THE PLASTIC DEFORMATION OF ORE MINERALS
PART 2. (CONCLUDED)

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ABSTRACT TO PART II.

In a previous installment,* experiments on the plastic characteristics of galena were described and the results explained in terms of atomic arrangement. In the present paper, the same methods are applied to sphalerite, chalcopyrite, and pyrrhotite.

Sphalerite deforms by gliding on {111}, but, contrary to Veit's conclusions, the character of the movement is that of secondary twinning, not translation. The lattice significance of twinning in sphalerite is briefly discussed.

Chalcopyrite was found to deform by translation on {111}. The translation direction was not obtained experimentally, but is predicted as [110] from a consideration of the atomic arrangement. Continued deformation tends to reorient [001] parallel with the load direction.

Pyrrhotite apparently deforms in a plastic way but experiments failed to give critical results.

No attempt was made to deform pyrite but probable geological evidence of its plasticity is drawn from the literature.

An hypothesis is presented to account for observed differences in plastic behavior. According to this hypothesis very pure minerals are expected to deform by translation while concentrated solid solution minerals are expected to deform by secondary twinning.

B. SPHALERITE

EXPERIMENTS.—After the writer had completed the experiments about to be detailed, he found that they had already been performed by Veit,[20] but with different results. Veit concluded that sphalerite deforms by translation on {111} planes in ? [21][11$\bar{2}$] directions. In what follows, it will be shown that sphalerite deforms by movement along {111} planes, but that the character of the movement is that of twinning rather than translation.

A preliminary experiment was carried out to ascertain whether sphalerite would be amenable to deformation by Kick's method.

* *Am. Mineral.*, **13**, pp. 1–17 (1928).

[20] Kurt Veit; Künstliche Schiebungen und Translationen in Mineralien, *Neues Jahrb. f. Min. Geol. u. Pal., Bl. Bd.* **45,** pp. 125–128 (1922).

[21] The question mark is Veit's.

The specimen used was one of the usual dark brown rounded crystals from Joplin (See Fig. 1-E). It could not be crystallographically oriented with certainty except by cleaving it and this was not attempted. It was placed in a copper tube 0.9 inches high and oriented as shown in Fig. 1-E. When so placed, its height was 0.55 inches. A load of 46,000 pounds was applied in 9 minutes. On removal of the matrix the crystal was found to measure 0.50 inches high along the previously measured direction. The color had changed to a lighter shade of brown, which is probably to be explained by the appearance of numerous small cleavage planes. The crystal was to all appearances as coherent as before deformation and could be repeatedly dropped without breaking. In addition to such of the total deformation (0.05 inches) as may have resulted from actual cleavage, much of it was certainly due to twinning or translation, for numerous, broad, offsetting bands, not noted previous to deformation, had been developed during the experiment. Examination with binoculars further revealed fine striae on perfectly transparent surfaces.

It should be stated that while the crystal was deformed when oriented as shown in Fig. 1-E, when the deformed crystal was re-photographed (Fig. 2-E) it was inadvertently placed in another orientation.

The foregoing preliminary experiment indicated that deformation could be accomplished in a plastic way by slip on some plane in sphalerite. It remained to determine (1) the plane of slip; and (2) the kind of deformation, whether true translation or twinning.

Accordingly, a second experiment was undertaken on sphalerite of known orientation. A cleavage piece of clear, transparent, yellow material from Santander, Spain,[22] was selected and trimmed to a column 0.60 inches long, whose long axis was parallel to three of the dodecahedral cleavage planes. This was mounted in an alum matrix within a copper tube one inch high in such a manner that the axis of the column was parallel with the axis of the tube. This permitted the application of load normal to one family of octahedral planes and at slight angles to three other such families of planes.

A load of 46,000 pounds was applied in 18 minutes. After

[22] It is interesting to note that Veit used sphalerite from the same locality. *Op. cit.*, p. 125.

removing the alum it was found that the test piece measured 0.55 inches long showing a total deformation of 0.05 inches. The specimen was no longer transparent but appeared somewhat cloudy. On handling it developed a parting plane normal to the length and therefore parallel to an octahedral plane. All the previously plane cleavage surfaces had become curved, and several of them had had developed on them very fine striations in three directions:

(1) Along the long diagonal of a dodecahedral cleavage face.

(2) Normal to one edge of the dodecahedral cleavage face; and

(3) Normal to another edge of a dodecahedral cleavage face.

This fixes the planes along which slip takes place as the octahedral planes. On the octahedral parting, previously mentioned, there were also striations making angles of 120° with one another although only one set was well-developed. This is a further check on the identity of the slip plane.

Since the shearing component of a force is a maximum at an angle of 45° to the direction of application of the force, and zero normal to and parallel with it, it was at once apparent, that since a slip in sphalerite is indicated along octahedral planes, and since in the preceding experiment these planes were oriented, one normal to, and three making slight angles with the applied load, the maximum ease of deformation was probably not obtained. The optimum conditions for simultaneous slip on all four octahedral planes would be realized when the load is applied normal to the cube face, i.e. parallel with a crystallographic axis.

This was tried. A sphalerite cleavage dodecahedron (See Fig. 11-A) was ground and polished parallel to the dodecahedral cleavages until it had a height of 0.83 inches and widths, measured normal to dodecahedral faces, of 0.65 and 0.61 inches. This was mounted within a one-inch copper tube in an alum matrix and a load of 55,000 pounds applied in 15 minutes. On removal from the matrix it was found that the upper corner of the dodecahedron had come in contact with the brass end plate, and had made a deep impression thereon. The sphalerite was highly deformed, measuring only 0.58 inches high. Since the sides were considerably bulged, only an average set of measurements for widths could be taken—0.67 by 0.96 inches.

Part of the deformation had occurred, especially near the top, by actual fracture and fragmentation. A great deal of it took

place, however, by flow, since all uncleaved, clear faces were highly rounded and warped. Several dodecahedron edges were almost completely flattened and others had become much more acute. Megascopically it could be seen that a displacement of about 0.1 of an inch had taken place along a primary octahedral twin plane whose attitude had been noted before deformation.

Binocular observation revealed again the presence of multitudinous fine striae covering most of the faces. Again these were disposed as previously listed on page thirty-six. (See Figs. 11-A and 11-B). This confirms our previous observations and gives as slip planes {111}.
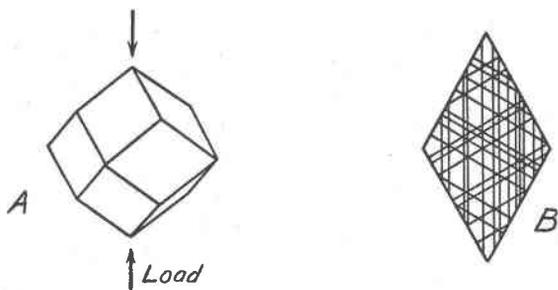

Figure 11.
A. Sphalerite dodecahedron showing direction of loading in the third experiment.
B. Detail of a single face of A, showing diagrammatically the directions of observed striations.

Up to this point the results are in entire accordance with those of Veit.[23] It is necessary to go further than the determination of the planes of movement however; it is imperative to know the character of the movement. This may be ascertained by etching tests. If simple translation occurs, all crystalline directions retain their original, mutual relations, and the crystal will yield a uniform etch. On the other hand if twinning occurs, the crystalline directions in deformed portions of the crystal will differ from those in undeformed portions, and etching on a random face will reveal the presence of twin bands.

To test out the nature of movement in sphalerite random faces were polished and etched with a dilute solution of potassium permanganate acidified with sulphuric acid. Twin bands were developed with startling clearness, showing beyond doubt that

[23] *Op. cit.*, p. 126.

deformation in sphalerite takes place, in part at least, by twinning on octahedral planes.

Several other experiments were undertaken to check these results and complete confirmation was obtained in each case. The experiments were substantially like the preceding ones and will not be detailed here.

Since twinning was observed on sphalerite from the same locality as that used by Veit, it must be concluded that this investigator overlooked twinning as a possible mode of deformation for this mineral.

The Mechanism of Secondary Twinning in Sphalerite.— Sphalerite crystallizes in the tetrahedral class of the isometric
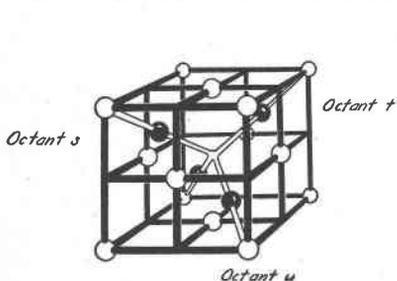

Figure 12. Unit cell of sphalerite. Either black or white balls may represent positions of zinc or sulphur atom centers.
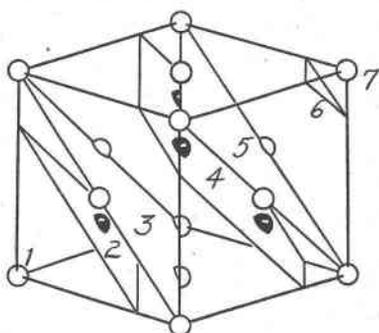
Figure 13. The seven octahedral planes of a unit cell of sphalerite. Plane 6 contains no atoms in the cell shown but includes atoms in adjacent cells.

system. Its atomic arrangement[24] consists of two, mutually interpenetrating, face-centered, cubic lattices, one for zinc and one for sulphur atoms. A unit cell, that is, the smallest possible atomic group having the symmetry of the entire crystal, and out of units of which the entire crystal may be constructed, is shown in Fig. 12. It is practically impossible to gain a conception of the entire lattice structure from a two-dimensional sketch of a single three-dimensional unit cell. With a model, however, it is possible to more easily visualize the lattice as a whole but a proper conception of the process of deformation is still difficult to obtain because of inability to move at will entire planes on a solid model. However, with a lattice model in view it is possible to reconstruct on glass

[24] International Critical Tables, vol. 1, pp. 339 and 342 (1926).

plates, the arrangement of atoms on any set of planes one pleases. By moving one plate with respect to another, the mechanism of deformation may be studied.

It is not the writer's intention to give here a complete treatment of secondary twinning in sphalerite. It is difficult to illustrate it by means of two-dimensional sketches, and it is beyond the scope of the present brief paper. Attention will be drawn only to three octahedral planes rather than the seven that are necessary to completely define the secondary twinning of a unit cell.

Fig. 13 shows the seven (111) planes in a single unit cell of sphalerite. To gain a complete conception of the atomic arrangement on these planes, a model of several unit cells must be examined. Plane 6, Fig. 13, for example, shows no atom, but atoms of adjacent cells are located in this plane.
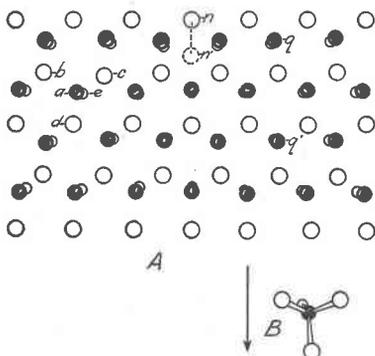

Figure 14. A—Perspective plan of octahedral planes 3, 4, and 5, Figure 13, looking in a [111] direction. See text for further details. B—Orientation of any single octant in the planes shown in A.
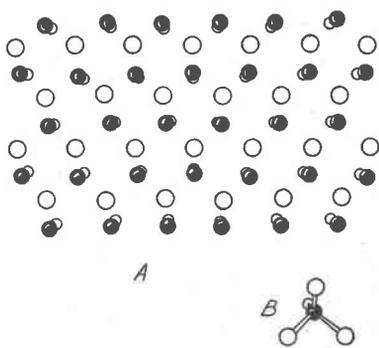
Figure 15. A—Same as Figure 14-A, but after twinning. See text for further details. B—The orientation of any single octant in the planes shown in A, after twinning. Compare with Figure 14-B, and note that a rotation of 180° of one about an axis normal to the plane of the paper, will bring it into coincidence with the other.

In Fig. 14-A a plan of planes 3, 4 and 5, Fig. 13, are shown. These give a complete picture of octants s, t, and u, Fig. 12, and of several other adjoining octants. Note that the black (zinc) atom, a, in the intermediate plane is equally distant from white (sulphur) atoms, b, c, and d, in the upper plane, and also from the white atom e, in the lower plane. This arrangement holds throughout

the figure, and a single octant exemplifying this is reproduced for convenience in Fig. 14-B. The arrow indicates a direction [11$\bar{2}$]. If, now, the entire upper plane is moved in the direction of the arrow until n occupies the dotted position n' with respect to the intermediate plane, and then both upper and intermediate planes are moved in the same direction past the lower plane until q occupies a position q', the next black atom in line, the whole assembly of atoms assumes the disposition shown in Fig. 15-A. Note now that any black atom is again equally spaced between the surrounding white atoms. For convenience the atomic orientation of an octant is shown separately in Fig. 15-B. Comparison of Figs. 14-B and 15-B shows at once that the orientation of the octants has been changed, and that one could be made to coincide with the other by a rotation of 180° about an axis normal to the plane of the figure; in other words twinning has taken place on the octahedral plane.

The above, admittedly incomplete and brief explanation gives a preliminary conception of how secondary twinning on the octahedral plane takes place in sphalerite. Space is lacking to complete the discussion for all seven planes including a unit cell. Why twinning occurs rather than pure translation will be discussed on another page.

C. CHALCOPYRITE

EXPERIMENTS.—The writer knows of no published data concerning the experimental deformation of chalcopyrite.* The tests described below were, therefore, made to ascertain its behavior under differential pressure.

The accepted, probable, atomic structure of chalcopyrite is very similar to that of sphalerite. Although chalcopyrite is sphenoidal

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* It has come to my attention, as proof of this paper is received, that Mügge (*Neues Jahrbuch*, pp. 30–31, 1920) has investigated chalcopyrite. Subjecting minute crystals (1–3 mm. in size) from Burgholzhausen to pressures of 15,000 to 25,000 atmospheres, he obtained striae parallel to (111) which could be followed over several faces. In attempting to apply the usual Biegeleitung criterion for the determination of gliding direction (that the gliding direction is normal to the axis of bending) it was found that the crystals were irregularly bent, and therefore no gliding direction could be given. The character of the movement was found to be translation from the fact that reflections from the striae were variable, and not regular, as required by twinning. Furthermore, examination of thin splinters between crossed nicols in intense transmitted (?) light showed no twin bands. These data are in excellent agreement with the experimental results detailed in the present paper, independently obtained on material from another source and using quite different methods.

while sphalerite is tetrahedral, its axial ratio, $a:b:c$, is so nearly 1:1:1 (actually 1:1:0.985) that for practical purposes the chalcopyrite lattice may be visualized as a sphalerite lattice in which the basal planes of zinc atoms are replaced alternately by planes of iron atoms and planes of copper atoms. It would appear on casual consideration, therefore, that chalcopyrite should deform by twinning on sphenoidal planes very much as sphalerite deforms by twinning on octahedral planes. This reasoning acted as a guide in the orientation of chalcopyrite in the following tests.

Well-developed chalcopyrite single crystals of sufficient size for experimental work are difficult to obtain. For accurate work the crystal must be easily oriented and free from twinning. Since the axial ratio, $a:b:c$, is 1:1:.985 the orientation is in itself difficult without goniometric measurements, and these measurements require flat bright faces.

The writer did not realize these ideal conditions but had to be content with experimenting on less desirable material. A crystal from French Creek was used in the first test (See Fig. 1-F). This had a longest dimension of approximately 0.7 inches before polishing. The predominant form was apparently the sphenoid while the corners were rounded by obscure rarer faces. All faces were dull and covered with growth lines, so the sphenoidal faces were ground and polished to facilitate subsequent metallographic study. Etching tests failed to reveal twinning.

Since the axial ratio of chalcopyrite so nearly approaches that of isometric crystals, the basal pinaciod could not be differentiated from the prismatic planes; hence while the specimen was oriented in a copper tube so that the load would be normal to some pinacoid, or prism plane, there is no means of knowing which one this was. When so oriented the specimen stood 0.50 inches high.

The crystal was embedded in alum within a copper tube 0.8 inches high and a load of 46,000 pounds applied in ten minutes. After deformation the height was still 0.50 inches, but all faces showed considerable curvature. The right hand point as shown in the photograph, Fig. 2-F, was bent down markedly. Several large and numerous small cracks were immediately apparent but the crystal was still very coherent.

Microscopic examination showed that all sphenoidal faces were covered with a network of minute striae parallel to sphenoid edges and intersecting at angles of approximately 60° and 120° (See Fig.

16). If the rough orientation of the crystal, above described, is correct, this can only mean that slip had occurred in some manner along sphenoidal planes. The presence of all three sets of striations on each of the four faces signifies the following with regard to direction of slip:

(a) That slip did not occur in a single direction parallel to one of the sphenoidal face edges. A consideration of Fig. 17 will show that if this did occur (slip of face A in the direction of the arrow, for example), the striations on face B in the direction shown by the dotted line, which can only be caused by a displacement of plane A, would be absent. This assumes, of course, that the polishing of the crystal was accurately done parallel to the natural sphenoidal faces, which is doubtful.
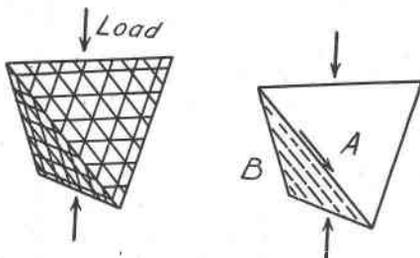

Figure 16. Diagram showing orientation of the chalcopyrite crystal deformed with respect to direction of loading The intersecting lines on the sphenoid faces represent the directions of observed striations.

Figure 17. Expected condition if planes parallel to A slip in direction of arrow: no striations on face B.

(b) That slip of plane A took place alternately in directions parallel to m and to n, Fig. 18, that is, alternately parallel to one sphenoidal edge and another. Slip of A parallel to m would leave no trace on plane B, but slip parallel to n would leave such a trace or:

(c) That slip occurred in some other direction; if plane A, Fig. 19, for example, slipped in the direction shown by the arrow, it would leave striations on all other faces.

It would, indeed, be remarkable if possibility (a) were true. If the sphenoidal edge is the slip direction, and the specimen symmetrically loaded there is no apparent reason why some A planes should not slip in direction m and some in n, Fig. 18. There is precedent for alternate slip of this sort as shown by the writer's experiments on galena.

It is important to discover whether the slip indicated involved twinning or pure translation. There is reason to suppose, from the similarity of atomic arrangements and experimentally determined planes of atomic movement, that chalcopyrite should deform by secondary twinning as does sphalerite, rather than by pure translation.
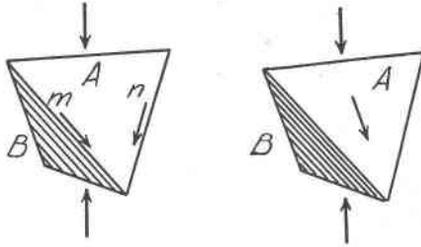

Figure 18. Expected conditions if planes parallel to A slip alternately in directions *n* and *m*: striations parallel to *m* produced on face B.

Figure 19. Expected condition if planes parallel to A slip in the direction of the arrow: striations produced on face B.

To test this supposition etching tests were very carefully made with a dilute potassium permanganate solution acidified with sulphuric acid and also with a saturated solution of potassium dichromate acidified with sulphuric acid. Before the reagent was applied to the deformed specimen, in each case a drop was applied to a polished section of twinned chalcopyrite as a blank test. Each blank test showed differential etching of twin bands on the chalcopyrite known to be twinned. The deformed test specimen was etched on numerous polished surfaces of known and random orientations but every etching test failed to reveal the least trace of twinning.

In order to check these results another chalcopyrite crystal was deformed with conditions the same as those in the first deformation test. Again negative results were obtained on etching numerous polished surfaces. The accordance of etching evidence seemed to disprove entirely the possibility of twinning in deformation of chalcopyrite and to determine the type of movement between {111} planes as pure translation.

THEORETICAL CONSIDERATIONS.—Assuming that the accepted, probable, crystal structure of chalcopyrite is the correct one, it is easy to see why the mineral should deform by translation on sphenoidal planes. In discussing the flow of galena certain general

principals were detailed relatively to the possibility of true translation: slip must take place in a direction parallel to lines of like charged atoms.

Attempting to apply these conditions to the chalcopyrite lattice one is confronted with the inability to determine chemically the charge of the iron atoms with respect to the copper atoms. Lattice considerations, however, because of the similarity of chalcopyrite and sphalerite structures, compel belief that the iron and copper atoms bear like charges. Hence the lines of similarly charged atoms may consist of:

> either (a) entirely copper or entirely iron atoms;
> or   (b) alternating iron and copper atoms.

Alignment (a) is found in [110] directions. A conception of the atomic arrangement may be gleaned from Fig. 20. The lines show traces of pairs of first order planes. Note that alternate pairs of (111) planes have the greatest spacing. Hence it follows that chalcopyrite might be expected to deform by translation on sphenoid planes along a [110] direction.
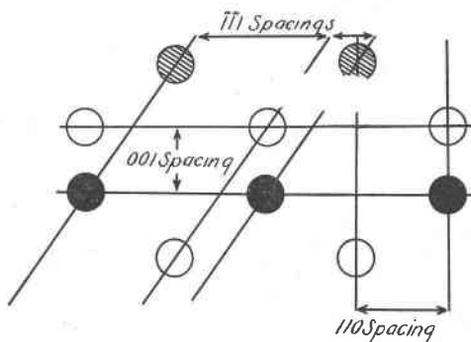

Figure 20. Atomic arrangement of chalcopyrite looking along a [1$\bar{1}$0] direction. The dots are end views of rows of identical atoms. The white dots represent atom centers of sulphur; black, copper; gray, iron. The lines show traces of (001), (110), and ($\bar{1}\bar{1}$1) planes. Note that there are two ($\bar{1}\bar{1}$1) plane spacings. Slip occurs along those alternate pairs of {111} planes of greater spacing.

Arrangement (b) is found along [011] directions. Except for alternation of copper and iron atoms and inappreciable discrepancies in spacing, the atomic rows are the same as shown in Fig. 12. From speculative considerations, slip should occur with less ease along these lines since the atomic volumes of iron and copper are different. A plane containing iron and copper, because of this

difference in volumes, would be a rougher plane than a plane containing iron alone or copper alone. Hence it might be expected to offer greater atomic friction to movement of the adjacent sulphur plane than would a plane containing only one atomic species.

The foregoing discussion explains the translation along sphenoidal planes in chalcopyrite. It fails to explain why the sphalerite lattice deforms by secondary twinning while the closely related chalcopyrite lattice deforms by pure translation. This will be discussed on another page.

REORIENTATION PHENOMENA.—As has been shown in the case of galena, a reorientation is experienced by a randomly oriented crystal subjected to plastic deformation. Without again detailing the demonstration, it can be seen that if a chalcopyrite crystal is deformed it will approach an equilibrium position such that one of the pinacoidal planes is oriented normal to the direction of the applied force.

D. PYRRHOTITE

No data exists, to the writer's knowledge, on the experimental deformation of pyrrhotite. For this reason it seemed desirable to make a few tests on this mineral using Kick's method.

A specimen from Ontario, Canada, was secured which contained a single anhedral crystal of pyrrhotite having the approximate dimensions of 2 by $\frac{3}{4}$ by $\frac{3}{4}$ inches. The crystal reposed in a matrix consisting chiefly of a large oligoclase crystal. In addition this specimen contained a large piece of glassy quartz, some coarse calcite, a little chalcopyrite and some undetermined, soft, galena-grey mineral with octahedral parting or cleavage, all in contact with the pyrrhotite. On the oligoclase there was also a large piece of some amphibole. These associated minerals are mentioned to give some idea of the origin and hence composition of the pyrrhotite.

A small piece of pyrrhotite was broken off, ground and polished on two sides parallel to the basal parting and on six other sides at right angles to these. The crystallographic orientations of these six last mentioned surfaces were unknown except that they must be random faces in a prismatic zone. The orientation was checked with the aid of the polarizing metallographic microscope. Using crossed nicols the basal planes were dark in all positions of rotation and the six vertical faces showed the usual color changes in a half rotation of the stage.

Etching tests proved that the pyrrhotite was untwinned. However, the single crystal block was found to contain several other minerals as microscopic inclusions. In a calcite veinlet cutting through the center of the block in a plane perpendicular to the base an unidentified whitish mineral, resembling marcasite, but showing strong polarization colors, was noted. Throughout the pyrrhotite two minerals were disseminated in small specks: pentlandite, and another, somewhat lighter than pyrrhotite. On the surface polished in the prismatic zone these could be seen arranged in streaks parallel to the basal parting.

Careful measurements were taken and appropriate sketches made before the deformation tests. These will not be detailed in view of the negative results obtained, except to note that the pyrrhotite plate approximated about one-half an inch across the basal faces and was about one-quarter of an inch thick.

Since pyrrhotite twins on the pyramid $(10\bar{1}1)$, an attempt was made in the first experiment to ascertain whether this mode of twinning could be produced as a result of deformation. Accordingly the specimen was oriented in the tube with its basal planes parallel to the tube axis. Thus the load would be applied along a basal plane and would have strong shearing components along the pyramidal planes.

Alum was employed as the embedding medium, and a copper tube one inch long was used. This allowed a clearance of about a quarter of an inch between the pyrrhotite test piece and the end plates. A load of 44,000 pounds was applied in 12 minutes. On dissolving away the alum it was found that the pyrrhotite had not reached the end plates during the test. Nevertheless it had cracked in several pieces without any visible sign of plastic deformation. The pieces, on polishing and etching, failed to reveal any sign of twinning.

Since no twinning occurred in this experiment another was devised to test the character of the basal plane as a glide plane. For this purpose another piece of pyrrhotite was polished, examined, measured and mounted as before but this time with the basal planes making an angle of 45° with the direction of application of the load. A three-quarters inch tube was used and alum again employed as an embedding medium. A load of 49,200 pounds was applied in 27 minutes. On solution of the alum it was found that the specimen had not made contact with the end plates, and further, that

no deformation was to be seen. Etching tests proved the absence of twinning.

From the results of these experiments it was thought that sufficient pressure had not been applied. Alum deforms so much more readily than pyrrhotite that it merely flows about this harder body on application of load. An experiment was, therefore, arranged in which the pyrrhotite could come in contact with the end plates. The specimen from the foregoing experiment and the large fragment from the first experiment were set one on top of the other in a three-quarters inch tube, one lying on its base, the other with the basal plane inclined to the axis of the load.

A load of 54,000 pounds was applied in 10 minutes. Removal of the test pieces showed that they had been in contact with the end plates and had received, therefore, a pressure much greater than the alum alone could transmit. The upper smaller piece had left a distinct imprint on the lower piece, and where it had overlapped, had been forced downward past the lower pyrrhotite block. Examination with binoculars showed that this deformation had taken place both by cracking and true flow. The latter was revealed by the presence of several uncracked but warped surfaces. Upon one of these were a number of fine striations parallel to the trace of the basal parting on this face, and resembling closely slip- or twin-bands.

From the above it will be recognized that there is some presumptive evidence for flow of pyrrhotite by gliding. However, since the striations were few and noted only on one face, the attitude of the possible glide plane cannot be definitely known. Further experimentation was curtailed by the immediate lack of suitable single crystals of pyrrhotite.

E. PYRITE

Adams[25] attempted to deform pyrite by the method described. He embedded a fragment of a pyrite cube in alum with the edge of the cube upward and applied a load of 43,000 pounds in 17 minutes. During the test the pyrite came in contact with the end plate which, therefore, transmitted a large part of the load. On removing the crystal by solution of the alum he found that it had been crushed and powdered "without showing any trace of plastic deformation."[26] It seemed useless to repeat the experiment with the same

[25] Frank D. Adams, *Jour. Geology*, 18, p. 509 (1910).
[26] Veit was also unsuccessful in attempting to deform pyrite. *Op. cit.*, p. 146.

method and apparatus so no further experimental work was carried out by the writer. However, it seems probable that even this hard mineral might be made to flow by employing a method which would afford much greater lateral support, such a method, for example, as was later used by Adams and Coker[27] in the study of the flow of marble.

The data given by Adams are sufficient, however, for some conclusions. When pyrite is subjected to a load transmitted by some hard mineral with which it is in contact, and embedded in material which flows with the same readiness as alum we should expect it to suffer crushing. Roughly speaking, galena flows with the same order of ease as alum, as shown by the experiments on galena in which this mineral readily deformed in an alum matrix without touching the end plates of the containing apparatus. Hence, in nature, if pyrite is found in a deformed galena deposit and in contact with quartz, for example, we would expect it to crush rather than to flow. That this is indeed the case is illustrated in the Slocan[28] and Coeur d'Alene[29] districts.

Whether or not pyrite will actually flow when embedded in a more resistant matrix is a subject which deserves experimental attention. Some geological evidence for *possible* flow of pyrite enclosed in a matrix of sphalerite and chalcopyrite (which are more resistant to flow than galena) is to be found in the ores of Rammelsberg described by Lindgren and Irving,[30] although these writers are inclined to interpret the elongated pyrite nodules as crushed residuals.[31]

DEFORMATION BY SECONDARY TWINNING

As noted on previous pages, the simple lattice theory of translation, while satisfactory for observed deformation by translation, fails to explain the unlike deformation behaviors of the struc-

[27] Frank D. Adams and Ernest G. Coker; An experimental investigation into the flow of rocks, *Am. Jour. Sci.*, (4) **29**, pp. 465–487 (1910).

[28] W. L. Uglow; Gneissic galena ore from the Slocan district, B.C., *Econ. Geol.*, **12**, 643–662 (1917).

A. M. Bateman; Notes on silver-lead deposits of Slocan district, B.C., Canada, *idem*, **20**, 562 (1925).

[29] W. A. Waldschmidt; Deformation in ores, Coeur d'Alene district, Idaho, *idem*, **20**, 577 (1925).

[30] W. Lindgren and J. D. Irving; The origin of the Rammelsberg ore deposit, *idem*, **6**, 311 (1911).

[31] *Op. cit.*, p. 313.

turally similar chalcopyrite and sphalerite lattices. By taking into account the impurities present, however, the reason for the apparently anomolous twinning of sphalerite becomes clear.

All crystals, leaving out of consideration any mechanical admixtures, are impure. Mineral crystals particularly, seldom more than closely approximate their theoretical formulae. The impurities present must form an inherent part of the orderly internal atomic arrangement although it is usually only when they are appreciable in amount that they receive recognition by the designation "solid solution." Because of the differing atomic volumes of the solute and solvent atoms (or, in certain cases, groups of atoms) structural distortions are certain to mark the presence of foreign atoms in the lattice, as shown by Rosenhain.[32] In the case of rather concentrated solid solutions, the foreign atoms distort the perfect flatness of translation planes causing them to become warped surfaces. Consequently, as Rosenhain has pointed out,[33] translation is more difficult in impure than in pure crystals due to the locking action of adjoining, distorted planes. Since translation, to become even microscopically visible, involves a localized slipping between planes for distances of many atom diameters, it may completely escape detection in concentrated solid solutions, because the extent to which translation takes place must be highly restricted in these greatly distorted lattices. On the other hand, deformation by secondary twinning involves a completely distributed[34] interplanar adjustment in the order of only one atom diameter, as shown in the case of sphalerite, and the resulting deformation is immediately apparent by etching due to the changed lattice orientation. Thus a very pure crystal would be expected to deform by translation while an impure one, having distorted planes upon which extensive slip would be attended by great friction, would be expected to deform by secondary twinning.

It is noteworthy that chalcopyrite when not associated with cubanite, is a very pure mineral, while sphalerite is notoriously impure, dark sphalerite containing from 1 to 18 per cent of iron in

[32] Walter Rosenhain; Solid solutions, *Trans. Am. Inst. Min. Met. Engs.*, **69**, pp. 1011–1017 (1923).

[33] *Op. cit.*

[34] That is, the same relief of pressure which when accomplished by translation of a few planes for long distances, can also be accomplished by a slight adjustment distributed on all planes throughout the entire crystal.

addition to appreciable quantities of other foreign metals.[35]   In confirmation of this it is found that in cases where cubanite is present as an unmixed structure in chalcopyrite, the latter also displays polysynthetic twinning on etching.[36]   Cubanite and chalcopyrite are known from Schwartz's investigations[37] to form solid solutions.   The inference is that the presence of cubanite in the chalcopyrite lattice before unmixing (or possibly its residue after partial unmixing) so distorts the lattice that twinning but not translation is possible.

Alling[38] notes that microcline (a solid solution mineral), untwinned before thin section grinding or before pulverizing, deforms by twinning during these operations, and that twinned microcline can be used as an indication that the mineral has been subjected to the action of excessive compressive forces, as for example, in the vicinity of a fault.   Among the other solid solution minerals to which secondary twinning is attributed may be mentioned: plagioclase,[39] garnet, pyrrhotite, pyroxene, calcite, and dolomite. These few examples tend to confirm the supposition that impurities engender secondary twinning rather than translation on deformation.

The writer takes this opportunity to gratefully acknowledge the aid given by Doctor W. H. Newhouse during the experiments.