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KOECHLINITE (BISMUTH MOLYBDATE), A NEW MINERAL.

ORIGIN OF INVESTIGATION.

Some years ago the writer[1] described a crystallized bismuth mineral from Nevada which occurred in hexagonal rhombohedral crystals and was optically uniaxial. Analysis of this mineral showed the presence of considerable water, and in accordance with the results obtained on bismuth ocher from California[2] the mineral from Nevada was considered to have the composition expressed by the formula $Bi_2O_3.3H_2O$. The crystals from Nevada are very different from those assigned to the anhydrous oxide of bismuth, Bi_2O_3, as given in Dana's Mineralogy.[3] It seems doubtful, therefore, whether the anhydrous oxide exists in nature as such, and a sharp outlook has been kept for natural occurrences of crystallized Bi_2O_3.

While the writer was at Vienna in 1912 he made an inquiry as to the presence of such specimens in the collections, and the custodian of the mineral collection of the Hof-Museum, Dr. Rudolf Koechlin, called particular attention to a specimen showing small greenish rectangular crystals which had been supposed to be torbernite but which Dr. Koechlin had found to give a strong bismuth reaction. On request, and on the approval of Dr. F. Berwerth, director of the mineralogic and petrographic division of the Hof-Museum, part of the specimen was given to the writer for study, and it is a great pleasure for him to express his thanks for the kindness and liberality of Drs. Berwerth and Koechlin in furnishing this valuable material.

The investigation showed that the mineral contained essentially only the oxides of bismuth and molybdenum, and the analyses yielded results from which the simple formula $Bi_2O_3.MoO_3$ was deduced.

The acquisition of the specimen by the Vienna Museum is thus described by Dr. Koechlin. The specimen was bought in 1884 from a Mr. Kulda who carried on a small trade in natural-history objects. The specimen of koechlinite, No. D. 3478 in the Vienna catalogue, was labeled torbernite. As Dr. Koechlin had found considerable bismuth in the mineral, however, it had been relabeled bismuth ocher. According to him the mineral somewhat resembles uranospinite. The only observed phase of the mineral consists of sharp, minute tabular crystals which are described in detail below, under the heading "Crystallography."

[1] Schaller, W. T., Bismite from Nevada: U. S. Geol. Survey Bull. 490, p. 33, 1911. Compare also Ransome, F. L., The geology and ore deposits of Goldfield, Nev.: U. S. Geol. Survey Prof. Paper 66, p. 121, 1909.

[2] Schaller, W. T., Bismuth ochers from San Diego County, Cal.: Am. Chem. Soc. Jour., vol. 33, p. 162. 1911.

[3] Dana, E. S., System of mineralogy, 6th ed., p. 200, 1892.

NOMENCLATURE.

The services of Dr. Rudolf Koechlin, both as investigator and as custodian of the mineral collection in Vienna, are too well known to call for any extended remarks, and in proposing the name koechlinite for the new bismuth molybdate herein described the writer takes a double pleasure, for not only the scientific attainments of Dr. Koechlin are thereby recognized, but in addition his charming personality and great willingness to help others, which were so manifest during the writer's stay in Vienna.

The formula of koechlinite is a simple one, but no other minerals were noted with which it could be closely related, and for the present it must be placed with other molybdates, although from analogy one might expect to find minerals similar in type but differing chemically, as, for example, the unknown compound $Fe_2O_3.SO_3$.

LOCALITY.

The locality as given originally by Mr. Kulda is the Daniel mine, Schneeberg, Saxony, Germany, and the already long list of secondary bismuth minerals found at this classic locality is now further extended.

PARAGENESIS.

The character of the matrix and its geologic relations are not known, but the specimens appear typically like parts of a mineralized quartz vein, rich in cavities lined with well-developed quartz crystals, upon which rest the crystals of koechlinite.

The associated minerals are massive white quartz and quartz in colorless crystals, forming the main part of the specimen; abundant native bismuth, in cleavable masses, in part strongly iridescent; abundant smaltite, in cubic crystals ({100}, {111}) about 1 millimeter thick (wrongly described as chloanthite by Mr. Kulda); a red mineral (realgar?) occurring sparsely as minute seams in the massive quartz; a few needle-like prisms of a gray metallic mineral (bismuthinite?, stibnite?) in the cavities with koechlinite; and three unidentified minerals found directly associated with the koechlinite.

The contents of some of the cavities were removed, and the larger crystals were picked out for measurement and analytical purposes. The remaining fine material was then embedded in cooked balsam dissolved in chloroform, which was then allowed to harden by gradual evaporation of the chloroform. The material in these microscopic slides was therefore not subjected to any heat. Many perfect crystals of koechlinite were found in this fine material, and their habit and optical properties could be well studied under the microscope. A group of three such crystals in parallel position is shown in figure 1. The very high index of refraction of the mineral gives all the crystals a thick black border, due to total reflection. The

striations on the tabular crystals are vertical and the bounding faces of the crystals are those of the unit pyramid. The angle of the edges (111)–$(\bar{1}1\bar{1})$: $(1\bar{1}1)$–$(\bar{1}\bar{1}1)$ is 90° 08′, thus giving the rectangular shape to the crystals.

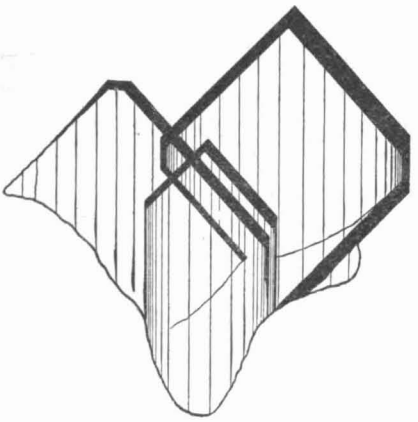

FIGURE 1.

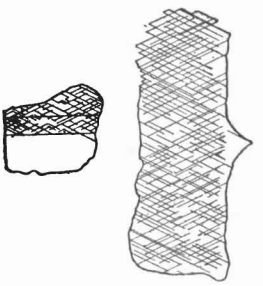

FIGURE 2.

FIGURE 1.—A group of three crystals of koechlinite in parallel position. The heavy black border is caused by total reflection due to the very high refractive index of the mineral.
FIGURE 2.—Sketch of unknown mineral A associated with koechlinite.

The associated minerals became concentrated in the material forming the slides by the removal of the larger koechlinite crystals, and the description of these associated minerals is based entirely on the microscopic observations made on the slides.

The metallic associaets have already been given. Besides quartz, three nonmetallic minerals, none of which could be identified, were observed with the koechlinite. It does not necessarily follow, however, that any of them are new. For convenience of description these three associated minerals are called unknown A, B, and C, respectively.

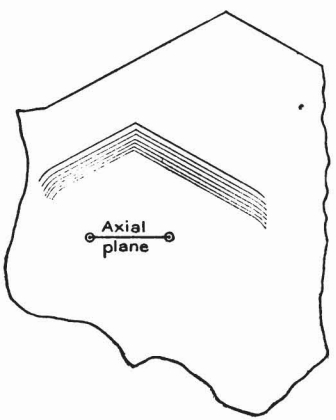

FIGURE 3.—Sketch of unknown mineral B associated with koechlinite.

Unknown mineral A was observed in about half a dozen pieces. Nearly all of them have an irregular outline which in small part is bounded by cleavage directions. A single fragment showed one apparently straight outline, bisecting the cleavage lines. The cleavage is very prominent and permeates the entire mineral, breaking up the fragment into numerous rhombs with an acute angle of about 52°. Figure 2 is a diagrammatic sketch of two such fragments. The color of the transparent and isotropic mineral is a light to dark brown. No interference figure could be obtained from any of the fragments.

Unknown mineral B is abundant as small mica-like scales, which for the most part are devoid of any regular outline, although here and there are scales that have a more or less regular boundary. The most perfect of these have a hexagonal shape and extinguish parallel to one pair of sides. One of the larger fragments observed is sketched in figure 3. The two straight sides at the top are inclined to each other at an angle of about 57°, and each was inclined about 62° to the extinction. The mineral is colorless and transparent and has a moderate to low double refraction. The parallel markings shown are parallel to the two straight sides. The axial angle is small and negative.

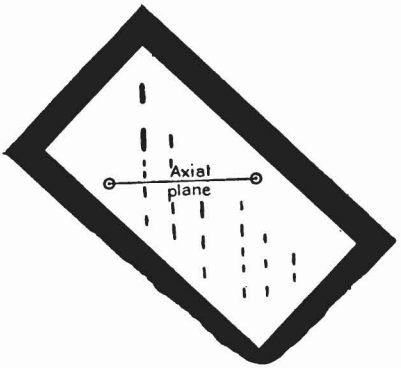

FIGURE 4.—Sketch of unknown mineral C associated with koechlinite.

Unknown mineral C was observed about a dozen times, either as well-formed isolated crystals or intergrown with koechlinite. The crystals have the same shape and orientation as those of koechlinite and consist of the macropinacoid {100} large, bounded by faces of the unit pyramid {111}. The crystals of unknown mineral C are at once distinguished from koechlinite by their lack of color and much lower double refraction. The very high index of refraction and the comparative thickness gives these crystals a very broad border of black, due to total reflection, as shown in figures 4 and 5. They have a more constant habit than koechlinite, nearly all of them being about twice as long as wide. The vertical striations are not prominent, and one crystal showed vertical lines of minute inclusions, as shown in figure 4, which well illustrates the shape and appearance of the crystals. The crystals of unknown mineral C are twinned similarly to those of koechlinite. One crystal, between crossed nicols, showed a complex twinning (as illustrated in fig. 5) very similar in kind to that exhibited by koechlinite and shown in figure 20 (p. 24).

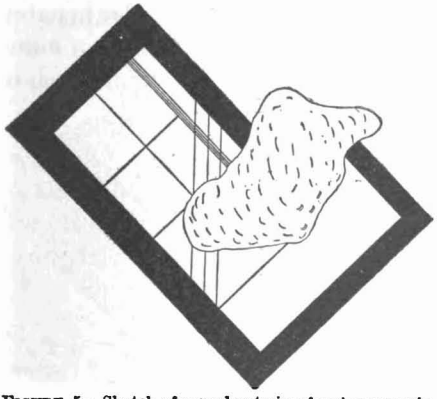

FIGURE 5.—Sketch of complex twin of unknown mineral C associated with koechlinite.

The crystals of unknown mineral C have a low birefringence, the interference colors being generally of the first order, even on the thicker crystals, whereas the thinnest cleavage plates of koechlinite seldom

show colors below the third order. The axial plane of unknown mineral C is parallel to $c\{001\}$, as in koechlinite, and the axial angle is very large, $2E$ being greater than the field of the microscope.

Koechlinite is clearly a secondary mineral formed in the cavities of the quartz rock by the reaction of different solutions, one containing bismuth and the other molybdenum. Some of the cavities lined with quartz crystals are free from any other mineral.

CRYSTALLOGRAPHY.

GENERAL CHARACTER OF CRYSTALS.

All the koechlinite occurs in distinct crystals. Eight of these were measured on the goniometer, but in addition a large number were examined under the microscope, for with the knowledge obtained from the goniometer measurements the combinations of the crystals seen under the microscope could be easily deciphered. The crystals measured average about 0.5 millimeter in greatest length. The crystals on the specimens range in size from minute ones to those having a length of about 1 millimeter. The width of the crystals is either equal to or about half the length, and the third dimension is very small, as the crystals are all very thin and tabular in habit.

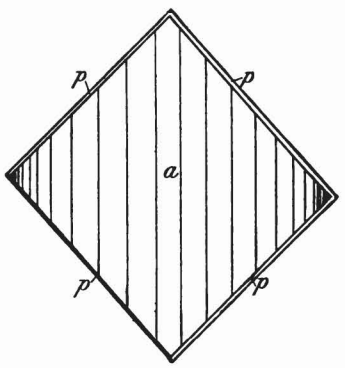

FIGURE 6.—Common appearance of crystals of koechlinite, simulating rectangular plates. Forms: $a\{100\}$, $p\{111\}$.

The combinations observed on many of the crystals are simple, and in fact most of the crystals show only two or three forms. The general appearance of the crystals is shown in figure 6, and as the angle between the opposite pyramids is nearly 90°, the crystals appear as rectangular plates with diagonal striations. A marked feature of these crystals which heightens the impression that they are rectangular plates is a tendency for distortion in that the crystal is elongated parallel to one of the intersection directions of $a\{100\}$ with $p\{111\}$, thus producing the effect shown in figure 7.

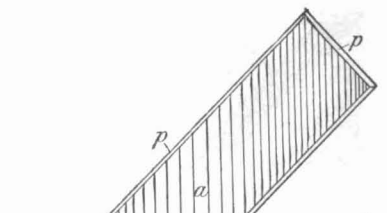

FIGURE 7.—Distorted crystal of koechlinite, elongated parallel to one of the intersected directions of $a\{100\}$ with $p\{111\}$.

Apparently the crystals should be so oriented that the edges $a\{100\}$: $p\{111\}$ are vertical and horizontal, but the direction of the striations on $a\{100\}$ shows the true position, which is verified by the angle measurements. The crystals are both simple and twinned.

CALCULATION OF ELEMENTS.

The crystals of koechlinite are orthorhombic, and the measurements of the unit pyramid are utilized for the calculation of the elements. The prism zone being vertically striated, the crystals were readily adjusted in polar position, and measured on the two-circle goniometer. The value for v_o was found by averaging the readings on $a\{100\}$ and the theoretic readings on $b\{010\}$ obtained by averaging the corresponding pairs of v readings of the unit pyramids $\{111\}$. The signals reflected from the large faces of $a\{100\}$ were sharp and bright, whereas those from the very narrow pyramid faces were mostly faint and not very distinct. The measurements on five crystals show fairly good agreement, though future measurements of larger and better crystals would doubtless yield more accurate results. The values obtained are as follows:

Measurements of unit pyramid.

Crystal 1.		Crystal 2.		Crystal 5.		Crystal 7.		Crystal 8.	
ϕ	ρ	ϕ	ρ	ϕ	ρ	ϕ	ρ	ϕ	ρ
° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
45 42	55 02	45 40	55 07	45 26	55 00	45 20	55 59	46 10	54 58
45 27	54 55	45 42	55 10	45 47	55 05	45 51	55 04	45 48	54 59
45 26	55 08	45 27	55 01	45 49	55 09	45 58	55 10	47 34	54 59
45 38	55 21	45 50	55 08	45 36	55 05	45 48	54 33	45 03	55 20

From the average of these measurements the values $p_o = 1.0258$, $q_o = 1.0026$, and the axial ratio $a : b : c = 0.9774 : 1 : 1.0026$ are obtained. The axial ratio of koechlinite is very close to the 1 : 1 : 1 ratio of the isometric system, but in its tabular habit and perfect cleavage parallel to $a\{100\}$, the mineral differs greatly from one of isometric character.

FORMS AND ANGLES.

A total of 13 forms was determined on the crystals of koechlinite. These are as follows:

Pinacoids: $b\{010\}$, $a\{100\}$.
Prisms: $l\{130\}$, $n\{230\}$, $j\{450\}$, $m\{110\}$, $h\{430\}$, $k\{210\}$.
Pyramids: $p\{111\}$, $r\{322\}$, $s\{533\}$, $u\{131\}$, $x\{362\}$.

The average of the measured angles as compared with the calculated values is shown in the following list:

Measured and calculated angles of koechlinite.

No.	Letter.	Symbol.		Measured.				Calculated.			
		Goldschmidt.	Miller.	ϕ		ρ		ϕ		ρ	
				°	′	°	′	°	′	°	′
1	*b*	0∞	010	0	29	90	00	0	00	90	00
2	*a*	∞0	100	90	00	90	00	90	00	90	00
3	*l*	∞3	130	17	46	90	00	18	50	90	00
4	*n*	∞$\frac{3}{2}$	230	34	55	90	00	35	32	90	00
5	*j*	∞$\frac{5}{4}$	450	39	20	90	00	39	18	90	00
6	*m*	∞	110	44	09	90	00	45	39	90	00
7	*h*	$\frac{4}{3}$∞	430	53	10	90	00	53	45	90	00
8	*k*	2∞	210	65	07	90	00	63	57	90	00
9	*p*	1	111	45	39	55	07	45	39	55	07
10	*r*	$\frac{1}{2}$1	322	55	56	60	54	56	55	61	26
11	*s*	$\frac{1}{3}$1	533	58	55	62	55	59	37	63	14
12	*u*	13	131	18	22	72	09	18	50	72	32
13	*x*	$\frac{1}{3}$3	362	27	13	73	21	27	06	73	31

a{100}. The macropinacoid, parallel to which there is a good cleavage, is the dominant form of koechlinite, and all the crystals are tabular parallel to this form. The faces are vertically striated. Nearest the prism faces the striations become prominent enough to round the face and to give a blurred distended reflection, but the larger part of the face gives a bright and clear reflection. The macropinacoid and the unit pyramid are the only two forms which were observed on all the crystals examined.

b {010}. The brachypinacoid was observed on four crystals, as small and narrow faces. The reflections were very poor and the ϕ measurements gave $-0°07'$, $+0°22'$, $+2°06'$, $-0°27'$, instead of $0°00'$. On crystal 8 the face was uneven and vertically striated.

l {130}. The single face of this form is a short line face giving a very poor reflection.

n {230}. The prism *n* is the third most prominent form, and although it was observed on only five of the eight measured crystals, it was determined to be present on many of the crystals studied microscopically. In fact, it is the dominant prism form of the mineral, many crystals showing only the three forms *a*, *p*, *n*. (Compare figs. 12, 13, and 14, on pp. 21, 22.) The measurements of this form are as follows:

Measurements of ϕ angle of $n\{230\}$.

Crystal No.	Size.	Reflection.	Measured.	Calculated.
			° ′	° ′
1	Minute	Glimmer[a]	34 18	35 32
1	do	do	34 50	35 32
1	do	do	33 03	35 32
2	Short, broad line face.	Poor	36 22	35 32
5	Line face	Glimmer[a]	36 04	35 32
5	do	do	36 09	35 32
6	do	do	37 42	35 32
6	do	do	33 03	35 32
6	do	Poor	35 00	35 32
7	do	Glimmer[a]	33 13	35 32
7	Broad line face.	Poor	34 26	35 32

[a] Measured by position of brightest illumination, which was generally only a glimmer.

j {450}. The two observed faces of j are mere line faces giving an exceedingly faint reflection. The measured ϕ angles (39°22′ and 39°18′) agree well with each other and with the calculated angle (39°18′).

m {110}. The unit prism was seen only once as a line face giving a poor reflection.

h {430}. The four faces of h, observed on as many crystals, are all line faces giving poor reflections. The measured ϕ angles are 51°41′, 52°33′, 53°41′, 54°46′ (calculated 53°45′).

k {210}. The single face of k is a line face yielding only a glimmer of light.

p {111}. The unit pyramid is the dominant terminal form, and is present on all crystals examined. It is as a rule long and narrow, rarely becoming broader, whereby the whole crystal becomes thicker. It is striated in the zone (100): (111): ($\bar{1}$11): ($\bar{1}$00).

r {322}. This pyramid occurs as a very narrow line face between a and p. The reflections were considerably distended on account of the minute width of the faces, and they could not be measured with great accuracy. The form was definitely determined on only one crystal (No. 2) but is probably present on some of the other crystals. The measured angles are as follows:

ϕ meas. = 56°33′ ϕ calc. = 56°55′. ρ meas. = 61°10′ ρ calc. = 61°26′.
ϕ meas. = 55°19′ ρ meas. = 60°37′

s {533}. The faces of s, like those of r, are the merest line faces, and their measurements are likewise not very accurate. The form was identified positively on four crystals but may be present on several more. The two forms r {322} and s {533} were not both determined on the same crystal. The measurements for s are given in the following table:

Measurements of s{533}.

Crystal No.	Measured.		Calculated.	
	ϕ	ρ	ϕ	ρ
	° ′	° ′	° ′	° ′
5	59 09	63 32	59 37	63 14
5	58 52	62 50	59 37	63 14
5	58 48	62 50	59 37	63 14
5	59 23	62 50	59 37	63 14
7	58 57	62 37	59 37	63 14
8	58 22	62 50	59 37	63 14

The following interfacial angles were measured on crystal 3. Only $a\{100\}$ gave good reflections.

Interfacial angles measured on crystal 3 of koechlinite.

Angle.	Measured.	Calculated.
	° ′	° ′
$a:p=(100):(111)$	54 27	54 05
$a':p'=(\bar{1}00):(1\bar{1}1)$	54 10	54 05
$a':p''=(\bar{1}00):(1\bar{1}\bar{1})$	54 00	54 05
$a:p'''=(100):(11\bar{1})$	54 05	54 05
$a:s=(100):(533)$	40 08	39 38
$p:s=(111):(533)$	13 52	14 27
$p:r=(111):(322)$	.....	11 28

$u\{131\}$ and $x\{362\}$. These two pyramids were measured only once, both forms showing a well-developed face on crystal 7 (fig. 28, p. 26). It is believed that additional occurrences of these forms were seen on other crystals under the microscope, but they could not be positively identified. On crystal 7 the face of $u(131)$, although striated somewhat in the zone $u\ a$, gave a fair reflection. The face of $x(362)$ is a line face between u and a and gave a poor reflection. The measured and calculated angles (given on p. 16) agree well.

From their occurrence the thirteen forms may be grouped as follows:

Common forms: $a\{100\}$, $p\{111\}$, $n\{230\}$.
Less common forms: $b\{010\}$, $h\{430\}$, $j\{450\}$, $s\{533\}$.
Rare forms: $m\{110\}$, $l\{130\}$, $k\{210\}$, $r\{322\}$, $u\{131\}$, $x\{362\}$.

COMBINATIONS.

The combinations observed on the eight crystals measured are shown in the following table:

Combinations of koechlinite crystals.

Form.	Crystal No.								Percentage of occurrence.	Illustrated in figures—
	1	2	3	4	5	6	7	8		
a{100}	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	100	6, 7, 11–14, 21, 23–29.
b{010}	*b*	....	....	*b*	....	....	*b*	*b*	50	11, 28.
l{130}	....	....	....	....	....	*l*	....	....	13	
n{230}	*n*	*n*	....	....	*n*	*n*	*n*	....	63	11–14, 21, 23–29.
j{450}	....	....	....	....	....	....	*j*	*j*	25	
m{110}	....	....	....	....	....	*m*	....	....	13	
h{430}	*h*	....	....	....	....	*h*	*h*	*h*	50	
k{210}	....	....	....	....	*k*	....	....	....	13	
p{111}	*p*	*p*	*p*	*p*	*p*	*p*	*p*	*p*	100	6, 7, 11–14, 21, 23–29.
r{322}	....	*r*	....	....	....	....	....	....	13	26.
s{533}	....	....	*s*	....	*s*	....	*s*	*s*	50	25, 28.
u{131}	....	....	....	....	....	....	*u*	....	13	28.
x{362}	....	....	....	....	....	....	*x*	....	13	28.

The common combinations observed on many crystals not measured are *a p*, *a n p*, *a b n p*, with occasional modifications due to rarer forms such as probably *h* and *s*.

ZONAL RELATIONS AND MARKINGS.

All the 13 forms of koechlinite lie in three zones, the prism zone, with *b l n j m h k a;* the pyramid zone *m p* with *m s r p;* and the pyramid zone *a x u*, as shown in figure 8. The three zones above named are all striated, and the intensity of the striation varies directly as the number of forms in that zone.

In addition to the regular striations there are markings of two other kinds on some of the crystals of koechlinite which deserve brief mention. Both kinds were observed under the microscope on the *a*{100} faces.

The surfaces of a few of the crystals are crowded with a mass of acute-angled markings, nearly equal in angle and nearly parallel. The acute points all face in one direction, as shown in the free-hand sketch reproduced in figure 9. The symmetry of such markings indicates hemimorphism.

The markings of the second kind consist of straight lines, forming regular closed figures, one side of which is parallel to the vertical axis and the other side parallel to the intersection edge *a p* (shown in fig. 10). The vast majority of the lines parallel to the intersection edge *a p* are in one direction. In the drawing shown in

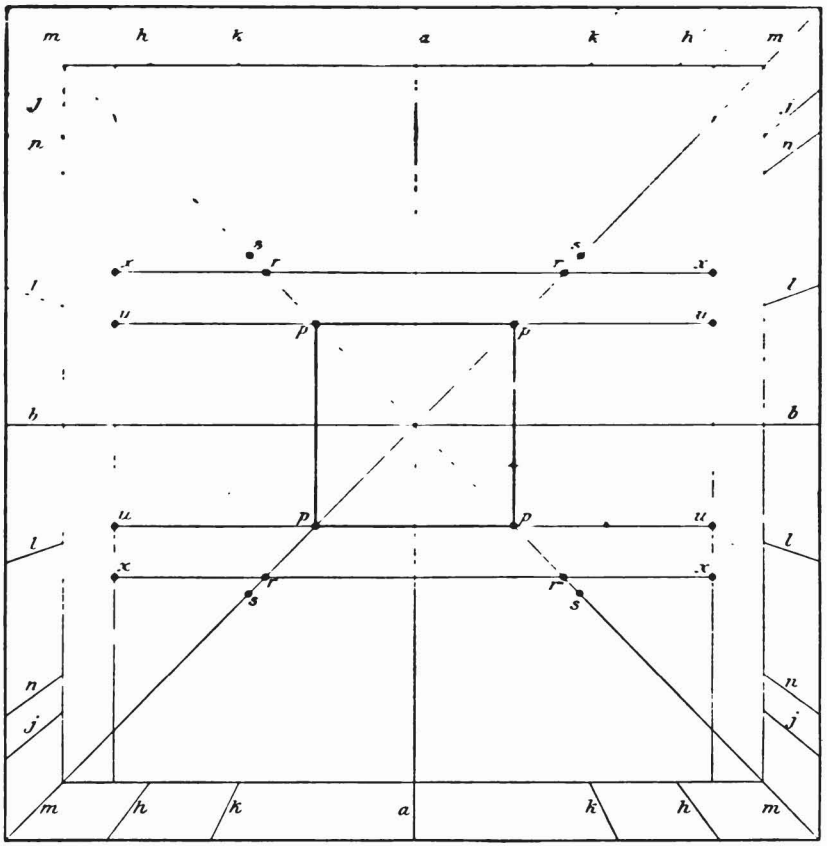

FIGURE 8.—Gnomonic projection of koechlinite forms.

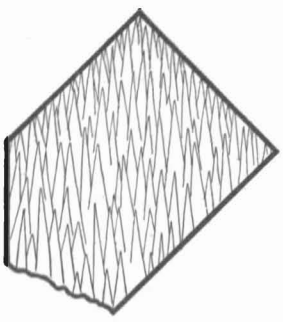

FIGURE 9.

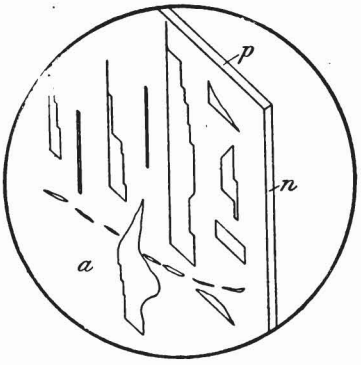

FIGURE 10.

FIGURE 9.—Acute-angled markings on $a\{100\}$, koechlinite.

FIGURE 10.—Regular markings on $a\{100\}$, koechlinite. Note excessive development of lines parallel to intersection $a(100)$–$p(111)$ over those parallel to intersection of $a(100)$–$p'(1\bar{1}1)$.

figure 10 only two of these lines are parallel to the edge (100)–(1$\bar{1}$1), whereas, as drawn, there are 31 lines parallel to the edge (100)–(111). The string of bubbles shown in the lower part of the figure are also approximately parallel to the edge (100)–(111). Such a preference to one of two supposedly equal directions naturally

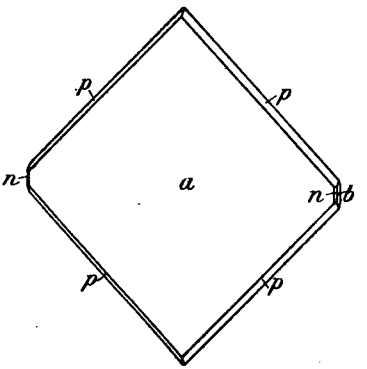

FIGURE 11.

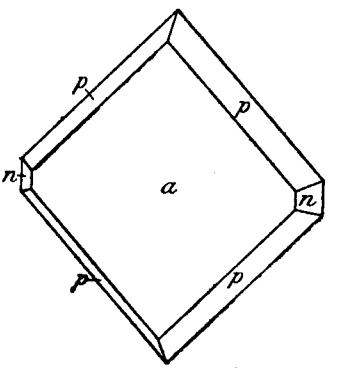

FIGURE 12.

FIGURE 11.—Square tabular habit of koechlinite (crystal 1). Forms: $a\{100\}$, $b\{010\}$, $n\{230\}$, $p\{111\}$.
FIGURE 12.—Stout tabular crystal of koechlinite. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

suggests hemimorphic development. The markings shown in figure 9 suggest hemimorphism in the direction of the vertical axis, whereas those shown in figure 10 suggest hemimorphism in the direction of the edge a p, which is inclined 45° to the vertical axis. The peculiarly distorted crystals (shown in fig. 7) in which the crystals are elongated parallel to one of the intersection edges of a and p also suggest the possibility of a hemimorphic development. Opposed to such an idea, however, are the holohedral distribution of the faces as determined on many crystals and the lack of conclusive evidence from the etch figures.

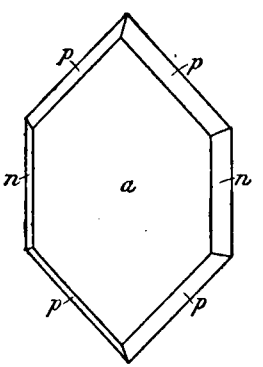

FIGURE 13.—Intermediate habit of koechlinite.

HABITS.

All the crystals of koechlinite are tabular in habit, but the thin tablets vary in shape from square ones to elongated ones, as already shown in figures 6 and 7.

The square tablets are very abundant and either consist of only the two forms $a\{100\}$ and $p\{111\}$ (see fig. 6, p. 14) or else have two of their edges modified by forms of the prism zone, as for example the first crystal measured, shown in figure 11.

A few crystals are not so thin as this one, and these slightly stouter crystals are also somewhat elongated parallel to the vertical axis. Such crystals were observed only under the microscope, but their

combination could be determined to be *a n p*, with possibly other forms present as line faces that would not modify the habit of the crystals. The approximate relative thickness and size of three such crystals, chosen to show the variation in habit, are reproduced in figures 12, 13, and 14.

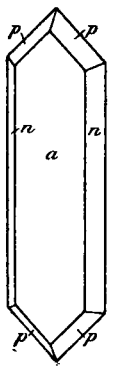

FIGURE 14.—Koechlinite crystal elongated parallel to the vertical axis.

Included in larger square crystals are a few small prismatic crystals which are an extreme example of elongation parallel to the vertical axis, as shown in figure 15. Such crystals were not observed by themselves, but as inclusions in larger ones they are not rare. They have a characteristic platy structure that was not seen on the individual short prismatic crystals (fig. 14). Figure 15 shows a sketch of a number of such minute prismatic crystals included in a larger square one. Some of these included prismatic crystals may be in twin position, either to each other or to their larger host, but not all of them are thus regularly oriented.

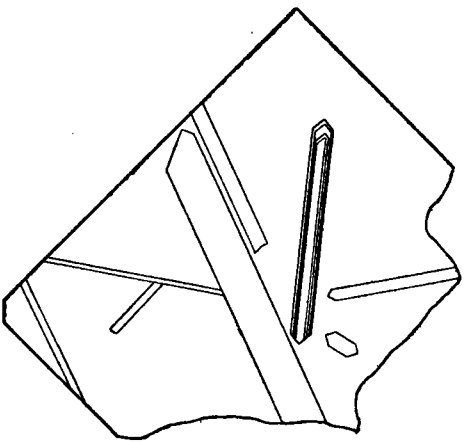

FIGURE 15.—Small prismatic crystals of koechlinite included in a larger square one.

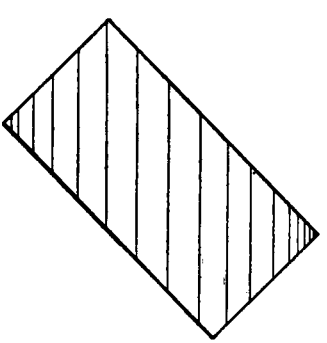

FIGURE 16.

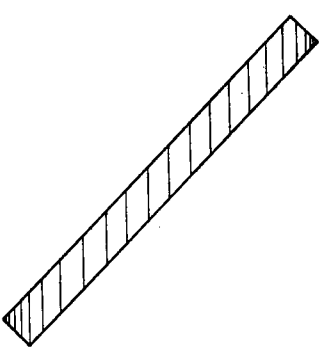

FIGURE 17.

FIGURE 16.—Common extent of elongation parallel to edge *a*(100) *p*(111) of crystal of koechlinite.
FIGURE 17.—Extreme case of distorted elongation parallel to edge *a p* noted on crystal of koechlinite.

Some of the tabular crystals are grouped together in parallel position and the individual crystals show neither exactly the same habit nor the same combination, although in general they are very similar. One such group, as it appeared under the microscope, is reproduced in figure 1 (p. 11). In this group the central crystal is decidedly elon-

gated parallel to the vertical axis, whereas the one on the right is nearly square.

In addition to the vertical extension of the prismatic crystals (figs. 13 and 14), the elongation parallel to one set of intersection edges of the unit pyramid p with the macropinacoid a is prominently developed. An example of such elongation has already been shown in figure 7 (p. 14), but the most abundant of such distortions occur where the elongation is about twice the width of the crystal, as shown in figure 16.

It is to be noted that contact twins of square habit will yield a crystal of similar shape to that shown in figure 16, but the difference in direction of the striations on $a\{100\}$ at once differentiates these twin crystals (compare fig. 18) from the simple ones. The extreme observed distortion in a single crystal along the edge $a\ p$ is shown in figure 17. The elongation of this crystal is 11 times its width.

TWINNING.

Twinning is common for koechlinite, and both contact and penetration twins occur. The twinning plane is the unit brachydome {011}, a form not observed on any of the crystals. By such twinning the faces of the macropinacoid a remain in the same plane, and as the angle (010) : (011) is 44° 56′, the angle between the twinned and untwinned adjacent faces of (011) is only 0° 08′, being thus so small as to be hardly detectable under the microscope. Consequently the different parts of a twin crystal extinguish so nearly the same that no difference can be seen under the microscope. In fact, in thin cleavage pieces a twin crystal can not be told from a simple one. On the thicker crystals a slight difference in shade of color, due to the pleochroism, can be noticed for the parts of a twin crystal. If the natural faces of $a\{100\}$ are present, the striations on it at once furnish a satisfactory means of deciphering the twinning structure.

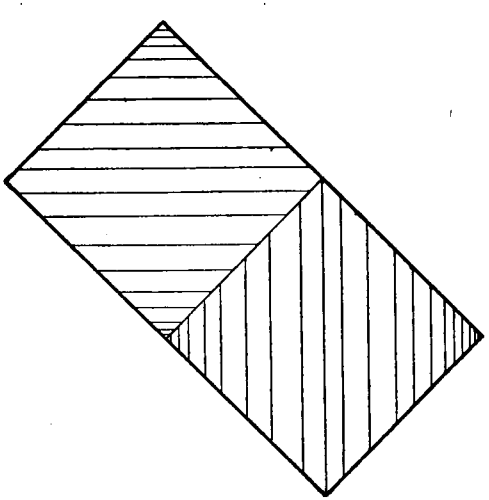

FIGURE 18.—Contact twin of koechlinite. Composition face is {011}. Compare figure 16.

In the contact twins the composition face is either {011} or {100}. If the twinning plane is the composition face, then the twinned crystal resembles in shape a simple crystal elongated parallel to the edge $a\ p$ (as shown in fig. 16), but the difference in striations on $a\{100\}$

suffices to differentiate them. Twins in which the composition face is $a\{100\}$ are rare. These two varieties of contact twins are shown in figures 18 and 19.

By a repeated or synthetic twinning with {011} as composition face, a complex crystal may be built up. Figure 20 represents a cleavage piece of such a twinned koechlinite observed under the microscope. In the absence of the guiding striations on $a\{100\}$ it is impossible to determine whether this is a repeated twin with {011} as composition face or a simple crystal with cleavage or parting lines parallel to $p\{111\}$. As no such cleavage or parting lines have been found on the mineral, however, it is more reasonable to refer the observed structure to repeated twinning.

A symmetrically twinned fourling, with {011} as composition face, would yield a regular figure, in which the parts would only lack a few minutes of forming a theoretically closed solid, such as is shown in figure 21. This sketch explains the structure of the penetration twins described in the following paragraphs. An example of a twin, with {011} as composition face, is afforded by crystal 6, drawn in clinographic projection (fig. 29, p. 27).

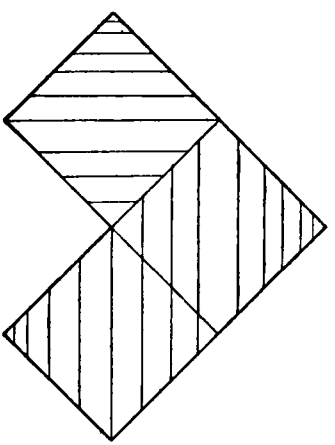

FIGURE 19.

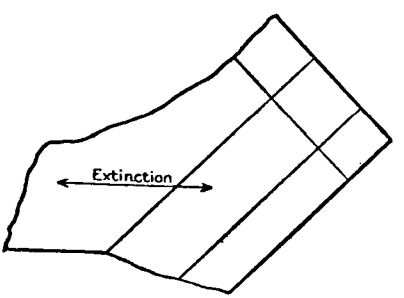

FIGURE 20.

FIGURE 19.—Contact twin of koechlinite. Composition face is $a\{100\}$.
FIGURE 20.—Cleavage piece of koechlinite, probably a polysynthetic twin with {011} as composition face.

Crystal 3 is an example of a crystal in which the two parts of a twin do not have the same combination. It is shown as it appeared under the microscope in figure 22.

The larger individual, elongated parallel to the edge a p, has the combination a p, whereas the smaller individual shows a prominent prism zone development. (Compare fig. 1, p. 11.)

The penetration twins are probably abundant, but unless the striated macropinacoid is present their detection is very difficult. Such a crystal, observed under the microscope, is shown in clinographic projection in figure 23.

A somewhat similar condition is presented by the imperfect crystal shown in figure 24 in orthographic projection on $a\{100\}$. The central part of the crystal (I) is in normal position, and III may

be considered as belonging to the untwinned central part (I). Part II, in twin position to I, lies between it and III. Part III may nevertheless be just as well considered as twinned to II, even though this brings it into parallel position with I. The crystal is thus similar to the one just described and illustrated in figure 23. By referring back to the theoretical twin shown in figure 21, it

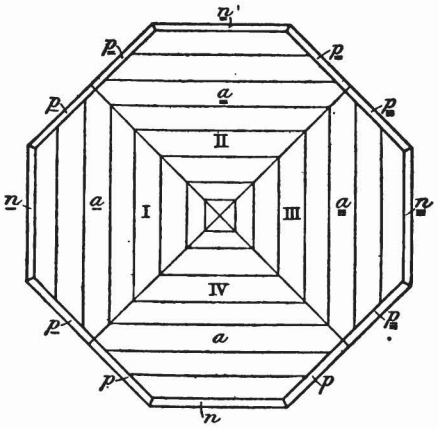

FIGURE 21.

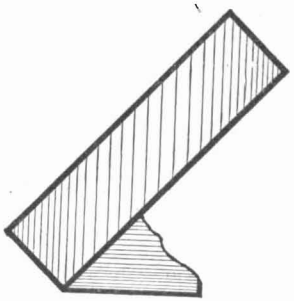

FIGURE 22.

FIGURE 21.—A theoretical fourling of koechlinite. Orthographic projection on $a\{100\}$. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

FIGURE 22.—Crystal 3, koechlinite. Contact twin with $\{011\}$ as composition face. The smaller individual has a different combination of forms from the larger one.

is seen that this can be interpreted in two ways. First I and III (fig. 21) may be considered as the same untwinned unit, to which II and IV (as one unit) are twinned. A preferable explanation, how-

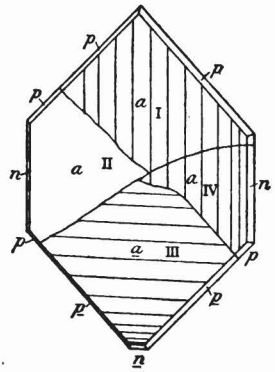

FIGURE 23.

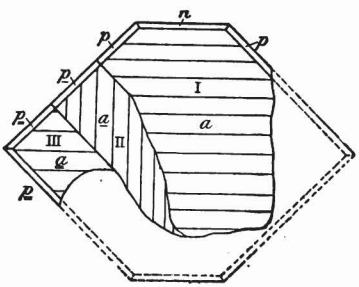

FIGURE 24.

FIGURE 23.—Clinographic projection of a penetration twin of koechlinite. The clear field (II) is free from striations, and its orientation is not known. The lower quadrant (III) is twinned on the upper one (I), and the remaining one (IV) may be considered as twinned on III; although it is in parallel position with the untwinned I. The continuity of the striations of I and IV would seem to indicate, however, that IV is not twinned but belongs inherently to I. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

FIGURE 24.—Orthographic projection on $a\{100\}$ of a penetration twin of koechlinite. Part II is twinned on I, and apparently III is twinned on II, yet III and I are in parallel position. Compare figure 23. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

ever, is that the drawing represents a fourling, in which I is twinned on IV, II on I, and III on II. A similar explanation is believed to hold for the crystals shown in figures 23 and 24.

MEASURED CRYSTALS.

Crystal 1, representing one of the square habit, with $a\{100\}$, $n\{230\}$, $b\{010\}$, and $p\{111\}$, is shown in figure 11 (p. 21). The form $h\{430\}$ is not shown in the drawing.

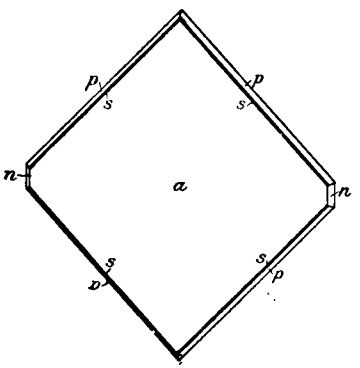

FIGURE 25.

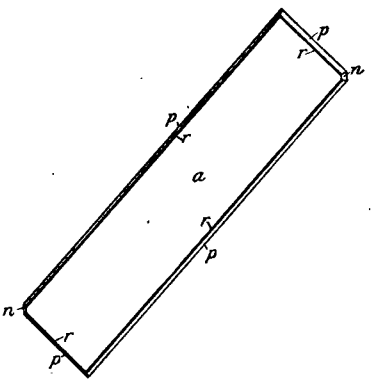

FIGURE 26.

FIGURE 25.—Crystal 5, koechlinite. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$, $s\{533\}$.
FIGURE 26.—Crystal 2, koechlinite. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$, $r\{322\}$.

Crystal 5 (fig. 25) represents one of similar habit, showing the line faces of $s\{533\}$. The rare prism $k\{210\}$, not shown in the figure, was observed only on this crystal.

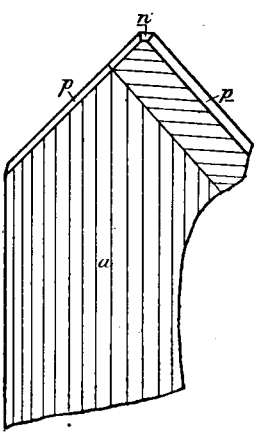

FIGURE 27.

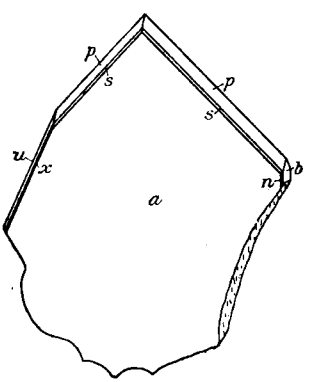

FIGURE 28.

FIGURE 27.—Crystal 4, koechlinite. Forms: $a\{100\}$, $p\{111\}$, $n\{230\}$.
FIGURE 28.—Crystal 7, koechlinite. Forms: $a\{100\}$, $b\{010\}$, $n\{230\}$, $p\{111\}$, $s\{533\}$, $u\{131\}$, $x\{362\}$.

Crystal 2 (fig. 26) is one of the distorted habit, elongated parallel to the edge a p. The pyramid $r\{322\}$ is present with $p\{111\}$.

Crystal 4 (fig. 27) is interesting as showing a twinned portion of the crystal with a face of $n\{230\}$ in the position of a macrodome.

The angle $a\{100\}$: $n\{230\}$ (54° 28′) is close to the angle $a\{100\}$: (203) (56° 10′).

Crystal 7 (fig. 28) is the only one on which the two pyramids $u\{131\}$ and $x\{362\}$ were definitely determined. In addition to the forms shown in the drawing, the two prisms $j\{450\}$ and $h\{430\}$ were observed on this crystal.

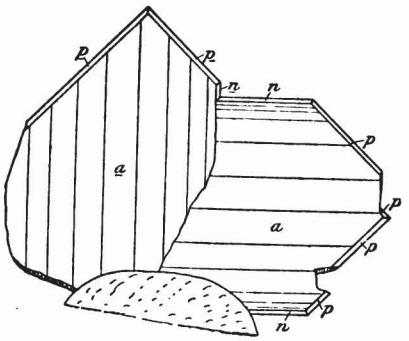

FIGURE 29.—Crystal 6, koechlinite. Orthographic projection on $a\{100\}$ of twin crystal. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

Crystal 6 is shown in orthographic projection on $a\{100\}$ in figure 29. The crystal is a well-developed contact twin with an irregular composition face, part of which appears to be $b\{010\}$ in the upper part of the drawing, but which is more likely rather irregular. In addition to the forms shown in figure 29, faces of $l\{130\}$, $m\{110\}$, and $\{430\}$ were determined on this crystal.

ETCH FIGURES.

The symmetry of the markings observed on some of the crystals, coupled with the prominent distortion along one set of intersection edges of a and p, strongly suggested a deviation from holohedral symmetry, and the concealing twinning might give the distribution of the faces an apparently higher grade of symmetry than the mineral in reality possessed. Recourse was therefore had to the effect of etching by dilute hydrochloric acid, and very interesting results were obtained, although the evidence is of an apparently conflicting nature and is thought not to justify decisive conclusions.

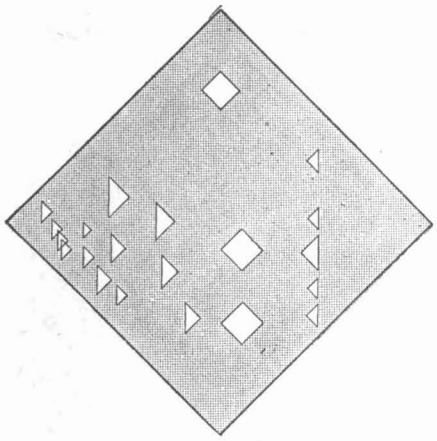

FIGURE 30.—First stage of etch figures produced on a symmetrically etched crystal of koechlinite.

Minute pits or etch figures are produced on the $a\{100\}$ faces of koechlinite in a few minutes when a crystal is immersed in cold dilute hydrochloric acid (about 1:5). If the acid is drained off and weaker

acid substituted the progress of the etching can be retarded and regulated. The effects produced can be readily studied by covering the crystal (on a glass slide) with a cover glass which, by its own weight, removes all but a film of solution from the *a* faces. The cover glass is then removed and fresh acid added to the crystal whenever it is desired to have the process of solution continue.

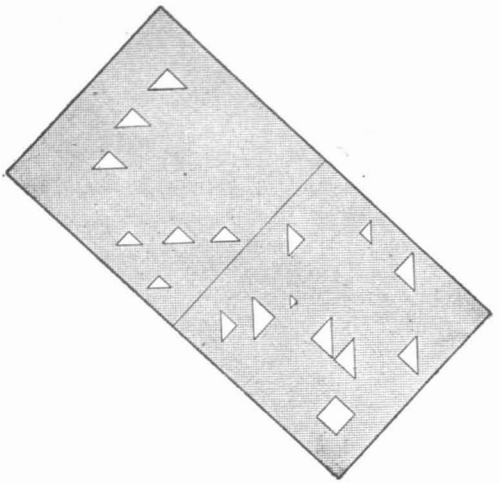

FIGURE 31.—First stage of etch figures produced on a winned crystal of koechlinite.

The process of solution of the crystal in hydrochloric acid, as observed, was not continuous, nor were the conditions constant, as the concentration of the acid, for example, was changed a number of times. It is not believed, however, that these interruptions are the cause of the apparent inconsistent facts observed.

The first etch figures produced are triangular and rectangular in shape. The triangular ones are symmetrical to a horizontal plane but not to a vertical plane. Moreover, some face to the right and others to the left. The rectangular figures may be conceived as a combination of right and left triangular ones. The distribution of these three kinds of figures does not necessarily bear any relation to the crystal itself. Each kind has been observed scattered over part of the entire crystal. An exceptionally symmetrically etched crystal is sketched in figure 30. As can readily be seen, the right-facing triangles are all on one side and the left-facing triangles are all on the other side. The rectangular figures, which may be built up of right and left triangles, occur only in the center.

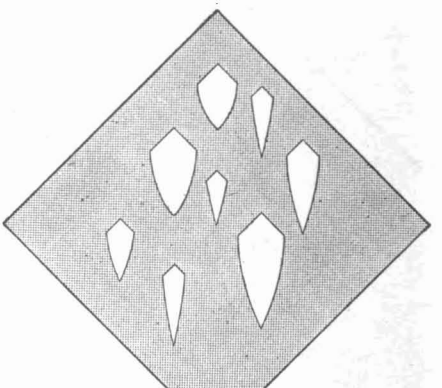

FIGURE 32.—Second stage of etch figures produced on koechlinite after the triangular figures.

A twin crystal shows similar etch figures, oriented in position with the twin part of the entire crystal, as shown in figure 31.

It is to be specially noted that these triangular etchings parallel with one another have an apparent hemimorphic symmetry in the direction of the *b* axis.

A little later etch figures are developed which, while hemimorphic in character, show this hemimorphism not in the direction of the *b* axis, like the triangular figures just described, but in the direction of the vertical or *c* axis. These etch figures are sketched in figure 32.

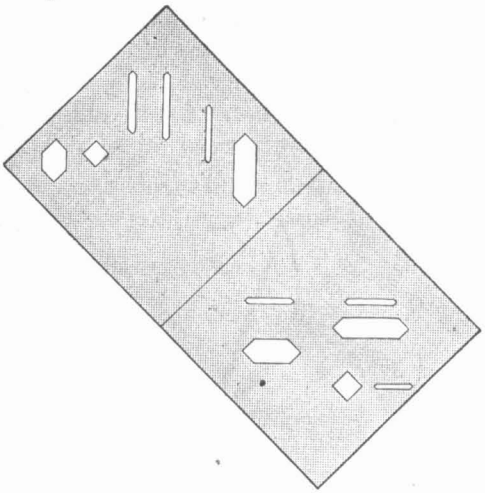

FIGURE 33.—Third stage of etch figures produced on a twinned crystal of koechlinite. All the figures now have holohedral symmetry.

At a still later period the triangular etch figures have all developed into rectangular ones and the vertically hemimorphic figures into hexagonal ones. They are shown in figure 33 as they were observed on a twin crystal. In a number of instances the gradual change in shape and symmetry from an original hemimorphic etch figure to the final rectangular or hexagonal one was continuously observed under the microscope, and the changes, as noted, are given in figure 34.

The final effect observed was most remarkable. The remnant of the crystal was bounded by sharply rectangular lines and its interior was full of similarly

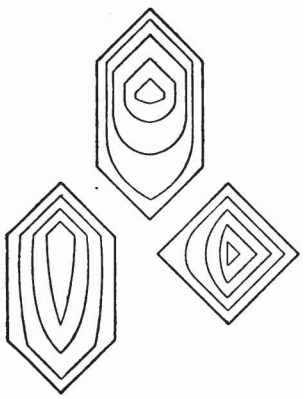

FIGURE 34.

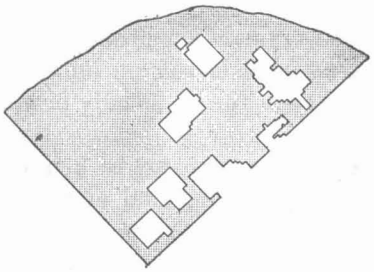

FIGURE 35.

FIGURE 34.—Last stage of etch figures produced on koechlinite. Change in shape and symmetry from figures with an original hemimorphic symmetry (inner outlines) to the final holohedral figures (outer outlines).

FIGURE 35.—Appearance of a corner of an etched and dissolving crystal of koechlinite.

sharply bounded rectangular holes, and the process of solution of the crystal continued in this way until the entire crystal was dissolved. The appearance of a corner of the crystal at a given moment is shown in figure 35.

The final etch figures developed on koechlinite by dilute hydrochloric acid are strictly holohedral in their symmetry, whereas those first produced are strongly hemimorphic. Is the symmetry of the figures first produced to be regarded as having no bearing on the symmetry of the mineral itself, or are the later holohedral etchings to be considered as twinned hemimorphic figures, thus ascribing to the mineral an intricate polysynthetic twinning? (See p. 21.)

The following observed facts seem to lend support to the idea of hemimorphic symmetry for koechlinite: The hemimorphic character of the markings observed on $a\{100\}$, the common distortion in un-

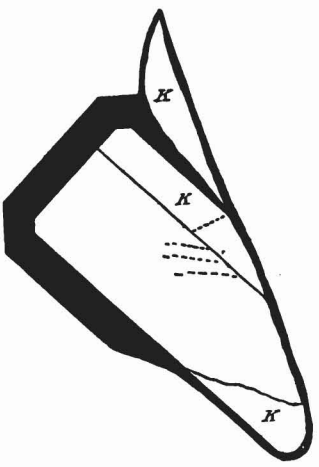

FIGURE 36.

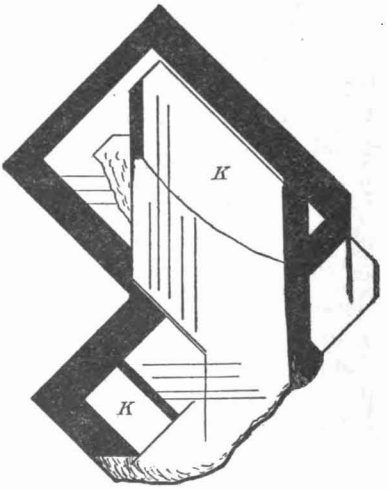

FIGURE 37.

FIGURE 36.—Intergrowth of unknown mineral C with koechlinite. The areas occupied by koechlinite are marked *K*.

FIGURE 37.—Intergrowth of unknown mineral C with koechlinite (*K*).

twinned crystals along one pair of edges *a p;* the unequal size of the different faces of a form on the same crystal; and the hemimorphic symmetry of the artificially produced etch figures, as shown in figures 30, 31, and 32.

Opposed to the idea of hemimorphic symmetry of the crystals are the facts that the final etch figures are strictly holohedral in their symmetry and that the distribution of faces on the crystals favors holohedral symmetry, although it must be said that the measured crystals were not developed perfectly enough nor were the terminal faces sufficiently large to warrant a definite conclusion.

INTERGROWTHS.

Intergrowths of koechlinite with the colorless mineral described on page 13 as unknown mineral C were observed several times. The two minerals are, so far as the observations go, in parallel untwinned position, the striations being parallel. The contact line is straight in some intergrowths and very irregular in others. In the typical example of an intergrowth shown in figure 36 the main mass of the crystal consists of the colorless unknown mineral C and there are three smaller portions of koechlinite.

In the best developed example of this intergrowth, reproduced in figure 37, the main mass of the crystal consists of unknown mineral C twinned, and each twin portion contains intergrown koechlinite.

RELATION TO OTHER MINERALS.

There are no known minerals with which koechlinite shows a close analogy in type of chemical formula. The mineral jeremejevite has the formula $Al_2O_3.B_2O_3$, which, in type, conforms to the formula of koechlinite, but jeremejevite is hexagonal, although the so-called eichwaldite, intergrown with jeremejevite, has been interpreted as orthorhombic, with axes which, if doubled, are not far from those of koechlinite:

Eichwaldite, $2a:b:2c=1.1046:1:1.0868$.
Koechlinite, $a:b:c=0.9774:1:1.0026$.

A number of hydrous minerals are analogous to koechlinite in composition except for the water, but crystallographically they seem to show no close relation to koechlinite. These hydrous minerals are listed below.

Koechlinite	$Bi_2O_3.MoO_3$	Orthorhombic.
Montanite	$Bi_2O_3.TeO_3.2H_2O$.	
Ferritungstite	$Fe_2O_3.WO_3.6H_2O$	Hexagonal.
Utahite	$Fe_2O_3.SO_3.\frac{1}{2}H_2O$?	Hexagonal.
Planoferrite	$Fe_2O_3.SO_3.15H_2O$	Orthorhombic.
Aluminite	$Al_2O_3.SO_3.9H_2O$.	

Attention may be called to a furnace product which in composition is similar in type to koechlinite but of which unfortunately few crystallographic data seem to be available. This is a crystalline compound described by Pearce [1] and having, according to his analysis, the composition expressed by the formula $As_2O_3.SO_3$. The crystallographic data are too meager to warrant any conclusion as to the relation of the compound to koechlinite. Pearce describes it as follows:

> The usual condition of the material was small spear-shaped crystals of a pearly luster. * * * These crystals were in many cases more than 1 inch in size and

[1] Pearce, Richard, On a remarkable crystalline compound of arsenious and sulphuric acids: Colorado Sci. Soc. Proc., vol. 3, p. 255, 1888-1890.

beautifully modified. The form will, in all probability, be found to be monoclinic. They are semitransparent to transparent; color, white; cleavage, perfect; luster, somewhat pearly and adamantine.

PHYSICAL PROPERTIES.

The cleavage of koechlinite is perfect parallel to the macropinacoid $a\{100\}$. A second imperfect cleavage seems to exist after some other form in the prism zone. The crystals are very brittle, breaking readily under the slighest pressure. The extreme thinness of most of the crystals naturally increases their tendency to break. The hardness and density are not known.

OPTICAL PROPERTIES.

The body color of the crystals is greenish yellow and corresponds to "oil-yellow" on Plate V of Ridgway's "Color standards.."[1] When heated but not fused the greenish-yellow crystals become brown, but on cooling they revert to their original color. The fused mineral becomes dark brown and on cooling suddenly changes to a very pale yellow which becomes white when cold. The luster is vitreous, slightly adamantine. The streak is pale greenish yellow. The crystals are transparent, the transmitted color being greenish yellow, like the body color.

A bisectrix emerges normal to the macropinacoid, and the trace of the axial plane is normal to the striations and therefore parallel to $c\{001\}$. The axial angle seen on $a\{100\}$ is very large and the obtuse bisectrix probably emerges normal to $a\{100\}$. On this assumption the orientation of the mineral is as follows:

$$\begin{aligned} a \text{ axis} &= Z \\ b \text{ axis} &= X \\ c \text{ axis} &= Y \end{aligned}$$

If the a axis is the direction of the obtuse bisectrix, then the mineral is negative.

The refractive indices are very high. Mr. Esper S. Larsen kindly determined the index by the embedding method[2] and found $\beta_{Li} = 2.55$ with an estimated birefringence of about 0.1.

The crystals have a very slight pleochroism, observable only on the thicker ones. As observed on $a\{100\}$, the mineral is not pleochroic, except that on the thicker crystals the color is slightly deeper normal to the striations than parallel to the striations.

[1] Ridgway, Robert, Color standards and color nomenclature, Washington, 1912.

[2] Merwin, H. E., and Larsen, E. S., Mixtures of amorphous sulphur and selenium as immersion media for the determination of high refractive indices with the microscope: Am. Jour. Sci., 4th ser., vol. 34, p. 42, 1912.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

The mineral fuses readily in a closed tube without giving off water or any sublimate. The color changes are described on page 32. The crystals dissolve readily in HCl but not so readily in HNO_3. The deep-blue color of a lower oxide of molybdenum is readily obtained by heating the mineral with concentrated H_2SO_4 and evaporating nearly to dryness in a white porcelain crucible. The bismuth iodide sublimate on charcoal is strong and characteristic.

QUANTITATIVE COMPOSITION.

The material analyzed was nearly free from inclusions except for admixed quartz. The three unknown minerals already described were present in only minute amounts in the samples analyzed, as the crystals of koechlinite were separately picked out of the material removed from the cavities. The mineral was at first taken to be Bi_2O_3, and as the first analysis totaled only 78.2 per cent, it was thought that a mistake had been made in the determination of bismuth. On a second sample a determination of bismuth gave the same result. As each analysis totaled less than 100 per cent, it was evident that an unrecognized constituent was present. Nearly all the remaining material was sacrificed in the determination of this unknown constituent, which was finally identified as molybdenum. Another specimen of the mineral had then to be utilized to obtain material for a quantitative determination of the molybdenum. The absence of the common bases and of any sulphate, phosphate, carbonate, borate, or tungstate radicle was qualitatively determined. The results obtained are shown below.

Analyses of koechlinite.

	1	2	3
Weight of sample.....gram..	0.0925	0.1003	0.0424
Bi_2O_3.....	73.0	51.6	71.9
MoO_3.....	Not det.	Not det.	21.2
H_2O (loss on ignition).....	.2	.....	.....
Quartz.....	5.0	34.1	5.4
	78.2	85.7	98.5

The results are restated below with the admixed quartz deducted, being thus reduced to a comparative basis.

Analyses and ratio of koechlinite with quartz deducted.

	1	2	3	Average.	Ratio.	Calculated.
Bi_2O_3	76.8	78.3	76.1	77.1	0.166 or 1.00	76.36
MoO_3	.....	.....	22.4	22.4	.155 or .93	23.64
H_2O	.2	.....	.....	.2	.....	.....
	77.0	78.3	98.5	99.7	.....	100.00

The ratio obtained leads to the formula $Bi_2O_3.MoO_3$, which can be interpreted as bismuthyl molybdate $(BiO)'_2.MoO_4$.

DIAGNOSTIC PROPERTIES.

The rectangular crystals with diagonal striations, and particularly the elongated distorted crystals, are very characteristic of koechlinite. The absence of water and a qualitative determination of bismuth and molybdenum on such crystals would positively identify koechlinite.