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The determination of the orientation of section planes of meteoritic irons.

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THE Widmanstetter figures on a general plane section of a meteoritic iron of the octahedrite class consist of kamacite bands running in four directions, the traces of the four planes of the octahedron, while tessellated octahedrites show three more sets of bands, the traces of the cube planes. The angles which these bands make with one another give data which are in principle sufficient to define the crystallographic axes of the iron, but in practice there does not appear to be any simple direct method of effecting this definition. In the following, two simpler cases are first discussed, followed by a method for the general case somewhat shorter than any published method[1] I am aware of, and by methods for orientation from the Neumann lines and from inclusions.

Mass with two non-parallel etched surfaces.[2]

If the iron has two etched surfaces meeting in an edge, it will in general be possible to measure the orientation of the kamacite bands on both

[1] A. Brezina, 1881; F. Becke, 1886; A. Himmelbauer, 1909; N. T. Belaiew, 1923; J. Leonhardt, 1928; C. S. Barrett, 1937. For references see list on p. 165.

[2] The methods described in this section had been previously used by the author for the construction of a crystal projection from drawings or photographs of the crystal from two (or more) directions making a known angle with one another. N. T. Belaiew (1923), R. F. Mehl and C. S. Barrett (1931), and D. W. Smith (1933) describe the use of two etched surfaces at right angles to locate the poles of inclusions or twin-planes, using the stereographic projection. C. S. Barrett (1937) outlines a method for the orientation of a plane from its traces on two etched surfaces which need not be at right angles, using the cyclographic projection (wrongly styled stereographic) and a Wulff net. Belaiew appears to have been the first to make full use of two etched surfaces, though Brezina and others used a second surface to eliminate ambiguities.

surfaces relative to this edge and the angle between the two etched surfaces; and by inspection of the edge, with a lens if necessary, it can be seen which pairs of bands on the two surfaces arise from the same kamacite plate. From these data it is a very simple matter to construct graphically a projection showing the relation of the two etched surfaces to the crystallographic axes, and if there is more than one crystal present, to determine their relative orientation. Two slightly different constructions are needed according as the angle between the two etched surfaces is between about 70° and 110° or outside these limits.

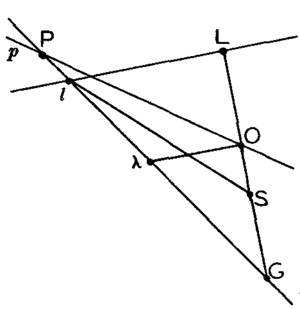

FIG. 1.

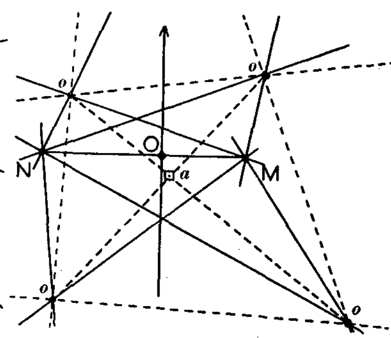

FIG. 2.

FIG. 1. Location of the gnomonic pole of a crystal plane from the traces of the plane on two surfaces at a known angle to one another, in projection on one of the two surfaces. Radius of projection 1·5 cm.

FIG. 2. Determination of the orientation of the left-hand crystal, *A*, of the Gibeon mass (B.M. 1941,1) from the traces of the octahedral planes on two etched faces, *M* and *N*. Gnomonic projection with radius 1·5 cm., on a plane in zone with the two etched surfaces. One of the cube poles is marked *a*, and the six cubo-octahedral zones are dotted.

If the angle is relatively small, one of the two etched surfaces is conveniently taken as plane of projection with centre *O* (fig. 1); on this plane are plotted the linear (*Ll*), gnomonic (*G*), and stereographic (*S*) projections of the other etched surface; the line *Ll* is parallel to the edge between the two surfaces. Now if *P* is the gnomonic projection[1] of any crystal plane, the line *OP* is normal to the trace of that plane on the plane of projection; hence a line *Op* through *O* making the same angle with *GSO* as the trace of *P* on the plane of projection does with the edge between the two etched surfaces must contain the pole *P*. Again, the

[1] The constructions are somewhat simpler in linear projection (see below, fig. 9), but the unfamiliarity of that projection probably outweighs the simpler constructions.

direction of the trace of P on the second etched surface can be found by the Goldschmidt (1891) construction for drawing crystals from the gnomonic projection; reversing this, if we draw a line through S making the same angle with GSO as the trace of P on the second etched surface does with the edge between the two surfaces and cutting the line Ll in l and join Gl, then Gl also must contain the pole P. Thus the gnomonic pole P is located by the intersection of Op and Gl.

Having located the poles of the octahedral planes, these are joined in pairs by straight lines, the other three intersections of which are the poles of the cube planes; the orientation of the etched surfaces in the crystal is fully defined by this projection and any angles desired may readily be measured, or if desired a new projection on any convenient plane may be prepared in the usual way. Unlike the two methods described below for the orientation of a mass with a single etched surface, this method always gives quite unambiguous results so long as the traces on the two etched surfaces can be paired off with certainty.

If the angle between the etched surfaces is too near 90° (between about 70° and 110°) the pole G will be so far from the centre as to make the above graphical construction impracticable. But if a projection plane is chosen in any position having a convenient known relation to the two etched surfaces, the reversed Goldschmidt construction can be applied twice. If the selected plane of projection is in zone with the two etched surfaces, as in fig. 2, the linear projections of the two etched surfaces will be parallel to one another and to the gnomonic projection of the edge between them; a knowledge of the direction of this edge is essential to the construction, forming the link between the measured angles on the two surfaces. If the selected plane of projection is not in zone with the two etched surfaces, the gnomonic projection E_G of the edge between the etched surfaces will be the line GG' (fig. 9 G), and its linear projection the point E_L where the linear projections L and L' of the two etched surfaces cut; now if GG' cuts the linear projections L and L' in g and g', the lines Sg, $S'g'$ replace GSO as the reference directions from which the lines Sl, $S'l'$ are set out at the observed angles; should g or g' lie unduly far from the centre, the directions of Sg, $S'g'$ may still be found readily, since they are at right angles to SE_L, $S'E_L$.

As an alternative to the selection of a different plane of projection when either L or G is unduly distant from the centre, the necessary distances and angles may be calculated: $\tan OGl/\tan OSl = LS/LG = \cos GO$; $Ll = R.\operatorname{cosec} GO.\tan OSl$ (where R is the radius of projection); if a line normal to GSO cuts Gl in λ, $O\lambda = R.\sin GO.\tan OSl$; and

$LlG = O\lambda G = 90° - OGl$ (fig. 1). It will almost always be possible to draw in Gl from a suitable selection of these angles, but should some particular line lie unduly distant from O, recourse must be had to the stereographic or the linear projection.

Two difficulties may arise in the application of this method. It may not be possible to make certain which set of traces on one etched surface corresponds to any particular set on the other etched surface; in this case we have four lines through O and four through G (fig. 1), and do not know how to pair them off. They can be paired off in 24 different ways, and it is necessary to find by trial which of these ways represents the projection of the octahedron planes of a cubic crystal. The gnomonic projection of an octahedron on a general plane is best recognized by joining all the faces in pairs; the six zone lines required meet in three additional points which, if the original four poles belong to a regular octahedron, will be the poles of the cube (a, figs. 2, 3); it is easy to test whether they are at 90° to one another. The difficulty may also be met by preparing a third etched face, in a known position relative to the first two; the three sets of lines now resulting will in general have only four, or at most ten, points of triple intersection; the selection of an octahedron from these will never be difficult.[1] This procedure is exemplified in fig. 3, which shows the orientation of a mass of the Butler iron from data for three etched surfaces given by A. Brezina (1881); the results agree well with Brezina's; one of the poles in fig. 3 lies too far from the centre for convenient gnomonic projection and has been treated stereographically. Secondly, it may not be convenient to prepare two etched surfaces which actually cut one another; yet it is absolutely necessary for the application of the method that the directions of the traces on both surfaces should be measured with respect to the line of intersection of the surfaces. This may readily be met by a variety of mechanical devices, of which the simplest is a pair of plates hinged together, each having an edge parallel to the axis of the hinge; if the plates are applied to the two etched surfaces, these two edges will both be parallel to the line of intersection of the surfaces, and reference marks can readily be made on both surfaces.

The above method has been applied to a mass of the Gibeon meteorite shower (B.M. 1941,1) described by Dr. L. J. Spencer (1941), which consists of two crystals with an irregular junction. On two etched surfaces at 84° to one another, the traces of the octahedron planes of one crystal

[1] This use of a third plane was proposed by R. F. Mehl and C. S. Barrett (1931) but never actually applied.

A (the left-hand one in fig 11, pl. II of Dr. Spencer's paper) are inclined at the following angles,[1] measured clockwise from [*MN*], the intersection of the etched surfaces: on surface *M* (the surface shown in the figure), 22°, 62°, 98°, and 135°; and for the same octahedron planes on

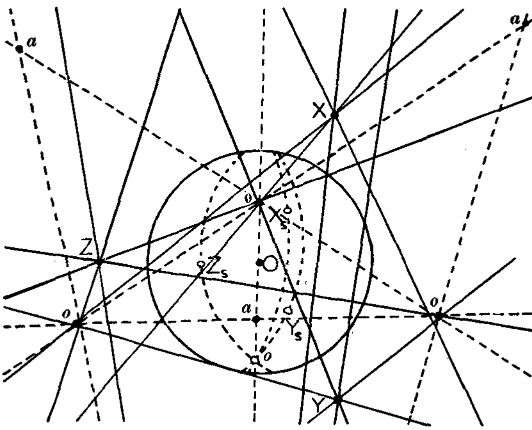

Fig. 3.

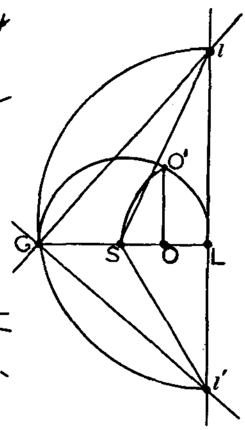

Fig. 4.

Fig. 3. An example of orientation from the directions of the traces on three etched surfaces (*X*, *Y*, *Z*): the Butler mass measured and figured by A. Brezina (1881). Mixed gnomono-stereographic projection, radius 1·5 cm.; stereographic poles shown as open circles. The six cubo-octahedral zones are dotted.

Fig. 4. Construction for determining the orientation of a cubic crystal from the traces of the cube faces on one reference face. Gnomonic projection, radius 1·0 cm.

surface *N* (which lies to the left in Dr. Spencer's figure, the edge [*MN*] being nearly parallel to the side of the figure), 106°, 38°, 150°, and 86° respectively. The second crystal, *B*, is only represented on surface *N* by a very small area, and it was not possible to measure all the traces accurately on this surface, nor to be sure of their correspondence with the traces on the surface *M*. On surface *M*, this second crystal shows seven traces, kamacite plates presumably parallel to the three planes of the cube being also present. The traces on surface *M* are inclined to the reference edge[2] at 7°, 28°, 56°, 88°, 122°, 135°, and 177° (measured clockwise), the 7°, 88°, and 177° traces probably being due to cube planes (the

[1] Taking the 135° trace as standard, Dr. L. J. Spencer's measurements (1941) place the other traces at 21°, 62°, and 98° to [*MN*].

[2] Taking the 135° trace as standard, Dr. L. J. Spencer's measurements (1941) place the other octahedron traces at 29°, 55°, and 124°, and the extra lamellae at 6°, 91°, and 176° to [*MN*].

7° trace is represented by a single kamacite plate); on surface *N*, there are traces at 44° and at roughly 85°, 115°, and 140° (these three angles are only very approximate); these appear to correspond with the 56°, 135°, 28°, and 122° traces on *M*, but owing to the small area of the surface it was not possible to be sure of this except for the first, nor even to be certain that the last three are octahedron and not cube traces.

Since one set of kamacite plates of the first crystal, *A*, gives traces at 135° and 86° on the two etched surfaces, and traces at about the same angles are observed in the areas occupied by the second crystal, though their common origin cannot be observed in this case, it appeared fairly probable that the two crystals had an octahedron face in common and were very possibly in twin position about [111].

No difficulty arose in locating the octahedron poles of the first crystal; a projection plane in the zone [*MN*], making an angle of 47° with *N* and 37° with *M*, was selected and the reversed Goldschmidt construction applied twice; the results are shown in fig. 2. The graphically determined poles are at angles of 67°, 73°, 69°, 71°, 74°, and 72° to one another, a reasonably good approach to the octahedral angle 70° 32′, and the poles of the two etched faces are located as follows: *M* at 82° to the octahedron pole *o* located by the 135° and 86° traces, in a zone at 19° clockwise to the zone [*oa*] (fig. 7), and *N* at 44° to the same pole *o*, in a zone at 69° anticlockwise to [*oa*]. This position gives calculated angles for the traces of crystal *A* on *M* of 23°, 63°, 97°, and 132°, and on *N* of 108°, 38°, 148°, and 87°, in good agreement with the observed values.

Since the correspondence of the traces of the second crystal, *B*, on the two etched surfaces (and indeed their positions on the surface *N*) is very uncertain, it seemed desirable to examine the 24 possible correspondences; only one (the one suggested by the observations and given above) gave poles roughly approximating to an octahedron, and this solution places the two crystals in roughly subparallel position, crystal *B* having an octahedron plane parallel to that plane of crystal *A* defined by the 135° and 86° traces on the two surfaces *M* and *N*, and being rotated about 10° relatively to crystal *A* about an axis normal to this common plane.

But owing to the difficulty of determining the positions of the traces of the planes of crystal *B* on the surface *N*, this result cannot be regarded as proven. However, we have reliable measurements of the positions of six of the seven traces of crystal *B* on the surface *M*, and any three of these should theoretically suffice to define the position of the crystal axes relative to the surface. There are four useful methods of procedure: by a graphical construction, the traces of the three cube planes may be used to define the crystal axes; or the traces of the four octahedron planes may be used by trial and error (C. S. Barrett, 1937), or by a semi-graphical method described below; or the angles between the traces of the octahedron planes may be calculated for all positions of the etched surface relative to the crystal axes, and a set of theoretical angles in reasonable agreement with the observed ones selected. This last method has been used by A. Brezina (1881), N. T. Belaiew (1923), J. Leonhardt (1928), and A. Himmelbauer (1909), but it is not particularly convenient.

Further, if the two crystals are in twin position (about a [111] axis) the second can only be in one of four positions relative to the first, and since the orientation of crystal *A* has been established without ambiguity, it is a simple matter to test whether any of the four possible twin relations gives traces at the angles observed. This has been done, but in none of the four possible twin positions do the graphically calculated positions of the traces agree with the observations.

Tessellated octahedrite with a single etched surface.

If the traces of the three cube planes on a reference surface are measurable, as they may be in a tessellated octahedrite, it is possible to determine the orientation of the crystal relative to the surface by a direct graphical construction. For suppose a gnomonic projection made on a cube face (fig. 4), and let *O* be the centre of projection, and *Ll* the linear, *G* the gnomonic, and *S* the stereographic projection of the etched surface; then the directions of the traces of the cube on the etched surface are normal to *SO*, *Sl*, and *Sl′*, where *l* and *l′* are found by drawing lines through *G* parallel to the two cube axes that lie in the plane of the projection to cut *Ll* in *l* and *l′*. To reverse this construction, we begin with a projection on a cube face, of unknown origin and radius of projection; with any convenient distance *SL*, draw *SL*, *Sl*, *Sl′* normal to the traces of the three cube faces, selecting *SL* so that it makes acute angles with both *Sl* and *Sl′*, while the angle *lSl′* is obtuse, and let *lLl′* be at right angles to *SL*; on *ll′* erect a semicircle, cutting *LS* produced in *G*; then *Gl* and *Gl′* are the directions of the two cube axes in the plane of projection. The origin and radius of projection are determined by erecting a semicircle on *LG* and striking an arc with centre *L* and radius *LS*, cutting the semicircle in *O′*; if *O′O* is made normal to *LS*, *O* is the origin and *OO′* the radius of projection, defining the position of the third cube axis relative to the reference surface. There is, however, one ambiguity; it is obvious that a turn through 180° about an axis normal to the etched surface will not alter the directions of the traces, and accordingly this method (or any other using a single etched surface) always leads to a pair of solutions which have this relation to one another.

This procedure was applied to the Gibeon mass (B.M. 1941,1), taking the three traces on *M* at 7°, 88°, and 177° given by crystal *B* as cube planes. The construction located the cube axes at about 46°, 44°, and 85° to the pole of the etched surface, the last lying nearly in the surface at a small angle to the edge between the two surfaces; this position, however, leads to angles for the traces of the octahedron poles of 36°, 89°, 93°, and 146° clockwise from [*MN*], in very poor agreement with observation, nor does any nearby position give better agreement, and there is reason to believe that the single kamacite lamella at 7° to the edge between the two etched surfaces does not represent a cube plane.

Octahedron traces on a single etched surface.

I have not been able to find a direct graphical solution for the orientation of a meteorite from the traces of the octahedron planes on a single etched surface, but the following procedure gives a solution by trial with a single variable. Trial with a single variable has several advantages over two-variable tables or over trial and error procedure with a Wulff net and a standard projection on tracing-paper (C. S. Barrett, 1931), giving greater certainty that no possible solution has been overlooked and allowing of interpolation with ease.

Let a gnomonic projection be prepared on one of the octahedron planes, and let *O* (fig. 5) be the centre of projection and pole of one octahedron plane, *Ll* the linear, *S* the stereographic, and *G* the gnomonic projections of the etched surface (position unknown); the gnomonic poles of the other three octahedron planes will lie 120° apart on a circle about *O*, of $70\frac{1}{2}°$ radius, which is drawn; *GSO* will be normal to the direction of one of the octahedron traces. Applying the reversed Goldschmidt construction, lines are drawn through *S* at the appropriate measured angles made by the other three traces with the one selected as *GSO*, to cut *Ll* in three points, *l*, *l′*, *l″*; then if the position of the etched surface in the projection was correctly chosen the gnomonic poles of the other three octahedron planes must lie at the intersections of *Gl*, *Gl′*, *Gl″* with the $70\frac{1}{2}°$ circle about *O*. It is a simple matter to carry out trials with values of *GO* at suitable intervals from 0 to 90°; any value of *GO* which leads to a sheaf of three lines *Gl*, *Gl′*, *Gl″* intersecting the $70\frac{1}{2}°$ circle at intervals of 120° is a possible solution and completes the orientation by locating the other octahedron poles with reference to *GSO*. There is, however, one ambiguity, for since a turn through 180° about the normal to the etched surface does not alter the directions of the traces, each solution obtained from the above construction will define two orientations of the crystal relative to the etched surface, having this relation to one another.

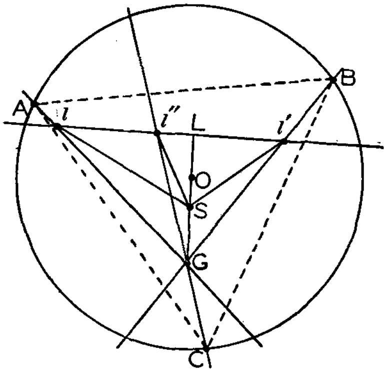

FIG. 5.

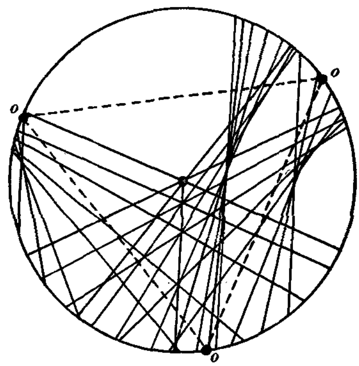

FIG. 6.

FIG. 5. Derivation of the directions of the octahedral traces on any section plane; gnomonic projection on an octahedron plane. Radius of projection 0·8 cm.

FIG. 6. Determination of the orientation of the section plane from the traces of the octahedron planes on one etched surface; this figure refers to the right-hand part of the Laurens County mass described by Himmelbauer. Gnomonic projection with radius 0·8 cm.

In practice, certain small modifications are necessary, for when GO is near 0°, Ll will be inconveniently distant from O; and when GO is near 90°, G will be inconveniently distant. But the angles OSl, OSl', OSl'' are the measured inter-trace angles, and $LS = R.\mathrm{cosec}\ GO$, and $LG = R\,(\cot GO + \tan GO) = LS.\sec GO$ (where R is the radius of projection). Hence $\tan OGl = \tan OSl.\cos GO$, and $Ll = R.\mathrm{cosec}\ GO.\tan OSl$. A table is therefore prepared of the angles OGl corresponding to the observed angles OSl and GO values at suitable intervals from 0° to 90°; the calculations may be carried out for 5° intervals in a few minutes, using a slide rule, as $\frac{1}{2}$° accuracy is quite adequate; values of Ll' are also calculated for GO values above 75°. It is now possible to dispense with the graphical construction of Gl, and to draw in the lines Gl, Gl', Gl'' directly from the tabulated angles for all values of GO up to 75°; for GO values above 75°, the appropriate lines Ll are drawn, the proper distances Ll measured off, and the lines Gl drawn in at angles $LlG = 90° - OGl$. The lines Gl will be found to form three families (fig. 6), each sweeping across the $70\frac{1}{2}°$ circle, and with the aid of a piece of thin celluloid or thick cellophane marked with three lines radiating at 120° and pivoted on a pin through O, all possible solutions are readily located.

There is only one complication; the angles OSl are measured angles, subject to errors of measurement, and hence the intersections of Gl with the $70\frac{1}{2}°$ circle will not lie at exactly 120° from each other even for the true position of G; and the departure may sometimes be quite considerable with unfavourable values of OSl and GO. It is therefore desirable to select that trace the direction of which can be most accurately measured as GSO, and whenever two only of the lines Gl, Gl', Gl'' intersect the $70\frac{1}{2}°$ circle at 120° to each other, to check whether the third 120° position leads to an inter-trace angle in fair agreement with observation. Experience with the method has led to some useful practical points; traces at small angles to the reference trace GO serve well to define the orientation of the triangle ABC relative to GO, but are apt to give uncertain values of GO, while traces at angles near 90° to GO define well the angle GO, but are apt to leave the orientation of the triangle imperfect. It is therefore often best to rely on the trace making the smallest angle with GO to define the orientation of the triangle ABC relative to GO, and take the mean of the GO values obtained from the three traces (other than GO) taken in pairs. Again, planes lying very near the section plane give no traces, or very broad ones of uncertain direction which would not be selected as GO; accordingly any solution giving a small value of the angle GO, or attributing an observed trace to a plane very near the section plane may be rejected unless the trace so attributed has the proper characters.

Where the etched surface shows only a single individual, the possible orientations may readily be described in terms of angles measured on the octahedral plane projection (figs. 5 and 6); but where two or more individuals are present, it will be preferable to change the projection plane so that the several individuals are all projected on the same plane; the etched surface will often serve as a convenient common projection plane. This transformation may be carried out without difficulty by the usual methods, either in gnomonic projection or after transformation to the stereographic. The reference line to which the measurements for the several individuals are referred is marked in, and all possible relative orientations of the individuals can be described without danger of error. Spinel-twinning will be obvious, even on such a chance plane of projection, since two crystals in twin position must have one face and the three cubo-octahedron zones through this face in common.

This method also has been applied to the Gibeon mass (B.M. 1941,1). The traces of the first (left-hand) crystal, *A*, on the first section plane *M* were taken as a test of the method; the octahedron plane giving rise to the 135° trace was selected as projection plane. The other three octahedron traces form angles with [*MN*] of 22°, 62°, and 98° (clockwise). Using the above construction, no three poles at 120° could be found, but several pairs of poles at 120° could be located; the only possible solution being with *GO* 77°, when the 62° and 98° traces give poles at 120° and the third trace should be at 27° (observed 22°). This solution places the pole of *M* at 77° from the pole *o* of the octahedron giving rise to the 135° trace, in a zone 24° clockwise from [*oa*] (fig. 7) and defines two positions of the crystal relative to the surface *M*, related by a turn through 180° about the normal *M*. One of these two positions brings the pole of *N* 133° from the pole of *o* in a zone 89° anticlockwise from [*oa*] and gives calculated positions for the octahedron traces on *N* of 38°, 70°, 124°, 144° (observed, 38°, 86°, 106°, 150°); this position can accordingly be rejected. The other approximates to that found by consideration of both etched faces, for which the angles were *M* 83° from *o* and 19° clockwise from [*oa*]; it would place the pole of *N* at 44° from *o* in a zone 72° anticlockwise from [*oa*] and give practically the same angles for the traces on *N*; the only difference between these last two positions is that one puts the error mainly on the 62° trace, the other mainly on the 22° trace, and any intermediate position would be equally acceptable.

Turning to the right-hand individual, *B*, the traces on *M* were treated by the above method, using the octahedron plane responsible for the 135° trace as projection plane. Again, no set of three poles at or very near 120° could be found, and the method used in the last paragraph was adopted; three possible solutions resulted, two of which are practically the same and were accordingly averaged, giving two solutions: the pole of *M* may be 77° from the octahedron plane *o* giving the 135° trace, in a zone at 7° clockwise from [*oa*] (solution *P*), or it may be 35° from *o* in a zone 3° clockwise from [*oa*] (solution *Q*). Each solution has two variants (P_1, P_2; Q_1, Q_2), related by a turn through 180° about the normal to *M*, which may be defined by reference to the pole of *N*: for P_1, *N* lies at 44° from *o* in a zone 89° anticlockwise from [*oa*]; for P_2, these angles are 132° and 105°; for Q_1, 60° and 125°; and for Q_2, 109° and 131°. Further study shows that positions P_1 and Q_2 are not very different from one another; but the difference is definite, and any intermediate position would give much worse agreement between the observed and calculated directions of the traces; positions P_2 and Q_1 are similarly related. If the cube traces or the traces on the etched surface N were better developed for this crystal, it would be possible to decide between these solutions; on the whole, position P_1 for crystal B gives the best agreement, but P_2 is nearly as good, Q_2 is fair, and Q_1 cannot be wholly excluded.

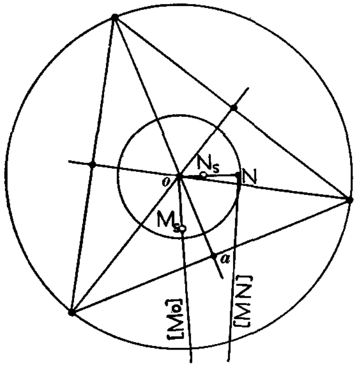

FIG. 7.

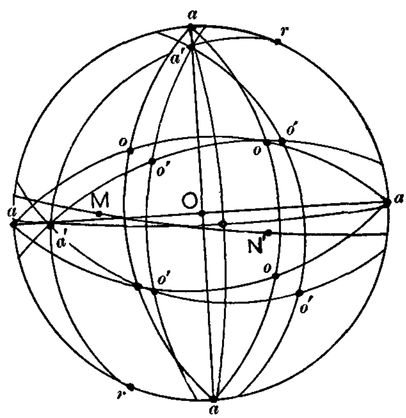

FIG. 8.

FIG. 7. The orientation of the left-hand crystal A, of the Gibeon mass (B.M. 1941, 1) with reference to the two etched surfaces M and N (M is the figured surface); in gnomonic projection on an octahedron plane. Radius of projection 0·8 cm.; the gnomonic pole of M falls outside the figure, so the stereographic pole is shown instead (M_s); the stereographic pole of N (N_s) is also shown.

FIG. 8. The relative positions of the two crystals of the Gibeon mass (B.M. 1941, 1) shown in stereographic projection on a cube face of the left-hand crystal, A. Radius of projection 2·5 cm. Pole of the rotation relating the two crystals marked r.

Elimination of ambiguities; true orientation of the Gibeon mass.

It has always been recognized that any method of orientation using only the directions of the traces on a single etched surface will necessarily give at least two solutions, related by a rotation of 180° around the normal to the etched surface, and may give more than one such pair. The means available for the elimination of these ambiguities were described by A. Brezina (1881): (1) subsidiary etched surfaces will normally prove very effective, but may fail if they are too small, while if they yield accurate measurements, these are best used by the first of the methods described above rather than as mere check values; (2) the approximate directions of one or more planes may be disclosed by natural features of the meteorite—weathering or cleavage cracks—and may prove sufficient; (3) in a deeply etched meteorite, the taenite plates may stand up sufficiently to give an oriented sheen which will decide their direction of inclination to the etched surface, but care must be taken that the origin of such a sheen is fully established;[1] (4) Brezina observed the frequent occurrence of pits of sufficient dimensions to furnish approximate goniometric measurements on sealing-wax imprints, but this appears to have been due to the methods of section cutting and etching in use, as such pits do not appear on modern sections; (5) since the apparent width of any kamacite band is $t \operatorname{cosec} \theta$, where t is its true thickness and θ its angle of inclination to the etched surface, the mean relative widths of the several sets of bands serves as a rough measure of their several inclinations and may decide between pairs of solutions.

The application of these methods to crystal B of the Gibeon mass (B.M. 1941,1) shows that solution P_1 is the correct orientation. For with solutions P the 122° trace is at 33°, and the 135° trace at 77° to the surface M, while with solutions Q these angles become 75° and 35° respectively (the difference between the angles for the other traces is too small to be of any use); hence the 122° trace should be 1·8 times the width of the 135° trace with solutions P but only 0·6 of the width with solutions Q; it is readily seen from Dr. Spencer's figure (1941) that the 122° trace is the wider, so the pair of solutions Q may be rejected. Reflections from the projecting taenite plates give a sheen at positions which indicate that the 122° and 135° traces are respectively due to plates the normals to which emerge towards the top right and the bottom left corners of Dr. Spencer's figure; this accords with solution P_1 (P_2 would require the reverse).

The correctness of this solution was subsequently proved by the preparation and examination of a third etched surface. This third surface N' is exactly parallel to N, and is to the right of Dr. Spencer's figure; it cuts crystal B only, and shows traces at 128°, 43°, 147°, and 74°, measured anticlockwise[2] from the edge $[MN']$, and corresponding respectively with the 28°, 56°, 122°, and 135° traces on M; this agrees with the directions predicted for position P_1. It also allows of a direct solution

[1] In very deeply etched sections the taenite plates may project sufficiently to give fair goniometric reflections (cf. R. F. Mehl and C. S. Barrett, 1931). Besides this oriented sheen, arising from projecting taenite, there is another arising from the etched surface of the kamacite, and originating from planes near the cube planes of the kamacite (O.B. Bøggild, 1927); since the possible positions of the kamacite cube planes relative to the octahedron planes of the taenite are known, this should provide an approximate orientation of the latter and serve to eliminate ambiguities; but its application for this purpose would be troublesome.

[2] Since N' is opposite to N, angles measured anticlockwise on N' correspond in direction to those measured clockwise on N. No cube traces could be found on the surface N'.

for both crystals by the first method described above and as this is the most accurate method, it has been used; the results show that the planes of the two crystals giving rise to the 135° trace on surface *M* are not so nearly parallel as was at first thought, the angle between them being about 9°; for crystal *B*, the pole of *M* lies 75° from *o* in a zone at 7° clockwise to [*oa*], and 47° from *N* in a zone at 90° to [*oa*], a solution agreeing closely with solution P_1 above. The two crystals are related to one another by a rotation of 15° about an axis lying in a cube face, and inclined 27° to the normal to that cube face which in crystal *B* gives rise to the 88° traces (fig. 8); the rotation is clockwise in passing from *A* to *B*.

The single kamacite plate in crystal *B* visible on surface *M* at 7° to the edge [*MN*] cannot be accounted for as an octahedron or a cube plane; its trace on *M* is a zone line having indices near [7.8.38], which suggests that it is probably really $(1\bar{1}0)$, which would give a trace at 11° to [*MN*]; but since it does not cross the edge [*MN*] its orientation cannot be definitely established.

The relative orientation of the crystals in polycrystalline meteoritic irons.

In view of the rarity of iron meteorites showing more than one large crystal in a mass, and of the fact that three such masses have been described as spinel-twins, it would be of interest to carry out a survey of iron meteorites to determine the nature of the association wherever more than one crystal is present. At the moment, the British Museum collections are dispersed for safety and not available for such a survey, but it is hoped to make one in due course. As a preliminary, the data available from the literature have been studied and the evidence that the three masses described are spinel-twins checked. In each case, the available data consisted of trace directions on a single etched face; at best, this will give a pair of solutions for each crystal, four results in all for the orientation of the two crystals in the mass, but only two for their orientation with respect to one another. If one of these two possible relative orientations is a twin position, it is very probably the correct one for otherwise a chance section plane must have cut a pair of crystals in chance relative orientation to give the same angles as if it had cut a twin—a very improbable event. In the following, the statement that a reported twin has been confirmed must (unless amplified) be read as indicating that re-examination of the available data leads to a pair of possible relative orientations one of which is a twin position; without further evidence, it is possible, though not probable, that the relation may be only a chance one.

The $1\frac{1}{2}$-kg. mass of the Laurens County fall in the Vienna collection was described by A. Himmelbauer (1909) as a spinel-twin, with a well-developed composition-plane. A re-examination of his data confirmed the twin relation he found; he states that the orientation was checked from small additional etched faces, but gives no details.

A 72 cm. square plate of the Gibeon (Bethany) shower in the Vienna collection was described by F. Berwerth (1902) and by Himmelbauer (1909) as a spinel-twin with irregular composition surface. Re-examination of their data indicated that this finding is probably correct, but another pair of positions for the right-hand crystal are possible and would not be in twin relation to the left half. Again, Himmelbauer states that the orientation was checked from additional etched faces, but gives no details.

Another mass of the Gibeon shower, the 178-kg. Mukerop mass, was cut into two masses of 86 and 61 kg. and a slice of 16 kg.; this slice, in the Stuttgart collection, was described as a spinel-twin with well-developed composition-plane and figured by A. Brezina and E. Cohen (1902); the 61-kg. piece in the Vienna collection was described by A. Himmelbauer (1909), and this piece and several slices into which J. Böhm had cut the 86-kg. piece were described by F. Berwerth (1902), the 61-kg. piece being figured (evidently the opposed face to that figured by Brezina and Cohen). The positions found by these authors are in agreement and are confirmed by re-examination of their data. The several slices of this mass described by Berwerth show that several crystals are present; all save one are in repeated twin relation about one axis, some with well-developed composition-planes, some with irregular junctions. But one individual does not belong to this series; unfortunately, Berwerth gives no numerical data, and his sketch figures are too small for more than rough measurements, even if they may be assumed angularly accurate. However, the trace directions to be expected for a crystal twinned on any [111]-axis to a crystal in either of the orientations of the repeated twin series have been determined, and none of the six possibilities agrees even roughly with Berwerth's sketch; it is therefore almost certain that this crystal (Berwerth's no. 6) is not in twin relation to any of the others. It is desirable that one or more of the slices in which this individual is present should be re-examined and its orientation definitely established; the specimen B.M. 85891, weighing 4320 grams, was bought from J. Böhm in May 1902 and may be suitable; it is hoped to examine it when it is again accessible for study.

Thus the scanty data at present available show that the crystals in polycrystalline iron meteorites may be in twin orientation about [111], either with an irregular junction or with (111) as composition-plane; or they may be in roughly subparallel position; and it is probable that quite irregular relative positions also occur. It is noteworthy that three of the four polycrystalline masses so far described belong to the Gibeon shower.

Use of projections other than the gnomonic.

In all the above constructions the gnomonic projection has been used almost exclusively. But precisely parallel constructions may be made in the other three crystallographically useful projections.

In the stereographic projection the Goldschmidt construction for crystal drawing is paralleled by F. Stöber's (1899), which may be reversed in just the same way—a series of great circles are constructed through the stereographic pole of the etched surface at the same angles to the projection of the reference direction as the several traces make; the poles of the planes giving rise to the traces must lie on these great circles. This construction (fig. 9 S) may be preferred by some, but unless a very large radius of projection is used (a step which has several disadvantages), I find it uncomfortably cramped; and for the orientation of an octahedrite from traces on a single etched surface, the multiplicity of circles becomes far more confusing than the families of straight lines obtained in the gnomonic projection. The stereographic projection was used by C. S. Barrett and co-workers (1931–37) for the orientation of a plane from its traces on two etched surfaces, using a Wulff net to lay out the necessary angles, and for the orientation of a plane from its traces on a single etched surface by trial and error with two variables.

The reversed Goldschmidt construction is readily adapted to the linear projection,[1] (fig. 9 L), but on the balance this has no particular advantages over the gnomonic projection except perhaps for the orientation of an octahedrite from the traces on a single etched surface. Here the replacement of an assemblage of lines by points may reduce the chance of confusion and outweigh the unfamiliarity of the projection; the appropriate distances LT along various trial positions of the section plane L are conveniently calculated from the equation $LT = R.\sec LO.\cot\theta$, where θ is the angle between the reference trace L (which in this projection lies at infinity) and the trace T of an octahedron plane on the etched surface; an example of the use of this projection is shown in fig. 11.

[1] See E. S. Fedorov, 1898, for the adaptation of the direct Goldschmidt construction to these projections.

In the cyclographic projection, the reversed Goldschmidt construction is again readily paralleled, but it is doubtful if the projection has enough advantages to outweigh its unfamiliarity. It has, however, been proposed by C. S. Barrett (1937) to orient a mass with two non-parallel etched surfaces.

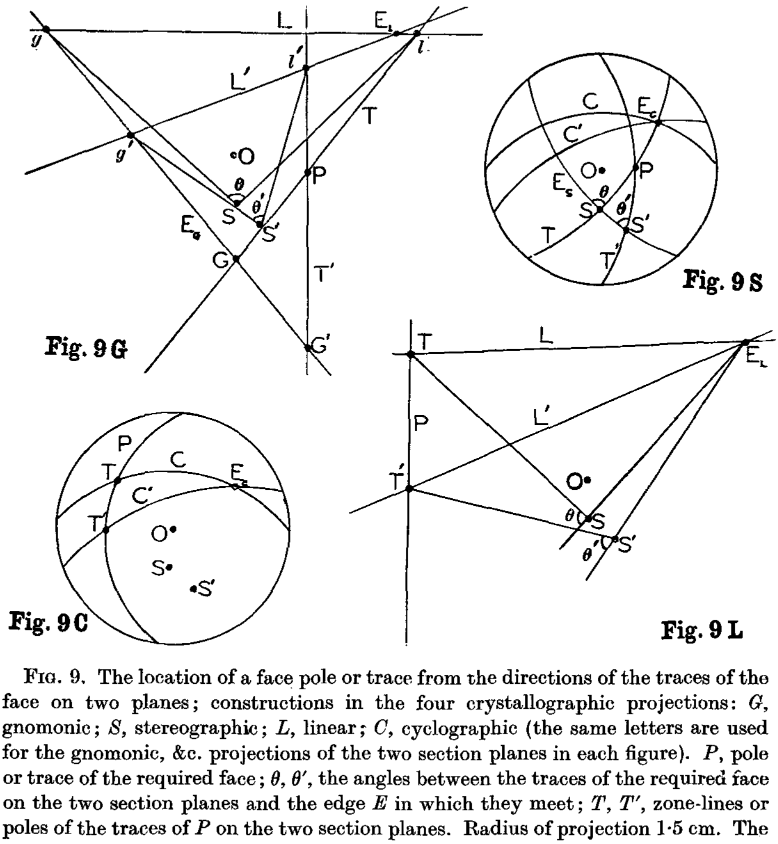

FIG. 9. The location of a face pole or trace from the directions of the traces of the face on two planes; constructions in the four crystallographic projections: *G*, gnomonic; *S*, stereographic; *L*, linear; *C*, cyclographic (the same letters are used for the gnomonic, &c. projections of the two section planes in each figure). *P*, pole or trace of the required face; θ, θ', the angles between the traces of the required face on the two section planes and the edge *E* in which they meet; *T*, *T'*, zone-lines or poles of the traces of *P* on the two section planes. Radius of projection 1·5 cm. The same angles are used in all four projections.

A combination of the gnomonic and stereographic projections was advocated for general crystallography by T. V. Barker (1922), those poles which are too distant from the centre for convenient gnomonic projection being treated stereographically, and the combination is very effective and trouble-free for the present purpose also. The same end could be attained by a combination of the gnomonic and linear projections, but the risk of confusion is greater when two straight-line projections are combined (unless different colours of ink are used for the two) than in the combined gnomono-stereographic projection, where it is obvious which zone-lines belong to which projection. An example of this combined projection is given in fig. 3.

Orientation of a meteorite from Neumann lines.

The above methods should allow of the orientation of any octahedrite (except perhaps a small section of a coarsest octahedrite); the Neumann lines should in principle allow of the orientation of any mass in which they are well developed, and attention was next directed to the problem of their utilization. Where two or more etched surfaces are available, the method described on p. 141 should lead directly to an unambiguous orientation, and is greatly to be preferred wherever possible.

But it may be desirable to orient a mass from the Neumann lines on a single etched surface; while the following methods may be rather tedious and may lead to several possible solutions, they have proved effective in practice. C. S. Barrett (1937) proposes to use a method of trial and error with a Wulff net and a 'standard projection' of (211) on tracing-paper; he does not give any practical illustration, and it is very doubtful if all possible solutions could be traced in this way except at an inordinate expense in time.

A well-marked line, the direction of which can be accurately established, is selected as reference direction on the etched surface, and the corresponding (211) plane as plane of projection; as in the method described on p. 148 values of *OGl* and *Ll* (fig. 1), or if the linear projection is to be used values of *LT* (fig. 9 L), are calculated for values of *GO* at 5° or 10° intervals from 0 to 90° for each of the other Neumann lines observed.

It is quite possible to seek out all possible solutions by trial and error, using a gnomonic projection of the form (211) on one of its faces, made on transparent material,[1] as a trial plate over a gnomonic projection showing as families of lines the observed Neumann lines projected for various values of the angle *GO* between the face of (211) chosen as projection plane and the etched surface; the procedure is much the same as for the orientation from the Widmanstetter figures on a single etched surface. But if the directions of the observed Neumann lines are numerous the families of lines tend to become confusing, while the gnomonic projection of the form (211) on one of its faces, including as it

[1] A drawing made on thin typing-paper may be rendered reasonably transparent by painting it on both sides with a suitable colourless lacquer; a solution of vinyl acetate polymer serves very well.

does four poles at 80° 24′ from the centre, is inconveniently large. For these reasons, the linear projection is decidedly preferable for this particular problem.

In the linear projection, the sheaf of lines *Gl* through the pole *G* of the section plane are replaced by points *T* on the linear trace *Ll* of the plane. For the orientation of a meteorite from the observed Neumann lines a drawing is made on tracing-paper of the linear projections of a series of trial section planes at angles from 15° to 90° to the plane of projection, marking in on each the points *T* corresponding to the observed angles between the Neumann lines, one of which serves as reference direction, and its generating (211) plane as plane of projection; the points *T* are joined to give the loci of the linear projections of the several Neumann lines for all values of *GO*. This projection is laid over a linear projection of the cubic form (211) on one of its faces, and rotated about a pin through the centre of both; if any relative position can be found in which all the points *T* on one trial section plane fall on lines in the projection of the form (211), that relative position and section plane define a possible solution. The possibility that the section plane will lie within 15° of the plane of projection is very small, for a slip-plane within 15° of the etched surface is not likely to give a well-marked set of Neumann lines on that surface; but if it is felt desirable, another pair of projections with half the normal radius of projection (a 5 cm. radius is suitable for most of the above constructions) will reduce the unexamined range to 7½°. In order that the trial projection on tracing-paper shall be kept to a reasonable size, the Neumann line selected as reference direction should be so chosen that it does not make a small angle with any other—if possible, not less than 20°, or better 30°. Allowance must be made for possible experimental error in the angles between the Neumann lines; loci drawn parallel to the loci of *T* at a distance equal to the estimated possible experimental error assist in this.

This method was tried for the orientation of the kamacite of the Piedade do Bagre meteorite, a medium octahedrite with well-developed Neumann lines, described and figured by Dr. L. J. Spencer (1930). In Dr. Spencer's fig. 8, pl. XII, the directions of the Neumann lines in several lamellae can readily be measured; four of the best were selected for study, and fig. 10 serves as a key for the identification of these in his figure. The boundary between lamella *D* and the adjacent plessite triangle was taken as reference direction, and the following angles are measured clockwise: lamella *A* belongs to a family at 112° to lamella *D*, and has Neumann lines at 18°, 35°, 106°, and 141°; lamellae *B* and *C*, also at 112° to D, have Neumann lines at 18°, 35°, 67°, 83°, 118°, and 151°; lamella D has Neumann lines at 12°, 18°, 41°, 93°, 136°, and 148°; and lamella E, at 45° to D, has Neumann lines at 89°, 103°, 132°, and 166°. The fourth, broad set of kamacite bands are not represented in Dr. Spencer's fig. 8, but according to his measurements they are at about 88° to D, and their generating plane is inclined about 20° to the etched surface.

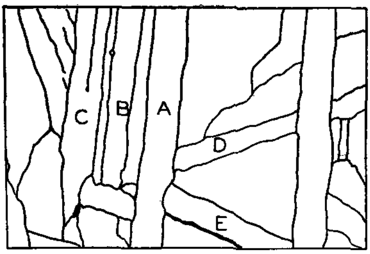

FIG. 10.

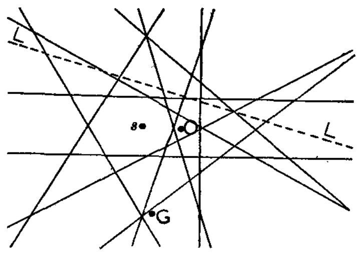

FIG. 11.

FIG. 10. Key to the kamacite lamellae selected for orientation by their Neumann lines from those shown in Min. Mag., vol. 22, pl. XII, fig. 8; medium octahedrite, Piedade do Bagre, Brazil. Scale ½ that of the plate.

FIG. 11. Orientation of a kamacite lamella (B) of the Piedade do Bagre meteorite from the Neumann lines; linear projection on a face of (211); six pairs of solutions agree with the observed directions of the lines; the one shown is the true solution. G, gnomonic pole and L linear projection of the etched surface; s, linear pole of [100]. Radius of projection 0·8 cm.

When studied by the above method, allowing each measurement an accuracy of $\pm 3°$, six pairs of solutions were obtained for the orientation of lamellae B and C; one of these is shown in linear projection on a face of the form (211) in fig. 11. For lamella D, eight pairs of solutions, and for A, forty-six pairs were obtained; lamella E was not studied. The immediate result of this work was to show that the method is a practical one, allowing of the orientation of the kamacite lattice from the Neumann lines on a single etched surface; the number of solutions obtained depends on the number of sets of Neumann lines observed and the accuracy with which their directions can be measured, and the present example is a particularly unfavourable one; at the same time, the results emphasize the desirability of using two etched surfaces where possible.

In many cases, a choice among the results obtained by the above method should be possible by utilizing the oriented sheen of the kamacite. As shown by O. B. Bøggild (1927) and by S. W. J. Smith, A. A. Dee, and J. Young (1928),[1] this sheen on a surface etched with nitric acid is due to planes vicinal to (100); the sheen thus serves to locate approximately one or more cube planes. In the present instance, the specimen is temporarily inaccessible, and this help was not available.

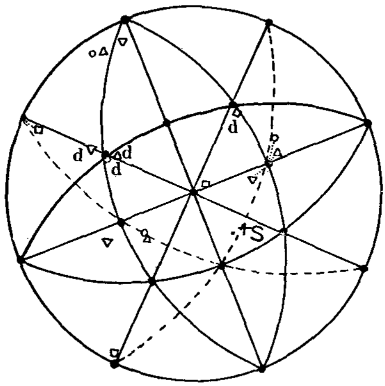

FIG. 12.

FIG. 12. The Piedade do Bagre meteorite; stereographic projection on a cube plane of the taenite, showing the stereographic pole, S, of the etched surface, and the orientation of several kamacite lamellae relative to the taenite. The poles of the taenite are shown as filled circles, of lamellae B and C (fig. 10) as open circles, of lamella D as squares, and of two possible positions of lamella A as upright and inverted triangles. The poles plotted are the cube poles of both kamacite and taenite, (111) and [110] of taenite, and that (110) pole, d, of each kamacite lamella which is normal to the Widmanstetter plane. The traces of the Widmanstetter planes are dotted.

The relative orientation of the kamacite and taenite.

The relative orientation of the kamacite and taenite in meteorites, and of the α- and γ-phases in artificial nickel-iron alloys and in plain carbon steels has been the subject of many studies. O.B. Bøggild (1927) used the oriented sheen and the included rhabdites as a means of orientation, while other authors have used X-ray methods.[2] While there are some differences of opinion as to the exact relative position of the two lattices, it is generally agreed that a (110) plane of kamacite is parallel to a (111) plane of taenite and to a plane of the Widmanstetter structure within

[1] Here it is also shown that when copper ammonium chloride is used for etching, the etch pits are bounded mainly by planes of (110).

[2] J. Young, 1926, 1930; G. Kurdjumow and G. Sachs, 1930; R. F. Mehl and D. W. Smith, 1934; Z. Nishiyama, 1934; R. F. Mehl and G. Derge, 1937; G. Derge and A. R. Kommel, 1937; S. W. J. Smith and J. Young, 1939; J. Young, 1939.

about 1°, while a [100] axis of the kamacite lying in the Widmanstetter plane is approximately parallel to a [110] axis of the taenite.

The orientation now obtained from the Neumann lines, while not approaching in accuracy that obtained by X-ray methods, provides independent confirmation of the truth of this approximate relative orientation: for of the six pairs of solutions obtained for lamellae *B* and *C*, only one shows any approach to a regular orientation, and this one has the (110) plane of the kamacite at about 3° to (111) of the taenite and a [100] axis of the kamacite about 13° from a [110] axis of the taenite in the Widmanstetter plane; of the eight pairs of solutions obtained for lamella *D*, the only one showing any approach to regular orientation has (110) of kamacite at 4° to (111) of taenite and a [100] axis of the kamacite about 6° from a [110] axis of the taenite in the Widmanstetter plane; and of the forty-six pairs of solutions obtained for lamella *A*, the Widmanstetter plane (111) of the taenite, coincides approximately with (111) of kamacite in three, with (211) in two, with (221) in three, with (210) in four, and with (110) in five pairs, while if the parallelism of (110) of kamacite with (111) of taenite be accepted, two of the ten solutions (five pairs) which fulfil this condition have a further regularity, namely an approximate coincidence of [100] kamacite with [110] taenite, the angles being 9° and 11° in the two cases. For lamellae *B*, *C*, and *D*, the confirmation of the accepted relative orientation of the kamacite and taenite is very satisfactory, while in the very unfavourable case of lamella *A* there is good agreement with the accepted orientation, but the data are not adequate to afford independent proof. The relative orientations of the taenite and these lamellae are shown, in projection on a cube plane of the taenite, in fig. 12.

The orientation of the tesseral lamellae of the Gibeon masses.

The orientation of the kamacite plates of typical octahedrites has thus been determined by both X-ray and purely morphological methods, with good agreement. But the orientation of those kamacite lamellae parallel to the cube plane of the taenite, which appear in the tessellated octahedrites, remains undetermined. J. Young (1939, p. 418) notes that it would appear possible that they might be oriented with one cube face of the kamacite and taenite parallel to one another and to the surface of the lamella, and a pair of dodecahedron planes of the kamacite parallel to the other two cube planes of the taenite; but from a study of F. Rinne's figures (1910) he considers it more probable that the kamacite in the tesseral plates has the normal orientation relative to the taenite.

The Gibeon mass (B.M. 1941,1) has been carefully examined and Young's suggestion is fully confirmed, for each tesseral plate studied was clearly seen to be continuous with one set of octahedral plates; the octahedral plates grow out from the tesseral plate in many places, and under suitable magnification, Neumann lines are visible, and can be seen to be parallel in a tesseral lamella and the set of octahedral lamellae having the same orientation. Referring to pl. II, fig. 11, of Dr. Spencer's paper (1941), the prominent double plate running vertically near the centre of the photograph consists of two plates in different orientations, the right-hand one being continuous with the octahedral lamellae at 28° to [*MN*], the left-hand one with those at 135°. Other lamellae have been examined with similar results. The single 7° lamella, possibly parallel to a face of (110), is of similar character and appears to be continuous with the octahedral lamellae at 56°.

The orientation of a meteoritic iron with the aid of inclusions.

Iron meteorites commonly carry inclusions of many kinds, some of which occur as rounded, featureless globules, while others form plates or needles in regular orientation relative to the matrix.[1] Where the relation

[1] O. B. Bøggild (1927) has shown that acicular rhabdites (schreibersite) in nickel-poor ataxites and octahedrites consist of square (tetragonal) prisms with their axes parallel to the [001] axes of the kamacite and their prism faces parallel to two faces of (210); Bøggild and also W. Borchert and J. Ehlers (1934) have shown that platy rhabdites (also schreibersite) are parallel to (221) and (100) of the kamacite. Brezina lamellae are large schreibersite plates parallel to (110) of taenite in octahedrites (A. Brezina, 1904), and cut across the octahedral structure. Shepard lamellae are thickish schreibersite plates enclosed in kamacite and arranged parallel to the Widmanstetter structure (J. D. Buddhue, 1938); it is not certain whether the kamacite swathing them has the normal orientation or not; if it has, the plates are parallel to (110) of kamacite. Curiously enough, R. F. Mehl, C. S. Barrett, and H. S. Jerabek (1934) have shown that platy inclusions of Fe_3P in manufactured iron do not follow any of these laws, but lie in a set of 24 planes near (310) of the iron; they also found that inclusions of Fe_4N form plates parallel to (210) of the iron. F. Heide, E. Herschkowitsch, and E. Preuss (1932) described the platy rhabdites of the Tocopilla (= Cerros del Buey Muerto) mass as parallel to faces of (100) (210), and (211) of the kamacite, but their proof is not satisfactory, and Borchert and Ehlers later showed that (100) and (221) are the true segregation planes. G. F. Kunz and E. Weinschenk (1892) described the platy rhabdites of the Indian Valley mass as parallel to the Neumann lines (and hence to (211) of kamacite); this requires confirmation. Troilite commonly occurs as rounded globules, but also as Reichenbach lamellae parallel to the cube planes of the taenite (G. Tschermak, 1872) or rarely to the dodecahedral planes of the taenite (F. Rinne, 1910). Plates of cohenite are commonly parallel to the Widmanstetter structure. Daubreelite is usually associated, often regularly, with troilite.

between inclusions and matrix is known, the above methods could obviously be applied to orient the matrix from the observed directions of the inclusions, preferably by using two etched surfaces; suitable material for a practical test is not at present available.

The orientation of the included phase relative to the matrix in segregate structures in general.

One of the commonest problems in dealing with segregate structures in general is to determine the orientation of the segregate with respect to the matrix.[1] The procedure most commonly used has been to determine the orientation of the matrix by X-ray methods, then to measure the directions of the traces of the inclusions on one or more etched surfaces and seek by trial and error a set of planes in the matrix capable of accounting for the observed traces.

This procedure employs more experimental data than are really necessary; the traces of the inclusions on two etched surfaces could be used by the above methods to determine the directions of the inclusions without difficulty, and once a projection has been obtained, the indexing of the segregation planes is simple. In theory the traces on a single etched surface are more than sufficient; the matter has been shortly dealt with by C. S. Barrett (1937), but without practical examples, and there is no evidence that any worker has succeeded in determining the orientation of the section planes of the inclusions in the matrix solely from the traces on a single etched surface except where the inclusions lie in the planes of the octahedron, dodecahedron, or cube. While the indexing of the planes of segregation in the matrix should normally be possible, the complete description of the orientation of the segregate with respect to the matrix will rarely be feasible from morphological data; for it requires recognizable structural features in the segregate, idiomorphic boundary planes, or the traces of cleavage or glide planes or inclusions in the segregate, which will rarely be available.

Summary.

Methods are described for determining the orientation of a plane section of a meteoritic iron from the Widmanstetter figures, the Neumann lines, or from oriented inclusions. The determination of the planes occupied by oriented phases in segregate structures in general is also

[1] O. B. Bøggild (1927) has used the acicular rhabdites to orient meteorites; his method was to etch rather deeply and then measure on the goniometer the positions of the prism faces of the rhabdites exposed by etching.

considered, and it is shown how this may often be attained without knowledge of the orientation of the section plane relative to the matrix. These methods have been applied to the determination of the relative orientation of the crystals in iron meteorites containing a few large crystals and to the determination of the relative orientation of kamacite and taenite in meteoritic irons.

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