Atacamite from Sierra Gorda, Chili.

By G. F. Herbert Smith, B.A.,

Assistant in the Mineral Department of the British Museum.

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In this paper are recorded the observations made upon four exceptionally good specimens of atacamite in the British Museum, which have been submitted to careful study with the object of determining the geometrical and physical characters of the mineral with greater accuracy than has hitherto been possible. The axial ratios have been calculated with the utmost refinement, an attempt has been made to determine the crystallographic symmetry by a study of the etched figures, and the values of the principal indices of refraction have for the first time been obtained.

The crystals are peculiar in habit, owing to the striking development of the pyramid forms. It may be mentioned that crystals of atacamite usually present a combination of the forms $b(010)$,[1] $m(110)$ and $e(011)$, and occur as long prisms whose edges are perpendicular to (001). Sometimes only one corner, in which m and e meet, is visible, in which case, since $mm''' = 67°$ and $ee' = 74°$ approximately, they resemble regular octahedra. In the case of the four specimens under consideration, the summit of the crystals is altogether altered in appearance; the dome form e still occurs, though often very small, but the pyramid faces, instead of being, as before, almost entirely absent, or at any rate barely visible, now form the most striking feature.

The four specimens may be taken as two pairs, the individuals of each being identical in all respects except that of size. The two specimens of one pair are from Sierra Gorda, in the northern part of the Desert of Atacama; the other two are *probably* also from the same region.

[1] The same letters are used for the faces as in Dana's *System of Mineralogy*, 6th edition.

1. *The axial ratios.*

The axial ratios given in Dana's *System of Mineralogy*, sixth edition, were calculated by Zepharovich from measurements made by himself and Klein on crystals from South Australia. There are in the British Museum numerous specimens from the Wallaroo mines. The crystals on these are good, but even the best cannot be compared with those from Sierra Gorda.[1] Some pains, therefore, were taken to obtain accurate values of the ratios. The faces of the form $m(110)$ unfortunately give as a rule so many images, with so much overlapping, that accuracy was out of the question, and, as will be seen later, considerable variations were obtained in the value of the prism angle. The angles best available for measurement were found to be $rr''(111 : \bar{1}\bar{1}1)$, $rr'''(111 : 1\bar{1}1)$, $rr'(111 : \bar{1}11)$ and nr (121 : 111). Only faces which gave perfectly definite images were employed; for this reason only the angle nr can be derived from the form n, the faces being often too small to give a sufficiently bright image. The goniometer used was a large Fuess instrument reading to 10 seconds, and by estimation to seconds. Only three crystals were thus measured. None of the others observed attained to the same degree of excellence, and would, if used, have only compromised the real accuracy of the results. After properly weighting the means of the four angles mentioned above, the axial ratios were calculated by the method of least squares. The result is as follows:—

$$a : b : c = 0{\cdot}66130 : 1 : 0{\cdot}75293.$$

For comparison, a list of axial ratios obtained by other observers is added:—

$a : b : c = 0{\cdot}66126 : 1 : 0{\cdot}75149$	Zepharovich and Klein[2]
$0{\cdot}66129 : 1 : 0{\cdot}75453$	Des Cloizeaux[3]
$0{\cdot}6613 : 1 : 0{\cdot}7501$	Lévy[4]
$0{\cdot}6703 : 1 : 0{\cdot}7581$	Miller
$0{\cdot}66186 : 1 : 0{\cdot}75302$	Brögger[5]
$0{\cdot}6683 : 1 : 0{\cdot}7506$	Zepharovich[6]

[1] Genth seems to have analysed similar crystals (see *Amer. Journ. Sci.* 1890, XL, 207), but no mention is made of any crystallographic or optical examination.

[2] *Ber. Akad. Wien*, 1873, 68(1), 120.

[3] *Nouvelles Recherches.*

[4] *Description d'une Collection de minéraux.*

[5] *Zeits. Kryst. Min.* 1879, III, 489.

[6] *Ber. Akad. Wien*, 1871, 63(1), 6.

Table I. gives the angles as calculated from the axial ratios and as observed :—

TABLE I.

Angle.	Calculated.	Observed Mean.	Diff.	Limits.	Edges.
111 : $\bar{1}\bar{1}1$ *rr''*	107°32′50″	107°32′21″	+29″	107°31′21″– 107°33′44″	5
111 : $1\bar{1}1$ *rr'''*	52 50 34	52 51 7	—33	52 50 24 — 52 52 0	4
111 : $\bar{1}11$ *rr'*	84 34 40	84 34 32	+ 8	84 34 28 – 84 34 40	4
111 : 121 *rn*	18 23 46	18 24 13	—27	18 23 19 — 18 24 52	7

The following are the calculated and observed values of *mm'''* on these crystals :—

Angle.	Calculated.	Observed Mean.	Limits.	Edges.
110 : $1\bar{1}0$ *mm'''*	66°57′12″	66°55′14″	66°41′40″—67°4′50″	5

2. *The face-indices and measurements.*

The general habit of the Sierra Gorda crystals is represented in fig. 1. *h* is a new and interesting form, whose faces are fairly large but invariably striated parallel to their intersections with *e*. As might, therefore, be expected, the observed values are not very accurate. This, however, will not account altogether for the very large variations noted; evidently vicinal faces are often present. The observed values fall more or less into groups, as given in Table II. It must be remarked that all these forms lie in the zone *me*. The simplest indices that can be assigned to *h* are (132), but the corresponding value is by no means the one most often met with, though it is the one observed when the face is least striated and the image most clear. On one crystal, indeed, two faces gave each two distinct images, which measurement showed corresponded to the forms (132) and (5·14·9), and could be plainly seen to be really double faces.

TABLE II.[1]

Angle.	Calculated.	Observed Mean.	Limits.	Edges.
110 : 253	41°42′ 5″	42°41′	41°49′—42° 0′	5
110 : 5.14.9	45 10 32	45 16	44 33½—45 58½	12
110 : 132	47 5 13	47 22½	46 35 —47 30	5
110 : 4.13.9	49 7 26	40 57	49 47 —50 8	3
110 : 275	51 51 5	52 25	51 41 —53 10	4
$1\bar{1}0$: 132	95 16 7	95 8	93 54 —97 11	6

[1] In Table II. and the following tables the measurements were made on a smaller Fuess goniometer reading to half-minutes.

The following forms have been observed on these crystals :—

b(010) Only twice seen ; probably then due to cleavage.

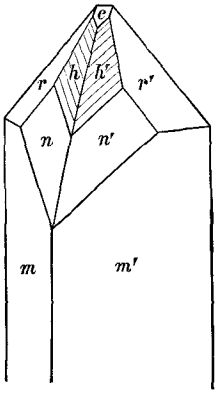
c(001) Infinitesimally small, no image given.

u(101) Seen twice only on one crystal, no image.

d(201) Very small, no image.

m(110) The principal prism form. As mentioned above, it gives multiple images.

FIG. 1.



s(120) Very small, no image.

e(011) Small, but images good.

r(111) Large faces : images beautifully distinct.

n(121) Faces not so large as in r, and often small : generally good images.

h(132), (5.14.9) ; see above.

The crystals used are from 3-5 mm. in length, but numerous smaller crystals are also present.

In Table III. will be found the calculated and observed values of the principal angles measured.

TABLE III.

Angle.	Calculated.	Observed Mean.	Limits.	Edges.
110 : $1\bar{1}0$ mm'''	66°57′ 12″	66°57′ 17″	66°17′ — 67°46′	12
111 : $\bar{1}\bar{1}1$ rr''	107 32 50	107 38 46	107 22 —107 56	6
110 : 121 mn	33 33 20	33 31 32	33 14 — 33 52	11
110 : 011 me	70 37 22	70 37 14	70 26 — 70 52½	16
$1\bar{1}0$: 111 $m'''r$	71 35 26	71 34 0	71 1 — 71 54	14

Associated with Atacamite on the first pair of specimens, and often mixed with it, is another mineral, which on examination was found to be caracolite. It generally occurs as a crystalline crust adhering to the vein-stuff on which it lies, but a few crystals resembling hexagonal tablets were noticed. Caracolite from this region has already been described by Mr. Fletcher,[1] and observations made on the present material agree closely with his. Goniometrical measurements, taken alone, would suggest that this mineral belongs to the hexagonal system; but, on placing one of these tablets between crossed nicols in the position which should give a uniaxial figure, no such figure can be seen, nor is it possible by rotating the nicols to obtain any variation in the light transmitted through the crystal. If, however, a fragment be first crushed and then examined between crossed nicols, minute twin-crystals may be seen, as has been remarked by Professor Websky,[2] who, therefore, concluded that the crystals are really orthorhombic, and imitate hexagonality by twinning about a prism face after the manner of aragonite. Indeed, some of the prism faces on these hexagonal tablets are distinctly double faces, and give two images about 40′ apart; and hence caracolite is probably orthorhombic with the angle $(110 : 1\bar{1}0)$ approximately 60°26′.

A qualitative analysis of the crust showed the presence of lead, sodium, chlorine and sulphur, which is in accordance with the formula determined by Professor Websky.

The other two specimens are also of considerable interest. In the case of each, innumerable crystals of atacamite spring from a matrix of the same mineral, and are covered with a reddish iron oxide. They have evidently been exposed to the air, and are (except in cavities) much weather-worn.

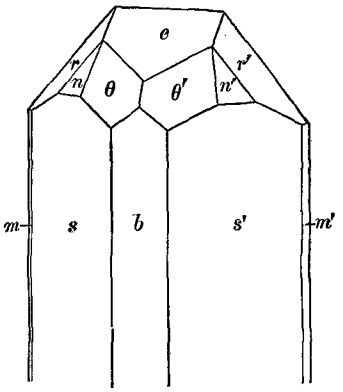
Curiously enough, in nearly the same position as on the Sierra Gorda crystals there is a new and peculiar form θ (fig. 2). It lies in the zone *bs*, whereas *h* is in the zone *bm*. Although the faces of this form are so large, only on two small crystals from a small cavity were they found sufficiently smooth to give images. Even when the other large faces gave good reflections, all that could be seen from the θ faces was a vague, dim blurr extending over some ten degrees. On the two crystals it was possible to measure five faces. They usually gave three images, whose relative positions varied with each face, and were never quite in the zone *bs* as they should be if the indices (273)—the simplest satis-

[1] *Min. Mag.* 1889, VIII, 172.

[2] *Ber. Ak. Berlin*, 1886, p. 1,045.

fying the conditions—are correct. There are probably three low vicinal pyramids on each face of θ. This form has apparently been noticed by Brögger[1] on a crystal from Chili. He suggested {142} as the probable symbol, but could obtain no measurements.

FIG. 2.



Besides θ there are four other new forms, namely, $\phi\tau\rho\sigma$; $\phi(131)$ has small faces giving single images, this form was only seen on the two crystals already mentioned; $\tau(890)$ or (9·10·0), indices doubtful, presents itself as a minute face between m and t; and finally, on one crystal two faces $\rho(443)$, $\sigma(332)$ were seen in the zone mr. The angles determining the various forms are given in the following table:—

TABLE IV.

Angle.	Calculated.	Observed Mean.	Limits.	Edges.
120 : 273 $s\theta$	30°34′ 24″	30° 5′	29°33′—30°48′	5
010 : 273 $b9$	35 32 37	34 56		1
120 : 131 $s\phi$	23 47 14	23 33½		1
010 : 131 $b\phi$	33 51 23	33 38	33°25′, 33°35′, 33°54′	3
110 : 890 $m\tau$	3 10 16	3 3	2°21′— 3°53′	10
110 : 443 $m\rho$	28 47 20	28 19	27°40′, 28°58′	2
110 : 332 $m\sigma$	26 2 0	25 30	24°36′, 25°40′, 26°15′	3

The other forms observed are:—

$b(010)$ Large; surface is rough, but gives good image.

$a(100)$ Very small, seldom seen.

$c(001)$ Very small, and always rounded.

[1] *Zeits. Kryst. Min.* 1879, III, 489.

x(140) Very small, but images fairly good.
k(130) Very small, diffused image.
s(120) Large; surface rough, but gives good image.
l(230) Very small, not often found, dim image.
t(560) Very small, not often found, dim image.
m(110) Small, but image distinct.
r(111) Very good face.
n(121) Not so large as r, but gives distinct image.
e(011) Large, and gives good image.
u(101) Very small, no image, only seen twice.

The crystals occur from 2·6 mm. in length.

The calculated and observed values of the principal angles are given in the following table:—

TABLE V.

Angle.	Calculated.	Observed Mean.	Limits.	Edges.
110 : $1\bar{1}0$ *mm'''*	66°57′ 12″	67° 6′ 42″	65°57′ — 67°40′	23
120 : $\bar{1}20$ *ss'*	74 11 14	74 20 34	74 0 — 74 57	23
011 ; $0\bar{1}1$ *ee'*	73 57 16	73 56 0	73 40 — 74 10	6
111 : $\bar{1}\bar{1}1$ *rr''*	107 32 50	107 33 50	107 32 —107 36	6
111 : $\bar{1}11$ *rr'*	84 34 40	84 34 0	84 32 — 84 36	6
111 : $\bar{1}11$ *rr'''*	52 50 34	52 51 50	52 38 — 53 5	5
120 : 011 *se*	61 19 42	61 23 9	61 9 — 61 39	27
120 : 111 *sr*	40 28 18	40 22 38	40 2 — 40 38½	22

The following forms noted by other observers have not been found on these crystals:—

δ(023), i(0.10.9), o(021), g(031), q(221), z(331), w(992), f(211), y(321), and v(762).

3. *The etched figures.*

Crystals of atacamite, though sometimes figured as if completely developed, are rarely doubly terminated. In the British Museum there is one large crystal, about 4 cm. in length, from the Wallaroo mines, which shows one face of the form e at the other end. Also the few Sierra Gorda crystals, which have grown on their side, give with the goniometer faint indications of faces underneath. It is not, therefore, possible to determine by simple measurement whether the mineral is truly holohedral, and recourse must be had to some other method, such as etching.

Atacamite is readily dissolved by dilute acids. Hydrochloric, nitric and sulphuric acids were used, and all give the same results; the first

named is the least convenient, owing to the deposition of copper chloride crystals.

The form *m*, which occurs well developed on crystals belonging to the first pair of specimens, is quickly attacked by acids. Large cavities are formed, whose intersections with the face—sometimes a little curved—are isosceles triangles. The faces produced by etching are sufficiently smooth to give measurable images. The unequal side is a prism face, probably *k*; the two equal sides are faces in the zone *mm*, either (132) and (13$\bar{2}$) or (231) and (23$\bar{1}$). Measurements are obtained corresponding to both sets.

TABLE VI.

Angle.	Calculated.	Observed.
110 : 132	21°35′	20°10′, 20°22′, 20°15′
110 : 231	14 40½	14°4′, 15°42′
010 : 130 *bk*	29 47	28°40′

The figures appear to be quite symmetrical above and below, indicating the holohedral character of the crystals, but when the form *b* on crystals taken from the second pair of specimens is etched, the result is not quite in accordance with this view. On applying the acid, small vertical marks are seen, distinctly larger at the top than at the bottom. They grow in number, though not in size, till the face is covered with them, and finally the crystal splits up. This face is but slowly attacked by the acid.

The form *s* showed no figures at all.

As no trace of electric polarity was observed on heating the crystals, the balance of evidence is in favour of holohedral symmetry.

4. *The Optical Characters.*

The refractive indices for this mineral have hitherto not been determined. There is considerable difficulty in finding them, since they are too high for the total reflectometer, and the crystals are, if of any considerable size, only slightly transparent. It was found, therefore, impossible to get any result by employing the monochromatic light given by a volatilising salt; but, since the mineral absorbs all light but the green, measurable images for this light were obtained at minimum deviation with a Welsbach burner.

As none of the large prism forms have their internal angles small enough, faces unsymmetrical with regard to the principal planes had to be used, the labour of calculation being thereby considerably increased.

Since there is an excellent cleavage parallel to b, a prism consisting of the refracting faces bm on the first pair of specimens could be utilised, whilst the second pair gave the prisms bs and be.

The section of the wave-surface by a principal plane is a circle and an ellipse. The image corresponding to the former involves only one index, but the other involves two.

Consider the section parallel to the plane (001)—

$$\left.\begin{aligned} x^2+y^2 &= c^2 \\ a^2x^2+b^2y^2 &= a^2b^2 \end{aligned}\right\}$$

From the first equation we obtain the ordinary formula—

$$\frac{1}{c}=\gamma=\sin\tfrac{1}{2}(\mathrm{A}+\mathrm{D})/\sin\tfrac{1}{2}\mathrm{A},$$

And from the second—

$$\frac{1}{C^2S^2}-\tfrac{1}{2}\left(\frac{1}{C^2}+\frac{1}{S^2}\right)(a^2+b^2)+a^2b^2-\tfrac{1}{2}\left(\frac{1}{C^2}-\frac{1}{S^2}\right)\cos 2\phi\,(a^2b^2)=0.^1$$

Where $C=\cos\frac{1}{2}(\mathrm{A}+\mathrm{D})/\cos\frac{1}{2}\mathrm{A}$, $S=\sin\frac{1}{2}(\mathrm{A}+\mathrm{D})/\sin\frac{1}{2}\mathrm{A}$.

ϕ is the angle which the plane bisecting the prism angle makes with the plane of a ($a > b$); A is the angle of the prism, D the angle of deviation, $a={}^1/\alpha$, $b={}^1/\beta$, $c={}^1/\gamma$; $\alpha\beta\gamma$ are the three principal indices of refraction.

The three prisms already mentioned yield three pairs of equations to determine the three refractive indices.

Before giving these equations, there are two points worth noting:— Firstly, the two images can be easily distinguished by means of a nicol; for the image corresponding to the circle must be brightest when any reflected image is brightest, and *vice versâ:* just the contrary is the case with the other image. Secondly, in all three cases $2\phi = \mathrm{A}$, and therefore—

$$\frac{1}{C^2S^2}=\tfrac{1}{2}\left(\frac{1}{C^2}+\frac{1}{S^2}\right)-\tfrac{1}{2}\left(\frac{1}{C^2}-\frac{1}{S^2}\right)\cos 2\phi;$$

a convenient check on the arithmetical accuracy.

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[1] G. G. Stokes, "On a formula for determining the optical constants of doubly refracting crystals," *Camb. and Dublin Math. Journ.* 1846, I. 183; *Math. and Phys. Papers, Cambridge*, 1880, I, 148; *Cf.* Liebisch, *Physikalische Krystallographie*, Leipzig, 1891, equation at bottom of page 393.

The six equations and the data for deriving them are—

Prism bm; circle $A = 56°31\frac{1}{2}'$ $D = 69°0'$

ellipse $D = 66°\ 9'$ $\quad \frac{1}{S^2} = \cdot2912$ $\quad \frac{1}{C^2} = 3\cdot3721$

$$\gamma = \frac{1}{c} = \frac{\sin 62°45\frac{3}{4}'}{\sin 28°15\frac{3}{4}'} = 1\cdot878 \qquad (1)$$

$$\cdot9820 - 1\cdot8316\ (b^2+a^2) + a^2b^2 = -\cdot8496\ (b^2-a^2) \qquad (2)$$

Prism bs; circle $A = 37°\ 5\frac{1}{2}'$ $D = 36°25'$

ellipse $D = 35°28'$ $\quad \frac{1}{S^2} = \cdot2890$ $\quad \frac{1}{C^2} = 1\cdot3832$

$$\gamma = \frac{1}{c} = \frac{\sin 36°45\frac{1}{4}'}{\sin 18°32\frac{3}{4}'} = 1\cdot882 \qquad (3)$$

$$\cdot3997 - \cdot8361\ (b^2+a^2) + a^2b^2 = -\cdot1364\ (b^2-a^2) \qquad (4)$$

Prism be; circle $A = 53°\ 1\frac{1}{2}'$ $D = 59°20'$

ellipse $D = 60°10'$ $\quad \frac{1}{S^2} = \cdot2860$ $\quad \frac{1}{C^2} = 2\cdot6423$

$$\alpha = \frac{1}{a} = \frac{\sin 56°10\frac{3}{4}'}{\sin 26°30\frac{3}{4}'} = 1\cdot861 \qquad (5)$$

$$\cdot7556 - 1\cdot4641\ (b^2+c^2) + b^2c^2 = -\cdot7085\ (b^2-c^2) \qquad (6)$$

Hence $\gamma = 1\cdot880$ ($\pm\cdot002$).

This value is now substituted in (6) and β found—

$$b^2 = \cdot2983$$
$$\beta = 1\cdot831$$

From (2) and (4) after substituting for b we find a and a—

$$a^2 = \cdot2892 \text{ and } \cdot2879$$
$$a = 1\cdot860 \quad ,, \quad 1\cdot863$$

Also direct from (5) $a = 1\cdot861$

Therefore $a = 1\cdot861$ ($\pm\cdot002$).

The refractive indices are then for green light—

$$\alpha = 1\cdot861$$
$$\beta = 1\cdot831$$
$$\gamma = 1\cdot880$$

Whence it may be seen that the axial plane is parallel to (100), and that the axis perpendicular to (010) is the acute bisectrix.

The angle between the optic axes for thallium light was measured in cedar oil, whose refractive index for sodium light was found to be 1·5312. Values were obtained varying from 95° to 97°.

The real angle between the axes $= 2 \sin^{-1} \frac{\beta}{\alpha} \sqrt{\frac{\gamma^2 - \alpha^2}{\gamma^2 - \beta^2}}$

which becomes in the present case 74°56′.

Further, the angle in oil is found on calculation to be 96°50′.