0
Irregular	—	—	8	7	5	—	4	1	10
Cubo-octa-dodec	—	—	0	0	0	—	0	0	0
Octa-dodec	—	—	0	0	0	—	0	0	0
Tetrahedra	—	—	0	0	0	—	0	0	0
Cryst. agg	—	—	0	0	0	—	0	0	0
Transparency									
Translucent	—	—	100	99	100	—	100	100	100
Opaque	—	—	0	1	0	—	0	0	0
Angularity									
Planar	—	—	3	3	1	—	1	1	5
Rounded	—	—	87	82	79	—	84	84	78
Regularity									
Regular	—	—	49	56	60	—	60	72	75
Distorted	—	—	24	26	32	—	31	24	13
Inclusions									
None	—	—	64	71	76	—	75	76	81
Few	—	—	18	19	14	—	19	20	15
Many	—	—	18	10	10	—	6	4	3
Colour									
Colourless	—	—	52	51	60	—	59	55	55
Yellow	—	—	10	11	11	—	10	17	21
Brown	—	—	3	5	4	—	3	6	14
Green	—	—	34	33	25	—	28	21	10
Orange & amber	—	—	0	0	0	—	0	0	0
Pink & mauve	—	—	0	0	0	—	0	0	0
Blue	—	—	0	0	0	—	0	0	0
Black	—	—	0	0	0	—	0	0	0
Multiple	—	—	0	0	0	—	0	0	0
Grey	—	—	0	1	0	—	0	0	0
Smokey	—	—	1	0	0	—	0	0	0
Frosting	—	—	8	8	11	—	6	20	19
Coats									
Transparent	—	—	34	32	25	—	27	20	10
Opaque	—	—	0	0	0	—	0	0	0
Graphite	—	—	0	0	0	—	0	0	0

Dreyers Pan had the highest percentage of crystal shapes, the other mines having high proportions of irregular forms. At Premier Mine no cubo–octahedra were noted over the size range examined (c.f. TOLANSKY and PUNGLIA, 1971).

In Fig. 2 these observations are represented graphically for the major crystal forms for the four mines.

Transparency

The proportion of opaque stones increased with increasing diamond size at Finsch and Premier but values remained fairly constant at Koffyfontein and virtually no opaque stones were found in the Dreyers Pan sample (Table 3).

Crystal Angularity and Crystal Regularity

There was no clear relationship between these two parameters and diamond size. In general almost all of the stones examined were rounded and distorted (see Table 3). Only in the Dreyers Pan sample did regular–shaped crystals exceed distorted ones.

Inclusion Content

The proportion of diamonds containing inclusions increased with diamond size for Premier and Koffyfontein Mines, a clear inverse relationship existing over the diamond size range examined, between diamonds with many inclusions and those with no impurities (Table 3). However, at Finsch, the relationship was not as clear, impurity levels remaining reasonably constant over the size range. In the case of larger–sized diamonds, Dreyers Pan stones had the fewest inclusions and Premier Mine diamonds the most.

Colour

In general, similar colours were recorded for the four mines, and the relationships between the principal colours and diamond size are shown in Fig. 3.

For diamonds from Finsch and Premier Mines there was an increase in yellow stones with increasing diamond size, and a decrease in brown stones for all three kimberlite sources. When present, green transparent–coated diamonds tended to be fairly constant or increase slightly in number with increasing diamond size.

The proportions of the different colours for each mine were clearly distinctive. For example:

(i) The high percentage of colourless stones, and the virtual absence of green diamonds (as defined above) at Koffyfontein.
(ii) The higher percentage of green diamonds at Dreyers Pan compared with Finsch.
(iii) The occurrence of blue diamonds (about $\frac{1}{2}\%$) only at Premier Mine (see Fig. 3).

Surface Features

A relatively high proportion of Dreyers Pan diamonds were frosted, this surface feature occurred on diamonds of different shapes and different colours. Frosting was also occasionally present on the larger diamonds from Finsch Mine, more generally at Premier, and was noted among Koffyfontein diamonds. Transparent green–coated diamonds were typical of Finsch and Dreyers Pan, while graphite–coated stones occurred predominantly at Premier Mine, although also some larger sized stones from Finsch were graphite coated.

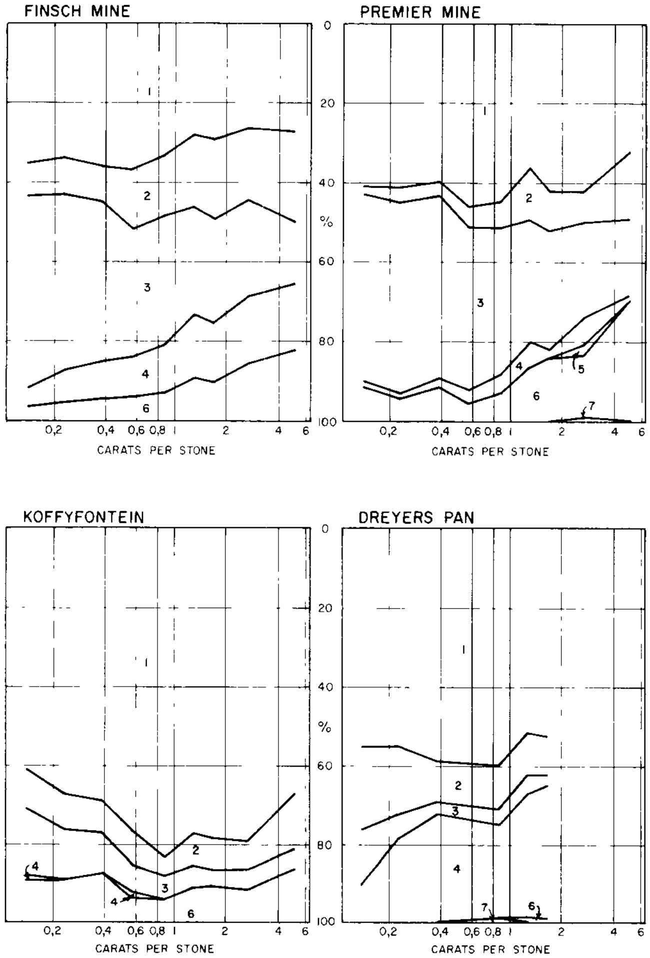

FIG. 3. Colour as function of size. 1 = Colourless. 2 = Yellow. 3 = Brown. 4 = Green. 5 = Blue. 6 = Grey and black 7 = Other.

Colour as a Function of Crystal Form and Size

This relationship for the four principal colours of the octahedra, dodecahedra, macles and irregulars is shown in Table 4 and in Figs. 4 and 5 for the Finsch and Premier Mines only. This more detailed relationship is not shown for Koffyfontein or Dreyers Pan, as insufficient diamonds have been examined from these sources.

From the tables and figures a number of features emerge:

(i) There was a general resemblance per mine of the colours for the four crystal shapes considered.

(ii) There was a similarity, which was particularly marked at Finsch, between the relative percentages of the principal colours in the octahedra and dodecahedra categories.

(iii) In both mines the largest proportion of colourless stones were macles.

TABLE 4. COLOUR AS FUNCTION OF CRYSTAL FORM AND SIZE

	Finsch Mine Sieve size									Premier Mine Sieve size								
	+7 −9	+9 −11	+11 −12	+12 −13	+13 −15	+15 −17	+17 −19	+19 −21	+21 −23	+7 −9	+9 −11	+11 −12	+12 −13	+13 −15	+15 −17	+17 −19	+19 −21	+21 −23
Octahedra																		
Colourless	30	34	35	37	33	29	26	27	28	24	28	27	37	38	35	38	39	42
Yellow	6	6	9	14	11	16	19	14	21	2	2	8	4	4	7	7	8	13
Brown	54	47	42	31	35	29	27	26	15	69	57	61	51	51	47	42	40	33
Green	10	12	12	17	19	23	26	28	27	–	1	1	2	4	5	4	8	6
Grey & Black	–	1	2	1	1	3	2	5	9	5	12	3	6	2	6	9	4	5
Others	–	–	–	–	1	–	–	–	–	–	–	–	–	1	–	–	1	1
Dodecahedra.																		
Colourless	35	35	33	39	31	28	30	27	31	28	26	34	31	36	34	35	32	34
Yellow	14	13	16	20	21	22	24	23	23	2	3	2	8	7	10	10	11	22
Brown	45	40	38	27	34	27	24	22	15	63	66	57	54	47	40	38	32	15
Green	5	9	10	10	11	18	17	20	24	–	1	–	3	7	7	1	10	1
Grey & Black	1	3	3	4	3	5	5	8	7	7	4	7	4	3	9	16	14	28
Others	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–
Macles:																		
Colourless	39	40	41	39	38	33	34	33	37	45	44	52	59	59	52	52	61	48
Yellow	3	7	7	16	13	15	23	21	24	3	4	7	4	6	10	10	3	15
Brown	49	43	35	30	26	21	21	20	7	44	47	37	31	29	25	23	18	13
Green	5	8	9	10	19	19	15	19	19	1	1	1	5	4	5	1	12	3
Grey & Black	4	2	8	5	4	12	7	7	13	7	4	3	1	2	8	14	6	20
Others	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Irregular:																		
Colourless	33	28	35	34	31	23	27	21	18	46	45	41	50	44	31	39	37	26
Yellow	5	7	3	11	12	17	15	14	25	2	5	3	4	7	16	10	9	18
Brown	52	49	45	37	36	32	29	25	18	42	42	44	38	34	29	30	23	22
Green	3	7	8	9	8	10	9	8	9	1	1	3	2	5	6	2	5	1
Grey & Black	7	9	9	9	13	18	20	32	30	9	7	9	6	10	18	19	22	33
Others	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4	–

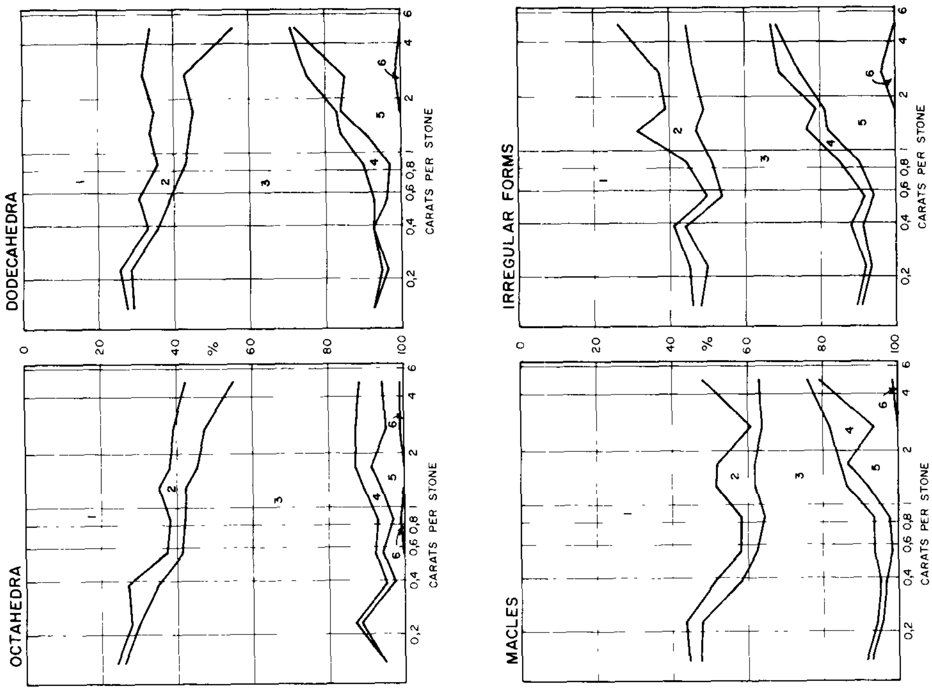

FIG. 5. Premier Mine—colour as function of crystal form and size. 1 = Colourless. 2 = Yellow. 3 = Brown. 4 = Green. 5 = Grey and black. 6 = Others.

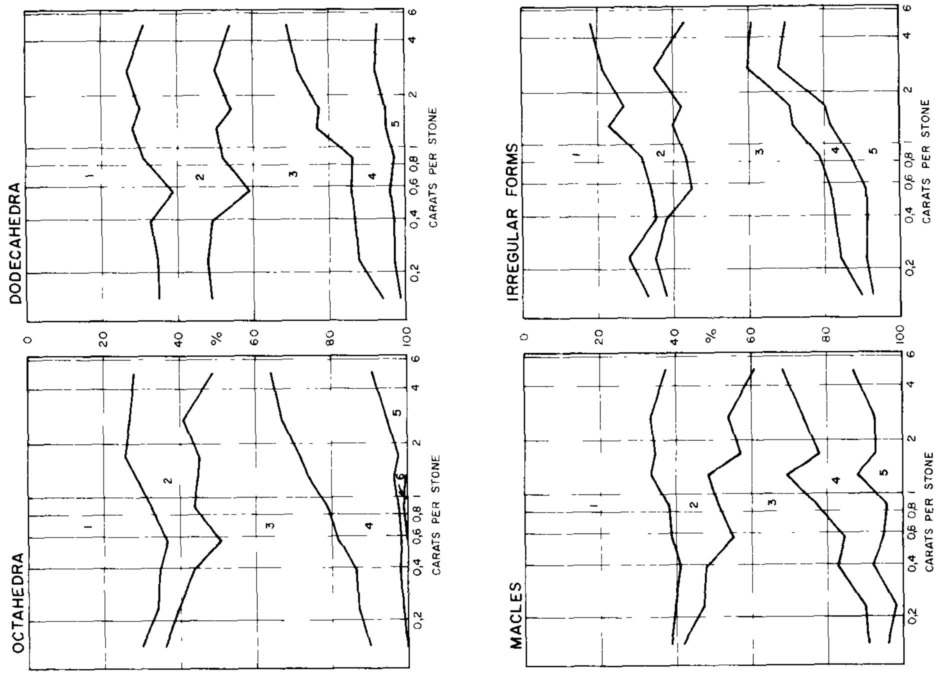

FIG. 4. Finsch Mine—colour as function of crystal form and size. 1 = Colourless. 2 = Yellow. 3 = Brown. 4 = Green. 5 = Grey and black. 6 = Others.

DISCUSSION

In the following discussions the degree to which the diamond–classification scheme has separated the four diamond sources is briefly evaluated, and then the possible geological significance of the results of the classification is considered.

With regard to the latter, only the major relationships are mentioned, and therefore not all the distinctive features which separated diamond sources are reported as part of this section.

Statistical Reproducibility of the Classification Scheme

Apart from the initial trial–and–error approach to determine roughly some measure of reproducibility (see before), a statistical analysis was carried out on various parcel sizes from each of the four sources, the mean, standard deviation, and coefficient of variation being calculated for the percentages of diamond in the major crystal form and colour groups.

The analysis showed high standard deviations for both crystal shape and colour, with coefficients of variation ranging between 12% and 20%. The high degree of variation is attributed to either possible observation inconsistencies or possible local variations in the diamond characteristics from the four sources.

The statistical F-test, which compares variances, and the T–test, which compares means, were also completed for the major crystal forms and colour groups, particularly for the parcels from the two separate samples taken from Premier and Finsch Mines in 1971 and 1973. These tests indicated that, in general, with a confidence of 95% there were no significant differences. However, the high standard deviations observed make these tests not very conclusive.

THE KIMBERLITE DIATREME DIAMOND SOURCES

(a) *Crystal Form Variations as a Function of Size*

As early as 1911 FERSMANN and GOLDSCHMIDT concluded that certain crystal forms of diamond, in particular the dodecahedron, did not represent a primary growth form, but resulted from a resorption or solution process operating on octahedra sometime after their formation. In attempting to assess aspects of the initial environment of the diamonds in the three kimberlite diatremes at Finsch, Premier, and Koffyfontein, two important parameters, therefore, need to be considered.

Firstly, it is necessary to separate the primary growth forms of diamond from the crystal forms resulting from secondary alteration processes and, secondly, it is important to consider the type of size distribution this original diamond population may have had prior to later modification of the diamonds.

Of particular relevance in this regard are the diamonds from a kimberlite diatreme at Koidu, Sierra Leone (GRANTHAM and ALLEN, 1960), and also the type of diamonds recovered from the kimberlite and alluvial sources in Zaire. These two sources are characterized by a number of features, which indicate that the original diamond populations became fossilized in the kimberlite before any major secondary alteration of the crystal population occurred. In Sierra Leone, for example, the transparent diamonds are predominantly sharp–edged octahedra showing various surface features indicative of diamond growth

(GRANTHAM and ALLEN, *loc. cit.*) and these crystals are associated with macles (an obvious growth form in view of its twin–plane). Very few dodecahedra crystals occur. The opaque-coated diamonds from this source include octahedra, macles and cubes. It is significant that of the few dodecahedra found none were coated (see Table 4, GRANTHAM and ALLEN, 1960). Although opaque coats on otherwise clear diamonds at Koidu indicate imperfect diamond growth, the presence of such coats is further evidence that this diamond population did not suffer any major resorption after crystallization.

Similar opaque–coated diamonds are found in various sources in Zaire (POLINARD, 1929) but in addition to the crystal forms found at Koidu, cubo–octahedra, cubo–dodecahedra, cubo–octa–dodecahedra, and octa–dodecahedra crystals occur and may also be considered primary growth forms of diamond. These so–called combined crystal forms are not generally a common natural form of diamond outside this part of Africa.

In view of these considerations it is suggested that the primary growth forms of diamonds in kimberlite are principally the octahedra and macle, with, in some cases, the cube and its various combined forms, together with aggregates of these crystals. It may be mentioned that this conclusion is supported by the growth forms of diamond crystals in synthetic systems (see, for example, STOLIN and GVOZHDYARA, 1971).

The size distribution of the original population is more difficult to assess, for this may vary from source to source, but from the Koidu kimberlite in Sierra Leone, it appears that a wide range of diamond sizes for the primary crystal forms existed, from 1 mm to 15 mm in diameter (cf. the sieve class of Table 2).

If it is assumed, therefore, that at Finsch, Premier, and Koffyfontein, the primary crystal populations consisted principally of octahedra and macles with large size variations (cubes or combined forms not being a common crystal form in Southern Africa), then an attempt can be made to explain the crystal habits of diamond in terms of an initial environment, the diamonds then being modified at a later date by secondary processes.

Finsch diamonds. Table 3 or Fig. 2 give the relationship between the diamond characteristics and size for Finsch, and an unusual feature emerges based on the assumptions discussed earlier.

The proportion of macles in the various size ranges includes crystal shapes and macle irregulars (see classification scheme), and as the table or figure shows, is reasonably constant through the +7 to +21 size range. Also the proportion of irregulars is moderately constant, these being made up of broken octahedra, dodecahedra and flattened dodecahedra. Hence if the two types of dodecahedra are solution forms of the octahedra (MOORE and LANG, 1969, and see below) then the proportion of original octahedra is also reasonably constant from +7 to +21. Therefore, the proportions of original octahedra and original macles at Finsch are essentially independent of the size of the diamond.

Figure 4 shows the marked similarity in the colour versus size for the octahedra and dodecahedra for the Finsch Mine. This similarity of colour suggests that these two crystal forms came from the same original population, and is considered to be further evidence in support of the experimental evidence of MOORE and LANG (1969) that the dodecahedron is a solution form of the octahedron.

Another important feature of diamonds from the Finsch mine is the inverse relationship which exists between the octahedra and the two dodecahedra as size varies (Table 3 or Fig. 2). This observation suggests that the original octahedra population not only varied in size but had been formed before the resorption processes reduced the octahedra to dodecahedra. There would be a greater percentage weight loss in the smaller octahedra than the larger when this reaction occurred, and hence more dodecahedra could be expected to form in the smaller diamond size ranges, as the results show (Table 3).

The processes which modified the diamonds at Finsch occurred relatively late in the evolutionary history of the diamond. This is reasoned from the likelihood that the breakthrough of the kimberlite produced most of the irregular diamonds and as many of these stones consist of broken dodecahedra, the solution event must pre–date breakthrough.

The absence of the dodecahedra in diamond synthesis in spite of varied chemical conditions and wide ranges of pressure and temperature indicates that this form of diamond is probably not a product of initial environmental conditions. It is suggested that the dodecahedra are a product of reaction between octahedra and the volatile constituents of the magma and the reaction probably occurred when the kimberlite was ascending to the Earth's surface.

If the diamonds at Finsch evolved in this way, then a similar trend should be noted in the revised macle classification. From preliminary results (only for Finsch), similar trends appear to be present, with the dodecahedra macle predominating over the other forms.

Premier and Koffyfontein diamonds. At Premier Mine the proportion of octahedra, dodecahedra, and flattened dodecahedra (except for the +19 and +21 stones) is fairly constant over the size range (Table 3 or Fig. 2). In this case, however, no reverse trend appears between the octahedra and the two dodecahedra. The absence of this trend might occur if the original octahedra population was not completely formed when resorption processes occurred, there being then little opportunity for relatively large numbers of octahedra crystals to survive. Figure 5 does, however, indicate that there is reasonable similarity of colour versus size for the octahedra and dodecahedra at Premier, suggesting they came from a single population.

Hence as the Premier diatreme consists of several distinct kimberlite injections, unlike Finsch and Koffyfontein, then alternatively, the overall morphological profile of the diamonds observed at Premier might be a consequence of variations in the degree to which the volatile content in each kimberlite attacked the diamonds.

At Koffyfontein the proportion of the original octahedra diamond population slightly decreased with increase in size, but here a reverse trend similar to Finsch can be seen (Table 3 or Fig. 2), and is explained in terms of the alteration of an original octahedral population of different sizes.

Both the diamond samples from Premier and Koffyfontein differ from Finsch, however, in the increasing proportion of macles with increasing diamond size, an observation also made by GRANTHAM and ALLEN (1960) for the diamonds from the kimberlite source in Sierra Leone. This trend is unlikely to be the result of an alteration phenomena unless macles are more susceptible, as otherwise more solution forms of diamonds should be present in Sierra Leone. Another explanation offered for this observation is that some environmental condition favoured initial and continuous nucleation of twinned diamond rather than octahedra.

(b) *Principal Colours and Their Variations in Diamonds as a Function of Size*

The cause of the main body colours in diamond—colourless, yellow and brown—has been, and still is, the centre of extensive discussions in the literature, and a review of early work is given by CLARK (1965). Although certain aspects of this problem still require clarification it is generally agreed that a single element, nitrogen, plays an important role in giving diamond its colour, this element first being quantitatively determined and related to diamond colour by KAISER and BOND (1959).

Nitrogen can occur in diamond in three ways; single atoms substituting for carbon, as small atomic aggregates within the diamond lattice, or larger numbers of atoms aggregated in platelet form in diamond (100) lattice planes (see, for example, DAVIES, 1972).

Colourless diamonds in general result from an impurity of platelet nitrogen (the so-called type Ia diamonds) or essentially contain no nitrogen at all (the so-called type IIa diamonds) (BRUTON, 1970). If small atomic aggregates of nitrogen are associated with the platelet nitrogen, then pale yellow or brown colours occur in type Ia diamonds, but if nitrogen substitutes for carbon in the diamond lattice of a type Ia diamond, canary-yellow or more amber-coloured diamonds result (the so-called type Ib diamonds). The latter two colours of diamond, however, are generally rare.

Brownish diamonds also occur in the type II (nitrogen free) diamonds due to weak absorption in the visible spectrum, the result of different concentrations of amorphous or graphitic carbon in the diamond lattice (CLARK *et al.*, 1956).

In general terms these colours can be related to the morphology of diamond (Dr. F. A. RAAL, private communication), the diamonds of the type I series, (with the exception of Ib diamonds), being of good morphology with octahedra a common crystal form and diamonds of the type II series tending to have no noticeable morphological characteristics.

The diamonds from the three kimberlite diatremes show similar principal colours which suggests that they formed in a similar, but not necessarily the same, environment. The main colours also show similar trends, the most noticeable feature being the increase of yellow diamonds and the decrease of brown stones as the size of the diamond increased (see Table 3 or Fig. 4).

These features might be explained, in general terms, if the initial growth of diamond took place in the presence of primordial nitrogen which became dispersed in, or substituted in the crystal lattice of the diamond as it grew. With continued favourable diamond growth conditions, the dispersed nitrogen could diffuse through the crystal lattice to form small atomic aggregates which later became aggregated as platelets. If this process continued the proportion of the colours (at least as seen on the Earth's surface) might progressively move, particularly among the larger stones, towards colourless diamonds. Yellow diamonds could form at the expense of browns, if an environmental condition favoured nitrogen aggregation at the N_3 centres (yellow diamonds) rather than the H_3 centres (brown diamonds) (see DAVIES, 1972).

The extent to which the nitrogen became aggregated in the type I series would depend on environmental factors, particularly temperature, but whether the process continued up to kimberlite breakthrough, or stopped at an earlier stage, is uncertain.

An explanation on these general lines would account for the varying proportions of the same colours in different diamondiferous kimberlites (cf., for example, Koffyfontein and Finsch), but the proposal does assume a dominant type I environment, which is perhaps not unreasonable if octahedra and macles are the primary crystal forms of diamond (see before). Type II diamond development could occur alongside type I diamond growth at those times when the nitrogen content of the growth environment became depleted. This type of evolution would then explain the higher proportion of type IIa diamonds in small diamond sizes (TOLANSKY and KOMATSU, 1967), as no nitrogen had been incorporated up to that time of the diamond's growth, but as the proportion of type IIa diamonds in the larger sizes is at present unknown, it is not possible to determine the exact growth relationships between the diamonds of the two series.

Green transparent–coated diamonds. These diamonds, which are usually colourless or very pale yellow in colour beneath the coat, probably result from natural α–particle bombardment from uranium or thorium atoms in the kimberlite, the damage occurring after the rock had solidified (VANCE *et al.*, 1973). The fairly even proportion of this type of diamond with diamond size at Premier Mine suggests that this coating occurred, after emplacement when there was a "fixed" size distribution of diamonds. The increase of green diamonds with size at Finsch is thought to be caused by the segregation of radioactive elements at high levels in the kimberlite (see VANCE *et al.*, 1973).

The alluvial Dreyers Pan diamonds. In the case of an alluvial source it is important to establish whether diamond characteristics can be related to a specific diamondiferous kimberlite. This is often difficult because more than one source may be involved, and it is likely, in view of the results of the work of LINHOLME (1973), that only the gem fraction of the original diamond population survives transportation to the alluvial source. LINHOLME (1973) considered the wear of various types of diamonds during ball milling, and showed that boart diamonds only survived a few hours under these conditions whereas gem–quality stones showed hardly any wear after 950 hours. The diamonds from Dreyers Pan, for instance, are low in the percentages of broken or irregular stones, of opaque diamonds, and of diamonds with many inclusions, compared with diamonds recovered from kimberlite (see Table 3), and this strongly suggests that diamonds which are structurally weak, suffer preferential transportation damage, and are probably crushed before reaching the final site of deposition.

The proportion of octahedra, dodecahedra and macles, however, varies with diamond size in a similar way to that of diamonds from kimberlite diatreme sources. These comparisons, however, may not be justified, as some size sorting of the gem diamonds may have occurred subsequent to removal from the kimberlite. There is, for instance, no clear consistency in the variations of colour and size between Dreyers Pan diamonds and the diamonds from the diatreme sources.

There are perhaps two original features retained in the Dreyers Pan diamonds. Firstly, there was probably an abnormally high proportion of flattened dodecahedral diamonds in the original kimberlite(s) and secondly, the high percentage of green transparent–coated diamonds suggests a much higher than usual radioactive element content in the kimberlite(s) (see VANCE *et al.*, 1973; DAWSON and MILLEDGE, 1973).

FINAL REMARKS

The results obtained from classifying diamonds demonstrate that, on the basis of their physical features, diamond samples from four specific sources in South Africa can be uniquely defined. The classification scheme will be used to detail the characteristics of other diamond sources, particularly those along the coast of Namaqualand and South West Africa, as an evaluation of such deposits might reveal characteristics which can be used to determine the source(s) of these diamonds. It is also hoped to consider the morphological profile of diamonds from other diatreme kimberlites particularly those in Botswana.

The results of this work have also shown that useful information regarding the initial environment of diamond can be obtained and the effects of secondary processes gauged by detailed classification of diamonds from different sources.

For the four mines considered in this work, the classification of diamonds as described also provides a structure in which other work on diamonds can be framed. Of particular relevance to the present results would be a detailed examination of the relationship between diamond colour, type I and type II diamond, crystal form, and diamond size. This would enable a more thorough evaluation to be made of the principal colour variation of diamonds from kimberlite sources. However, also of importance would be an evaluation for example, of the possible relationships between diamond size and colour in the primary diamond forms, and co-genetic mineral inclusions, or an examination within the framework of this scheme of the luminescence, optical anisotropy or degree of perfection of the crystal lattice of diamond, as all these approaches might lead to a greater understanding of the environment in which the diamond grew and evolved.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to Mr. M. A. Harris and the personnel of the De Beers Diamond Sorting Office, Kimberley, for their co-operation during the course of this work and to Diamond Developments Ltd., for permission to examine diamonds from Zaire and to the Bobbejaan Mining Co. Ltd., for permission to examine diamonds from Bellsbank, South Africa.

Thanks are also due to Miss J. Burkinshaw and Mr. G. von Mollendorf for assistance with the computation of the results and Mr. C. R. Clement, Mr. B. A. Wyatt and Dr. R. Caveney for constructive criticism of the manuscript.

We would also like to place on record the value of the work completed by Mrs. E. Wehmeyer who died tragically in July 1973 just as the work was completed.

Finally we wish to thank De Beers Consolidated Mines Ltd. and De Beers Industrial Diamond Division Ltd., for permission to publish this paper.

REFERENCES

Bobrievich, A. P., Bondarenko, M N , Gnevushev, M A , Krasov, A M , Smirnov, G I and Yurkevich, R K (1959) *The Diamond Deposits of Yakutia*, Moscow. State Scientific and Technical Publishing House.

Bruton, E. (1970) *Diamonds*, N.A.G. Press Ltd., London.

Clark, C. D., Ditchburn, R W and Dyer, H B (1956) Absorption spectra of irradiated diamonds after heat treatment. *Proc. Roy. Soc.* (Lond.), A **237**, 75 89.

Clark, C. D. (1965) Optical Properties of natural diamond In· *Physical Properties of Diamond* (ed for R. Berman), pp 295-324, Oxford· Clarendon Press

Cotty, W. F and Wilks, E. M. (1971) Differences between diamonds from different sources. *Diamond Research*, pp. 8–11.

Davies, G. (1972) Some properties of nitrogen in diamond *Diamond Research*, pp 21 -30

Dawson, J B and Milledge, H. J (1973) Uranium, thorium abundances in some hypabyssal South African kimberlites *Mineral Mag.* (in press).

Fersmann, A von and Goldschmidt, V (1911) *Der Diamant*, Heidelberg University Library Publication

Gorina, I F. (1971) The crystal morphology of diamonds from the Anabar -Olenek Interfluve In *Kimberlite*

Volcanism and Prospects for Primary Diamond Content in the North-eastern part of the Siberian Platform (editors M. I RABKIN, V. A. MILASHEV and L. S. YEGOROV), pp 90-107, Leningrad· Arctic Geology Research Institute of the USSR ministry of Geology.

GRANTHAM, D. R and ALLEN, J B. (1960) Kimberlites in Sierra Leone. *Overseas Geology and Mineral Resources*, **8**, 5 25

GRANTHAM, D. R (1964) The diamond deposits of Panna, Central India *Ind. Diamond Rev* **24**, 30–35

KAISER, W. and BOND, W. L (1959) Nitrogen, a major impurity in common type I diamonds. *Phys. Rev.* **115**, No 4, 857 63.

LINHOLM, A A L (1973) *The Occurrence, Mining and Recovery of Diamonds*. A publication by De Beers Consolidated Mines Ltd , London

MENDELSSOHN, M J (1971) The Etching of Diamond and the Associated Minerals Garnet and Olivine. Ph.D Thesis, University of London

MILASHEV, V. A. (1965) *Petrochemistry of the Kimberlites of Yakutia and Characteristics of their Diamond Mineralisation*. Leningrad "NEDRA" publication.

MOKIEVSKY, V. A , TITOVA, V M. and BARTOSHINSKY, Z. V. (1962) Occurrence of plastic deformation in diamond and problems connected with laminated nature of diamond crystals *Zap. VMO*, Part 91, No 4

MOORE, M and LANG, A. R (1969) Growth horizons in rhombicdodecahedral diamonds Diamond Conference Abstracts. Article 1.

ORLOV, Yu L. and PROKOPCHUK, B I (1965) Diamonds from the alluvial deposits of the River Motorchune (Prilensk diamond-bearing region). Acad. of Sci. USSR Publication No. 16, pp. 155-65

POLINARD, E (1929) *Les Diamants Translucides et Opaques des Gisements de la Bushimaie* Ann. Soc. Geol de Belge, Special Pub

STOLIN, O. and GVOZHDYARA, P. (1971) Morphological evaluations of synthetic diamonds after grading. In *Proceedings International Conference on Application of Synthetic Diamonds in Industry*, Kiev

SUTTON, J. R. (1928) *Diamond, a Descriptive Treatise*, Thomas Murby and Co , London

TOLANSKY, S. and KOMATSU, H. (1967) Abundance of type II diamonds. *Science* **157**, 1173-5

TOLANSKY, S and PUNGLIA, J (1971) Truncated cubo-octahedroids in Premier Mine small diamonds Diamond Conference Abstracts, Article 28.

VANCE, E R , HARRIS, J W and MILLEDGE, H J (1973) Possible origins of α-damage in diamonds from kimberlites and alluvial sources. *Mineral Mag.* (in press).

WAGNER, P. A. (1914) *The Diamond Fields of Southern Africa* Transvaal Leader, Johannesburg. Reprinted 1971 Struik (Pty) Ltd., Cape Town

WHITELOCK, T K (1973) Morphology of the Kao Diamonds. In *Lesotho Kimberlites* (editor P. H NIXON), pp. 128–40

WILLIAMS, A. F. (1932) *The Genesis of the Diamond*, Benn Ltd., London