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ART. XLVIII.—*On the Crystallization of Native Copper*; by EDWARD S. DANA. With Plates X to XIII.

Literature.

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Historical summary.—The early writers give but little information about the crystallization of native copper. Haüy, and Mohs (1822) figure only the simple crystals showing the combination of the cube, octahedron and dodecahedron. Haüy, however, speaks of a crystal consisting of a low hexagonal pyramid with a short hexagonal prism, which seems to be the same form described by Haidinger in 1824. This latter crystal was from the Nalsö, and showed the tetrahexahedron e (210, i-2) shortened in the direction of an octahedral axis and probably twinned parallel to the octahedral plane normal to this axis (compare figures 20, 21, Plate XI).

The first important contribution to the subject is that of Rose in 1837. He added to the planes before observed the tetrahexahedron *k* (520, *i*-$\frac{5}{2}$) and trisoctahedron *m* (311, 3-3), both on crystals from the Ural. He also gives an interesting description and explanation of the complex crystalline growths afforded by the Siberian mines. He shows that in these forms the branching takes place in the direction of the edges of an octahedral face, that is, at angles of 60°, while the upper and lower parts of the plates are in twinning position to each other. The whole growth consequently forms a single twin, in which the twinning-plane is the octahedral plane in which the branches extend. Rose gives two large figures, projections upon the octahedral twinning-plane which show clearly the ideal relations of the parts of these complex forms.

Lêvy about the same time (1837) described twin crystals with *e* alone, and also with *a*, *d*, *o* and *e*; he also mentions the pseudo-hexagonal forms resulting from the distortion and twinning of the tetrahexahedron *e*. Haidinger in 1863 described peculiar hexagonal twins from Burra-Burra in Australia, formed by a combination of the dodecahedron and cube. Schrauf in 1872 gave further obervations of the Australian copper, describing pentagonal dodecahedrons of the form *e*. In 1873 the same writer figured a twin crystal of artificial copper in which *m* (311, 3-3) was prominent. Zerrenner in 1874 mentioned a crystal from Bolivia with *e* and *t* (421, 4-2), but gave no measurements to support the latter form.

Seligmann in 1876 described crystals from the Friedrichssegen mine in Nassau showing pseudohexagonal symmetry, and also twins with orthorhombic symmetry, not unlike forms from Lake Superior explained on a later page. Jérémejew in 1877 described crystals from the Altai with the form *f* (310, *i*-3). G. vom Rath in 1877 gave an interesting account of some Lake Superior crystals with the new hexoctahedron *y* (18·10·5, $\frac{18}{5}$-$\frac{9}{5}$); also of a complex combination of this form with the tetrahexahedron *k*, showing a secondary growth of the first form on the second. He gave, too, a brief account of a dendritic crystalline growth analogous to the forms described by Rose.

Fletcher in 1880 added the following new forms: *h* (410, *i*-4), *ε* (730, *i*-$\frac{7}{3}$), *δ* (740, *i*-$\frac{7}{4}$), *l* (530, *i*-$\frac{5}{3}$), *ω* (511, 5-5), *μ* (411, 4-4), and *v* (531, 5-$\frac{5}{3}$). Of these, Lake Superior specimens yielded all except *δ* and *ω*. Lasaulx in 1882 described twin crystals of copper from the Ohligerzug mine near Daaden, on the Sieg. They were polysynthetic octahedral twins, in part with enclosed twinning lamellæ, and in part star-shaped, formed by the grouping of five octahedral crystals about a common center. A form similar to that last mentioned was described in 1883 by Foullon; it was from Schneeberg, in Saxony. The most recent contribution to the subject in hand is that by W. G. Brown in the last number of this Journal. The crystals described by him were artificial and showed some interesting peculiarities of twinning structure.

The list of forms thus identified upon crystals of native copper is as follows:

Cube *a* (100, i-i), dodecahedron *d* (110, i), octahedron *o* (111, 1); tetrahexahedrons *h* (410, i-4), *f* (310, i-3), *k* (520, i-$\frac{5}{2}$), *ε* (730, i-$\frac{7}{3}$), *e* (210, i-2), *δ* (740, i-$\frac{7}{4}$), *l* (530, i-$\frac{5}{3}$); trisoctahedrons *ω* (511, 5-5), *μ* (411, 4-4), *m* (311, 3-3); hexoctahedrons *t* (421, 4-2)?, *y* (18·10·5, $\frac{18}{5}$-$\frac{9}{5}$), *v* (531, 5-$\frac{5}{3}$).

Through the kindness of Mr. Clarence S. Bement of Philadelphia, the writer has had an opportunity to make a careful study of his beautiful collection of specimens of native copper from Lake Superior, numbering upwards of sixty. A considerable part of these were collected by Mr. Norman Spang, whose exceptional opportunities in this direction, extending over a number of years, were most zealously used; to these Mr. Bement has himself made many important additions. It is not too much to say that these specimens taken together form the finest collection ever made of the crystallized native copper from this remarkable locality, while many of the individual specimens are wholly unique. As will be seen from the descriptions in the following pages the collection offers many points of scientific interest and novelty. In addition to this suite of specimens and a few others from foreign localities, the writer has also had the use of a large number belonging to the cabinets of Professor G. J. Brush and of the Yale College Museum. These have served in some important respects to supplement the Bement collection.

List of planes observed.—The planes which have been observed on the specimens named are: *a*, *d*, *o*; tetrahexahedrons *h*, *k*, *e*, *l*; trisoctahedrons *m*, *n* (211, 2-2); hexoctahedrons *y*, *x* (11·6·1, 11-$\frac{11}{6}$), *z* (12·3·2, 6-4)?. Of these *n*, *x*, *z* are new to the species.

Description of simple forms.—Figures 1 to 12, on Plate X, show the more important of the simple forms in their normal symmetrical development, which have been observed on the Lake Superior specimens. Decidedly the most common type is that of the tetrahexahedrons, and of the four included in the above list *h* and *k* occur most frequently, especially the former. This form *h* (410, i-4) is shown alone in fig. 4; it is the most obtuse of the tetrahexahedrons observed on this species and thus approximates most nearly to the cube; its interfacial angles (supplement) are: over $a = 28° 4'$, over $d = 61° 56'$, and over the edge A $(410 \wedge 401) = 19° 45'$. Fig. 6 on the other hand gives the tetrahexahedron *l* (530, i-$\frac{5}{3}$), which approaches nearest to the dodecahedron, it is interesting to note that its angles over a and d respectively are the same as those of h over d and a. The form h is usually combined with the cube (fig. 5) or with the cube, dodecahedron and octahedron (fig. 7); not infrequently h and k appear together both beveling the cubic edges (fig. 8). In fig. 9 we have the dodecahedron modified by the planes of this same tetrahexahedron. The faces of h are commonly striated in a direction normal to the cubic edges owing to an oscillatory combination of the planes of a hexoctahedron which, as noted later, has probably the symbol 12·3·2 (6-4). Not unfrequently, however, the faces of h are smooth and free from striations. The form k also occasionally shows similar striations.

Of the primary forms of the system, the cube alone is a rather common occurrence, and the dodecahedron occurs though less frequently. The octahedron by itself, however, is not represented at all on the specimens in hand; this may be due in part to accident but seems to show that the octahedral form alone is at any rate much less common than is the case with the other isometric native metals. Fig. 1 gives the nearest approach to the simple octahedron observed, and in fig. 11 the octahedron is shown modified by the hexoctahedron y. The octahedron is also prominent in the complex crystalline growth shown in fig. 48.

Fig. 2 represents the only case in which the trisoctahedron m (311, 3-3) was observed; this, as will be remembered, is a very common form with gold. Fig. 3 shows a combination, which will be recognized at once as the common garnet form, it is, however, very rare with this species and is only represented by one specimen. The faces of the trisoctahedron are slightly uneven with the tendency to striation common with the species, and hence no exact measurements were possible. The true symbol is obvious, however, since these faces truncate the edges of the dodecahedron; strictly it should perhaps be said that the symbol 211 (2-2) is the one toward which the form closely approximates.

Fig. 10 illustrates a type of crystal represented by several specimens and similar to that described by vom Rath; it is a dodecahedron with the planes of the hexoctahedron y (18·10·5, $\frac{18}{5}$-$\frac{9}{5}$). This symbol was assigned by vom Rath with some question, as his measurements were not very precise, but the writer's observations go to confirm his conclusion. The angles of the hexoctahedron are as follows:

Edge *A*.	Edge *B*.	Edge *C*.
$18\cdot10\cdot5 \wedge 18\cdot5\cdot10$	$18\cdot10\cdot5 \wedge 18\cdot10\cdot\bar{5}$	$18\cdot10\cdot5 \wedge 10\cdot18\cdot5$
$19°\ 12\frac{1}{2}'$	$27°\ 17\frac{5}{6}'$	$30°\ 58'$

Also

$100 \wedge 18\cdot10\cdot5 = 31°\ 50\frac{3}{4}'$, $110 \wedge 18\cdot10\cdot5 = 20°\ 52\frac{1}{8}'$, $111 \wedge 18\cdot10\cdot5 = 36°\ 44\frac{1}{8}'$.

The only one of the above angles which could be measured with really satisfactory precision was the inclination of two opposite faces on the dodecahedral plane; these were found to be 20° 59′ and 21° 0′, which correspond very closely with the calculated angle 20° 52$\frac{1}{3}$′. Also for 18·10·5 ∧ 18·5·10 was obtained 19° 14′, required 19° 12$\frac{1}{2}$′. On two of the specimens the faces of this hexoctahedron were striated coarsely parallel to the edge *C*, owing to the oscillatory combination of this form with a second hexoctahedron approximating closely in position to it. It was not possible to obtain a reliable symbol for the second form.

Another hexoctahedron is shown in fig. 12, which approximates closely to the dodecahedron. Many of the crystals on the specimen giving this combination showed the dodecahedral faces simply divided by faint striations into four fields. Other crystals showed the hexoctahedron distinct, two faces, over the tetrahexahedral edge (*B*), being in oscillatory combination and hence producing a fine striation. In one or two cases the faces were large and smooth enough to yield distinct images with the compound goniometer, and in this way were obtained

11·6·1 ∧ 11·1·6=33° 12′ and 11·6·1 ∧ 11·6·$\bar{1}$=9° 15′.

The various angles for 11·6·1 or 11-$\frac{11}{6}$ are:

Edge *A*.	Edge *B*.	Edge *C*.
11·6·1 ∧ 11·1·6	11·6·1 ∧ 11·6·$\bar{1}$	11·6·1 ∧ 6·11·1
32° 40$\frac{1}{8}$′	9° 7$\frac{1}{2}$′	32° 40$\frac{1}{8}$′

Also

100 ∧ 11·6·1=28° 56$\frac{1}{2}$′, 110 ∧ 11·6·1=16° 59$\frac{3}{4}$′, 111 ∧ 11·6·1=34° 14′.

The agreement is close enough to establish the symbol given as at least representing very closely the position of the form in question. Some of the crystals of this specimen showed the cube also as a prominent form.

Still another hexoctahedron is exhibited by the twin crystal figured on Plate XI (fig. 32). This form is interesting because it is clearly the one whose oscillatory combination produces the fine striation often observed on the faces of the tetrahexahedron *h*. This fact fixes the ratio of two of the axes as 4 : 1 and the measured angle on *a*, the only one obtainable with anything like accuracy serves to establish as the probable symbol 12·3·2 (6-4), which, however, needs confirmation.

100 ∧ 12·3·2=16° 43$\frac{1}{2}$′ calculated, =16° 30′ measured. The principal angles for this form are:

Edge *A*.	Edge *B*.	Edge *C*.
12·3·2 ∧ 12·2·3	12·3·2 ∧ 12·3·$\bar{2}$	12·3·2 ∧ 3·12·2
6° 28$\frac{1}{4}$′	18° 22$\frac{1}{6}$′	60° 18$\frac{1}{2}$′.

A number of the specimens showed more or less indistinctly planes of one or more hexoctahedrons, but it was only rarely that it was possible to obtain measurements accurate enough to admit of their determination. The question as to whether they were to be identified with already known forms had usually to be left undecided.

Irregularities of structure of the simple forms.—Native copper is like gold in the frequency with which its crystals show hollow and cavernous forms and other related peculiarities of structure. One specimen consists of a group of simple dodecahedrons, the faces of which show deep irregular cavities. In another the forms are hardly more than skeletons, the crystal, although nearly perfect, being in fact a mere shell. In other cases the edges of the crystal were salient and the faces deeply depressed. One example is given in fig. 15 where the cubic face is depressed, the sides of the depression being taken by the dodecahedral planes. The faces of the cubic planes especially are often thickly covered with quadrilateral pits formed by the dodecahedral planes (fig. 15) or by those of one of the common tetrahexahedrons. Striated faces and faces with wavy irregular surface are also frequently observed. Other irregularities, sometimes of an accidental nature, might be mentioned.

It is also common to observe cases of more or less distinct and regular elevations, triangular or quadrilateral or hexagonal, upon the larger faces. Sometimes these can be referred to known forms, but in others they are too indistinct to be determined. A vicinal tetrahexahedron on the cubic faces is occasionally noted. A prominent example of distinct and regular elevations is given in fig. 13, where at the extremities of the cubic axes there are the projecting pyramids formed by the faces of the tetrahexahedron l (530, i-$\frac{5}{3}$), a form which, as already stated, bears a peculiar relation to h.

Figure 13 also illustrates another point in the peculiarities of crystalline structure. One angle of the cube is here cut off by a broad octahedral face, at the center of which the planes of the tetrahexahedron h appear forming a small six-sided pyramid. Other crystals show the same thing in greater or less symmetry of development, sometimes several of the octahedral angles being treated in the same way. The octahedral face may be made up of a series of plates with parallel edges, upon which a number of minute pyramids are present, formed in the same way. This peculiarity is interesting because it introduces us to a point immediately to be considered, the tendency of the crystals to develop with rhombohedral symmetry. Thus a number of specimens consist essentially of flattened plates, corresponding to an octahedral plane, whose surfaces are covered with six-sided tabular and pyramidal elevations, the latter often very small and thickly crowded together. These pyramids are always formed by the six planes of a tetrahexahedron, which meet at the extremity of an octahedral axis. When the tetrahexahedron is the form *h*, the angles (supplement) of the scalenohedral pyramid are 61° 56′ and 19° 45′, while the angles at the base of the pyramid are 87° 55′ and 152° 12′ respectively. This is shown in fig. 14. When, however, the elevations are formed by planes of the tetrahexahedron *e* (210, *i*-2), the pyramid is a regular hexagonal pyramid with a pyramidal angle of 36° 52′, and each of the angles at the base is 120°; the latter is more common; it is illustrated in fig. 52.

A secondary growth over an original crystal is sometimes observed. One remarkably symmetrical case of this has been already spoken of as described by vom Rath. Usually the result is to partially obliterate the original form. Thus in one specimen the crystals show numerous tuberose sproutings, suggestive of a fungus growth; in another two large dodecahedral crystals are partially enclosed, each by a rough mass of copper showing only a trace of crystalline form.

Distorted forms and those showing pseudo-symmetry.—Cases showing irregular distortion are common, but among the simple crystals hardly more so than is the case with many other crystallized species. The distortion, on the contrary, usually exhibits a certain degree of regularity, being in the direction of one of the inter-axes of the crystal and thus giving rise to forms with marked pseudo-symmetry. Elongation in the direction of a cubic axis is frequently observed and where symmetrical, produces pseudo-tetragonal forms as shown in fig. 16; compare also figures 48 and 49 described later. Where the elongation is in the direction of one extremity of a cubic axis the forms are hemimorphic in type and more or less irregular.

A symmetrical development of a crystal about an octahedral axis gives rise to forms with rhombohedral pseudo-symmetry and these cases are so frequent and interesting that they are described at length below. Elongated wire- and band-like forms of varied shape, often much curved and twisted, and showing some crystalline markings on the surface, are common but these forms are generally very indistinct, and are hardly to be spoken of as crystals.

Crystals with rhombohedral symmetry.—It is an interesting fact in connection with the crystallization of the native metals, gold, silver and copper, that they so often show a tendency to develop with rhombohedral instead of isometric symmetry. Many cases of this kind have been noted; one striking example has been recently described by the writer,* in which crystals of native gold had essentially the form of an acute rhombohedron ($4R$); these were arranged in parallel position so as to form slender strings of rhombohedrons developed in the direc-

* This Journal, xxxii, 132. August, 1886.

tion of a trigonal axis of the trisoctahedron (3-3), the other planes of the trisoctahedron forming a pyramid $\frac{4}{3}$-2 and obtuse rhombohedron $\frac{2}{5}R$.

Frequent examples of this tendency have been observed among the specimens of copper under examination, though none so marked as that just mentioned. The following list includes some of the common forms of the isometric system with the symbols that belong to them when placed with an octahedral axis (normal to 111) vertical, taking the cube with a rhombohedral angle of 90° as the unit form. The vertical axis is then $\dot{c}=1{\cdot}22474$.

	Isometric.			Rhombohedral.	
Cube	a O,	100,	a	$10\bar{1}1$,	R
Octahedron	1,	111,	o	0001,	O
		$11\bar{1}$,	$o_{\prime}$	$02\bar{2}1$,	$-2R$
Dodecahedron	i,	110,	d	$01\bar{1}2$,	$-\frac{1}{2}R$
		$10\bar{1}$,	$d_{\prime}$	$11\bar{2}0$,	i-2
Trisoctahedrons	2-2,	211,	p	$10\bar{1}4$,	$\frac{1}{4}R$
		$11\bar{2}$,	$p_{\prime}$	$10\bar{1}0$,	∞R
		$21\bar{1}$,	$p_{\prime\prime}$	$12\bar{3}2$,	$-\frac{3}{2}$-$\frac{3}{2}$ or $-\frac{1}{2}^{3}$
	3-3,	311,	m	$20\bar{2}5$,	$\frac{2}{5}R$
		$31\bar{1}$,	$m_{\prime}$	$22\bar{4}3$,	$\frac{4}{3}$-2
		$3\bar{1}\bar{1}$.	$m_{\prime\prime}$	$40\bar{4}1$,	$4R$
Tetrahexahedrons	i-2,	210,	e	$11\bar{2}3$,	$\frac{2}{3}$-2
		$20\bar{1}$,	$e_{\prime}$	$21\bar{3}1$,	3-$\frac{3}{2}$ or 1^{3}
	i-$\frac{5}{3}$,	530,	l	$23\bar{5}8$,	$-\frac{5}{8}$-$\frac{5}{3}$ or $-\frac{1}{8}^{5}$
		$50\bar{3}$,	$l_{\prime}$	$53\bar{8}2$,	4-$\frac{8}{5}$ 1^{4}
	i-$\frac{5}{2}$,	520,	k	$32\bar{5}7$,	$\frac{5}{7}$-$\frac{5}{3}$ or $\frac{1}{7}^{5}$
		$50\bar{2}$,	$k_{\prime}$	$52\bar{7}3$,	$\frac{7}{3}$-$\frac{7}{5}$ $1^{\frac{7}{3}}$
	i-4	410,	h	$31\bar{4}5$,	$\frac{4}{5}$-$\frac{4}{3}$ or $\frac{2}{5}^{2}$
		$40\bar{1}$,	$h_{\prime}$	$41\bar{5}3$,	$\frac{5}{3}$-$\frac{5}{4}$ $1^{\frac{5}{3}}$

Among the specimens of native copper two showed rather distinctly the acute rhombohedral form ($-2R$) of fig. 17. The rhombohedral angle is here 70° 32′ and the plane facial angle 60° at the summit. The basal plane which is needed to fill out the eight faces of the normal octahedron was not distinctly present, and in fact the crystals were all lacking in sharpness, though there seems to be no doubt about the interpretation of the form.

Another specimen (fig. 18) showed a long hexagonal prism i-2 ($d_{\prime}$) terminated by an obtuse rhombohedron $-\frac{1}{2}R$ (d), with also subordinate planes of the rhombohedrons $R(a)$, $-2R(o_{\prime})$; in a normal isometric crystal this would be simply a combination of dodecahedron, cube and octahedron. A basal projection (fig. 23) shows the rhombohedral symmetry very clearly. The tetrahexahedron e (210, i-2) is frequently developed according to rhombohedral symmetry, as was early noted by Haüy (see above, p. 413), Haidinger, Lévy and others. As shown in the above list it then corresponds to a hexagonal pyramid of the second or diametral series ($\frac{2}{3}$-2) and a scalenohedron 1^{3}. The twelve planes of the latter form are often subordinate or nearly absent, and the result is then the pyramid shown in fig. 21; it is this pyramid which, as remarked before, so often covers the surface of broad octahedral plates. In such a form as fig. 21 there is nothing to indicate whether we are dealing with a simple crystal or a twin. If two opposite pairs of these planes are extended the result is an orthorhombic prism terminated by an obtuse pyramid.

Various more or less complex rhombohedral forms occur according as the planes just mentioned are modified by the faces of the cube, dodecahedron or octahedron. Thus in fig. 20 we have the planes of three of these forms together; this represents a simple crystal such as has been repeatedly observed, although twins of similar habit also occur.

One interesting crystal was observed which was a rhombohedral penetration-twin of the tetrahexahedron i-$\frac{5}{3}$ (530) and cube. Of the faces of the first mentioned form the twelve, comprising in the rhombohedral position the negative scalenohedron $-\frac{1}{8}^{5}$, were prominent, those of the other scalenohedron indistinct; the cubic faces were all present, six above and six below. The twinning plane was the basal (octahedral) plane. The other tetrahexahedrons i-4 and i-$\frac{5}{2}$ are also developed at times, more or less distinctly, after the rhombohedral type, especially the former. The scalenohedron $\frac{2}{5}^{2}$ forms common six-sided elevations on the octahedral plates, as shown in fig. 14 already alluded to.

Twin crystals.—The specimens of native copper from Lake Superior occur very frequently in twin crystals, although the remark of Rose in regard to the Siberian specimens that simple crystals are rare would not be true of those under examination. The law of twinning is always the same—the twinning-plane a face of the octahedron—but the variety and complexity of these twinned crystals is truly remarkable. The twins are with very rare exceptions contact twins; a few penetration twins have been observed, as also a few cases of repeated twinning.

A penetration-twin of rhombohedral type, with l (530, i-$\frac{5}{3}$) as the predominating form has been spoken of in a preceding paragraph. Another interesting case is shown in fig. 26. The predominating form is the tetrahexahedron k, though the allied form h occurs subordinate, and the octahedron and dodecahedron are both present. From one point of view the crystal appears as a nearly symmetrical cruciform twin, while looking down upon the central octahedral face (as in fig. 26) the habit is rhombohedral. It appears at first sight to be a compound twin but the three octahedral faces in twinning position may all be referred to the same individual; the symmetry of the crystal is nearly equal to that of the drawing.

Figure 22 shows a simple contact twin of the cubo-tetrahexahedron with the usual re-entering angles; this is similar to the forms figured by Lévy. Contact twins of simple habit and normal development are very rare. Octahedral twins of the spinel type have been noted only in a complex growth similar to that represented in fig. 54, and described later.

The spinel law applied to the cube yields the form represented in fig. 25. This is the common type of twins among the Siberian specimens as noted by Rose. Among those from Lake Superior, however, crystals of exactly this form are very rare. Almost invariably, these cubic twins are shortened in the direction of the twinning axis, thus yielding a form consisting of two similar triangular pyramids placed base to base. This form, noted by Sadebeck,* on the native silver from Kongsberg, is represented in fig. 24, and again in fig. 27, the latter in the orthorhombic position as mentioned below. These triangular twin crystals have a most anomalous appearance when they occur alone, suggesting a tetrahedron, or a hemi-tetragonal trisoctahedron, at first sight. One specimen from the cabinet of Professor Brush shows a broad surface of copper thickly sprinkled with very minute forms (1^{mm} to $\frac{1}{4}^{mm}$), some of them cubes, others tetrahexahedrons; and not a few are these triangular twins, like fig. 24 or fig. 31, and usually implanted by an acute trihedral angle.

Cases are rare, however, in which these cubic forms appear with this normal development. Generally they are elongated in a direction of a diagonal of the octahedral twinning-face and thus assume the symmetry of a (hemimorphic) orthorhombic crystal. Figure 27 shows this twin in the position corresponding to the latter symmetry. As this method of development is so common it is interesting to note the symbols of the common isometric forms when so placed. Accepting as the fundamental or unit pyramid, two of the cubic faces (100 and 010), the angles of this pyramid are 90° (brachydiagonal edge), and 70° 32′ (front or macro-edge formed by twinning). The plane angle at the summit is 45°. The orthorhombic axes are accordingly:

$$\breve{a} : \bar{b} : \dot{c} = 0{\cdot}8165 : 1 : 1{\cdot}4142$$

The direction of the vertical axis coincides with a diagonal of the octahedral twinning-plane, that of the brachydiagonal

* Min. petr. Mitth., i, 295, 1883.

axis with the edge of the plane normal to this diagonal, and that of the macrodiagonal axis is the twinning-axis, normal to the twinning-plane.

With respect to these axes the isometric forms met with on these copper twins group themselves as in the following table; the different forms into which the single isometric form separates are indicated, as in the preceding table, by subscript accents.

		Isometric.	Ortho-rhombic.			Isometric.	Ortho-rhombic.
Cube	a	100	111	Octahedron	o	111	014
		010	$\bar{1}11$			$1\bar{1}\bar{1}$	$01\bar{4}$
	a_I	$00\bar{1}$	$01\bar{2}$		o_I	$\bar{1}11$	$\bar{2}12$
						$\bar{1}\bar{1}1$	212
Dodecahedron	d	110	011			$\bar{1}1\bar{1}$	$\bar{2}1\bar{2}$
	d_I	$1\bar{1}0$	100			$\bar{1}\bar{1}\bar{1}$	$21\bar{2}$
	d_{II}	101	103		o_{II}	$1\bar{1}1$	$0\bar{1}0$
		011	$\bar{1}0\bar{3}$			$11\bar{1}$	010
	d_{III}	$10\bar{1}$	$12\bar{1}$				
		$01\bar{1}$	$\bar{1}2\bar{1}$				
	etc.						
Tetrahexahedrons	k	520	377		h	410	355
	k_I	$5\bar{2}0$	733		h_I	$4\bar{1}0$	533
	k_{II}	502	539		h_{II}	401	436
	k_{III}	$50\bar{2}$	571		h_{III}	$40\bar{1}$	452
	k_{IV}	$20\bar{5}$	$27\bar{8}$		h_{IV}	$10\bar{4}$	$15\bar{7}$
	etc.				etc.		
	e	210	133		e_{II}	201	214
	e_I	$2\bar{1}0$	311		e_{III}	$20\bar{1}$	230
					e_{IV}	$10\bar{2}$	$13\bar{3}$

It will be seen from the table that the brachypinacoid (010, i-$\breve{i}$), is formed by one of the octahedral planes (o_{II} $11\bar{1}$), the macropinacoid (100, i-$\bar{i}$) by a dodecahedral plane (d_I, $1\bar{1}0$); also one of the planes of the tetrahexahedron e is a prism (e_{III} $20\bar{1}=230$, i-$\breve{\tfrac{3}{2}}$).

All of the planes given in the above list play an important part in these twins. The transformation from the isometric symbol $(h_1h_2h_3)$ to that of the corresponding orthorhombic form $(p_1p_2p_3)$ is easily accomplished by aid of the equations:

$$p_1=h_1-h_2 \qquad p_2=h_1+h_2-h_3 \qquad p_3=h_1+h_2+2h_3$$

The way in which these twin crystals are developed will be clear from the following descriptions. One specimen of rare beauty and perfection consists of a group of elongated prismatic forms, the longest about $1\frac{1}{2}$ inches in length. In each of them the extremity is formed by a smooth and symmetrically developed pyramid of the form just described, while the elongation in the direction of the diagonal of the twinning-face is somewhat obscure. Figure 33 represents* one of the

* In the drawing of figures 33, 34, 35, 36, 37, 38, 51. 52, 53, 54, the writer has had the assistance of Mr. J. H. Emerton.

simpler of these forms, as true to nature as possible; figure 35 gives another quite small tapering crystal. In fig. 37 the extremity of a more complex form is represented; here there is a cluster of cubes in parallel position on one side of the form. Other crystals have similar clusters on both sides in their respective twinning positions; they thus serve to reveal the true nature of the terminal pyramid which, taken by itself, might be a serious puzzle, appearing as it does far off from normal isometric forms. The front edge, as seen in fig. 37, is often made up of a series of jagged points formed by a repetition of the lower extremity of the trigonal twin. One of these crystals is so complex a combination of jagged projections on the edges, front and rear and on both lateral edges as to hardly admit of adequate representation.

Another specimen of scarcely less beauty than that just described consists of a group of twin crystals of the same type, but more complex and irregular. In them the common tetrahexahedron *h* (410, *i*·4) is prominent, four planes of this form, those about the cubic face 100, namely 410 (h), $4\bar{1}0$ (h_{I}), 401 (h_{II}), $40\bar{1}$ (h_{III}), correspond respectively in the rhombic position to the pyramids 355 ($\breve{1}$-$\frac{5}{3}$), 533 ($\frac{5}{3}$-$\frac{\bar{5}}{3}$), 436 ($\frac{2}{8}$ $\frac{4}{3}$) and 452 ($\frac{5}{2}$-$\breve{\frac{5}{4}}$); compare figure 30. Each of these crystals, as is also true of the smaller crystals on the specimen before mentioned, demands a special study before its form can be understood, and this is no easy matter, since exact measurements are out of the question. An adequate illustration of the subject would require an almost indefinite number of ideal as well as artistic figures, since the variety of form is so great.

In fig. 28 the trigonal cubic twin is shown in combination with the octahedron, not an uncommon form, though the crystals of this type are also usually more or less irregularly elongated somewhat as in figures 33, 35 and 37. Figure 31 shows a similar trigonal twin combined with the cube and part of the planes of the tetrahexahedron *h*; this in the orthorhombic projection appears as in fig. 29. Fig. 30 is another more complex trigonal twin similar to fig. 31, and fig. 32 exhibits the same habit, but instead of the tetrahexahedron we have the hexoctahedron *x* already described.

Crystals of the type represented in figs. 29 and 30, when developed after the orthorhombic type, form acute, flattened spear-head crystals, as shown in the drawings (figures 36 and 38). In these cases the crystals are flattened in a direction *normal to* the twinning-plane, but in other cases the flattening is parallel to it, as described in the next paragraph. Very frequently on one or both sides some trace of the cube is shown by which the form can be orientated, and not infrequently the tetrahexahedral planes can be seen on the cubic faces in their normal development. The front edge is sometimes sharp and jagged in the way described, by the repetition of the lower angle of the trigonal twin. Figure 34 shows this point well; it is drawn (like the simple figure 40) with the twinning-plane parallel to the plane of the paper instead of normal to it, as in all the figures previously spoken of. These simpler specimens often show traces of the complex growth along lines at angles of 60°, and thus pass into such forms as that represented in fig. 51. Other specimens show other forms of the same type, but differing most widely according to the planes present and according to their relative development. In almost all of these the tendency to develop in orthorhombic symmetry is strongly marked.

The tetrahexahedron *e* is an interesting case, since it gives a prismatic form, 230 (i-$\frac{3}{2}$), terminated above and below by a brachy-pyramid 133 (1-$\breve{3}$). This form, which is not an uncommon one, and appears as a spear-head crystal flattened *parallel* to the twinning-plane, is especially noteworthy because it is in this position a normal orthorhombic form, not hemimorphic like the others. The same form may come without twinning from the shortening of the tetrahexahedron in the direction of an octahedral axis and a simultaneous elongation parallel to the middle pair of planes (compare fig. 21 and p. 421).

Another type of twin crystal, somewhat related to those just described, but of very different aspect, is shown in fig. 44. The first crystal studied proved to be a problem of some difficulty, especially as it was very small and only a few planes gave distinct reflections. At first sight it appeared to be a square prism terminated somewhat acutely by an octagonal pyramid and with several small modifying planes. The measurement of a few angles served to unravel the form. The pyramidal angles of two corresponding pairs of planes, measured with fair precision, were found to be

38° 55′ and 39° 7′;

the angles of the other approximately measured gave

30° to 31°.

The first angles given correspond to the angle between two adjacent planes of a twinned octahedron:

$$o \wedge \underline{o} = 38° 56′.$$

The other pyramidal angle corresponds to that (30° 27′) between two planes of the tetrahexahedron *k* (520, i-$\frac{5}{2}$). Other angles, measured with more or less accuracy, served to show that the planes present included the cube (*a*), octahedron (*o*), dodecahedron (*d*) and tetrahexahedron *k* (520, i-$\frac{5}{2}$). Figure 44 shows it in ordinary projection, and in fig. 43 a basal projection is given; the rather close approximation to a tetragonal crystal is obvious at a glance ($o_{II}\ d_{I} = 90°$).

The same specimen showed other crystals perplexingly like those just described, especially in that they were terminated by a pair of planes looking very similar to the pair of cubic planes in fig. 44. The measured angle between them was, however, about 39° (38° 56′) instead of 70° 32′ (the angle between two cubic faces in twinning position), and they were thus seen to be octahedral faces in twinning position to each other. These forms proved to be the complementary half of the crystal just described, as is shown in fig. 45, which is a projection upon the twinning plane; here both parts, not in fact observed together on the same crystal, are represented together. In fig. 45 the octahedral edge is placed above, to correspond with the symbols given on p. 423. The forms shown in figs. 43–45 are spoken of further in a later paragraph, where the method of grouping (see figs. 46 and 54) is described. The understanding of this type of twin will be facilitated by reference to the simple forms in figs. 39 to 42, all drawn with the twinning-plane parallel to the plane of the paper. Figure 39 is a simple octahedral twin of the spinel type; fig. 40 the trigonal cubic twin already fully described. In fig. 41 the octahedral twin is shown, but much flattened and with the cubic faces on the angles; this is also a copper form. Finally, fig. 42 is the cubic twin with the octahedral faces.

Still another type of twin is represented in fig. 47, which, like those already described, very rarely shows a re-entrant angle. The figure is a projection upon the twinning-plane. The crystals of this type are elongated prisms, one edge formed by two octahedral planes ($o_{,} \wedge \underline{o}_{,} = 38° 56'$) and the other by the pseudo-planes ϑ ($\vartheta \wedge \underline{\vartheta} = 90° 54'$). The figure is placed so as to show the prismatic development, but to understand it, it must be turned so that the plane o_{I} is parallel to the same plane in fig. 45; then h and h_{III} correspond to the tetrahexahedron k and k_{III} present there, etc. The pseudo-planes ϑ and ϑ' are formed by the oscillatory combination of two adjacent tetrahexahedral planes h and h_{III}, etc., and are in fact only a series of fine ridges. Were they real planes the symbol for ϑ would be $81\bar{1}$ (S-8) in the isometric system, or 7·10·7 in the orthorhombic position. Twins of this type are sometimes very regular and symmetrical and again highly irregular, and varying much from the simple prismatic form.

Methods of grouping.—The specimens of native copper very commonly show, instead of an irregular combination of crystals, a grouping in parallel position with sharply defined lines of growth. Two methods of grouping are most common. In the first the lines of growth (the "tectonic axes" of Sadebeck) of the adjoining crystals or parts of crystals (sub-individuals) are the cubic axes; in the second they are axes inclined 60° to each other and generally coinciding with the diagonals of an octahedral face, that is, the lines normal to its edges and bisecting the facial angles. A third method, quite different from the others, has also been observed.

The first method is common with many isometric species, and is represented here in several different forms. Thus one specimen is made up of small cubes grouped in this way. In another there are several series of octahedrons each having a common vertical axis, and each octahedron made up of many small partial octahedrons (like fig. 1), the whole specimen a wonderfully delicate and beautiful arborescent growth. Figs. 48 and 49 show interesting cases of the same thing. In fig. 48 the predominating forms are the octahedron and dodecahedron, though the terminal crystals are sometimes as complex as fig. 16. On this specimen we have sometimes a long wire with projecting points of small octahedrons; then more complex growths with branchings and rebranchings, and again a close even network of rectangular ribs. In fig. 49 the form involved is the tetrahexahedron *h* (410, *i*-4) and the lines of growth are uniformly the cubic axes; as will be inferred from the figure the specimen is one of much beauty and interest.

The second method of grouping is, however, the more interesting, especially so in that the crystals taking part in it are generally twins. Here the twinning-plane is the plane in which the lines of growth lie and these axes are three lines crossing at 60° and situated as described. The explanation of an analogous method of grouping was given by Rose in his description of the complex growth among the Siberian crystals already spoken of. The Lake Superior specimens differ from the Siberian in that, although the branching is also at 60°, the directions are almost always those of the *diagonals* of the octahedral face, not of the *edges*. This statement is true of all the Lake Superior specimens the writer has had the opportunity to examine with a single exception, while one beautiful specimen from Siberia in Mr. Bement's collection agrees with the description of Rose. It may be noted here that Sadebeck describes both these systems of "tectonic axes" as occurring in the dendritic growths of native silver, and he also mentions having observed the diagonal method of growth himself in copper. The Lake Superior specimen described by vom Rath is stated to have conformed to the method given by Rose.

An ideal representation showing the common method of growth spoken of, of the trigonal cubic twins, is given in fig. 50. The actual forms are, however, most complex, for instead of simple cubes we may have either one of the commoner tetrahexahedrons or a combination of one or more of them with each other or with the cube, octahedron and dodecahedron. Moreover, we have sometimes an open series of cubic twins, and from these we pass to more compact forms and finally to specimens which are simple plates with broad octahedral surface showing the characteristic spear-shaped twins only occasionally at the edges and with the hexagonal lines of growth only slightly accentuated. In the latter cases the octahedral surface is commonly covered over, often very thickly, with hexagonal elevations formed by one of the common tetrahexahedrons as already described. Still further, a number of these branching dendritic growths may be grouped in slightly diverging position about a common center, thus producing arborescent crystallizations of great beauty.

The twinning is also often somewhat complex; for it may be not simply a case of a single twin growth with the upper surface in twinning position with respect to the lower, but on the same side any one of the tectonic axes may be taken by a series of cubic twins in reversed position to those adjoining, or a single crystal in twinning position may appear in the midst of the others.

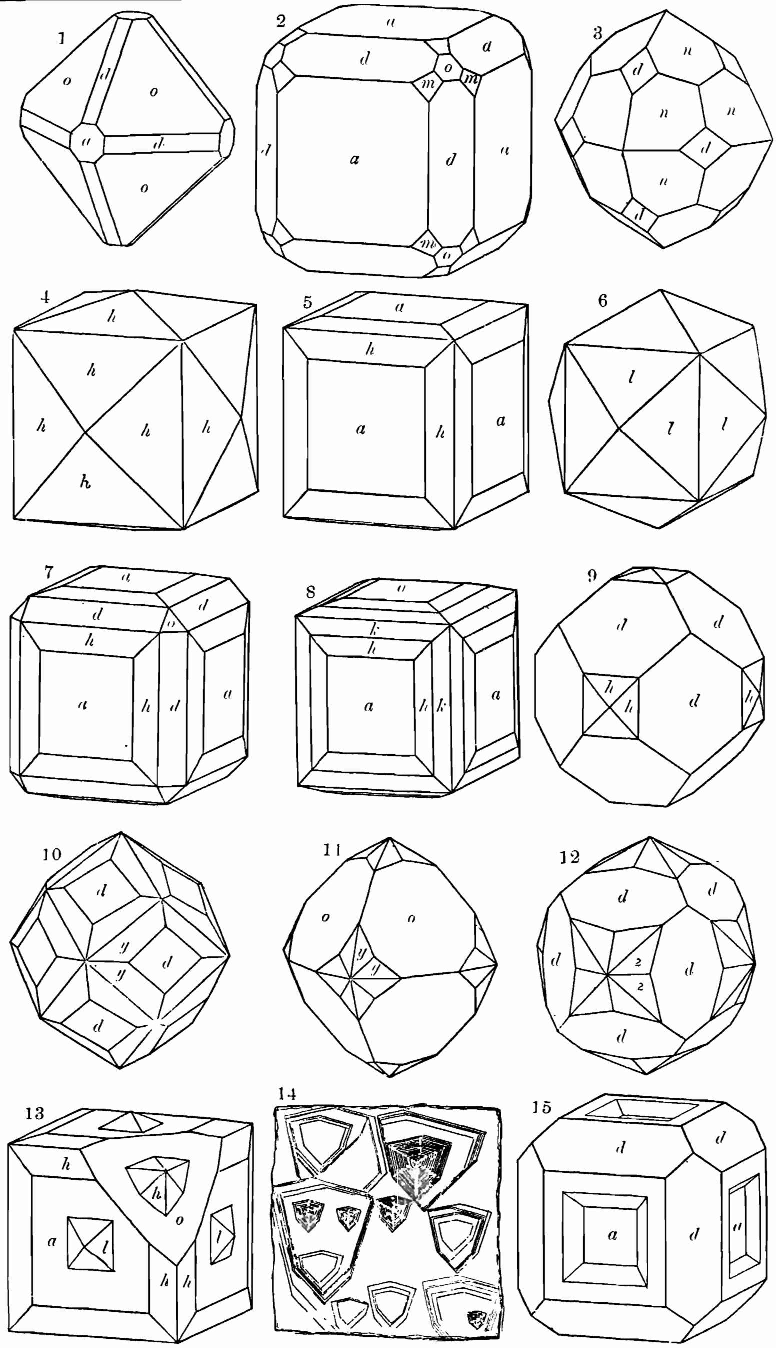
Fig. 51 represents ($\frac{4}{5}$ths natural size) one of the finest of these remarkable specimens. It illustrates admirably the method of growth and the remarkable complexity of the resulting forms. The spear-head forms at the extremities are here well seen. It is to be noted also, in illustration of a point just made, that for the lower part of the specimen the crystals are in twinning position with reference to the majority of the others, and this is true also of isolated cubes at various other points as at *a*, *a*. Fig. 52 shows one of the tabular forms in which the octahedral plane predominates, and it is only on the central and branching ribs that the other—tetrahexahedral—forms are distinct. The surface is thickly covered with hexagonal plates and low pyramids, which the drawing only in part represents.

In fig. 53 a partially satisfactory representation is given of a very delicate moss-like dendritic crystallization which is especially interesting because careful examination proves that the tectonic axes here are situated diagonally with reference to the common method, in other words it is like the forms figured by Rose. The specimens are nearly an inch in length and very thin and fragile. The octahedral surface is prominent, though cubes in thin plates, or in normal forms, project from it sometimes in one position, sometimes reversed—over one surface there are a number of tetrahexahedrons with rhombohedral (scalenohedral) development implanted on the octahedral surface; these are also in both positions.

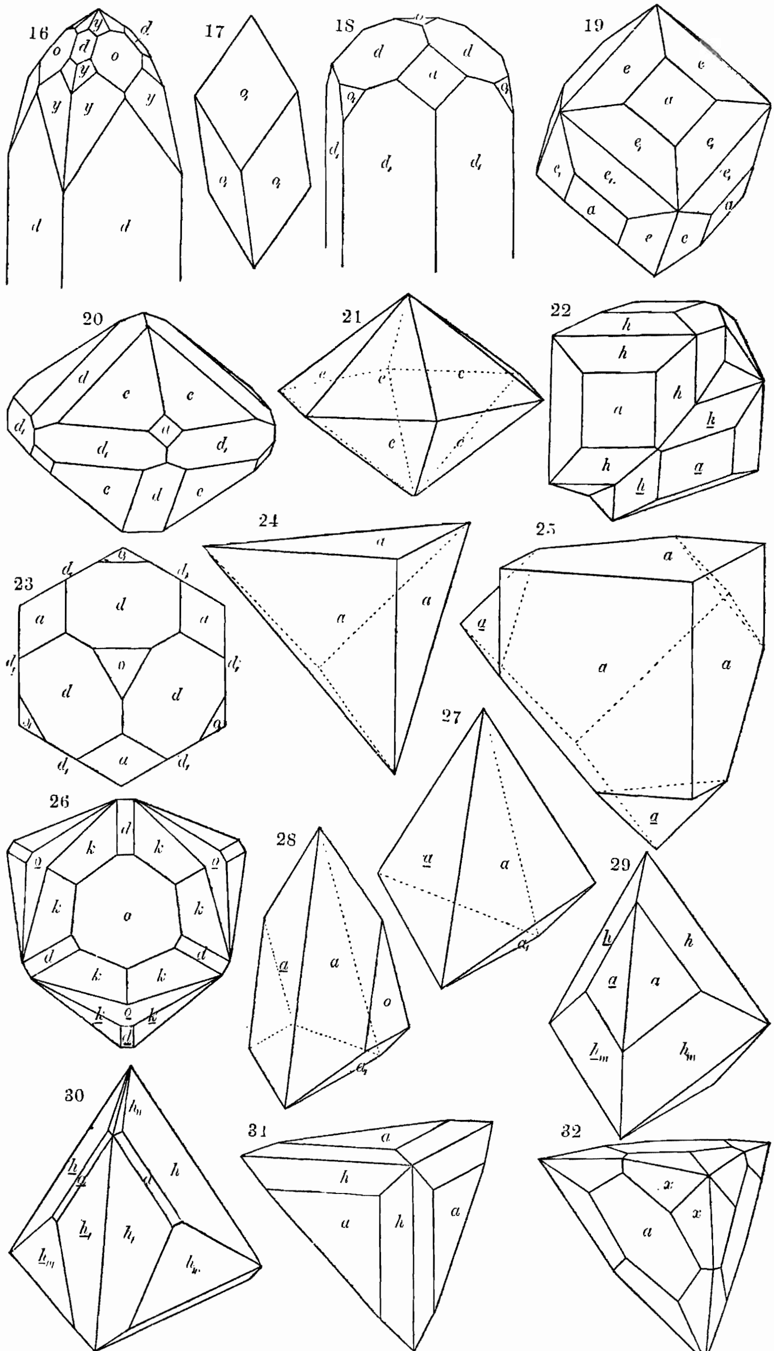
A novel and interesting method of grouping, different from those described, is represented by several fine specimens. The crystal individuals taking part in it have already been partially described (see figs. 43, 44, 45). The larger specimen, as shown in the drawing, fig. 54, consists essentially of a long slightly curved line, deeply grooved along the center, from which project above and below, in two directions crossing at angles of 70° 32′ and 109° 28′, a series of small (2^{mm}) partial crystals. This line of elongation is one edge of the twinning octahedral plane. The crystals above and below form the two parts of fig. 45. Those below terminating in the cubic twinning-edge have a rather constant habit as shown in fig. 46. The crystals above, however, which terminate in an octahedral twinning-edge, vary much, and have a marked tendency to develop in forms similar to those below by elongation to one side in a direction normal to the cubic edge. This is suggested by the forms in fig. 46; but other crystals are very much more elongated and incline to one side at a sharp angle. Others of these crystals are broad plates showing but few planes except at the edges.

The smaller specimens of this type show also more distinctly a second similar line about the same axis and crossing the others at the octahedral angle of 70° 32′. Fig. 55 gives a cross-section in outline, and makes clear what the relations of the two series are. The individuals I and II are in twinning position with the octahedral edge above. The individuals III and IV are also in twinning position with the adjacent octahedral plane as twinning-plane, and in such a manner that the first twinning-plane is parallel to the octahedral face of III which forms the edge of III and IV. Another specimen showed the same method of complex growth, though the component crystals were simpler, some of them being simple spinal twins like fig. 39. The lines in all these cases when naturally terminated, taper off to a rather fine point.

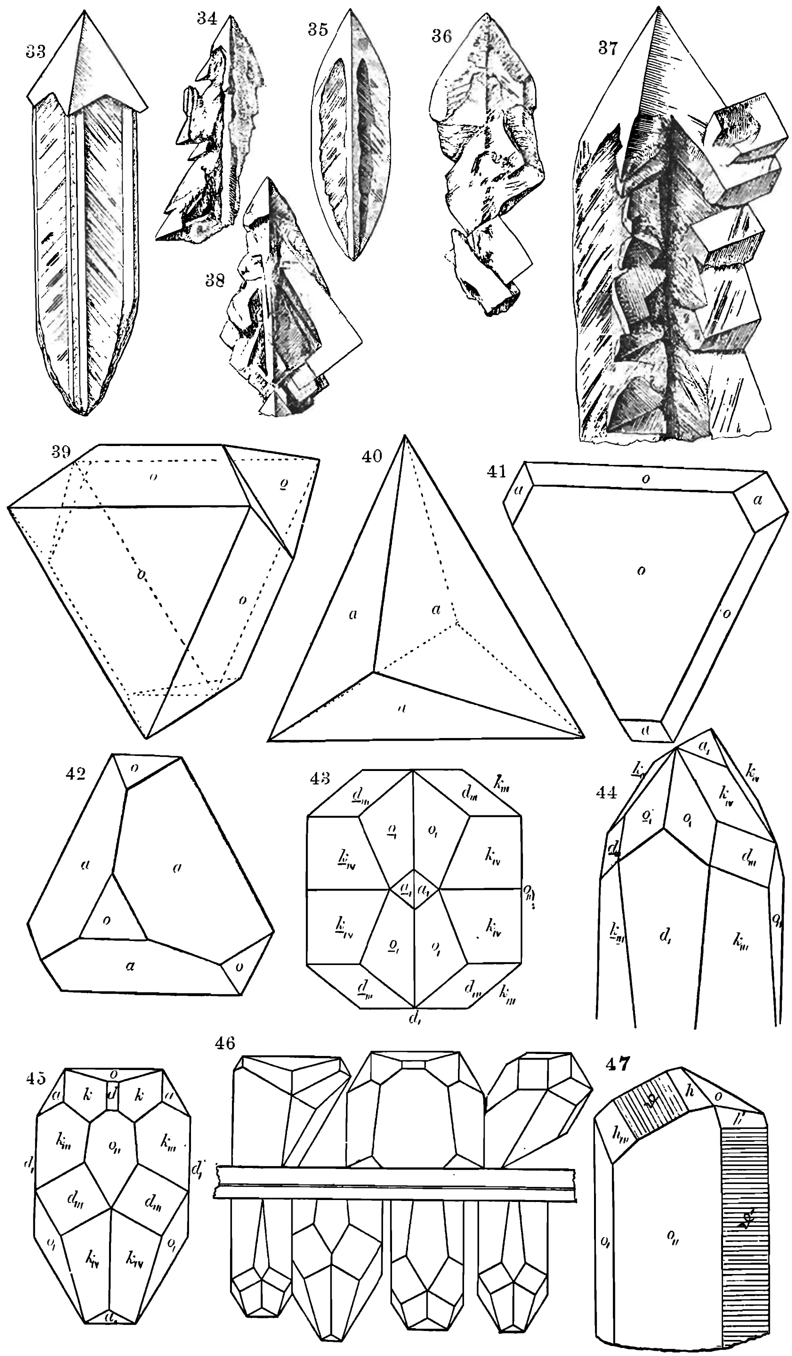
In concluding this paper, upon a subject which cannot by any means be regarded as exhausted, the writer would express his thanks to Mr. Clarence S. Bement for his kindness in allowing him the free use of his valuable collection for several months, and also for the substantial support which has made so liberal a degree of illustration possible.



Native Copper—Lake Superior.



NATIVE COPPER—LAKE SUPERIOR.



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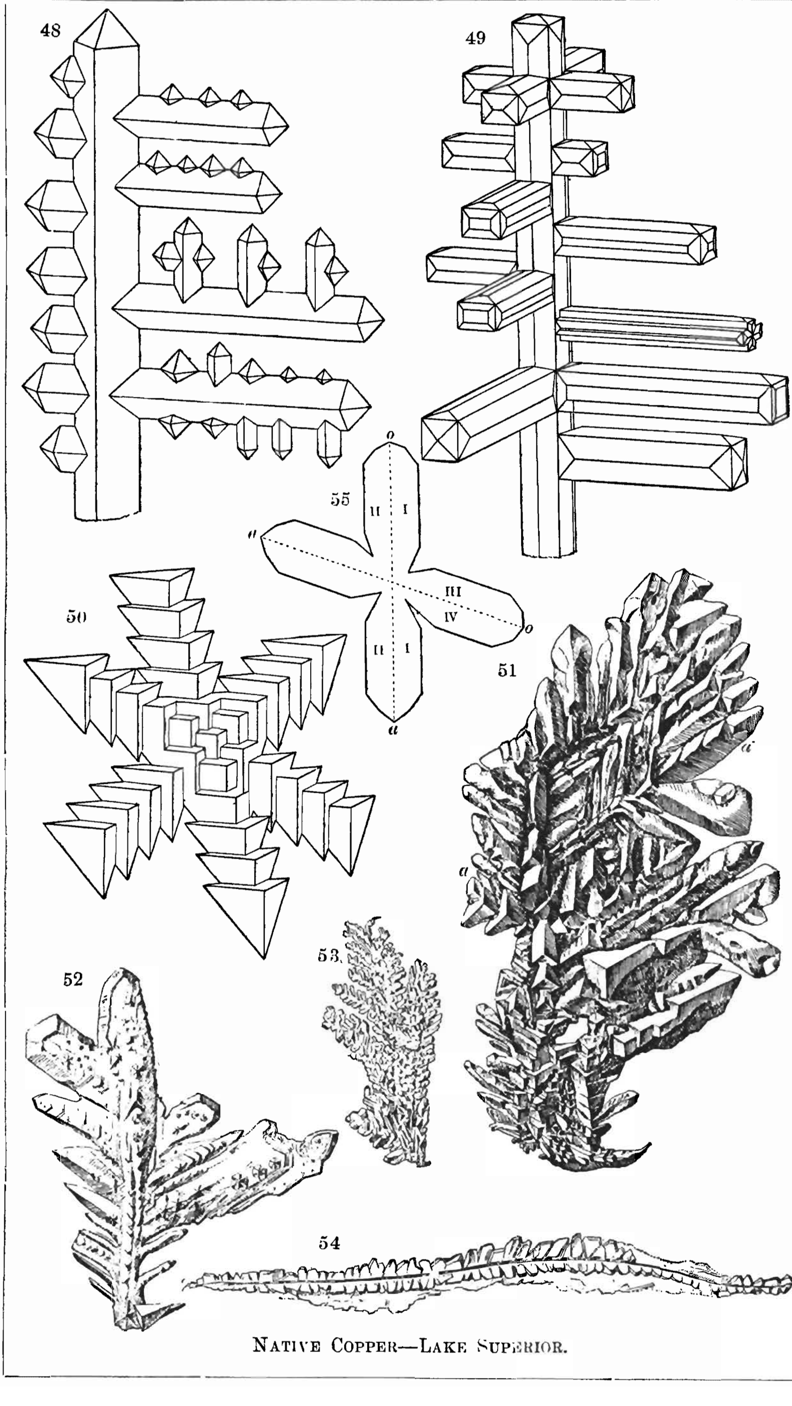

NATIVE COPPER—LAKE SUPERIOR.