A CONTRIBUTION TO THE STUDY OF THE DIAMOND MACLE.

With a Note on the Internal Structure of Diamond.

By J. R. Sutton, M.A., Sc.D., F.R.S.S.A., Hon. Memb. R.Met.S., Hon. Memb. S.A.S.C.E.

"Composite crystals often occur, in which the several portions have different orientations governed by regular and definite laws. When the crystallisation of a substance held in solution is hurried by rapid evaporation of the solvent, the crystals usually grow together in groups, in which the arrangement of the several members is purely accidental. But it was observed at a very early date that crystals of certain minerals, in particular those of cassiterite and spinel, are joined together in a regular and constant manner to form a well defined individual. . . .

"Romé de l'Isle was the first to attempt an explanation of the composite character of the crystals of spinel and cassiterite, and he introduced the word *macle* to denote a kind of composite crystal which we now call a twin. Werner employed the word *zwilling* (= a twin), at present used by German crystallographers, and later on Haüy introduced the word *hemitrope* (from ἡμι = half, and τρόπος = a turn), for he perceived that the orientation of the two portions of every well-defined twin known to him is given by the following law: A complete crystal, bounded by the forms observable on the twin, is divided along a central plane which is parallel to a possible face; and the half on one side of the plane is then turned through 180° about the normal, the two halves remaining in contact to form the twin. This law gives in very many cases the relative orientation of the two portions united together in a twin crystal; it offers no suggestion as to the cause of twinning, and supplies no explanation of the growth of the twin" (Lewis, 'Crystallography,' 1899, p. 461).

It is rarely, however, that a diamond macle is equivalent to two halves of a complete crystal, or that the length of an edge is 1·225 times the thickness between two opposite triangular faces, or that its "central plane" is a plane at all. Mostly it is of tabular habit, and its aspect is pretty much what would be obtained if two rough flakes, not necessarily of equal thickness—one from each of two opposite faces of an octahedron, or one from each of two opposite corners of a rhombic dodecahedron—were rotated 60° or 180°, either way round, and joined together. At the same time the opposite faces tend to accurate parallelism. Since very few diamonds have sharp edges it can be understood why the majority of diamond macles have not indented (swallow-tail) corners, the indentations having disappeared in the process which rounded the edges. Hence the corners of most of these macles are blunt; though not a few, and especially those with dodecahedral characteristics, taper gradually with a lenticular section to a sharp edge.

An uncommon sort of macle is known in which the central plane is not a hexagon but a perfect triangle larger than the parallel faces, and everywhere falling outside the orthogonal projection of the faces; and in this case (which is difficult to understand) the edge faces meet in fairly sharp edges and carry the usual facial triangular indentation (see Fig. 1).*

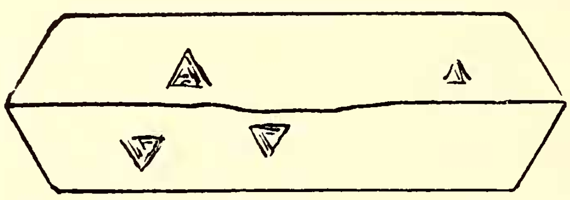

Fig. 1.—Wesselton glassy macle, enlarged six times.

Pretty often one of the halves of a macle projects beyond the other, as though the two halves had worked to combination planes of different size, or as though a flake from one diamond had been joined at random, excepting as to orientation, to a flake from another larger one. Fig. 2 is an illustration of a Wesselton macle of this kind. In Fig. 2 (A), CB and CF are the two halves seen edgewise. The projecting portion AD of the twinning plane is indented with shallow triangles standing the opposite way to those on the outer face EF, as shown in plan in Fig. 2 (B). That is to say, the lower half CF in Fig. 2 (A) partakes of the character of a proper octahedral tabular crystal. We should infer from this that either half may have grown independently of the other to some extent.

Fig. 3 shows an edge of a Bultfontein macle of a type intermediate between those of Figs. 1 and 2.

Frequently the edges of glassy macles are deeply indented with pyramidal terraced depressions, the triangles of one half being opposed base to base to those of the other half. Quite as often, however, only one of the halves has these depressions, the other half being quite independent of them.

* According to current theories this specimen would be regarded as a macled form of the plus and minus tetrahedron. *Cf.* Spencer, 'Ency. Brit.,' 1910, art. "Crystallography"; and Rutley's 'Mineralogy,' 1916, p. 70.

Composite types and irregular forms are common:

Ex. 1.—A nearly complete Bultfontein crystal with rounded edges and a "shield" face not indented with triangles. On a cleavage plane roughly

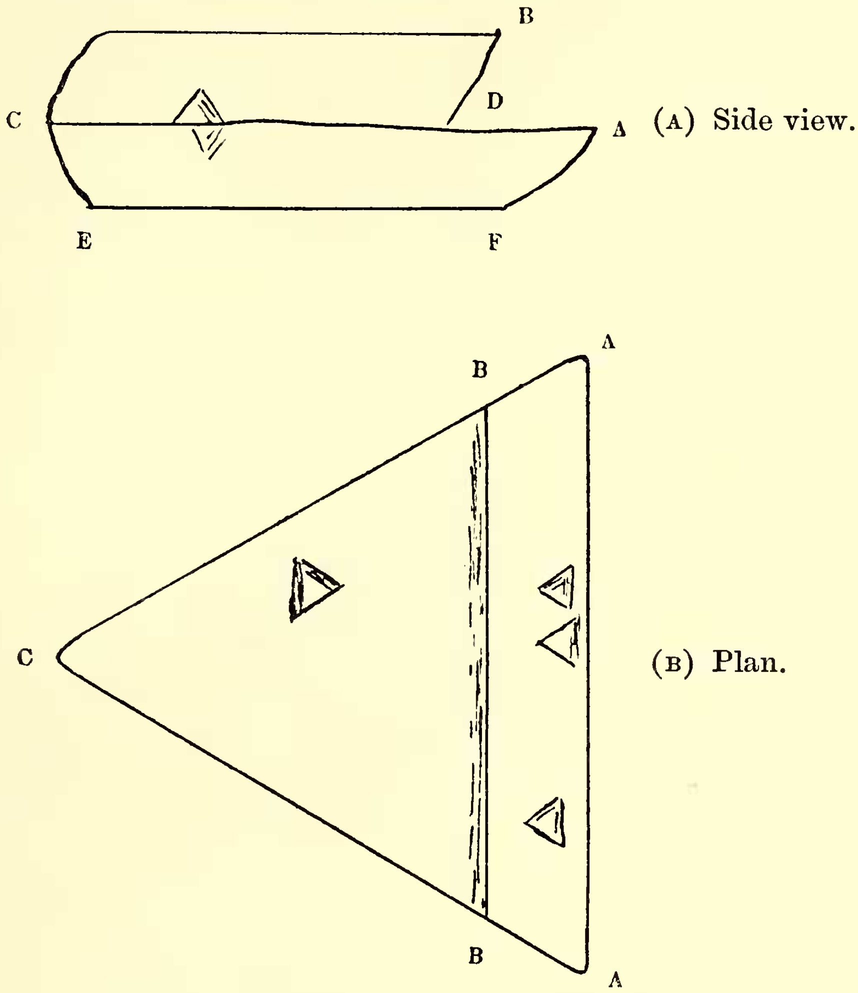

Fig. 2.—Wesselton macle, enlarged.

parallel to the shield a thin flake had grown macling the diamond. This flake was much less rounded than the rest and had numerous triangular indentations on its face.

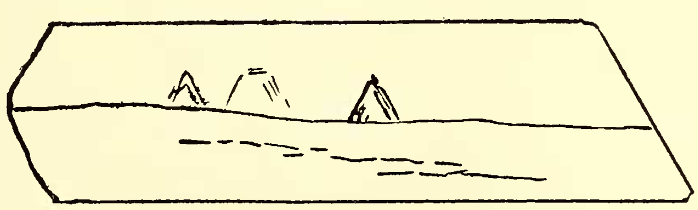

Fig. 3.—A Bultfontein macle.

The dimensions of the diamond were:

Length of edge, 7·6 mm.

Thickness of whole diamond perpendicularly to the twinning plane, 6·3 mm.

Thickness of macling flake, 0·8 mm.

Ex. 2.—A macle with one half dodecahedral, the other half inclining to octahedral.

Length of edge, 6·5 mm.

Thickness, 3·8 mm.

Ex. 3.—In the case of many Dutoitspan macles the combination plane is almost circular in plan even when the faces are flat.

Ex. 4.—In the case of many Koffyfontein specimens, especially those of dodecahedral affinities, the combination plane is isosceles. Others are scalene. The spread dodecahedral macles from Jagersfontein often show the same irregularity.

The diamonds found in the principal mines of Griqualand West and the Orange Free State may be classified for convenience into two holohedral groups, namely octahedral and dodecahedral, albeit there is no hard and fast demarcation between them. Practically every octahedron carries

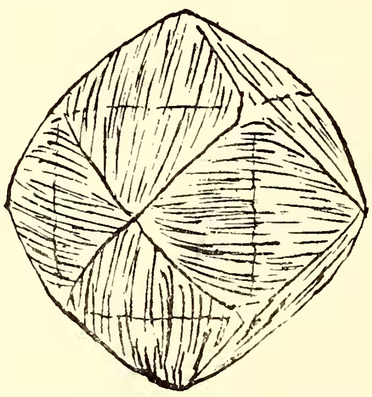

Fig. 4.—A typical large yellow diamond from Dutoitspan.

dodecahedral striations more or less developed, and nearly all dodecahedra show traces of an octahedral lineage; and this is so even when the dodecahedron declines into the tetrahexahedron, as in Fig. 4. From the infrequent octahedron on the one hand almost to the cube on the other there is an unbroken gradation. There are curious intermediate combinations, in which the edges of the rhombic dodecahedron, or tetrahexahedron, invade the faces of the octahedron, the said edges existing in embryo side by side with the (evanescent) triangular indentations belonging to the octahedron. These combinations have been mistaken for triakis- and hexakis-octahedra.

Of the macle the same may be said: There is the same unbroken progression from the one group to the other, including the illusory triakis- and hexakis-octahedra.

Generally speaking, swallow-tail corners on macles are a function of thickness. The thicker a macle relatively to the length of its edges, the greater the chance that the twinning plane is truly hexagonal. Otherwise the swallow-tails are only seen on macles whose octahedral characteristics are the most pronounced. Such macles will then have fourteen more or less perfect faces. Oscillation types may have two octahedral faces and three rounded edges. Dodecahedral types may have no more than six, or twelve usually somewhat arched faces. These last are met with often enough at Jagersfontein, and occur also at Wesselton and Bultfontein, where they are most common in the smaller sizes.

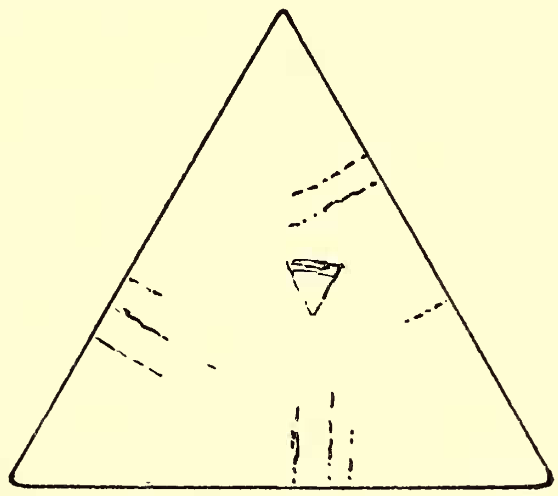

Fig. 5.—Macle, showing flawed edges.

The fracture of a macle is curious. A smashed diamond crystal, not macled, nearly always shows conchoidal fracture dominated by the so-called perfect cleavage. But in the case of the macle perfect cleavage scarcely counts, for it breaks easily enough parallel to an edge, and still more easily at right angles to an edge. In the first case the fracture is somewhat irregular and conchoidal; in the second it is remarkably direct, showing, moreover, a herring-bone " grain." Many spotted glassy macles have flawed

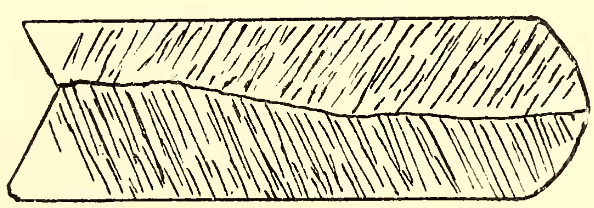

Fig. 6.—Herring-bone grain of macle.

edges, the flaws indicating the directions of easy breakage perpendicularly to the edges. Fig. 5 depicts a Wesselton macle with flawed edges, and Fig. 6 the grain of a macle broken at right angles to an edge.* It may be noted here that the straight breakage surface of a macle at right angles to an edge reveals much better than a natural edge does that the twinning plane is not necessarily a true plane at all, but rather an irregular surface, or at best a series of small planes on different horizons approximating to parallelism with the triangular faces of the macle.

* See the " Note on the Internal Structure of Diamond," below.

Among diamonds the macle-forming tendency does not appear to be strong, though some mines have it more than others. Some test-countings gave the following proportions by weight which macles bear to the total yield:

Bultfontein . .	about	1	per cent.
Wesselton . .	,,	1½	,,
Dutoitspan . .	at least	3	,,
De Beers and Kimberley	,,	5	,,

The low percentage shown by Bultfontein is remarkable, that being the mine above all others where groups and clusters of diamonds abound, and where irregular twinning is so prominent a feature as to be almost a nuisance to the diamond merchant. The above percentages suggest, though they may not prove, that where regular twinning is most in evidence there irregular twinning will be least.

The most striking peculiarity of the diamond macle is of course its prevailing tabular habit. Untwinned crystals are pretty often flattish, and now and then, particularly at Bultfontein, tabular octahedra—the "portrait stones"* of the diamond market—are met with. These, saving that they are nearly always elongated, are equivalent to octahedra from which opposite facial blocks have been cleaved off, so that they have hexagonal faces. Measurements of four of these Bultfontein portrait stones gave the following dimensions:

	Length.	Breadth.	Thickness.
1.	11·0	6·0	2·5 mm.
2.	5·9	4·0	1·8 ,,
3.	9·7	?	2·3 ,,
4.	7·7	?	2·2 ,,

As articles of merchandise they are much to be preferred to macles, but their philosophical interest is incomparably less. Superficially the chief differences between tabular crystals and macles are:

(1) The triangular indentations of the two opposite faces of a tabular crystal are oriented in opposition from any one point of view, whereas those of the macle are oriented the same way. This difference is very pleasingly shown if the crystal and the macle are held up to the light, side by side.

(2) The crystal breaks normally, the macle symmetrically.

(3) The crystal is glassy with a shining lustre, the macle not characteristically so.

(4) The macle is peculiarly tabular, the tabular crystal is rare.

The last clause is perhaps the most important. The ordinary crystal is by preference a regular solid whose axes are equal in length. And it seemed worth while to attempt to determine whether there is a standard of dimen-

* So called because they serve as glazing for small miniatures.

sions to which macles also tend to conform. Clearly there is no hard and fast necessity that a macle should be tabular seeing that now and then one comes across a macle which is made up exactly of two halves of a regular octahedron; but it is a question whether such a one is to be regarded as representing a standard from which all others are departures or whether it is itself a departure from whatever the standard may be. If it be the standard, then although the average spread (*i. e.* the ratio of length of edge to thickness) of all together may be much greater than its own, yet the actual numbers of the thinnest ones (ratio large) will be less than the actual numbers of the thickest ones (ratio small).

With the object of determining, first, the average spread, and, second, whether that average signifies a standard dimensional ratio or is merely a numerical median value, measurements of diamond macles of good geometrical symmetry have been made as opportunity offered. The results are set forth in the tables below.

TABLE 1.—*Octahedral Macles.*

Mine.	Edge shorter than 5 mm.			Edge from 5 to 7·9 mm.			Edge 8 mm. and longer.		
	No.	Average edge.	Spread E/T.	No.	Average edge.	Spread E/T.	No.	Average edge.	Spread E/T.
		mm.			mm.			mm.	
Koffyfontein .	8	3·4	2·28	4	6·3	2·38	1	8·2	3·73
Jagersfontein .	1	4·5	1·64	5	6·4	2·15	3	13·7	1·82
Dutoitspan .	3	4·1	3·04	10	6·5	2·55	6	13·5	2·55
Bultfontein .	50	3·6	2·74	40	6·5	2·82	15	9·3	2·49
Wesselton .	9	3·6	2·86	27	6·6	2·66	31	9·9	2·57
Total .	71	3·6	2·70	86	6·5	2·68	56	10·3	2·53

TABLE 2.—*Rhombic-dodecahedral Macles.*

Mine.	Edge shorter than 5 mm.			Edge from 5 to 7·9 mm.			Edge 8 mm. and longer.		
	No.	Average edge.	Spread E/T.	No.	Average edge.	Spread E/T.	No.	Average edge.	Spread E/T.
		mm.			mm.			mm.	
Koffyfontein .	8	4·3	2·16	6	6·0	2·68	—	—	—
Jagersfontein .	4	4·4	2·15	9	6·8	2·44	6	9·6	2·33
Dutoitspan .	3	3·8	1·85	7	6·5	2·23	6	12·4	1·99
Bultfontein .	25	3·4	2·06	36	6·2	2·30	3	8·9	1·97
Wesselton .	23	3·8	2·32	30	6·4	2·42	13	9·3	2·50
Total .	63	3·7	2·18	88	6·3	2·38	28	10·0	2·30

Table 1 gives, for five mines, particulars of the ratio of length of edge (E) to thickness (T) of macles of prevailingly octahedral character, arranged in three sets according to length of edge.

Table 2 gives corresponding particulars for macles of prevailingly rhombic-dodecahedral character.

From Tables 1 and 2 we gather that, on the whole, the smaller octahedral macles appear to have a slightly greater spread than the larger ones, the opposite being the case for the dodecahedral ones. Measurements of a very much larger number of specimens, however, would be required to definitely prove that it is so. What is clear is that the octahedral types have a larger spread than the dodecahedral; for the 213 macles of Table 1, with an average edge of 6·5 mm., have an average spread of 2·65, whereas the 179 macles of Table 2, with an average edge of 6 mm., have an average spread of 2·30. This is partly (but only partly) to be accounted for by the fact that the thicknesses in Table 1 are measured from face to face, whereas many of those of Table 2 had to be taken between two opposite coigns.

Table 3.—*Number of Octahedral Macles of Given Spread.*

—	E/T under 2.	2 to 2·99.	3 to 3·99.	4 to 4·99.	5 to 5·99.	6 upwards.
Koffyfontein .	6	3	4	—	—	—
Jagersfontein .	4	5	—	—	—	—
Dutoitspan . .	4	10	5	—	—	—
Bultfontein .	17	52	28	6	1	1
Wesselton . .	12	36	17	2	—	—
Totals . .	43	106	54	8	1	1

For the whole 392 macles measured the average edge was 6·3 mm. and the spread 2·49. Whence it would appear that the average thickness of a macle is very closely one-half that of the regular octahedron standing on an equal base. The question now is, Has this ratio anything more than a chance significance? To test this query we must determine the actual number of specimens of given ratios in our list. Table 3, therefore, gives the numbers of octahedral macles in ascending grades of spread (E/T), and Table 4 gives corresponding particulars for the dodecahedral types.

A comparison of Tables 3 and 4 confirms the evidence of Tables 1 and 2 to the effect that, excepting at Jagersfontein, octahedral macles have a larger spread than dodecahedral ones. Indeed, in the case of two Bultfontein specimens included in the numbers of Table 4 the thickness was actually greater than the length of edge; and out of sixty-four Bultfontein dodecahedral macles no less than eight had a spread-ratio less than 1·5.

Again, of the whole number measured (= 392), considerably more than half had a spread-ratio between 2 and 3, whereas only about a quarter had a lesser spread. Thus it is proved that the average spread, 2·49, deduced above is the spread to which the diamond macle tends to conform, and therefore that the *standard* macle is not rightly to be regarded as consisting of two halves of the standard octahedron. More than that, a macle which is equivalent to two halves of an octahedron is as much abnormal as a macle of four times its spread.*

It is a curious circumstance that although dodecahedral stones are common at Bultfontein, where quite a half of the yield is prevailingly of this type, and that Wesselton is a mine of stones inclining to the octahedral, yet more glassy and octahedral macles are found at the former place than at the latter. In fact, of the whole 169 Bultfontein macles dealt with in Tables 1 and 2, 105 (= 62 per cent.) were of the octahedral type, whereas only about a half of the Wesselton macles were so. Bultfontein octahedral macles, however, average smaller than Wesselton ones do—at any rate among diamonds exceeding one-tenth of a carat each.

TABLE 4.—*Number of Dodecahedral Macles of Given Spread.*

—	E/T under 1.	1 to 1·99.	2 to 2·99.	3 to 3·99.	4 to 4·99.	5 upwards.
Koffyfontein .	—	2	11	1	—	—
Jagersfontein .	—	4	15	—	—	—
Dutoitspan . .	—	8	7	1	—	—
Bultfontein .	2	27	26	8	—	1
Wesselton . .	—	15	41	10	—	—
Totals . .	2	56	100	20	—	1

The greatest spread-ratio hitherto observed by me is 6·37 (E = 5·1 mm., T = 0·8 mm.) on a glassy macle from Bultfontein. Spread-ratios of 5 on Bultfontein macles are not uncommon.

A Note on the Internal Structure of Diamond.

The grain which appears in herring-bone pattern on a broken macle is sometimes shown in straight pattern on a broken simple diamond crystal. This will be when the fracture happens to lie at right angles to an octahedron edge, *i.e.* parallel to a dodecahedral plane of symmetry. This grain is parallel to the plane of a continuous line of edges of the hexakisoctahedron; it is parallel to a plane joining any two opposite edges of the cube, or what is the same thing, to a plane joining any two opposite shorter diagonals of

* I am unable to say how this result compares with the average twin of spinel. Lewis (p. 467) observes that the twin of spinel *often* "acquires a more or less strongly-marked tabular habit by the disproportionate development of the faces parallel to the combination plane." An excellent little twin of Burma spinel in my possession has a spread-ratio of 1·40.

the rhombs of the dodecahedron. The grain, therefore, is equally inclined along six planary directions of the three rectangular axes.

Taking any complete set of six planary directions:

(1) They meet a face of the octahedron in two sets of three each, of which one set is at right angles to the face, the other inclined 54° 44′ to the normal. The grain of the first set is inclined 35° 16′ to the normal; that of the second runs parallel to the surface.

(2) They meet a face of the rhombic dodecahedron, one of them at right angles, the grain being also parallel to the shorter diagonal of the rhomb, one flush, as also the grain, with the longer diagonal, and four inclined at 30° to the normal, while the respective grainings of these are inclined at 54° 44′ to the edges.

(3) They meet a face of the cube, two being at right angles to this, themselves intersecting at right angles, the grain of each being parallel to a diagonal of the face, and four at equal inclinations of 45°, as also their grainings.

Hence, having regard to these planary directions, if a diamond crystallises in dependent grained parallel laminæ, then the octahedron, the rhombic dodecahedron and the cube, are the regular forms most likely to occur. Transition forms such as the triakis- and hexakis-octahedron, if there be such things, would be due to accelerated growth in the central parts of the planary directions cutting the faces of the octahedron; but there is no obvious reason why diamonds alleged to be of such forms should have the exquisite symmetry assigned to them in treatises on crystallography.

The geometrical patterns displayed on the faces of diamonds appear to be due to the grainings which run parallel to a face. Thus are derived the shallow triangular indentations on the faces of the octahedron—shallow, because their sides are normally parallel to similarly oriented dodecahedron faces, and the square indentations on the faces of the cube, these squares being apparently mostly confused by the intrusion of the grainings which meet the faces aslant. Again, the parallel striations appear whenever the grain of a planary direction runs flush with a face, as in the rhomb of the dodecahedron, and across a bevelled edge of the cube.

Rounded forms are entirely a dodecahedral effect. To be quite precise, there is no such thing as a rounded octahedron, though the term may pass for the sake of convenience. An octahedron can only be thicker through the middle of opposite faces than at the edges when its edges are terraced by the imposition, step upon step, of smaller and smaller triangular slices—the form which for some reason has been classed as a tetrahedral twin.* The

* The tetrahedral theory introduces much mental complexity into the study of the crystallisation of diamond. And although it may be invoked with some appearance of justification to explain a single-grooved edge to a diamond (*cf.* Lewis, p. 481), or a macle such as Fig. 1, it is less satisfactory when there are many grooves (and these with striated, not smooth edges), as is usually the case.

rounding arises solely from the per saltum curtailment of the areas of superimposed grained laminæ on the rhombs of the dodecahedron, as can be easily seen under magnification : Imagine a number of tiny parallel rivulets, some a little stronger than others, of viscous matter to run from the middle each way nearly to the edge of a rhombic plane and to solidify; then a second lot to overflow them in the same direction though not so far; then a third lot, and a fourth, and so on, each lot in succession having a weaker driving "head." In the end we shall have a somewhat irregular-terraced sulcate elevation, rounded if the "head" has diminished at an increasing rate, sloping uniformly upwards to a ridge if the "head" has diminished uniformly. And this is about what the rippled, or sulcate surface of a typical Dutoitspan yellow dodecahedron looks like under the microscope. The rivulets here are actually due to the exposed grain of the diamond; the rounded elevation is that of the rounded dodecahedron; the uniform rise to a ridge is that of the tetrahexahedron.

Brewster seems to have been the first to detect the internal grain of a diamond. He noticed that the flat surface of a certain plano-convex lens of diamond was covered with minute parallel bands, and he concluded, not quite correctly, that "all the bands were the edges of veins or laminæ whose visible terminations were inclined at different inclinations not exceeding two or three seconds [of arc] to the general surface." He added that "had this surface been an original face of the crystal there would have been nothing surprising in its structure" ('Phil. Trans.,' 1841). If, however, my argument above is sound, then the plane face of Brewster's lens must have been cut parallel to a face of the rhombic dodecahedron. Parallel bands would not have been seen on a plane cut in any other direction.*

The term "grain" is used in the diamond-cutting industry, yet not quite in the same sense as here. Eg. Cattelle ('The Diamond,' 1911) says, "Cut with or against the grain of a diamond, and the wheel makes little impression; it must be cut across the grain" (p. 114). Again, "Imperceptible as it is to an inexperienced eye, diamonds have a grain along which they can be split as wood is split, only much more evenly and exactly. This grain is parallel with the faces of the octahedra" (p. 126). Mineralogists have tried to say much the same of crystals in general in less homely language. Rutley (p. 41), *e. g.*, says that "In the plane of cleavage the molecules composing the mineral are closely packed together, whilst at right-angles to this plane the packing is not so close. This last direction is,

* Evidently Brewster's lens could not have been polished up to the vitreous stage so as to have acquired the "flowed layer of amorphous phase" which Beilby has suggested may be produced by purely mechanical means on the hardest crystal. Occasional dodecahedra from De Beers and Koffyfontein have an amazingly fine natural polish. Possibly their surfaces are in the vitreous stage. Boutan ('Le Diamant,' 1886, p. 37) ascribes the bands seen on Brewster's lens to multiple macling. I hope to return to this matter again in a future paper.

therefore, a direction of least cohesion, and hence splitting or cleavage easily occurs along it." Also P. von Groth ('B. A. Report,' 1904) tells us that those planes which are parallel to the greatest density of structure—whatever that term may be supposed to mean precisely—are identical with the cleavage planes. Of course, what these authorities really mean to say is that the molecules are probably most closely packed in some given direction because a cleavage plane runs that way. By saying the other thing they put the cart before the horse. But it would seem that a diamond is most readily cleavable parallel to an octahedron face because the grain of each of three planary directions runs parallel to a face. It is not so easily cleavable parallel to the faces of the cube, because only the grain of each of two planary directions is parallel to a face, and it is still less easily cleavable parallel to a rhomb of the dodecahedron because the grain of only one planary direction runs that way; so that in the last case it is only across the thin edge of a macle that we should expect to get this sort of cleavage to the best advantage. All the same, it is surprising how good such cleavage from a simple crystal may be on occasion. Plates of cleavage parallel to a dodecahedral plane of symmetry are met with on the sorting tables in which both cleavage faces are as nearly parallel to each other as the faces of a portrait stone, and, moreover, are almost as natural looking as a face of the dodecahedron itself. Fractures parallel to a cube face are much less elegant as a rule.

We may summarise the last paragraph by saying that there [illegible] three orders of diamond cleavage:

First, that parallel to an octahedron face;
Second, that parallel to a cube face;
Third, that parallel to a dodecahedron face;

whence the cleavage of diamond is not so much a question of "density of structure," or concentration of molecules, as it is of array of molecules.

It may be of interest to note here that the great Robert Boyle failed to distinguish between the true grain of a diamond and the "grain" as understood by diamond cutters. He had observed the thin plates exposed on the broken surfaces of "New English *Granats*," "and to try whether this observation would hold even in the hardest Stones, I had recourse to a pretty big Diamond unwrought, which being plac'd in a Microscope, shew'd me the Commissures of the Flakes I look'd for, whose Edges were not so exactly dispos'd into a plain, but that some of them were very sensibly extant like little Ridges, but broad at the Top above the level of the rest. And these Parallel flakes together with their Commissures, I could in a somewhat large Diamond plainly enough discern even with my unassisted Eyes. And for further satisfaction I went to a couple of Persons, whereof the one was an Eminent Jeweller, and the other an Artificer, whose Trade was to cut and polish Diamonds, and they both assur'd me upon their repeated and constant Experience, and as a known thing in their Art, that 'twas almost impossible (though not to break, yet) to *split* Diamonds, or cleave them smoothly cross the Grain (if I may so speak) but not very difficult to do it at one stroke with a Steeled Tool, when once they had found out from what part of the Stone, and towards what part the splitting Instrument was to be impell'd: By which 'tis evident that Diamonds themselves have a grain, or a flaky Contexture not unlike the *fissility*, as the Schools call it, in Wood" ('An Essay about the Origine and Virtues of Gems,' 1672, p. 21).

If the grain of a diamond, as revealed either by a fracture at right angles to an edge of the octahedron or by the natural face of the dodecahedron, represents lines of crystal growth (as seems not unreasonable as a first assumption), then it follows that the proximate primitive form of diamond is not an octahedron but a six-rayed figure defining cubical space—each ray joining the mid points of pairs of opposite edges of the cube and delineating the respective directions of accretion. Thus let AG, Fig. 7, be a cubical ray space (or space lattice), a, b, c, d . . . . , the mid points of the respective edges. Then am, bn, ck, dl, eg, fh, are the directions of the rays. The crystallisation may be supposed to proceed by successive symmetrical impositions, edge to edge, of like cubical spaces containing the rays, each cubical ray space being surrounded by twelve others, that is, a second ray space A′ G′ will be applied to AG in such a way that E′ F′ lies along DC, a third A″ G″ so that A″ B″ lies along HG, and so on. The overall outline of the first 13 ray-spaces will define a cubical space equal to 27 primitive cubes of which 14 are empty. The addition now of a ray space opposite each face of the central one gives an octahedron of 17 ray spaces. If, further, we may venture to regard a, b, c, d . . . . , each as indicating the place of a carbon particle, then each particle in a diamond crystal will be surrounded symmetrically by six others b, n . . . . , at equal distances p (where p is the length of an edge of the cube), in directions db, dn . . ., parallel to the edges of the cube; by eight others a, c, h, e . . . . , at equal distances $p/\sqrt{2}$, in directions da, dc, dh, de, . . . , parallel to the edges of the octahedron; by twelve others, R, S, ... , at equal distances $\sqrt{3}\,p$ in directions dR, dS, dT′, dU′ . . . (where dR, dS pass through P and Q the middle points of the cubic faces AF, DG; and dT′, dU′, are parallel to BQ, BP) parallel to the edges of the rhombic dodecahedron. In short dn $(=p)$, dl $(=\sqrt{2}\,p)$,* dS $(=\sqrt{3}\,p)$, delineate in magnitude and direction one edge of a cubical, octahedral, and dodecahedral space respectively. Again each particle in the crystal of this proximate structure is surrounded by 32 others, the whole forming a system of 33 contiguous particles. An interesting feature of the configuration is the

* $dl = 2\,da = 2\,(p/\sqrt{2})$.

fourfold grouping of six particles in a ring, by which every particle is at a corner of each of four hexagonal rings of six particles apiece in one plane, of which *d h m l f a* is one.

Note.—For any assigned volume R : C : O = 118 : 105 : 100,
where R is the surface of the rhombic dodecahedron,
where C is the surface of the cube,
where O is the surface of the octahedron.

This is perhaps as far as inference, based on mere eye observations of fracture, can carry any theory of the internal structure of diamond; and such a theory could only be proximate—in other words, it could tell us

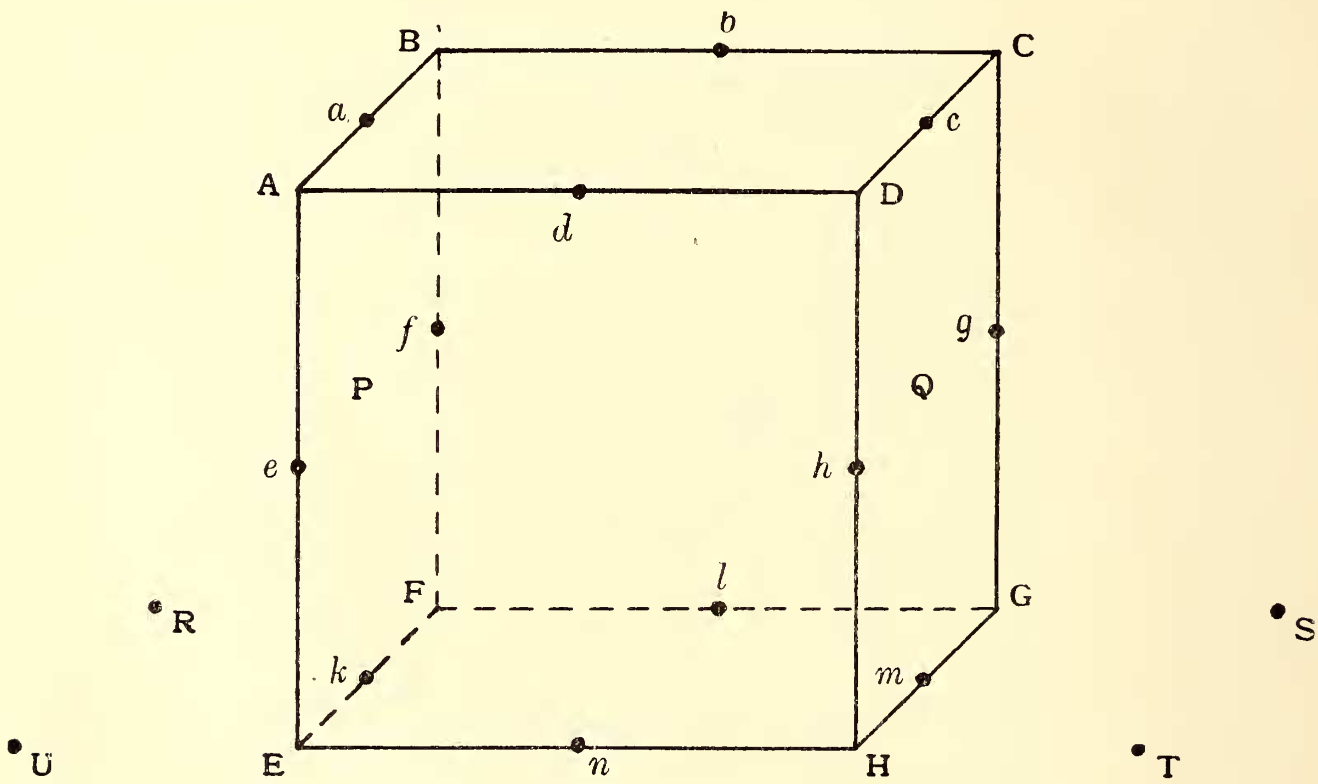

Fig. 7.—Grouping of carbon particles in diamond.

nothing of why the carbon particles should spread in a six-rayed framework, nor whether the particles may be regarded as ultimate atoms. A search for outside evidence bearing on this point did not at first sight seem to hold out much encouragement seeing that most published accounts of the diamond are wrong in their facts and, therefore, not likely to be right in their theories. Bragg's fundamentally important X-ray work on the structure of the diamond ('B. A. Report,' 1913) proved, however, to contain the sort of evidence that was required. It was perhaps unfortunate for me that owing to various distractions, arising mostly because of the war, I had overlooked his results before working out—and writing out as above—my own; but otherwise there is some satisfaction in finding that eye observations alone can carry a theory so far as it does. Bragg deduces a somewhat more intricate grouping of atoms than that of the "particles" shown in Fig. 7. He finds a primitive cube, and draws it so that the points C, D, H, G, of Fig. 7 would be the mid points of its edges, and then deduces atoms correspondingly with *a, b, c, d, e, f, g, h, k, l, m, n,* but finds another atom point at the mid point of PQ, together with four others asymmetrically placed. To quote his own words: "When all the information is put together we find that the element of volume of the diamond is a face-centred cube; a cube having, that is to say, a carbon atom at each corner and one in the middle of each face. In the same cube are also four carbon atoms at the centres of four of the eight small cubes into which the large cube may be divided." In other words his cube coincides with mine excepting that its outline is shifted aside by half an edge, and that it contains five extra atoms which are not represented by particles in my drawing, and which I have been unable to derive. The spacing between the planes of atoms parallel to the faces of the cube (100), the dodecahedron (110) and the octahedron (111) is the same as for the "particles," namely as $1 : \sqrt{2} : \sqrt{3}$, whether the five extra atoms are included or not.

By placing a particle at the origin (O) of the six-rayed figure, *i. e.* at the centre of the cube in Fig. 7, we should have

$$dO : db : dg = p/\sqrt{2} : p : \sqrt{3}p/\sqrt{2}$$
$$= 1 : \sqrt{2} : \sqrt{3}.$$

In this case successive ray-spaces might be placed face to face, whence the juxtaposition of adjacent halves of the ray-spaces would give a true lattice of face-centred cubes. The outside halves, however, would be derelict and the development of the octahedron not easily imaginable.

Rutherford seems to have had some difficulty with the structure found by Bragg, for in describing it ('Ann. Rep. Smithsonian Inst.,' 1915) he calls it cubical but complicated, and the "atoms are all equidistant, but the general arrangement differs markedly from that of rock salt. It is seen that each carbon atom is linked with four neighbours in a perfectly symmetrical way, while the linking of six carbon atoms in a ring is also obvious from the figure. The distance between the plates containing atoms is seen to alternate in the ratio 1 : 3." But neither this account nor the picture of the model made to illustrate it seems quite to agree with what Bragg said.