III. Crystallographic Study.

As the sulphides of iron are all opaque, the ordinary optical tests are not available and the mineralogic study is confined to the determination of the color, luster, cleavage, magnetic properties, crystal form, chemical properties, etc. Color and magnetism are important diagnostic properties of the sulphides of iron, while the crystal form and the chemical properties give positive evidence of the identity of the artificial preparations with the natural minerals. In general the synthetic iron sulphides prepared in the dry way or by the inversion of one form into another in the solid state are massive and without crystal form, and only the color, magnetic and chemical properties can be determined. The iron sulphides precipitated from solutions usually consist of a network of crystals, or of drusy crusts. Some preparations have crystals which are large enough for measurement on the Goldschmidt goniometer; most of the crystals measured are from 0·2 to $0{\cdot}4^{mm}$ in length, though one crystal of β-pyrrhotite is about a millimeter in length, and one crystal of marcasite is even a little larger. In many of the preparations the crystals are all very minute—less than a tenth of a millimeter in length and often much less—and the crystallographic study was confined to an examination of the material under the microscope. The crystal habit, however, of each of the four minerals is characteristic, and even the minute crystals can usually be determined.

Pyrite.

In some preparations the larger crystals of pyrite are half a millimeter across and can be easily recognized with a pocket lens by their color and crystal form. Much smaller crystals can be determined by the use of the microscope. The crystals usually show both the cube and the octahedral faces, but both forms also occur alone; pyritohedrons were not observed; the faces are always much warped and very imperfect. For the several crystals measured on the goniometer, the angles were seldom over half a degree from the theoretical value, and a closer agreement cannot be expected.

Marcasite.

The color of the synthetic marcasite is identical with that of the natural mineral, but the color test is not altogether satisfactory on minute crystals, even when brightened by heating in acid. The crystal habit, however, is characteristic, and the goniometric measurements of some of the larger crystals show a very close agreement with those of the natural mineral.

The common habit of the synthetic marcasite is shown in clinographic projection in fig. 15. The crystals are twinned with the face *m* (110)* as twinning plane, they are tabular parallel to the twinning plane and elongated along the vertical axis. The prisms *m* {110}, especially the large faces parallel to the twinning plane, are deeply striated parallel to the base. The domes *e* {101} and *l* {011} are also prominent. Crystals of a second habit, which are common in some preparations, are more symmetrical in their development and less often twinned; in them the domes, *e* {101} and *l* {011}, are characteristic forms and the striated prisms, *m* {110}, are usually prominent. The crystal represented in fig. 16 is of this habit, but the prisms and pyramids *s* {111} are more prominent than usual. Several crystals were seen under the microscope which resemble the fiveling pictured by Dana.† A preparation formed as usual, but at room temperature, consists of strings of minute crystals which have a rhombic outline under the microscope, and sometimes the obtuse angle of the rhombs is truncated by a face which is probably the prism, *m* (110).

Fig. 15.

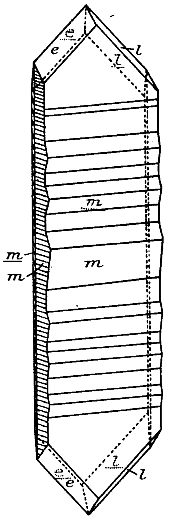

Fig. 16.

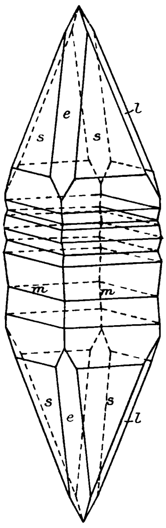

Fig. 15. Artificial marcasite showing the forms *m* {110}, *e* {101}, and *l* {011}. Twinned after (110).

Fig. 16. Artificial marcasite showing the forms *m* {110}, *e* {101}, *l* {011}, and *s* {111}.

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*Throughout this paper parentheses are used to indicate crystal faces; brackets, to indicate the entire crystal form.

† System of Mineralogy, 6th edition, p. 95.

Crystals of marcasite large enough for measurement on the goniometer were found in several preparations; most of them are only a few tenths of a millimeter in length, but a few are about a millimeter long. Seven fairly satisfactory crystals from two different preparations were measured. Only one of these is not twinned. The signals were seldom sharp, blurred signals, striated zones, and vicinal faces being the rule. The faces of {111} usually gave fairly sharp reflections, but between (111) and (11$\bar{1}$) there was a more or less complete band of signals, and that for the face (110) seldom stood out sharply from the others. In some of the tabular twinned crystals the faces of {110} which are parallel to the twinning plane yielded bright signals, or else there were several bright signals near these faces. The reflections from the faces of {011} were usually bright, but vicinal development often made their exact position uncertain. Between (011) and (01$\bar{1}$) there was usually a dim series of signals, but the reflection signals of the faces of {011} did not stand out from the others. The faces of {101} gave fairly sharp signals. In one crystal the reflections of the faces of {772} took the place of those from {111} at the ends of the series of signals of this zone. Most of the twinned, tabular crystals gave a dim but nearly continuous line of signals from the large faces (110) through the face (011) and the corresponding face $\underline{(011)}$ to $\underline{(\bar{1}\bar{1}0)}$. The faces {10$\bar{1}$} of both individuals lie on this zone, whose symbol is $h+l=k$. It is poorly developed on the untwinned crystal.

Crystal angles of synthetic marcasite.—Of the seven crystals to be described, the first five were from a preparation of October 16, 1908, and were formed by the action of H_2S on an acid solution of $FeSO_4$ for four days at a maximum temperature of 300°. The crystals of this preparation are all of the habit shown in fig. 15. Crystals 6 and 7 were from a preparation of October 28, 1908, and were formed at a maximum temperature of 220°. The common habit of the crystals of this preparation is shown in fig. 16, but the pyramids and prisms are often less prominent; there are some twinned crystals similar to those shown in fig. 15.

Table IX lists the weighted average of the angles measured for each crystal, the crystal constants of synthetic marcasite, and the corresponding constants of the natural mineral as given by Gemacher and Goldschmidt.

The agreement shown by Table I between the angles and axial ratios of natural marcasite and those of the synthetic mineral is very good. Both commonly show twinning with (110) as twinning plane, and both have the two unit domes and the pyramids as common faces. The base, however, which is

TABLE IX.

Crystal angles measured on synthetic marcasite.

No. of Crystal	No. of meas.	Polar angle of (011)	No. of meas.	Polar angle of (111)	No. of meas.	Polar angle of (101)	No. of meas.	(110) (010)	No. of meas.	Angle between twin after (110)	No. of meas.	Polar angle of (772)
1	1	50° 58′		----		----	2	52° 41′	3	74° 42′		----
2	2	50° 40′		----	2	58° ±	1	52° 12′	1	74° 33′	3	81° 50′
3	3	50° 44′		----		----	6	52° 36′	2	74° 20′	6	81° 48′
4	6	50° 18′		----		----	6	52° 35′	1	75° 12′		---
5	5	49° 55′	8	63° 40′	3	57° 27′	5	52° 34′	3	74° 47′		----
6	2	49° 55′	6	63° 29′	2	58° 10′	5	52° 38′		----		----
7	4	50° 40′	3	63° 22′	2	57° 50′	4	52° 28′	2	75° 18′		----
Weighted av....		*50° 27′*		*63° 29′*		*57° 48′*		*52° 35′*		*74° 49′*		*81° 48′*
Computed......		50° 36′		63° 29′		57° 52′		52° 35½′		74° 49′		81° 53½′
Gemacher*.....		50° 36′		63° 30′ 54″		57° 55′ 59″		52° 41′		----		----
Goldschmidt†...		50° 29′		63° 30′		57° 59′		52° 50′		----		----

$a:b:c = 0{\cdot}7646 : 1 : 1{\cdot}2176$ Larsen, synthetic marcasite
$a:b:c = 0{\cdot}762256 : 1 : 1{\cdot}216698$ Gemacher*
$a:b:c = 0{\cdot}7580 : 1 : 1{\cdot}2122$ Goldschmidt†
$a:b:c = 0{\cdot}75241 : 1 : 1{\cdot}18473$ Hausmann
$a:b:c = 0{\cdot}766172 : 1 : 1{\cdot}23416$ Sadebeck

* Natural marcasite, Gemacher, Zs. Kryst., xiii, 242, 1888.
† Natural marcasite, Goldschmidt, Winkeltabellen, Berlin, 1897.

usually prominent in the natural mineral, was not observed on the synthetic crystals, while the prism zone is often more prominent on the artificial crystals. The natural mineral is described as having the brachydomes and pinacoids deeply striated parallel to the edge (010) (001); the synthetic mineral is similarly striated, the pyramid and prism zones are even more prominently striated parallel to the base, and the zone $h + l = k$ on some of the crystals is a more or less continuous series of faces due to striations.

Pyrrhotite.

The experiments of Rinne and Bœke* show an inversion in FeS with 7 per cent, the maximum amount, of dissolved iron at 138°. On decreasing the amount of dissolved iron to 5 per cent the absorption of heat takes place between 90° and 98°. Although they were not able to observe a heat absorption in FeS with less than 5 per cent of dissolved iron or in natural pyrrhotite, they state that the inversion takes place but is too sluggish to be observed. Ferrous sulphide with a little carbon showed the inversion at 134·5°, while meteoric troilite with a little carbon inverted at about 143°.

The present crystallographic study tends strongly to confirm the work of Rinne and Bœke. The low temperature form or β-pyrrhotite appears to be hexagonal, while the high temperature form or α-pyrrhotite appears to be orthorhombic. The measured interfacial angles for the two forms are near together and the fact that these angles vary with the amount of sulphur in excess of that required for FeS, together with the impossibility of determining the chemical composition of the measured crystals, makes a comparison of the crystal constants of the two forms impossible. However, the crystal habit, the twinning, and the development of the faces on the two forms afford good evidence for the view that they belong to different crystal systems.

The color of the synthetic pyrrhotite is similar to that of the natural mineral. That prepared by melting iron and sulphur together is a little darker and has more of a grayish cast than the natural mineral. The crystals from some preparations of α-pyrrhotite are only slightly magnetic while those from others are strongly so. The crystals always show polarity with the poles along the a-axis. The poles for β-pyrrhotite are along the c-axis in the one crystal observed.

α-Pyrrhotite.

Twenty-two fairly satisfactory crystals of α-pyrrhotite, representing four different preparations, were measured on the

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* Zs. anorg. Chemie, liii, 338–343, 1907.

goniometer. The crystals are almost certainly orthorhombic in symmetry, although the angles in the prism zone are very nearly 60°. In the following discussion, the crystals are treated as orthorhombic. The crystals are usually twinned with the twinning plane (023); one crystal is twinned only after (021), and two crystals are twinned after both laws. The twinned crystals are tabular parallel to the base and elon-

FIG. 17.

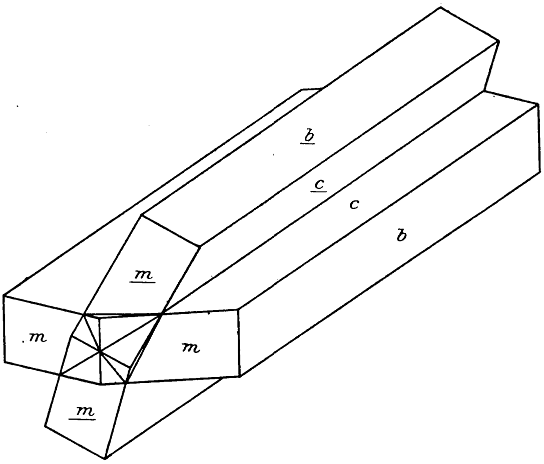

FIG. 17. Artificial *a*-pyrrhotite showing the forms *m* {110}, *b* {010}, and *c* {001}. Twinned after (023).

FIG. 18.

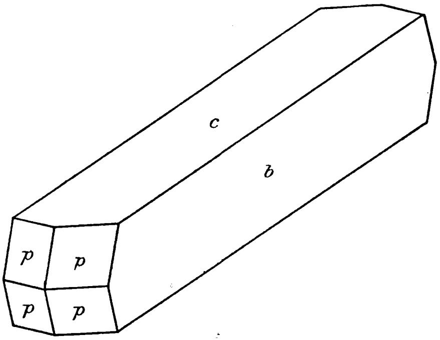

FIG. 18. Artificial *a*-pyrrhotite showing the forms *b* {010}, *c* {001}, and *p* {111}.

gated in the direction of the *a*-axis. The untwinned crystals are also nearly always much elongated along the *a*-axis, and have as their principal forms {001}, {010}, {111}. Tabular crystals of hexagonal shape are rare.

Crystals A to H are from two different preparations formed by the action of H_2S on an acid solution of $FeSO_4$ at a maximum temperature of 225° C. They are about 0·3 × 0·15 × 0·05^{mm} in dimensions. Most of the crystals are tabular parallel to the base and elongated along the *a* axis; they are twinned after (023); {001}, {010}, and {110} are the dominant forms. Fig. 17 shows one of these crystals. Crystal H simulates a tabular hexagonal crystal; it is not twinned and is bounded by the forms {001}, {010}, {110}, {011}, {112}, {021}, and {111}. Crystals of this type are uncommon.

FIG. 19.

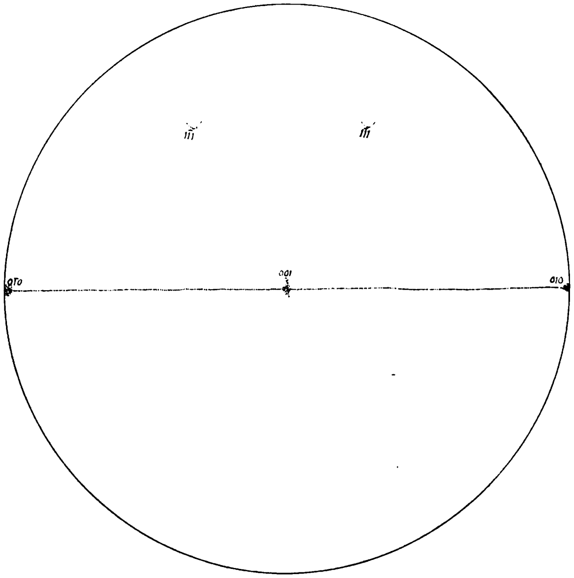

FIG. 19. Stereographic projection of a simple crystal of *a*-pyrrhotite showing the development of the striation and vicinal faces.

A third preparation was formed at about 200° C. The inside tube contained 3 g. $FeCl_2$, 1^{cc} 20 per cent HCl, and 25^{cc} boiled H_2O. After heating at about 200° C. for several days, the sealed tube was allowed to stand at room temperature from June 16, 1909 to March 23, 1910. There was a considerable yield of pyrrhotite crystals. They are strongly magnetic and show polarity with the poles along the *a* axis. Many of them are about 0·3^{mm} in length and about a fifth as thick and broad. Twinning is rare and the base resembles a hexagon much elongated along one diameter and delicately striated parallel to the six sides. There are a very few hexagonal tablets and twinned crystals similar to those of preparations 1 and 2. The six measured crystals, I to N, are all similar in habit to the crystal shown in fig. 18, and the dominant forms are {001}, {010}, and {111}. One crystal showed also the form {021} poorly developed, and another crystal showed {091}. Fig. 19 is the stereographic projection of crystal I. The crystals were mounted along the *a* axis. They did not, in general, give sharp signals and measured angles between (001) and (010) were in some cases out as much as 2°; while the measurements for the faces {111} were only a little better.

Fig. 20.

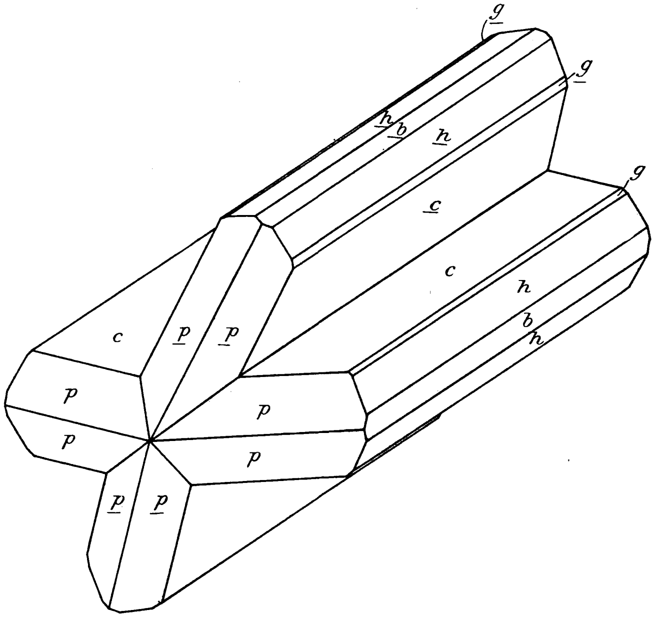

Fig. 20. Artificial *a*-pyrrhotite showing the forms *c* {001}, *b* {010}, *p* {111}, *h* {021}, and *g* {011}. Twinned after (021).

A fourth preparation was formed by the action of H_2S on a solution of acid FeCl at a maximum temperature of 210°. Nearly all of the crystals are tabular parallel to the base and elongated along the *a* axis. Several of them are 0·5^{mm} in length. Out of seven crystals measured, one is twinned after the law: twinning plane (021); three are twinned after the law: twinning plane (023); two after both laws, and one crystal is an untwinned hexagonal tablet. The crystals resemble the untwinned crystals of lot 3 in that the dominant forms are {001}, {010}, and {111}, but {021}, {011}, {0.1.20}, {110}, and {112} were also recognized. Fig. 20 represents one of these crystals twinned after (121). Fig. 21 is the stereographic projection of crystal U, which is twinned after both (023) and (021). One of the individuals of the twin after (023) is poorly developed on the part of the crystal shown.

Fig. 21.

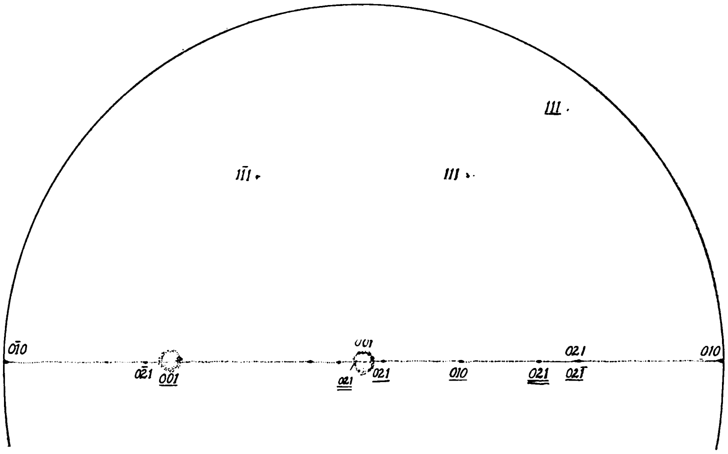

Fig. 21. Stereographic projection of a crystal of *a*-pyrrhotite twinned after both (021) and (023). The half of the crystal represented on the projection shows few of the faces of one of the individuals after (023). The faces of the crystal twin after (021) are underscored once, those of the twin after (023) twice.

Table X gives a summary of all the crystals of *a*-pyrrhotite which were measured. The designation of the crystal is given in column one and the number of the preparation from which it came in column two. Column three lists the faces recognized on the crystal, and column four gives the average of the angle between the faces (110) and (010). The eight succeeding columns give the weighted averages of the measured interfacial angles each followed by the value of p_0 computed from that angle. Next to the last column lists the weighted averages of the constant p_0 which is equal to the vertical axis, *c*. The final column gives all measured angles not listed in any of the previous columns.

A comparison of the different values of p_0 with the average value, c, for any crystal shows that the difference is greater than 2 per cent only for crystal A, and in this case the angle from which p_0 was computed was so unreliable that it was not considered in computing the average. In all cases where the angle from which any p_0 was computed seemed to be reliable the difference between p_0 and c is less than 1 per cent of c. An error as large as 1 per cent in c may, therefore, be regarded as exceptional. One possible exception is crystal I, as the measurements on it were unsatisfactory and it has, therefore, been discarded in the discussion to follow. If, however, we compare the value of c for the different crystals we find a maximum difference of 0·0660 between crystals M and T or a difference of nearly 7 per cent of their mean value. Moreover, the two extremes are neither exceptionally high nor exceptionally low but the other crystals are pretty evenly distributed between them. It seems certain, therefore, that the crystal constants of α-pyrrhotite vary considerably in accord with the variable composition of the mineral.

A further study of Table II shows that while the crystals of a given preparation show a considerable difference in the constant, c, yet those of preparation 3 are uniformly high, those of preparation 4 generally low, and those of preparation 1 and 2 intermediate. Unfortunately it was not found possible to determine the relation between the value of c and the chemical composition, as, even were any of the crystals large enough for an analysis, it is probable that they are built up of successive shells of different composition.

No consistent variation in the angle (100) (110) was recognized but it probably varies with c. The measurements were usually not good but the average value of 59° 55′ is probably within 15′ of the true value. Computing the axial ratios of α-pyrrhotite for the limiting values given by crystals M and T we have: $a:b:c$ 0·5793 : 1 : 0·9267 to 0·5793 : 1 : 0·9927. It is probable that the limits are considerably greater than this. Table XI lists the observed faces and the interfacial angles as computed from the above values of the axial ratios.

The symmetry and crystal constants of α-pyrrhotite.—The evidence that α-pyrrhotite is orthorhombic in symmetry is good, although it may not be conclusive. The angles in the prism zone were not proven to differ from sixty degrees, but the habit of the crystals consistently indicates orthorhombic rather than hexagonal symmetry. A very few crystals resembled hexagonal tablets. Nearly all of the crystals of the first two preparations were developed much like the crystal shown in fig. 17, although small domes and pyramids were found on many of the measured crystals. The habit and

TABLE X.—SUMMARY OF CRYSTAL

Crystal	No. of Preparation	Faces represented	(010) (110)	Angle betw. basal pinacoids of twin after (023)	p_o	Angle betw. basal pinacoids of twin after (021)	p_o	(001) (021)
A	1	(001) (010) (110) (112)	60° ±	66° 30′	0·9834	------	------	------
B	1	(001) (010) (110)	59° 32′	65° 35′	0·9850	------	------	------
C	1	(001) (010) (110)	59° 50′	65° 7′	0·9578	------	------	------
D	2	(001) (010) (110) (100) (011) (023)	60° 10′	65° 27′	0·9639	------	------	------
E	2	(001) (010) (110)	59° 57′	63° 59′	0·9376	------	------	------
F	2	(001) (010) (111) (221)	60° ±	64° 5′	0·9388	------	------	------
G	2	(001) (010) (110) (992)	59° 57′	65° 57′	0·9732	------	------	------
H	2	(001) (010) (110) (021) (111) (011) (112)	60° ±	------	------	------	------	62° 44′
I	3	(001) (010) (111)	60° 22′ ±	------	------	------	------	------
J	3	(001) (010) (111) (091)	59° 56′	------	------	------	------	------
K	3	(001) (010) (111)	60° 5′	------	------	------	------	------
L	3	(001) (010) (111)	59° 36′	------	------	------	------	------
M	3	(001) (010) (111)	60° 4′	------	------	------	------	------
N	3	(001) (010) (021) (111)	59° 59′	------	------	------	------	63° 15′
O	4	(001) (010) (021) (111) (011) (112)	59° 53′	65° 30′	0·9648	------	------	62° 31′
P	4	(001) (010) (021) (111)	60° ±	------	------	------	------	62° 14′
Q	4	(001) (010) (021) (111) (071)	60° ±	------	------	55° 18′	0·9545	62° 19′
R	4	(001) (010) (110) (021) (111) (0·1·20)	60° ±	65° ±	------	------	------	62° 26′
S	4	(001) (010) (110) (021) (111) (011)	59° 44′	66° 10′	0·9772	------	------	62° 18′
T	4	(001) (010) (021) (111) (011)	60° ±	62° 50′	0·9160	52° 25′ ±	------	61° 38′
U	4	(001) (010) (021) (111) (011) (1.1.34)	60° 30′ ±	64° 40′	0·9495	55° 30′	0·9503	62° 8′

the development of different faces in the zone (*0 k l*) from those in the zone (*h h l*) strongly indicate orthorhombic symmetry. The crystals of the third preparation were, with few exceptions, developed as is the crystal shown in fig. 18. The development of the zonal and vicinal faces is shown in fig. 19, which is a stereographic projection of crystal I. The other crystals of this lot are much like this, although the striations of the zone (*0 k l*) are not usually so prominent. The crystals

MEASUREMENTS OF *a*–PYRRHOTITE

p_o	(001) (111)	p_o	(001) (011)	p_o	(001) (112)	p_o	Average $p_o = c$.	Other measured angles
-----	------	-----	------	-----	43° 50′	0·9610	0·9834	-----------------
-----	------	-----	------	-----	------	-----	0·9850	-----------------
-----	------	-----	------	-----	------	-----	0·9578	-----------------
-----	------	-----	44° 10′	0·9713	------	-----	0·9639	(001) (021) = 32° 27′
-----	------	-----	------	-----	------	-----	0·9376	-----------------
-----	61° 48′	0·9372	------	-----	------	-----	0·9380	(001) (221) = 74° 59′
-----	------	-----	------	-----	------	-----	0·9732	(001) (992) = 83° 41′
0·9701	62° 44′	0·9750	43° 59′	0·9646	43° 59′	0·9675	0·9725	-----------------
-----	63° 24′	1·0035	------	-----	------	-----	1·0035 ±	-----------------
-----	63° 1′	0·9878	------	-----	------	-----	0·9878	(001) (091) = 83° 17′
-----	62° 55′	0·9827	------	-----	------	-----	0·9827	-----------------
-----	62° 32′	0·9667	------	-----	------	-----	0·9667	-----------------
-----	63° 9′	0·9927	------	-----	------	-----	0·9927	-----------------
0·9920	63° 4′	0·9891	------	-----	------	-----	0·9891	-----------------
0·9614	62° 34′	0·9681	43° 51′	0·9607	44° 12′	0·9772	0·9669	-----------------
0·9497	62° 14′	0·9545	------	-----	------	-----	0·9521	-----------------
0·9530	------	-----	------	-----	------	-----	0·9530	(001) (071) = 81° 40′
0·9578	------	-----	------	-----	------	-----	0·9578	(001) (0.1.20) = 2° 42′
0·9524	62° 40′	0·9772	43° 50′	0·9601	------	-----	0·9660	-----------------
0·9262	61° 58′	0·9437	43° 10′	0·9380	------	-----	0·9267	-----------------
0·9456	62° 10′	0·9517	------	-----	------	-----	0·9485	(001) (1.1.34) = 3° 10′

of the fourth preparation are usually twinned, and the common habit of these crystals is shown in fig. 20. This crystal is twinned after (021) and the crystals which are twinned after (023) are similar, except for the twinning law. These crystals are also elongated along the *a* axis and show a very different development in the zone (*0 k l*) from that in the zone (*h h l*). Fig. 21, which is a stereographic projection of crystal U, shows the development of the zonal and vicinal faces. Several other

TABLE XI.—Computed interfacial angles of α-pyrrhotite for different values of the axial ratios.

	$c = 0{\cdot}9267$	$c = 0{\cdot}9927$
(001) (011)	42° 49′	44° 47′
(112)	42° 42′	44° 40′
(021)	61° 39′	63° 16′
(111)	61° 36′	63° 13′
(010)	90° 0′	90° 0′
(110)	90° 0′	90° 0′
(100)	90° 0′	90° 0′
(023)	31° 42′	33° 30′
(221)	74° 52′	75° 50′
(010) (110)	59° 55′	59° 55′
(100) (100)	90° 0′	90° 0′
Angle between twins after (023)	63° 24′	67° 0′
Angle between twins after (021)	56° 42′	53° 28′

preparations were made up largely of crystals of high-temperature pyrrhotite, and, although no measurable crystals were found, the microscopic study showed that they were very similar in habit to the measured crystals. On the other hand, the crystals from the three preparations which were formed at 100° C. and below, invariably had a very different habit (p. 231).

β-Pyrrhotite.

Three crystals of pyrrhotite formed below the inversion temperature were measured. They were each from a different preparation and should give a fair idea of the crystal habit and crystal constants of β-pyrrhotite. Their habit and the measured angles afford good reasons for supposing that β-pyrrhotite is hexagonal. The most prominent faces recognized were those of *m* $\{10\bar{1}0\}$ and *z* $\{20\bar{2}1\}$, but those of *c* $\{0001\}$ were rather prominent on one crystal, and the vicinal form z_a $\{16.0.\overline{16}.7\}$ on two crystals; the faces of the form *x* $\{50\bar{5}1\}$ were subordinate on one crystal. All three of the crystals were twinned with $(10\bar{1}1)$ as the twinning plane, giving cruciform twins with an angle of approximately 90° between the two individuals. Figures 22 and 23 are clinographic projections of the two habits of the crystals.

The best crystal came from a preparation which was formed by heating for 8 days at a maximum temperature of 80° C. a sealed glass tube which contained a dilute solution of $FeSO_4$ saturated with H_2S at 0° C. The yield of β-pyrrhotite was small and consisted of the measured crystal which was about 1^{mm} in length, a crystal about half as large and a few crystals less than $0{\cdot}2^{mm}$ in length. All were twinned and otherwise similar to the measured crystal. This crystal, which was mounted on the goniometer along the *c*-axis of one of the individuals, gave blurred and multiple signals, but it was not striated, and most of the faces could be located to within about ten minutes. The only forms developed were the prisms $\{10\bar{1}0\}$ and the steep pyramids $\{20\bar{2}1\}$. Figure 22 is the clinographic projection of the crystal. Six fairly good measurements of the angle $(20\bar{2}1) \wedge (20\bar{2}\bar{1})$ gave values of 53° 29′, 53° 30′, 53° 31′, 53° 6′, 53° 15′, 53° 41′, averaging 53° 22′; hence the polar angle of $(20\bar{2}1)$ is 63° 19′. Two good measurements of the angle between $(10\bar{1}0)$ and $(\underline{10\bar{1}0})$ were 89° 41′ and 89° 49′, averaging 89° 45′. The twinning plane is therefore $10\bar{1}1$. The angles measured between the prisms were never over 30′ from 60°.

Fig. 22.

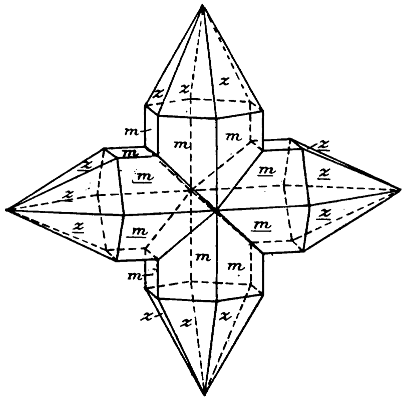

Fig. 23.

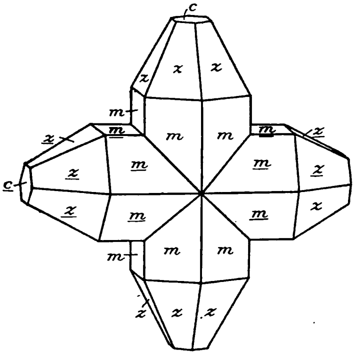

Fig. 22. Artificial β-pyrrhotite showing the forms *m* $\{10\bar{1}0\}$ and *z* $\{20\bar{2}1\}$. Twinned after $(10\bar{1}1)$.

Fig. 23. Artificial β-pyrrhotite showing the forms *m* $\{10\bar{1}0\}$, *z* $\{20\bar{2}1\}$, and *c* $\{0001\}$. Twinned after $(10\bar{1}1)$.

The conditions of formation of the second crystal were similar to those of the first but the maximum temperature was about 100°* and the tube was allowed to stand at room tem-

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* We do not know the inversion temperature of FeS with an excess of sulphur and can not, therefore, be certain that this and the following crystals were formed below that temperature. Their habit, however, is evidence that they belong to the low temperature form.

perature for about three months before opening. A considerable number of small, twinned crystals similar to the measured crystal and in no case over $0{\cdot}15^{mm}$ in length were formed. The measured crystal was similar in its development to crystal 1, except that the pyramids were somewhat striated parallel to the base and $\{16.0.\overline{16}.7\}$ was the dominant pyramid. The reflections were not quite so good as those of the first crystal. Six measurements of the polar angle of $(16.0.\overline{16}.7)$ varied from 66° 0′ to 66° 31′, averaging 66° 18′. The signals for the face $(20\bar{2}1)$ did not stand out sharply from the other signals of its zone, but three measurements of the angle between the points where the strings of signals for the pyramid zones of the two individuals intersected gave 52° 47′, 53° 32′, and 52° 34′, averaging 52° 58′. The polar angle of $(20\bar{2}1)$ is, therefore, 63° 31′. One good measurement of the angle between the prism faces of the two individuals was 90° 14′. The angles in the prism zone may differ as much as 30′ from 60°.

The third preparation was formed as was the second but the crystals differed in that the base was rather prominent and the form $\{50\bar{5}1\}$ was present. The habit of these crystals is shown in fig. 23. The measured crystal which was less than $0{\cdot}2^{mm}$ in length gave rather poor signals, and many of the faces were very poor or missing. There was a continuous line of signals from the prisms to the pyramids $(20\bar{2}1)$ and the angle between the intersections of these zones belonging to the two individuals measured 52° 34′ and 52° 0′, averaging 52° 20′. Therefore the polar angle of $(20\bar{2}1)$ is 63° 50′. The angle between the bases of the two individuals measured 90° 7′. Three measurements of the polar angle of $(16.0.\overline{16}.7)$ averaged 66° 25′ with a maximum deviation of 19′. Five measurements of the polar angle of $(50\bar{5}1)$ averaged 78° 55′ with a maximum deviation of 26′. The angles between the prisms could not be measured accurately but they differed from 60° by less than 20′.

The data for the three measured crystals of β-pyrrhotite are assembled in Table XII. The table shows the principal interfacial angles as measured on each crystal and as computed from the average value of the constant p_0, the faces observed on each crystal and the value of the vertical axis c. There is a close agreement between the measured and the computed angles and it seems certain that the difference in the value of p_0 for the different crystals represents an actual difference in the crystal constants. Their difference is easily accounted for, as the amount of sulphur in pyrrhotite varies considerably.

A comparison of the two forms of pyrrhotite.—The following criteria for distinguishing between the two forms of pyrrhotite applied to all of the artificial crystals which were examined and should serve as more or less reliable means of distinguishing between the two forms in both natural and synthetic crystals:

1. The habit of β-pyrrhotite is hexagonal and the dominant forms are the prism, and a steep pyramid, and sometimes also the base (figs. 22 and 23). α-pyrrhotite, on the other hand, is always tabular parallel to the base; a few of the crystals appear to be hexagonal, but most of them are much elongated in the direction of the *a* axis and the orthorhombic symmetry is further shown by the common association of the forms {001}, {100}, and {111} (figs. 17, 18 and 20).
2. The low temperature form (β) is almost invariably developed as cruciform twins with an angle of about 90° between the two individuals (twinning plane $10\bar{1}1$), while the high temperature form (α) is usually twinned after (023) with the two individuals at about 65° to each other, and sometimes also after (021) with the two individuals at about 55° to each other.
3. The constant p_0 for the measured crystals of β-pyrrhotite varied from 0·9967 to 1·0100, while for α-pyrrhotite it varied from 0·9267 to 0·9927. While crystals for which the value of p_0 was approximately 1·0000 were found in both

TABLE XII.

Crystal data of β-Pyrrhotite.

	Crystal 1		Crystal 2		Crystal 3	
	Observed	Computed p_0— 0·9967	Observed	Computed p_0=1·004	Observed	Computed p_0=1·01
Polar angle of $(20\bar{2}1)$	63° 19′	63° 19′	63° 31′	63° 32′	63° 50′	63° 40′
Angle between twins	89° 45′	89° 42′	90° 14′	90° 14′	90° 7′	90° 34′
Polar angle of $(50\bar{5}1)$	----	----	----	----	78° 55′	78° 48′
Polar angle of $16.0.\bar{16}.7)$	----	----	66° 18′	66° 27′	66° 25′	66° 35′
Faces	$(10\bar{1}0)$ $(20\bar{2}1)$		$(10\bar{1}0)$ $(20\bar{2}1)$ $(16.0.\bar{16}.7)$		$(10\bar{1}0)$ $(20\bar{2}1)$ $(16.0.\bar{16}.7)$ $(000\bar{1})$ $(50\bar{5}1)$	
c	0·8632		0·8695		0·8742	

forms and the unknown limiting values would introduce a greater ambiguity, yet crystals for which p_0 is considerably less than 1·0000 are likely to be α-pyrrhotite while those for which p_0 is considerably greater than 1·000 are probably β-pyrrhotite.

Natural Pyrrhotite.

Pyrrhotite has generally been considered hexagonal, but as early as 1878 Streng* suggested that it was orthorhombic and isomorphous with sternbergite. However, in 1882 he† concluded that the mineral was hexagonal from a study of the crystal form, etch figures, heating curve, and magnetic properties. Vrba,‡ Frenzel,§ and Dom Pedro von Sachsen-Coburg‖ measured crystals whose angles indicated orthorhombic symmetry. Crystals associated with limestone containing garnets are described by Roth¶ as elongated along a horizontal axis and hence orthorhombic in habit. Nicol** described crystals with a "decided orthorhombic appearance." Recently Weiss†† studied the magnetic properties of pyrrhotite and concluded that it was probably monoclinic but that it could not have a higher symmetry than orthorhombic. Kaiser‡‡ concluded, from a study of magnetic and other properties, that the mineral occurred in twinned orthorhombic crystals.

There has also been a lack of agreement in the measured angles and length of the vertical axis. Table XIII gives the important crystal data for the eleven measured crystals of natural pyrrhotite which seemed to be most reliable. The first column contains the name of the author; the second, the observed faces in the order of their prominence on the crystal giving the hexagonal symbol assigned by Dana; the third column gives the habit of the crystal; the fourth column, the most probable value of p_0. The occurrence and associated minerals are listed in the fifth column. The values for the constant p_0 are reliable only for the crystals of Busz, Nicol, Seligmann, Kenngott, Rose, and perhaps Shephard. The crystal of D'Achiardi gave values of p_0 ranging from 0·9658 to 1·0240 depending on which pyramid was used in the calculation. That of Dom Pedro gave no good measurements. The two crystals of Streng and the one of Dana afforded measurements on only one pyramid and the value of p_0 depends upon the symbol assigned to it.

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* Jahrb. Min., p. 797, 1878.

† Jahrb. Min., i, p. 183, 1882.

‡ Zs. Kryst. Min., iii, p. 190, 1879.

§ Min. Petr. Mitt., iii, 297, 1881.

‖ Min. Petr. Mitt., x, 451, 1888.

¶ Z. Kryst. Min., ix, 309, 1884.

** Zs. Kryst. Min., xxxi, 53, 1899.

†† Jour. de Phys., pp. 469 and 829, 1905; Centralbl. Min., p. 338, 1906.

‡‡ Centralbl. Min., p. 261, 1906.

Table XIII. Measured Crystals of Natural Pyrrhotite.

Author	Faces	Habit	p_o	Occurrence and associations
1. Busz	(0001) $(10\bar{1}2)$ $(10\bar{1}0)$	Tabular (0001)	0·9407	Andreasburg. Crystals on calcite.
2. Nicol	(0001) $(10\bar{1}0)$ $(20\bar{2}1)$ $(40\bar{4}1)$ $(10\bar{1}1)$	Decided rhombic appearance Tabular after (0001)	0·946	Fontenac County, Canada. Calcite apatite, pyrite.
3. Seligman ..	(0001) $(10\bar{1}0)$ $(40\bar{4}1)$ $(10\bar{1}1)$	Tabular after (0001)	0·9528	Cyclopean Isle. In analcite basalt with molybdenite, etc.
4. Kengott ...	(0001) $(10\bar{1}0)$ $(20\bar{2}1)$	....	0·9995	Kongsberg, Norway.
5. Streng	(0001) $(10\bar{1}0)$ $(20\bar{2}1)$	....	1·1195 ?	Kongsberg, Norway.
6. D'Achiardi	(0001) $(10\bar{1}0)$ $(20\bar{2}1)$ $(40\bar{4}1)$ $(60\bar{6}1)$	Tabular (0001)	1·000 ±	Bottino. On argentiferous galena.
7. Rose	$(20\bar{2}1)$ (0001) $(10\bar{1}0)$ $(12\bar{1}0)$ $(24\bar{2}1)$ $(10\bar{1}1)$	....	1·002	Meteorite. Augite and feldspar.
8. Shephard ..	(0001) $(20\bar{2}1)$ $(10\bar{1}0)$ (?)	....	1·0029	Meteorite.
9. Dana (E. S.)	$(20\cdot 0\cdot \overline{20}\cdot 3)$?, (0001)	Twinned after $(10\bar{1}1)$	1·0035	Elizabethtown, Ontario. Pyrite, talc, calcite, plagioclase, etc. Magnetic poles at sides of crystals in (0001).
10. Dom Pedro Augusto von Sachsen Coburg	(0001) $(10\bar{1}0)$ $(10\bar{1}1)$ $(40\bar{4}1)$	Tabular after (0001)	1·0412 ±	Minas Geraes, Brazil. Gold vein with pyrite, arsenopyrite, chalcopyrite, albite, calcite, apatite, cronstedtite, scheelite, etc.
11. Streng	$(10\bar{1}0)$ $(10\bar{1}2)$	....	1·0972	Chanarcillo, Chile.

1. N. Jahrb. Min., i, 124, 1895.
2. Zs. Kryst. Min., xxxi, 53, 1899.
3. Zs. Kryst. Min., xi, 343, 1886.
4. Ber. Ak. Wien, ix, 575, 1852.
5. N. Jahrb. Min., 925, 1878.
6. Proc. Soc. Tosc. Sc. Nat. Pisa, xiii, 140, 1903.
7. Pogg. Ann., iv, 180, 1825.
8. This Journal, xvi, 201, 1829.
9. Ibid., xi, 386, 1876.
10. Min. Petr. Mitt., x, 451, 1888.
11. Loc. cit.

The results of the different investigations are brought into agreement by the recognition of the two forms of pyrrhotite and also of the change in p_0 with a change in the composition of the mineral. The early view of Streng* that pyrrhotite is orthorhombic and belongs to the chalcocite group holds true for α-pyrrhotite, while β-pyrrhotite is hexagonal. Further investigation may show that other members of these groups are dimorphic.

A further study of Table XIII shows that most of the eleven crystals were probably formed as α-pyrrhotite. Crystals 1 to 3 have low values for p_0, tabular habits, and crystal 3, at least, has an association which would indicate the high temperature form. Crystal 2, in particular, is described as having a "decided orthorhombic appearance" and the orthorhombic axis is shown by the elongation along it and the development of the form {221} but not {041}, and of {011} but not {112}. Crystals 4 and 5 from Kongsberg might belong to either form, but their tabular habit suggests α-pyrrhotite. Crystal 6 has the tabular habit of α-pyrrhotite. Crystal 10 has a tabular habit and is, in addition, associated with minerals which indicate the high temperature form. The occurrence of crystals 7 and 8 in meteorites places them as α-pyrrhotite. The hexagonal development and the twinning of crystal 9 indicate β-pyrrhotite, but the association with feldspar, etc., and the position of the magnetic poles are not consistent with this view.

Any list of the faces which have been found on α-pyrrhotite will be somewhat uncertain since some of the measured crystals might belong to either form, and, besides, the variable character of p_0 makes it impossible to assign a symbol to some of the measured pyramids. The following list omits doubtful faces and marks with a star those found only on synthetic crystals.

c (001)
b (010)
a (100)
m (110)
l (310)
f (012)
e (023)*
g (011)
h (021)
i (041)
j (061)
n (201)
q (114)
v (112)
p (111)
r (221)
s (331)
u (623)

* Loc. cit.