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THE PLASTIC DEFORMATION OF ORE MINERALS

A PRELIMINARY INVESTIGATION: GALENA, SPHALERITE, CHALCOPYRITE, PYRRHOTITE AND PYRITE

PART I

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ABSTRACT TO PART I

With a view of eventually using the data for the purpose of studying deformed ore mineral aggregates, the plastic characters of single crystals of several species have been investigated. The experimental method consists essentially of subjecting the single crystal to compression while embedded in a matrix which supplies a hydrostatic retaining pressure. Galena, whose plastic characteristics are, in several respects, simple, is first considered.

The positions of slip striations on deformed galena indicate that it deforms by translation along cube planes. The absence of striations on cleavage faces parallel with the load, when the latter is directed normal to a dodecahedral plane, gives the translation directions as [110].

It is shown that deformation of galena involves a reorientation of crystallographic directions such that a [111] direction tends to become parallel with the load.

The significance of the above phenomena is brought out in terms of atomic arrangement, and general principles are presented for the prediction of translation planes and directions in other simple lattices.

INTRODUCTION

In many ore deposits, of which those of Coeur d'Alène, Idaho, and adjoining districts of the same group are noteworthy examples, the ore minerals have suffered intense deformation resulting in the production of "sheared" galena, sphalerite and other minerals. Hand specimens from such localities often show ore with the textural aspects of gneisses or even schists. The galena shows, in detail, curved cleavage faces which, in polished sections, may be recognized by the contorted arrangement of the cleavage pits, especially where this soft mineral is in contact with a harder, more resistant material.

In deposits of this sort, the evidence of ore deformation is so clear that no reasonable doubt exists as to the sequence of events which gave rise to the character of the present ores. The ore minerals were first deposited by filling and replacement—by just what mechanism is not of immediate concern—and subsequently were subjected to enormous compressive forces which distorted the original crystals. The evidence shows that the softer minerals were deformed through flowage, while often the harder ones, such as pyrite and quartz, were broken or crushed.

Besides this class of clearly deformed deposits, there exists a structurally related class whose origin is not so easily ascertained: deposits, especially of the pyrite-pyrrhotite-chalcopyrite type, whose ore bodies are arranged in lenses or tabular masses parallel, or nearly parallel, to the foliation of the obviously deformed country rock (usually a schist). On the basis of large-scale relations, the disposition of many such deposits can be accounted for by either of the two following hypotheses:

1. The ore was deposited, and later both ore and country rock were simultaneously deformed.

2. The country rock was first deformed, and subsequently, by a process of metasomatism, the ore replaced, preferentially, certain bands of the deformed rock, or was injected along its lines of foliation.

Field relations may yield evidence favoring one or the other of these possibilities, but often do not give all that is to be desired in the way of uncontrovertible criteria; they may appear to support equally well both views.

It seems desirable, therefore, to find evidence of another type and to develop criteria not immediately dependent on field relations. The study of individual crystals of the ore minerals and the consideration of the relations of one crystal to its neighbors, it is believed, will afford data which may be of value in determining how such a genetically doubtful ore-body has reached its present condition.

The problem of crystal criteria may obviously receive treatment in either of two ways:

1. By a study of the crystals from ore-bodies known on geological evidence to have been deformed simultaneously with the country rock.

2. By a study of crystals experimentally deformed.

Of these two methods of attack, the first is undesirable because it leads to rather empirical results. To make real progress in the development and intelligent application of crystal criteria, a clear understanding of the nature of crystal deformation is necessary. The second, experimental, method of attack not only has the advantage of leading to a rational development of crystal criteria, but it should afford results which rest upon known grounds and are independent of geological reasoning. In addition, the conditions of experimentation may be varied within certain limits and controlled so that one variable at a time is changed.

It is primarily with the purpose of developing fundamentals, rather than presenting criteria that this paper is presented. Moreover, since a great number of ore deposits of the genetically doubtful type contain large proportions of pyrite, pyrrhotite, chalcopyrite, sphalerite and galena, attention will be particularly directed to such of these minerals as can be conveniently treated in an experimental way.

Probably because of its more immediate economic significance, the greatest amount of recent experimental work on crystal deformation has been conducted on metal crystals.[1] In the realm of mineral crystals, Adams,[2] Adams and Coker,[3] Veit,[4] and others have investigated plastic flow, but without special consideration to the mechanism of the attendant reorientation phenomena. The writer will give these processes some consideration in the following discussion since it is preliminary to a later development of criteria for the recognition of deformed ores.

[1] See, among others, the following papers: M. Polanyi, Deformation von Einkristallen: *Zeit. Krist.*, **61**, pp. 49–57 (1924–25). K. Weissenberg, Zur Systematik und Theorie der Wachstums und Deformationsstrukturen, *idem*, **61**, pp. 58–74 (1925–26). H. Mark, Über die Methode und die Ergebnisse der experimentallen Bestimmung von Wachstums und Deformationsstrukturen, *idem*, **61**, pp. 75–91, (1924–25). Orlando E. Romig, Preparation of Metallic Single Crystals and Twinning in Zinc and Zinc Single Crystals, *Proc., Institute of Metals Division, Am. Inst. Min. Met. Engs.*, pp. 90–112, (1927). Samuel L. Hoyt, Plastic Deformation of a Zinc Single Crystal, *idem*, pp. 116–132, (1927). C. H. Mathewson and Albert J. Phillips, Plastic Deformation of Coarse grained Zinc, *idem*, pp. 143–189, (1927). J. T. Norton and B. E. Warren, Plastic Deformation of Metals, *idem*, pp. 350–366, (1927).

[2] Frank D. Adams, An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks, Employing the Process Suggested by Professor Kick, *Jour. Geology*, **18**, pp. 489–525 (1910).

[3] Frank D. Adams and Ernest G. Coker, An Experimental Investigation into the Flow of Rocks, *Am. Jour. Sci.*, (4) **29**, pp. 465–487 (1910).

[4] Kurt Veit, Künstliche Schiebungen und Translationen in Mineralien, *Neues Jahrb. f. Min. Geol. u. Pal.*, Bl. Bd. **45**, pp. 121–148 (1922).

THE EXPERIMENTAL METHOD

Many crystals, such as those of the very pure, ductile metals, can be made to suffer great deformation without the development of cleavage, parting, or irregular cracks. This is probably due to the unique properties of free electrons in the lattice. Frangible crystals, relatively low in, or entirely lacking these electrons, may also be made to flow provided an external pressure, in a certain sense replacing these electrons, is applied. In nature, otherwise brittle minerals have flowed readily when aided by the lateral support which the retaining force of the surrounding crystals afforded.

Lateral support can be provided experimentally by an ingenious method devised by Kick,[5] which has been used with great success on the softer minerals by Adams[6] and others. In brief, the method consists of embedding the crystal in a matrix, which can later be removed by fusion or solution, within a tube of ductile metal. The ends of the tube are capped by means of brass plates and the whole subjected to a load applied parallel to the axis of the tube. The initial application of load causes the tube to sink somewhat into the end plates, effectively sealing the arrangement against any escape of embedding material. Further load compresses the matrix and this continues until the hydrostatic pressure combined with the axial load on the tube causes the latter to bulge equatorially. When this occurs the matrix and crystal are enabled to flow laterally restrained by the centripetal pressure exerted by the bulging tube. Since an initial force of a certain finite amount is required before the matrix undergoes plastic flow the crystal is subjected to a differential pressure which is essentially equivalent to a hydrostatic retaining pressure upon which is superimposed a direct load.

Adams used tubes of copper and employed for embedding medium: paraffine wax, fusible metal, sulphur, and alum in various experiments. He found alum to give the best results due to its greater resistance to flow.

In the experiments to be described on the following pages Kick's method was used because of its cheapness and convenience

[5] Friedrich Kick, Die Prinzipien der mechanischen Tecknologie und die Festigkeitslehre, *Zeit. des Ver. Deut. Ingen.*, **36**, pp. 919–923, (1892).

[6] *Op. cit.*

and the writer has followed Adams closely, partly with the hope that the results might prove, in a rough manner, comparable, and partly to avoid useless experimentation. Copper tubes of the same dimensions, except length, as those described by Adams were utilized. These were of commercial stock known as one-inch iron pipe size; although irregularities occurred these had the following average dimensions:

Internal diameter 1.063 inches.
External diameter 1.125 inches.

Brass plates one-tenth of an inch thick and two inches square were used for end pieces, and these were in turn capped by wrought iron blocks one-half inch thick and two inches square.

In all cases, except in two unsuccessful experiments with paraffine, U. S. P. potassium aluminum alum was used as an embedding medium. This was melted and a little poured into the copper tube. The crystal then could be supported by forceps and partially immersed in the molten alum until the latter congealed. When this occurred, the remaining space was filled with alum and the tube and its contents set aside to cool. After solidification, that portion of the alum projecting beyond the tube was cut off and filed to make a flat surface flush with the end of the tube.

An axial load was applied by submitting the tube and its contents, capped by brass and iron end plates, to compression in a long-column Olsen testing machine having a capacity of 100,000 pounds. Except with the last chalcopyrite crystal deformed, the load was applied at a rate of .03 inches per minute.

Usually the applied load mounted rapidly in the beginning of each test. As soon as the tube and its contents started deforming in a plastic way (as noted by the incipient equatorial bulge of the tube) the load remained constant for some minutes, and later increased slowly.

In comparing maximum loads, one should remember that too great weight does not attach to these values. As pointed out by Adams,[7] it is impossible to calculate accurately the stresses set up in the enclosed specimen; so many variables are involved (size of specimen, length of tube, variability of alum due to melting processes, etc.) that the values themselves are only the roughest sort of a measure of the force used to deform the particular specimen.

[7] *Op. cit.*, p. 495.

EXPERIMENTS ON SINGLE CRYSTALS OF CERTAIN SPECIES AND THE LATTICE SIGNIFICANCE OF THE RESULTS

A. Galena

Previous Work.—The original literature on the deformation of galena is largely hidden in old and unavailable publications, but a good summary is given by Hintze.[8]

Weiss[9] described the galena percussion figure consisting of one or more cracks parallel to cube edges, developed by means of a sharp blow on a steel needle in contact with a cleavage face. More interesting is the pressure figure.[10] Pressure applied to a cleavage face by means of a rounded point produces a pyramidal hole whose sides are parallel to cube-face diagonals. A corresponding pyramidal hill is simultaneously developed on the under side of the cleavage flake. Bauer interpreted these phenomena as a gliding on dodecahedral planes.

Mügge[11] noticed that galena crystals from Rhodna which were bent about an axis parallel to a cube-face diagonal, were covered with fine striae parallel to cube edges, which intersected in such a manner as to preclude the possibility of their being growth lines. Mügge explained these as traces of gliding planes which had sustained translation in the direction of the cube-face diagonal. He confirmed these conclusions by several experiments. In one he placed a cleavage cube of galena upon one side of a shallow V-shaped groove in such a manner that a cube-face diagonal was parallel to the dip of this side of the groove. Then by pushing upon the uppermost corner of the galena cube he was able to deform it into a blunt parallelopiped. Four sides of the galena block (in one zone) were found to be covered with translation striae parallel to the other two cube faces.[12] In another experiment he supported two adjacent corners of a cleavage cube, leaving the rest of the edge joining these corners unsupported. By pressing the middle of the opposite edge, he was able to (ap-

[8] Carl Hintze, Handbuch der Mineralogie, Erster Band, Lfg. 1, *Leipzig*, pp. 461–464 (1898). Also O. Lehmann, Flüssige Kristalle, p. 106, *Leipzig* (1904).

[9] Weiss, *Zeit. der deutschen geol. Gesell.*, **29**, pp. 208–211 (1877).

[10] Max Bauer, Beiträge zur Mineralogie: 5, Über des Vorkommen von Gleitflächen am Bleiglanz, *Neues Jahrbuch für Min. Geol. u. Pal.*, I, pp. 138–150 (1882).

[11] O. Mügge, Über Translationen und verwandte Erscheinungen in Krystallen, *Neues Jahrbuch für Min. Geol. u. Pal.*, I, pp. 123–138 (1898).

[12] See Mügge's figures 32 and 33, *Op. cit.*, p. 126.

parently) bend the crystal, with the production of translation striae parallel to the end cube faces. Mügge thus concluded that galena deforms by translation on {100} planes in [110] directions. Critically analyzing the percussion figure of Weiss and the pressure figure of Bauer, he re-explained these as translation on {100} combined with bending.

Cross[13] has described galena from Bellevue, Idaho, with striations parallel to (110) and explains this as due to translation along dodecahedral planes as in the case of Bauer's experiments. He also notes indications of twinning on (331) and (111). These effects, he concludes, are secondary and to be ascribed to pressure.

The writer repeated Mügge's experiments with essentially the same results and conclusions. In order to ascertain whether the same results would be expected under natural conditions, in which the pressure is not directed in any particular manner, but is completely at random with respect to crystal orientation, and in which, in addition, it has superimposed upon it a hydrostatic pressure, he carried out the following investigation.

Experiments.—Several experiments were tried on galena with a load normal to an octahedral plane. In the first a crystal from Dubuque, Iowa, was used. This showed the octahedron predominating with rather small cube-faces modifying octahedral corners. The faces were not equally developed but were essentially free from any notable curvature. The surfaces were dull and contained many small irregularities, some of which were presumably etch pits. In order, therefore, to facilitate observation of any slip to be produced in deformation, several of the faces were polished.

The specimen was embedded in alum within a copper tube .9 inches high, and oriented so that the load was normal to an octahedral face. This orientation is reproduced in Fig. 1-A. When so orientated the crystal was .50 inches high. After applying a load of 37,700 pounds the crystal was removed by solution of the alum and found to have been reduced in height to .41 inches (See Fig. 2-A). The specimen displayed only the slightest traces of cracking and true cleavage and was very coherent. All originally plane-polished faces were curved. Obviously galena deforms in a plastic way with relatively great ease.

[13] Whitman Cross, *Proc. Colorado Sci. Soc.*, 2, pt. 3, p. 171 (1885).

Microscopic observation showed that the polished faces were minutely striated parallel to cubo-octahedral edges as shown in Fig. 3.

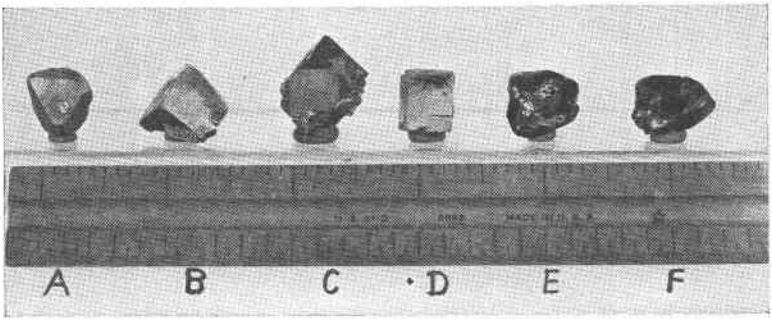

Fig. 1. Photograph of six of the single crystals used in the deformation experiments. Except in the case of C, these specimens are oriented as they were within the copper tube, the loads being applied in a vertical direction. It was intended to deform C when oriented as shown, but the crystal was dropped during the embedding process and the load was applied at an angle of 45° to the plane of the paper.

A, B, C, and D.............................galena
E.. sphalerite
F.................................... chalcopyrite

The scale shown is in inches.

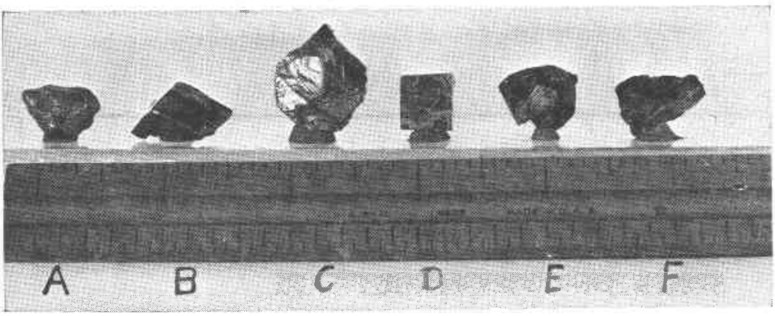

Fig. 2. Photograph of the same six crystals shown in Fig. 1 but after deformation. Note the flattening of A and B normal to a vertical direction and of C in a direction oblique to the plane of the paper. Note also the bending of F. Notation and scale are the same as in Figure 1.

To check these observations, other experiments were made. A slightly curved cubic crystal from Joplin was obtained. It was incomplete, having one ragged surface by which it had evidently been attached. As in the case of the preceding specimen, the faces were polished before deformation.

The specimen was embedded in alum in a .9 inch copper tube and oriented so that a load could be applied normal to an octahedral plane. The original height was .60 inches (See Fig. 1-B). After applying the load of 36,000 pounds its height had been decreased to .54 inches (See Fig. 2-B). The previously polished faces had become quite curved and were coarsely striated due to the gouging action of the alum. Although a number of cleavage cracks had developed, the crystal was very coherent and showed no tendency to break on repeated dropping.

Detailed observation with binoculars and metallographic microscope showed that, in addition to the coarse alum grooves, the curved cube faces were covered with fine lines parallel to the cube edges (Fig. 4). Along the grooves produced by the alum sliding over the galena (where deformation must have been highly localized and very intense) these lines were especially abundant. The spacings of these lines were highly variable; the smallest spacing between striae actually measured was approximately .001 millimeters. Other spacings were as large as .01 millimeters, or more. Where lines of wide separation were noted under the binocular, the metallographic microscope showed still finer lines between these.

A third experiment was conducted in a manner similar to the above with identical results.

All the observed slip band traces are in harmony with a translation occurring on cube planes. Several experiments were next conducted to check this hypothesis.

If slip occurs on cube planes, a load directed normal to one cube plane and therefore parallel to two others should have no components in these planes and consequently no translation is to be expected under these conditions. The validity of the inference as to the location of the planes of easiest slip was accordingly put to a test by attempting to deform in the usual way a cleavage cube with a load of 33,800 pounds applied normal to a cube face. No measurable deformation was attained and no slip striae appeared (compare Figs. 1-D and 2-D). Two other cleavage cubes were similarly loaded to 51,000 and 57,000 pounds, respectively, without measurable deformation or production of slip lines. In these cases, however, the harder alum crystals impressed themselves on the bases of the test pieces with a formation of hills and depressions similar to those seen in pressure figures. Finally, a fourth cleavage cube was mounted so that the pressure could be applied almost, but not quite, normal to a cube face. A load of the same magnitude as the preceding brought about an appreciable deformation and covered the cube with translation striae parallel to cube edges.

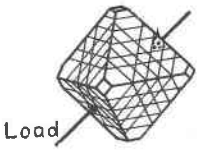

Fig. 3. Diagrammatic representation of striation directions on the first galena crystal deformed, with the load normal to an octahedral plane.

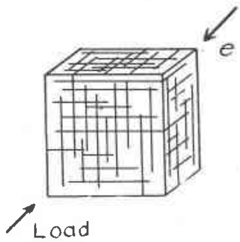

FIG. 4 Diagrammatic representation of striation directions on the second galena crystal deformed with a load normal to an octahedral plane

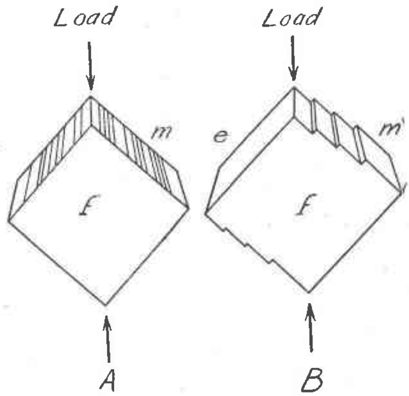

FIG. 5. Striations resulting from slip on cube planes if the cube edge, [100], is the translation direction. A shows the actual cube. B is a diagrammatic representation of striation production if only one set of cube planes, *e*, slip. Actually both sets, *e*, and *m*, slip and produce striations on faces *m* and *e* as shown in A. Note that no striations appear on face *f*.

These experiments seem to indicate that under moderate load galena will deform by translation on {100} planes. The structural significance of this will be brought out on another page.

It is of importance to know not only the translation plane but also the translation direction in galena. Mügge deduced [110] as the translation direction from the fact that deformed galena crystals were apparently bent about a cube-face diagonal. It is desirable to have additional evidence on this point since this deduction rests, in a measure, on the "Biegegleitung" hypothesis.

Since the cube edge and cube-face diagonal are the only first order directions in the cube plane, slip must, from theoretical considerations, occur in one of these directions. If the cube edge is the translation direction, then a load applied to a cleavage cube normal to a dodecahedral plane should produce no striations on the cube face parallel with the load direction. This is shown diagrammatically in Figs. 5-A and 5-B. If, on the other hand, the cube-face diagonal is the translation direction, striations should appear on these faces, as shown in Figs. 6-A and 6-B.

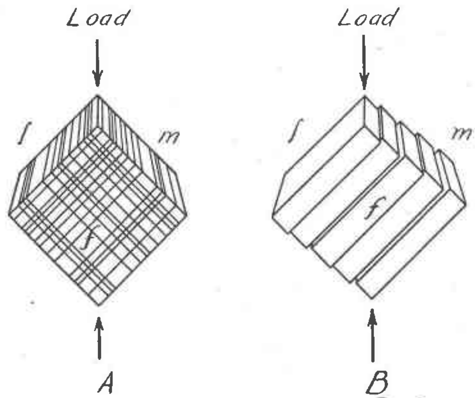

FIG. 6

Striations resulting from slip on cube planes in the direction of cube face diagonals, [110]. A shows the actual cube. B is a diagrammatic representation of striation production if only one set of cube planes, *l*, slip. Actually both sets, *l* and *m*, would slip and produce striations on faces *m* and *l* as shown in A. Note that in this case striations appear also on face *f*.

Several polished cleavage cubes were deformed with a load normal to a dodecahedral plane and in each case the striations observed were those shown in Fig. 6, proving that [110] is the translation direction. Our results are, therefore, in agreement with Mügge's conclusions.

REORIENTATION PHENOMENA.—Figure 7 shows diagrammatically that slip along a single plane results in a reorientation of crystal directions, the plane of slip tending to assume a position nearer normal to the direction of the applied load. When slip occurs on two planes at once, the reorientation processes are more complicated. The shearing component (which is responsible for slip) is greatest in directions making angles of 45° with the direction of the force and zero parallel with and perpendicular to it. Hence if slip occurs simultaneously in two directions not at right angles. to one another it will occur most easily and therefore most rapidly in that direction which makes an angle nearest 45° with the load. This tends to rotate the entire crystal so that the more rapidly slipping plane makes an angle with the initiating force which is less favorable to slip, and so that the less rapidly slipping plane makes an angle with the force which is more favorable to slip.

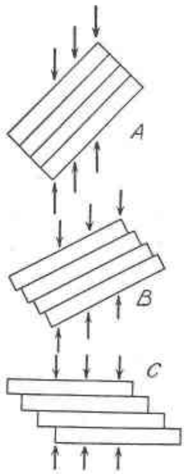

FIG. 7

Diagrammatic representation of the reorientation process of a crystal having only a single family of possible translation planes. Arrows indicate system of loading.

Eventually a condition of equilibrium is approached in which slip takes place as easily on one plane as on the other. This occurs when the direction of the force bisects the angle between the directions of slip as has been shown by Norton and Warren.[14]

When, as in the case of galena, slip occurs in three different directions (cube-face diagonals in galena) the mechanism is a little more difficult to visualize. In the general case, however, the same reasoning applies. Translation in the direction most favorably located for slip tends to rotate the whole crystal so that that

[14] J. T. Norton and B. E. Warren, Plastic Deformation of Metals, *Proc., Institute of Metals Division, Am. Inst. Min. Met. Engs.*, p. 353 (1927).

direction assumes a less favorable position while the other two directions are rotated into more favorable positions. A condition of equilibrium is approached on long-continued deformation in which all slip directions make equal angles with the deforming force.

A crystal of galena of random original orientation, then, should be expected, after sufficient deformation, to be so oriented that the deforming force makes equal angles with three cube-face diagonals. In such an orientation the crystal will have the cube diagonal, [111], parallel with the force.

In addition to this random original orientation two special orientations must be considered:

(1) If the original orientation with respect to the load is such that two cube planes make random angles with the direction of the force and the third is parallel with the load, there is no component of slip in the latter plane. Slip may occur in [110] directions on both cube planes which are not normal to the load, however, and the crystal approaches an equilibrium position such that the load bisects the dihedral angles between these two planes, that is, the load becomes parallel to a dodecahedral direction.

(2) The experiments show that easy deformation occurs only when the cube face is not approximately normal to the applied load. When it is nearly normal, slip along cube planes is so difficult and slow that the previously mentioned reorientation can not be expected to take place. While the experiments are incomplete on this point, speculations detailed on another page compel belief that a galena crystal so oriented will deform by slipping on dodecahedral planes along [110] directions. In this case there are four directions of simultaneous slip and since these all make initially equal angles with the deforming force the crystal is in an equilibrium position and retains its original orientation.

Since a single crystal of random original orientation, when subjected to deforming forces, tends to assume the equilibrium position with an octahedral direction aligned parallel to the load, it might be supposed that a deformed galena aggregate could be recognized (as having been deformed) by the shape of the cleavage pits on a surface polished normal to the load direction; the pits would be expected to be all equilateral triangles in outline on such a surface. The reorientation phenomena are not so simply applied, however, since, in deformed ore-crystal aggregates several complicating features[15] are present. A casual examination of moderately deformed ore will show that on surfaces polished normal to the presumed load direction, the galena cleavage pits, although curved, do not display the expected uniformity of character, *i. e.*, all pits are not equilateral triangles in outline, nor do they more than remotely approach this condition.

For the practical recognition of reorientation and its deformation significance in aggregates, recourse must be had to the more delicate and statistical X-ray method employed so successfully by Mark[16] and Warren and Norton[17] on the metals.

STRUCTURAL CONSIDERATIONS.—X-ray analysis has shown that a true crystal is built up of an orderly array of atoms (more strictly ions) arranged in a regular manner on points of an imaginary space-lattice.[18] The concept is too well known to require

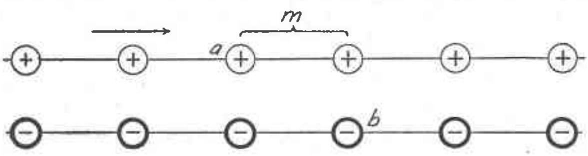

FIG. 8

A possible translation direction (Galena: two (001) planes seen looking in a [110] direction). Translation of the upper plane past the lower one for a distance *m* will bring positively changed ion, *a*, to a position above negatively changed ion *b*. This final disposition of changes is identical with the original and no inherently unstable configuration is approached during movement.

exposition here. In the simpler crystalline compounds, at least, the atomic volume requirements practically necessitate, according to Foote,[19] a figurative squeezing off of valence electrons from those atoms in the structure having chemically positive tendencies, and acquisition of these squeezed off electrons by those atoms having chemically negative tendencies. The net result is a structure of positively and negatively charged ions.

Plastic deformation has been observed to occur by two processes: translation and twinning. Translation involves a slipping movement between adjoining portions of the crystal along certain

[15] To be discussed in a later paper on criteria.

[16] *Op. cit.*

[17] *Op. cit.*

[18] Ralph W. G. Wyckoff, The Structure of Crystals, *New York* (1924).

[19] Paul D. Foote, The Relation between Metallurgy and Atomic Structure, *Trans., Am. Inst. Min. Met. Engs.*, 73, p. 647 (1926).

planes in such a manner that the crystalline bands are not destroyed during the process but merely shifted, or handed on along the slipping planes. The bands are conceivably of three kinds: the electrostatic attraction between ions due to their unlike charges, the gravitational attraction between ions due to their masses, and the magnetic attraction between ions due to their magnetic fields. Any two adjacent planes in a crystal may be conceived of as cohering to one another by reason of these three sets of forces, although the first greatly predominates; the electrostatic attraction is the conditioning cohesive one.

The planes will continue to remain in cohesive contact during translation provided that the displacement between planes takes place in a direction such that the mutual relation of charged atoms

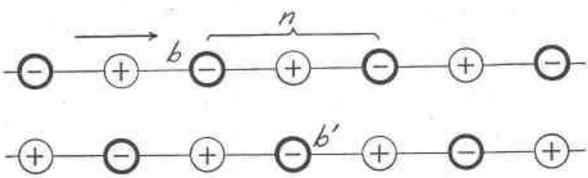

FIG. 9

An impossible translation direction (Galena: two (001) planes seen looking in a [100] direction). An attempt to slide the upper plane past the lower one for a distance, *n*, would give a disposition of changes identical with the original, but such a movement would necessitate having negatively charged ion *b* above negatively charged ion *b'* at some time during the process. Such a configuration is unstable due to the enormous repulsive forces between like charges and a directed attempt to initiate translation in the direction indicated would result in instant cleavage between the two planes.

(ions) in one plane, with respect to those in the other, is the same in the final configuration as it was originally; and provided further that no inherently unstable configuration between planes is approached during the process. Figures 8 and 9 will serve to illustrate this point. If, in Figure 8, translation of the upper plane past the lower one for a distance *m* (or any multiple thereof) is caused to take place in the direction of the arrow, positively charged ion, *a*, is moved to a position above negatively charged ion, *b*. This final disposition of charges is identical with the original, and no inherently unstable configuration is approached during movement. On the other hand, with the translation direction as shown in Figure 9, it will be noted that while the final position would be identical with the original (in the sense of charge distribution) if the upper plane is displaced a distance, n, in the direction of the arrow, the movement would require the like charged ions of adjacent planes to approach closely one another at some time during the displacement (b would be above b', for example). Should an attempt be successful in initiating translation in the direction indicated, therefore, instant cleavage would result due to the enormous repulsive forces between like charges in adjoining planes.

These considerations may be summarized in the following principle: Translation may occur only in those crystallographic directions which are parallel to rows of consecutively like charged ions in the lattice. Although the *direction* of translation is thus completely fixed for a given crystal structure by the disposition of charged ions, the kind of *planes* between which actual displacement can occur may vary with the conditions of loading. For a crystal of random orientation with respect to the direction of loading, the translation plane can be predicted from the following considerations:

While any plane containing a translation direction is at least a potentially possible translation plane (merely because it contains the translation direction), translation will occur along that one presenting the least resistance to slip. The slip resistance is due to,

(1) The restoring forces arising from displacing elastically the ions of adjacent planes against their mutual electrostatic, gravitational, and magnetic attractions.

(2) Interatomic friction, resulting presumably from an interpenetration and disturbance of atomic spheres of influence during movement.

For two isolated ions, the three factors of (1) vary inversely as the square of the distance between ions. Certainly the integrated effect of all ions in retarding slip along a given pair of planes, both for reasons (1) and (2), will decrease rapidly with the spacing of the planes. Therefore, translation will be highly favored along the planes of greatest spacing. Should the direction of application of the load be normal or parallel to all such planes of greatest spacing, slip will be favored along those planes of next greatest spacing.

To summarize these translation conditions: Translation will occur along that family of planes containing a translation direction, which has the greatest interplanar spacing. It can be seen that the translation direction, although difficult to obtain experimentally, is of greater *fundamental* importance than the translation plane, which is easily determined by observation of slip striations.

To intelligently apply the translation conditions to a given crystal, a lattice model must be constructed since a two-dimensional representation of the lattice gives only a difficultly grasped conception of atomic planes and lines. Galena utilizes the sodium chloride arrangement in crystallizing, and a single unit cell of this structure is shown in Figure 10. By examining a large model consisting of many unit cells, it is at once apparent that there are six directions in which atoms of like charges are

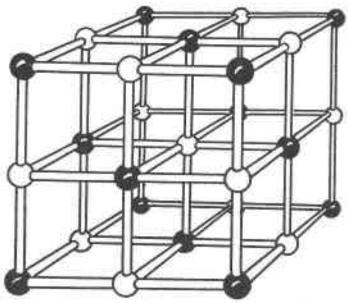

FIG. 10
Unit cell of galena. Either black or white balls may be taken to represent centers of lead or sulphur atoms.

consecutively arranged. These are the directions normal to the six dodecahedral planes, *i. e.*, [110] directions. The model shows at once that the planes of greatest spacing are the cube planes. Dodecahedral planes have the next greatest spacing and octahedral planes have the least spacing of the first order planes. Hence, a galena crystal in random orientation would be expected to deform by slip along cube planes in [110] directions. This is in complete harmony with the experimental evidence previously detailed.

(*To be continued*)