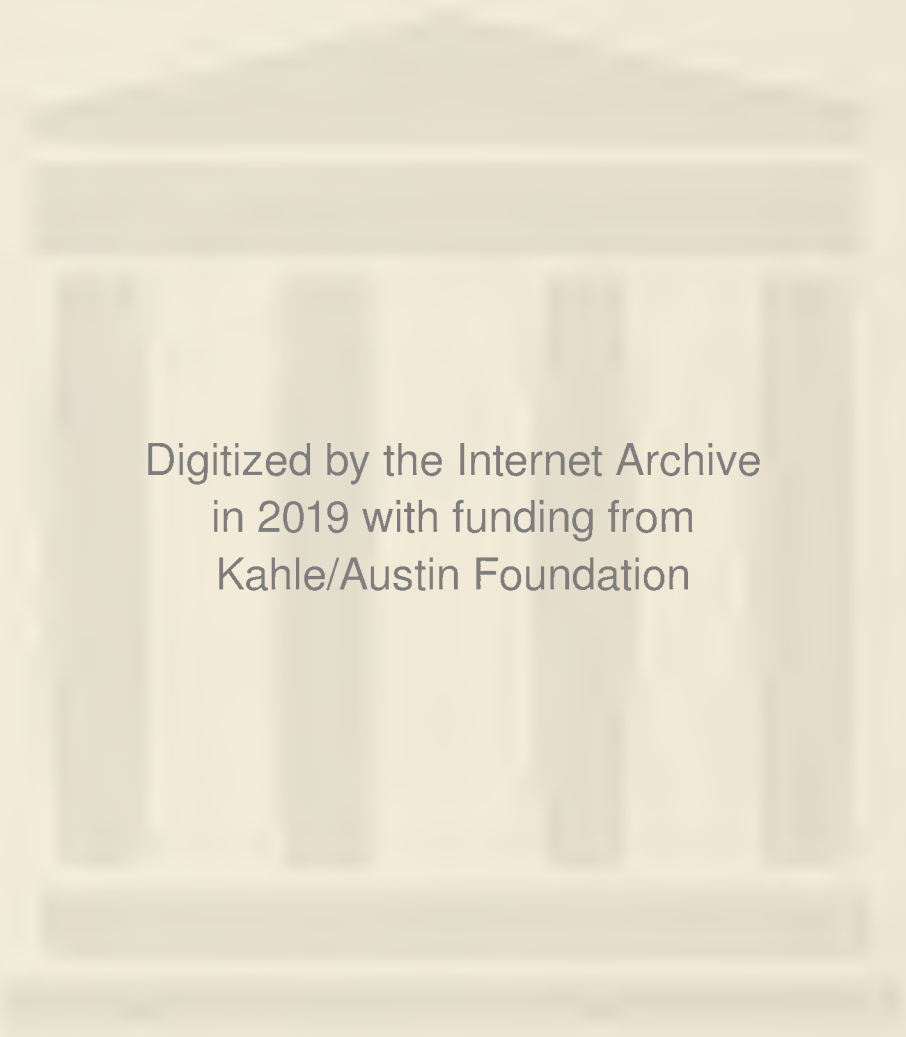

CRYSTAL CHEMICAL CLASSIFICATION OF MINERALS

Volume 2

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Volume 2

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The original one-volume Russian text, published for Naukova Dumka in Kiev in 1966, has been extensively revised and updated by the author for the present edition. The English translation is published under an agreement with Mezhdunarodnaya Kniga, the Soviet book export agency.

KRISTALLOKHIMICHESKAYA KLASSIFIKATSIYA MINERAL'NYKH VIDOV
КРИСТАЛЛОХИМИЧЕСКАЯ КЛАССИФИКАЦИЯ МИНЕРАЛЬНЫХ ВИДОВ
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Volume 2

CLASS 4. BORATES

Type III. Oxygen compounds
Class 4. Borates

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1																	H 80	
2	Li 1	Be 3											B 99	C 4	N 2	O 09	F 2	
3	Na 16	Mg 32											Al 5	Si 2	P 2	S 2	Cl 13	
4	K 3	Ca 40		Ti 2			Mn 13	Fe 7			Cu 1				As 2			
5		Sr 5												Sn 2				
6	Cs 1	Ba 1	TR 1		Ta 1													
7																		

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
		6	2			38	15	13	5	15	5

Subclass 1. Framework

1. Boracite $Mg_3[B_3B_4O_{12}]OCl^3_\infty$ group
2. Rhodizite $Cs\{Al_4(LiBe_3B_{12})O_{28}\}^3_\infty$ group
3. Metaborite $H[BO_2]^3_\infty$ group

Subclass 2. Insular

Division A. With Simple $[BO_4]$ or $[BO_3]$ Radicals

Subdivision 1. Without Water and Additional Anions

I. With $[BO_4]$ Radical

1. Behierite $Ta[BO_4]$ group
2. Sinhalite $MgAl[BO_4]$ group

II. With $[BO_3]$ Radical

1. Nordenskiöldine $CaSn[BO_3]_2$ group
2. Kotoite $Mg_3[BO_3]_2$ group

Subdivision 2. With Additional O or OH and Additional Radicals

1. Jeremejevite $Al_6[BO_3]_5(OH)_3$ group
2. Ludwigite $(Mg, Fe)_2Fe[BO_3]O_2$ group
3. Johachidolite $Na_2Ca_3Al_4[BO_3]_5(OH; F)_5$ group
4. Hambergite $Be_2[BO_3]OH$ group
5. Fluoborite $Mg_3[BO_3](OH, F)_3$ group
6. Gaudefroyite $Ca_4Mn_3[BO_3]_3[CO_3]O_3$ group

Subdivision 3. With Additional Radicals and H_2O Molecules

I. With $[B(OH)_4]$ Radical

1. Cahnite $Ca_2[AsO_4][B(OH)_4]$ group
2. Frolovite $Ca[B(OH)_4]_2$ group

II. With $[B(O, OH)_3]$ Radical

1. Wightmanite $Mg_9(H_2O)_2[BO_3]_2(OH)_{12}$ group
2. Seamanite $Mn_3(H_2O)_3[BO_3][PO_4]$ group
3. Sulfoborite $Mg_3(H_2O)_4[BO_2OH]_2[SO_4]$ group

Division B. With $[B_2(O, OH)_{5-7}]$ Double Radicals

Subdivision 1. Without Water and Additional Anions

I. With $[B_2O_5]$ Radical

1. Suanite $Mg_2[B_2O_5]$ group

Subdivision 2. With Additional OH Anions

I. With $[B_2O(OH)_6]$ Radical

1. Pinnoite $Mg[B_2O(OH)_6]$ group
2. Nifontovite $Ca[B_2O(OH)_6]$ group

II. With $[B_2O_5]$ Radical

1. Wiserite $Mn_4[B_2O_5](OH)_4$ group

III. With $[B_2O_4(OH)]$ Radical

1. Szájbelyite $Mg_2[B_2O_4OH]OH$ group
2. Roweite $CaMg[B_2O_4OH]OH$ group

IV. With $[B_2O_2(OH)_4]$ and $[B_2O_3(OH_3]$ Radicals

1. Uralborite $Ca[B_2O_2(OH)_4]$ group

Subdivision 3. With Additional Radicals and H_2O Molecules

I. With $[B_2O_5]$ Radical

1. Carboborite $Ca_2Mg(H_2O)_{10}[B_2O_5][CO_3]$ group

II. With $[B_2O(OH)_4]$ Radical

1. Lüneburgite $Mg_3(H_2O)_6[PO_4]_2[B_2O(OH)_4]$ group

Division C. With Complex $[B_mB_nO_p(OH)_q]$ Radicals

I. With $[B_2BO(OH)_5]$ Radical

1. Inderite $Mg(H_2O)_5[B_2BO_3(OH)_5]$ group
2. Kurnakovite $Mg(H_2O)_5[B_2BO_3(OH)_5]$ group

II. With $[B_2B_2O_5(OH)_4]$ Radical

1. Halurgite $Mg_2(H_2O)[B_2B_2O_5(OH)_4]_2$ group
2. Borax $Na_2(H_2O)_8[B_2B_2O_5(OH)_4]$ group

III. With $[B_2B_3O_6(OH)_5]$ Radical

1. Biringuccite $Na_2[B_2B_3O_6(OH)_5]$ group

IV. With $[BB_4O_6(OH)_4]$ Radical

1. Larderellite $NH_4[BB_4O_6(OH)_4]$ group

V. With Complex (Heterogeneous) Radicals

1. Ginorite $Ca_2(H_2O)_2[B_4O_5(OH)_4][B_5O_6(OH)_4]_2$ group

Subclass 3. Chain

Division A. With Simple Chains

I. With $[B_2O_2(OH)_4]$ Chains

1. Vimsite $Ca[B_2O_2(OH)_4]^1_\infty$ group

II. With $[B_2O_4]$ Chains

1. Calciborite $Ca[B_2O_4]^1_\infty$ group

Division B. With Complex Chains

I. With $[B_2BO_4(OH)_3]$ Chains

1. Hydroboracite $CaMg(H_2O)_3[B_2BO_4(OH)_3]_2{}^1_\infty$ group
2. Colemanite $Ca(H_2O)[B_2BO_4(OH)_3]^1_\infty$ group

II. With $[B_2B_2O_6(OH)_2]$ Chains

1. Kernite $Na_2(H_2O)_3[B_2B_2O_6(OH)_2]^1_\infty$ group

III. With $[BB_2O_4(OH)_2]$ Chains

1. Aksaite $Mg(H_2O)_3[BB_2O_4(OH)_2]_2{}^1_\infty$ group
2. Teruggite $Ca_4Mg(H_2O)_4[BB_2O_4(OH)_2]_4[AsO_4]_2{}^1_\infty$ group

IV. With $[B_4BO_7(OH)_5]$ Chains

1. Tertschite $Ca_2(H_2O)_7[B_4BO_7(OH)_5]^1_\infty$ group

V. With $[B_3B_2O_7(OH)_4]$ Chains

1. Preobrazhenskite $Mg_3(H_2O)[B_2B_2O_7(OH)_4]^1_{2\infty}$ group
2. Probertite $NaCa(H_2O)_3[B_2B_2O_7(OH)_4]^1_\infty$ group

VI. With $[B_2B_3O_7(OH)_3]$ Chains

1. Ezcurrite $Na_2(H_2O)_2[B_2B_3O_7(OH)_3]^1_\infty$

VII. With $[B_3B_3O_8(OH)_5]$ Chains

1. Kaliborite $KHMg_2(H_2O)_4[B_3B_3O_8(OH)_5]^1_{2\infty}$ group

Subclass 4. Layer

Division A. With Layers of $[B(O, OH)_4]$ Tetrahedra

1. Garrelsite $Ba_2[B_3SiO_7(OH)_3]^2_\infty$ group

Division B. With Layers of $[BO_3]$ Triangles

1. Sassolite $H_3[BO_3]^2_\infty$ group

Division C. With Layers of $[B(O, OH)_4]$ Tetrahedra and $[B(O, OH)_3]$ Triangles

1. Fabianite $Ca[B_2BO_5(OH)]^2_\infty$ group
2. Tunellite $Sr(H_2O)_3[B_3B_3O_9(OH)_2]^2_\infty$ group
3. Hilgardite $Ca_2[B_3B_2O_8(OH)_2]Cl^2_\infty$ group
4. Veatchite $Sr_2(H_2O)[B_2B_3O_8(OH)_2][B(OH)_3]^2_\infty$ group
5. Howlite $Ca_2(H_2O)[B_5SiO_{10}(OH)_3]^2_\infty$ group

Division D. With Layers of $[B(OH)_4]$ Tetrahedra and Other Atoms

1. Bandylite $Cu[B(OH)_4]Cl^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Framework

1. BORACITE GROUP. Cubic → orth.

α-Boracite subgroup. Cubic, $T_d^5 - F\bar{4}3c$, $Z = 8$

			a	Transformation temperature, °C
β-Boracite	(cuboborocite)	$Mg_3[B_3B_4O_{12}]OCl^3_\infty$	12.10	265
β-Ericoite	(cuboericoite)	$Fe_3[B_3B_4O_{12}]OCl^3_\infty$	12.18	312
β-Chombersite	(cubochombersite)	$Mn_3[B_3B_4O_{12}]OCl^3_\infty$	12.25	407

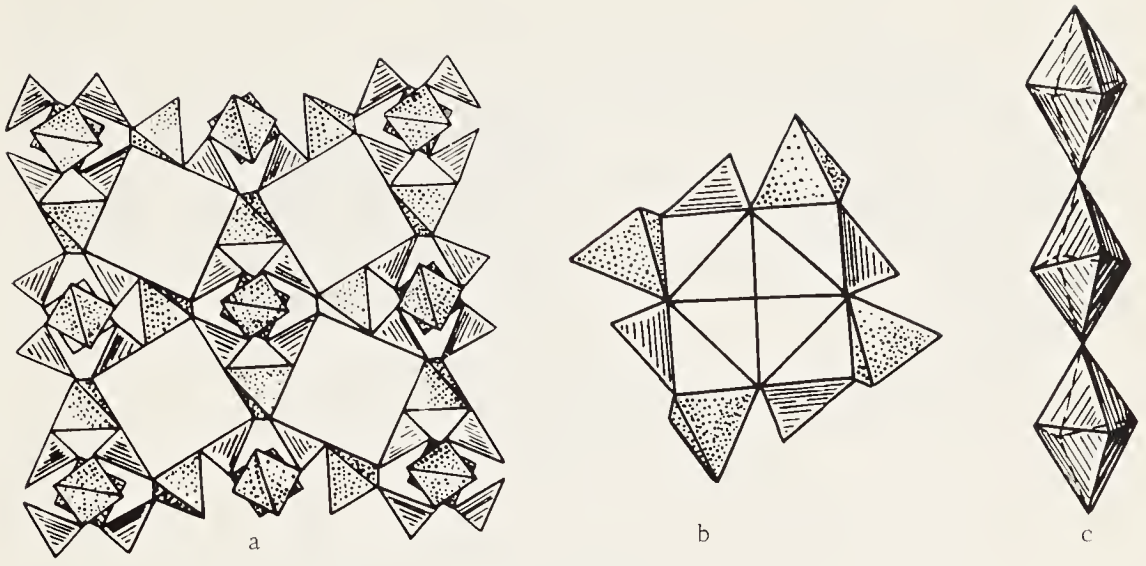


Fig. 212. Structure of boracite: a) framework of B—O triangles and tetrahedra, b) position of Mg octahedron in square section of the framework, c) chain of distorted Mg octahedra.

Str. A framework consisting of regular BO_4 tetrahedra and BO_3 triangles (ratio 3:4) with large square holes (Fig. 212a). The divalent atoms are in distorted sixfold coordination and lie in holes linked into chains (Fig. 212c). At the vertices of octahedra in these chains lie Cl atoms, each of which lies at the vertices of six octahedra, because three such chains mutually intersect in the holes. The other four coordinating atoms are oxygen, being in common with the O in the B—O unit (Fig. 212b). Interatomic distances in β-boracite: $B-O_4 = 1.48$; $B-O_3 = 1.39$; $Mg-O_4Cl_2 = 2.04$ and 3.02 (Ito et al., 1951 [264]). Mainly the low-temperature species occur in nature; the cubic crystals of boracite are pseudomorphs after α-boracite.

Boracite subgroup. Orth. (pseudotetr.), $C_{2v}^5 - Pca2_1$, Z = 4

		a	*b*	*c*	*ρ*	H
Boracite	$Mg_3[B_3B_4O_{12}]OCl$ $^3_\infty$	8.54	8.54	12.07	2.93	7—7.5
Ericaite	$Fe_3[B_3B_4O_{12}]OCl$ $^3_\infty$	8.58	8.65	12.17	3.3(?)	(7)
Chambersite	$Mn_3[B_3B_4O_{12}]OCl$ $^3_\infty$	8.68	8.68	12.26	3.5	7—7.25

Str. Only slightly different from that of the high-temperature species (orthorhombic homology); stable at normal temperature. Interatomic distances vary only in the Mg (or Fe or Mn) polyhedra.

Chem. Variable. The Mg in boracite is replaced by Fe (≤36%), while ericaite contains Mg (≤6.7%) and Mn (≤2.3%), and chambersite contains Fe (≤2%).

Var. Fe-boracite, Mg-ericaite, Mn-ericaite, Fe-chambersite.

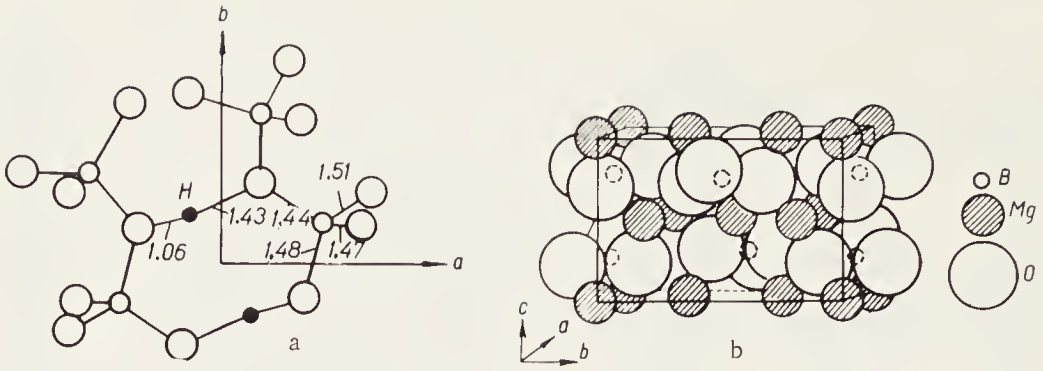


Fig. 213. Structures of metaborite and kotoite: a) bonds in metaborite framework, b) general view of packing in kotoite.

2. RHODIZITE GROUP. Cubic, $T_d^1 - P\bar{4}3m$, $Z = 1$

		a	ρ	H
Rhodizite	$Cs\{Al_4(LiBe_3B_{12})O_{28}\}^3_\infty$	7.32	3.4	8

Str. Subframework (Buerger, 1966 [839]), with Al in sixfold coordination forming isolated Al_4O_{16} groups, which are linked by Li, Be, and B in fourfold coordination. The Cs atoms lie in large holes. The mean interatomic distances are: $Cs-O_{12} = 3.24$; $Al-O_6 = 1.91$: $Be-O_4 = 1.63$; $B-O_4 = 1.48(2)$ and $1.50(2)$[1147].

Chem. Composition very variable (Palache et al., 1944 [140]; Frondel and Ito, 1965 [840]). Cs is replaced by K, Rb, and Na to a considerable extent. The Li content varies from 7.2% to 0.7%. The Be and B contents also vary substantially, probably from replacement of Li.

Phys. Imperfect cleavage on (111).

3. METABORITE GROUP. Cubic, $T_d^4 - P\bar{4}3n$, $Z = 24$

		a	ρ	H
Metaborite	$H[BO_2]^3_\infty$	8.89	2.47	5.5

Str. The proton makes this structure very unusual. The BO_4 tetrahedra are linked by common vertices into a framework, but the H atoms lie between the nearest O atoms of adjacent tetrahedra to balance the valencies, so oxygen has CN = 3 (two Si + one H) (Fig. 213a). The proton does not lie half-way between the two O atoms (O–O = 2.49) but at distances of 1.06 and 1.13, so the B–O distances in each tetrahedron differ in pairs, being on average 1.45 and 1.49 (Zachariasen, 1963 [265]).

Chem. Composition constant. Observed in halite (Lobanova and Avrova, 1964 [266]).

Phys. Isometric, imperfect cleavage on (100).

Subclass 2. Insular

DIVISION A. WITH SIMPLE $[BO_4]$ OR $[BO_3]$ RADICALS

Subdivision 1. Without Water or Additional Anions

I. With $[BO_4]$ Radical

1. BEHIERITE GROUP. Tetr., $D_{4h}^{19} - I4_1/amd$, $Z = 4$

		a	c	ρ	H
Behierite (tanbarite)	$Ta[BO_4]$	6.21	5.47	7.9	7.5—8

Str. Zircon type, CN = 8/4 (Fig. 166).

Chem. Composition known from x-ray spectra; about 5% of Ta replaced by Nb [269].

Phys. Isometric, pseudooctahedral, moderate cleavage on (110) and (010).

2. SINHALITE GROUP. Orth., $D_{2h}^{16} - Pnma$, $Z = 4$

		a	b	c	ρ	H
Sinhalite (magalbarite)	$MgAl[BO_4]$	4.33	9.88	5.67	3.5	7—7.5

Str. Isostructural with olivine and chrysoberyl (Figs. 103 and 169a). Mg and Al have CN = 6, while B forms a slightly distorted tetrahedron. Interatomic distances: $Mg-O_6 = 2.12$ (2), 204 (3), and 2.21; $Al-O_6 = 1.85$ (2), 1.88 (2), 1.97 (2); $B-O_4 = 1.46$ (3) and 1.58 (Fang and Newnham, 1965 [841]).

Chem. Mg and Al partly replaced by Fe^{2+} and Fe^{3+}.

Phys. Isometric, cleavage imperfect.

II. With $[BO_3]$ Radical

1. NORDENSKIÖLDINE GROUP. Trig., $C_{3i}^2 - R\bar{3}$, $Z = 1; 3$

		a_{rh}	α	a_h	c_h	ρ	H
Nordenskiöldine	$CaSn[BO_3]_2$	6.01	47°42′	4.86	15.95	4.2	6—6.5

Str. Isostructural with dolomite (Fig. 58); Ca and Sn have CN = 6.

Phys. Thick plates, perfect (0001) cleavage.

2. KOTOITE GROUP. Orth., $D_{2h}^{12} - Pnnm$, $Z = 2$

		a	b	c	ρ	H
Kotoite	$Mg_3[BO_3]_2$	4.51	8.42	5.40	3.1	6.5
Jimboite	$Mn_3[BO_3]_2$	4.66	8.74	5.67	4.0	6

Str. Generally similar to that of olivine (Figs. 169a and 213b), with almost regular BO_3 triangles and MgO_6 octahedra; mean distances in kotoite $Mg_1-O_6 = 2.03$ and $Mg_2-O_6 = 2.09$, $B-O_3 = 1.38$; in jimboite $Mn_1-O_6 = 2.12$, $Mn_2-O_6 = 2.22$, $B-O_3 = 1.44$ (Sadanaga, 1948 [271]; Sadanaga et al., 1965 [842]).

Chem. Kotoite contains a little Fe (≤2.1%); jimboite has Mn replaced isomorphously by Mg (≤3.3%) and Fe (≤1.6%).

Phys. Isometric crystals (granular masses), perfect cleavage on (011), parting on (101).

Subdivision 2. With Additional O or OH and Additional Radicals

I. With $[BO_4]$ Radical

None

II. With $[BO_3]$ Radical

1. JEREMEJEVITE GROUP. Hex., $C_{6h}^2 - P6_3/m$, $Z = 2$

		a	c	ρ	H
Jeremejevite	$Al_6[BO_3]_5(OH)_3$	8.56	8.18	3.3	7—7.5

Str. $Al(O, OH)_6$ octahedra placed on horizontal edges, which serve to link them along the c axis into pairs (Fig. 214b). The inclined edges of

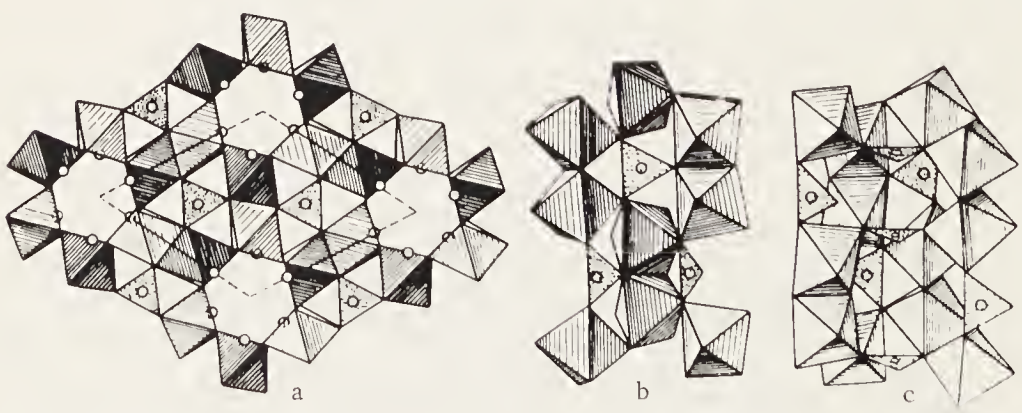


Fig. 214. Structure of jeremejevite: a) projection on (001), the circles being boron atoms in triangles lying in plane of drawing and normal to it, b) and c) vertical projections.

these pairs join them into zigzag chains (Fig. 214c), which are linked together via common OH vertices and via BO_3 radicals. There are two types of through hole, hexagonal and trigonal (Fig. 214a); the first contain the BO_3 triangles, which are vertical (parallel to a side of the hexagon), while the second contain BO_3 triangles lying horizontally (ratio of vertical to horizontal triangles 3:2). Interatomic distances: Al—O = 1.90; Al—OH = 1.79; B—O_3 = 1.38 (Golovastikov et al., 1956 [272]).

Chem. Al partly (≤4%) replaced by Fe.

Phys. Columnar, parting on (0001).

2. LUDWIGITE GROUP. Orth.→mon.

	S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Warwickite $Mg_3Ti[BO_3]_2O_2$	D_{2h}^{16} — *Pnma*	9.20	3.01	9.45	2	3.3	6.5
Ludwigite $(Mg, Fe)_2Fe^{3+}[BO_3]O_2$	D_{2h}^{9} — *Pcma*	9.23—9.44	3.02—3.07	12.16—12.28	4	3.6—4.7	6—5.5
Orthopinokiolite $Mg_3MnMn_2^{3+}[BO_3]_2O_4$	D_{2h}^{12} — *Pnnm*	18.45	6.07	12.70	8	3.9	6
Pinokiolite $Mg_3MnMn_2^{3+}[BO_3]_2O_4$	C_{2h}^{2} — $P2_1/m$	5.36	5.98	12.73 $\beta = 120°34'$	2	3.9	6
Hulsite $Fe_3Fe^{3+}Sn[BO_3]_2O_3OH$	C_2^1 — *P*2	10.68	3.10	5.44 $\beta = 94°09'$	1	4.5	(6)
Azoproite $Mg_7Fe_2^{3+}Ti_2[BO_3]_4O_8$	D_{2h}^{9} — *Pcma*	9.26	3.10	12.25	1	3.6	6

Str. All are similar (Fig. 215, a-f). Mg, Ti, Fe^{3+}, and Mn^{3+} has octahedral coordination, the octahedra being linked via horizontal edges into columns along the b axis (parameter 3.01-3.05) and at an angle to the c axis, and also via common vertices. Warwickite and ludwigite have fourfold and five fold columns, while pinakiolite has infinite ones, as in seidozerite (Fig. 178). The tirgonal channels between the octahedra contain the BO_3 triangles, which bind the structure together. All BO_3 triangles lie in the (010) plane with one side strictly parallel to the c axis (which corresponds to the needle habit). The corresponding interatomic distances vary somewhat. The BO_3 triangles are rather distorted, which points to stress in the structure. The mean distances for warwickite, ludwigite, and pinakiolite respectively are: B—O_3 = 1.37, 1.43, and 1.41; Mg—O_6 = 2.08, 2.08, and 2.04; Fe^{3+}—O_6 = 2.10; Mn^{3+}—O_6 = 2.08 (Takeuchi et al., 1950 [843]).

Chem. Variable; perfect Mg—Fe isomorphism in ludwigite, so we have the subspecies magnesioludwigite and ferroludwigite. In addition, the Fe^{3+} in ludwigite is replaced by Al (≤11%), while Mg in warwickite is replaced by Fe^{2+} (≤9%) and Ti by Fe^{3+} (4.8%) and Al (3%). The Mn^{3+}

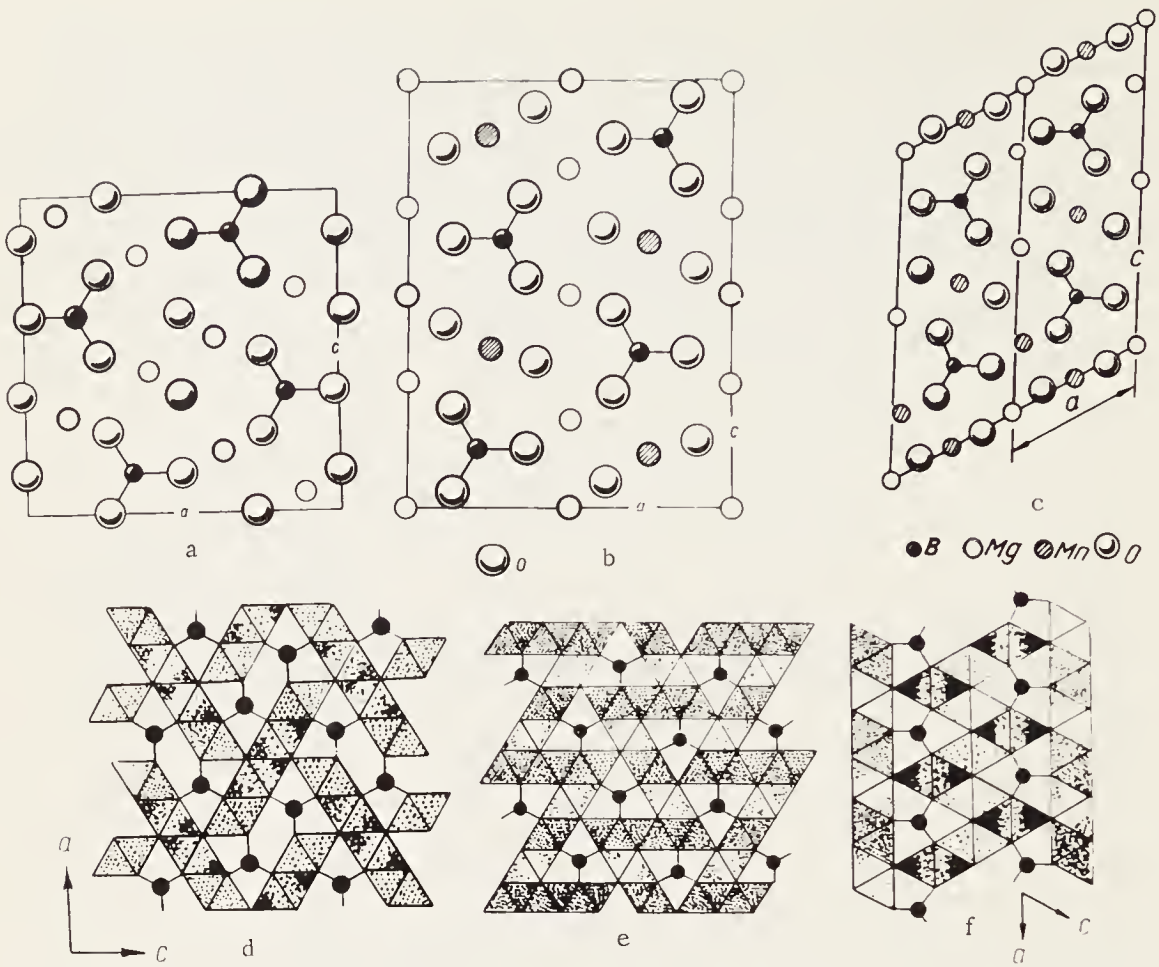


Fig. 215. Structure of a) warwickite, b) ludwigite, c) pinakiolite in projection on (010); the same structures in polyhedral representation: d) warwickite, e) ludwigite, f) pinakiolite.

in orthopinakiolite is replaced by Fe^{3+} (10.5%) and the Mn^{2+} by Ca and Pb ($\leq$1.3%). Pinakiolite shows similar but more restricted replacement. Azoproite shows essential isomorphism between Mg, Fe^{2+}, Fe^{3+} and Ti [1307].

Var. Al-magnesioludwigite, Fe^{2+}-warwickite, Fe^{3+}-warwickite.

Phys. Columnar, platy, acicular to fibrous; warwickite has perfect (100) cleavage, but none is observed in ludwigite; orthopinakiolite has perfect (001) cleavage.

3. JOHACHIDOLITE GROUP. Orth. (?)

		a	*b*	*c*	ρ	H
Johachidolite	$Na_2Ca_8Al_4[BO_3]_5(OH; F)_5$	—	—	—	3.4	6.5—7

Str. Not known. The formula $Na_2Ca_3Al_4[B_2O_5]_{2.5}(OH;F)_{10}$ [1322] is also possible.

Phys. Isometric (and platy?).

4. HAMBERGITE GROUP. Orth. →trig., $Z = 4$; 1

			a	b	c	ρ	H
Hambergite	$Be_2[BO_3]OH$	$D_{2h}^{15} - Pbca$	9.75	12.20	4.43	2.36,	6.5—7
Berborite	$Be_2[BO_3]OH \cdot H_2O$	D_3^2—$P321$ (?)	4.43	.-	5.33	2.20	(3.5—4)

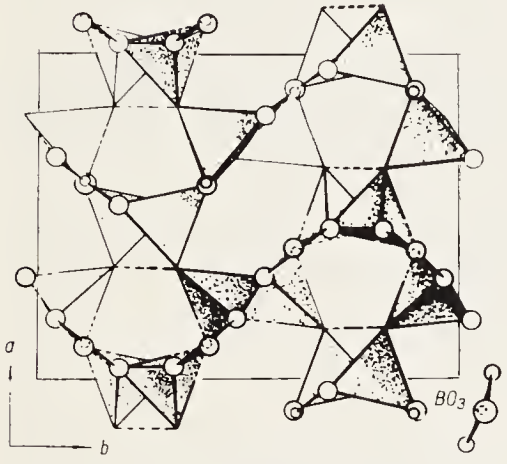


Fig. 216. Structure of hambergite in polyhedra.

Str. Subframework; BeO_3OH tetrahedra and BO_3 triangles are joined by common vertices, with each O atom in a BO_3 triangle common to two BeO_3OH tetrahedra, while two adjacent Be tetrahedra are linked via common OH (Fig. 216). Interatomic distances: $B-O_3 = 1.36$, 1.37, and 1.37; $Be_I-O_3OH = 1.63$, 1.67, 1.62, and 1.62; $Be_{II}-O_3OH = 1.64$, 1.61, 1.64, and 1.63. The hydroxyl is split by the Be into H—O and lies between two adjacent O at distances of 0.93 and 2.04 (Zacharia-sen et a., 1963 [844]).

Var. F-hambergite (≤6% F), F-berborite [1308].

Phys. Columnar, perfect (010) cleavage, (100) moderate. Berborite has perfect (0001) cleavage.

5. FLUOBORITE GROUP. Hex., $C_{6h}^2 - P6_3/m$, $Z = 2$

		a	c	ρ	H
Fluoborite	$Mg_3[BO_3](OH, F)_3$	9.06—8.86	3.06—3.13	2.85—2.98	4

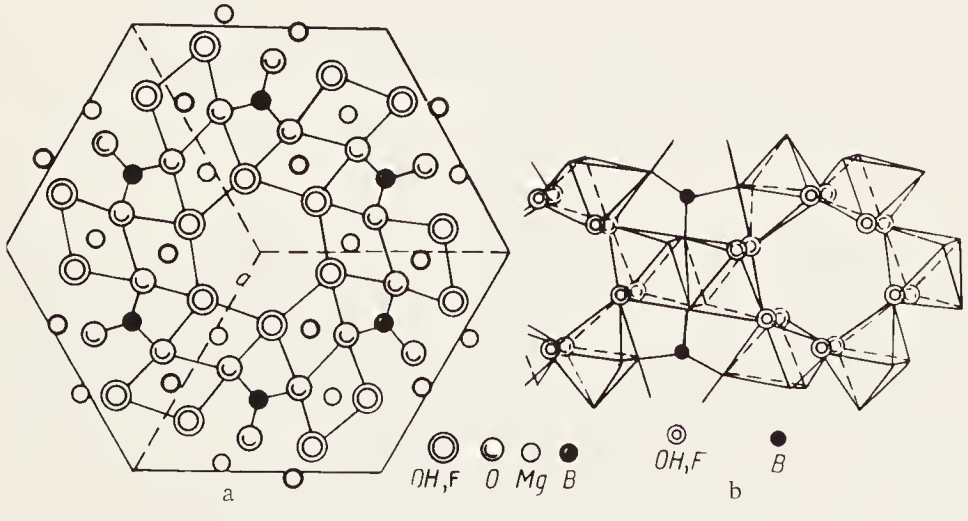


Fig. 217. Structure of fluoborite: a) basal projection, b) disposition and links of Mg octahedra.

Str. Rings of six $MgO_3(OH, F)_3$ octahedra in the (0001) plane linked by O–OH edges to form hexagonal tubes along the c axis (Fig. 217a). The tubes adjoin on O–O edges to adjacent octahedra (Fig. 217b) to leave triangular channels, in which the BO_3 triangles lie parallel to (0001) (the O atoms in BO_3 are common also to two octahedra). Interatomic distances: $B–O_3 = 1.50$ (3); $Mg–O_3(OH, F)_3 = 1.99$ (2) and 2.33, 2.03 and 2.33 (2) (Takeuchi, 1950 [845]).

Chem. Perfect OH–F isomorphism, so we have the subspecies hydroxylfluoborite and fluorfluoborite. Mg is replaced to a small extent by Zn, Mn, and Fe.

Phys. Needles (on c axis), imperfect (0001) cleavage.

6. GAUDEFROYITE GROUP. Hex. → mon., $Z = 2$

		S.g	a	b	c	ρ	H
Gaudefroyite	$Ca_4Mn_3[BO_3]_3[CO_3]O_3$	$C_{6h}^2 - P6_3/m$ (?)	10.6	—	5.90	3.3	6.5–6.75

Str. In gaudefroyite BO_3 and CO_3 triangles are combined with Ca and Mn polyhedra, forming typical insular structure [1310].

Chem. Composition is constant, but some Mn^{3+} is oxidized to Mn^{4+} [1311].

Phys. Gaudefroyite columnar, moderate cleavage on prism.

Subdivision 3. With Additional Radicals and H_2O Molecules

I. With $[B(OH)_4]^{1-}$ Radical

1. CAHNITE GROUP. Tetr., $S_4^2 - I\bar{4}$, $Z = 2$

		a	c	ρ	H
Cahnite	$Ca_2[AsO_4][B(OH)_4]$	7.11	6.20	3.2	3.5

Str. Formally identical with that of zircon, with As and B in place of Si and Ca in place of Zr (Fig. 218a); but the hydroxyl-hydrogen bonds make it better to consider the structure as derived from that of KH_2AsO_4. Interatomic distances: $As–O_4 = 1.68$; $B–(OH)_4 = 1.47$; $Ca–O_8 = 2.14$ (4) and 2.54 (4) (Prewitt and Buerger, 1961 [846]).

Chem. Composition constant, Ca partly replaced by Pb and Zn.

Phys. Isometric, perfect cleavage on (110).

2. FROLOVITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 2$

		a	b	c	ρ	H	Cl.
Frolovite	$Ca[B(OH)_4]_2$	7.80	5.70	7.95	2.14	3.5—4	None (?)
		$\alpha = 71°30'$		$\beta = 101°30'$	$\gamma = 72°$		
Pentahydroborite (calchydroborite)	$Ca(H_2O)[B(OH)_4]_2$	7.90	6.62	8.09	2.00	3	None (?)
		$\alpha = 68°30'$		$\beta = 111°$	$\gamma = 74°$		

Str. Not known; formulas written from a detailed study of $Ca(H_2O)_2 \cdot [B(OH)_4]_2$ (Kravchenko, 1964 [275]). Parameters of frolovite identical with those of β-$Ca[B(OH)_4]_2$ (Zeigan, 1966 [847]).

Phys. Morphology not adequately studied (Petrova, 1957 [273]; Malinko, 1961 [274]); frolovite from Siberia forms fibrous and foliated aggregates (Lisitsyn et al., 1965 [848]).

II. With $[BO_3]^{3-}$ or $[BO_2OH]^{2-}$ Radicals

1. WIGHTMANITE GROUP. Tricl. (pseudohex.), $C_i^1 - P\bar{1}$, $Z = 1$

		a	b	c	ρ	H
Wightmanite (Maghydroxyborite)	$Mg_9(H_2O)_2[BO_3]_2(OH)_{12}$	11.73	11.44	3.09	2.60	5.5
		$\alpha = 96°09'$	$\beta = 97°45'$	$\gamma = 105°52'$		

Str. Not known.

Phys. Columnar, perfect (010) cleavage, moderate (100).

2. SEAMANITE GROUP. orth.→cubic, $Z = 4$

		S.g.	a	b	c	ρ	H
Seamanite	$Mn_3(H_2O)_3[BO_3][PO_4]$	$D_{2h}^{16} - Pbnm$	7.85	15.17	6.72	3.1	4
Sakhaite	$Ca_{12}Mg_4(H_2O)[BO_3]_7[CO_3]_4(OH)_2Cl$	O_h^5—$Fm3m$(?)	14.64	—	—	2.80	5-5.5

Str. Not known, but sakhaite is very similar to harkerite in structure [1312].

Chem. Composition constant; Mn replaced to a small extent by Ca, Mg, and Fe.

Phys. Seamanite columnar, moderate (001) cleavage. Sakhaite isometric (octahedra), no cleavage (Ostrovskaya et al., 1966 [849]).

3. SULFOBORITE GROUP. Orth., $D_{2h}^{16} - Pcmn$, $Z = 4$

		a	b	c	ρ	H
Sulfoborite	$Mg_3(H_2O)_4[BO_2OH]_2[SO_4]$	7.79	12.54	10.14	2.44	4—4.5

Str. Not known. Thermal analysis (Braitsch, 1961 [850]) indicates BO_2OH as the probable structure of the radical. According to the infrared absorption spectra data, B has fourfold coordination and the formula is: $Mg_3[B(OH)_4]_2[SO_4](OH)_2$[1139].

Chem. Composition constant.

Phys. Columnar to thick plates, perfect (110) cleavage, moderate (001).

DIVISION B. WITH $[B_2(O,OH)_{5-7}]$ DOUBLE RADICALS

Subdivision 1. Without Water and Additional Anions

I. With $[B_2O_5]^{4-}$ Radical

1. SUANITE GROUP. Mon.→orth., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Suanite	$Mg_2[B_2O_5]$	$C_{2h}^5 - P2_1/a$	12.10	3.12	9.36	104°20′	2.91	6
Kurchatovite	$Ca_6Mg_5Mn[B_2O_5]_6$	D_2^3—$P2_12_12$	11.15	36.4	5.55	—	3.03	5

Str. Suanite has MgO_6 octahedra linked via common edges into chains along b axis, which are cross-linked by B_2O_5 radicals (Fig. 218a); the six O atoms of the Mg octahedron belong simultaneously to five B_2O_5 radicals (Takeuchi, 1952 [277]).

Chem. Mg in suanite partly replaced by Ca (≤5%), in kurchatovite by Fe (1.5%).

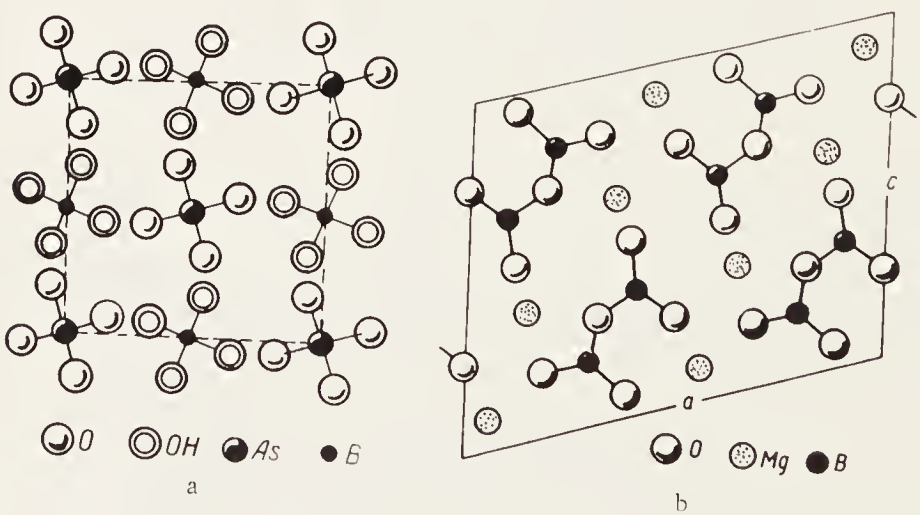


Fig. 218. Structure of: a) cahnite in projection on (001), b) suanite in projection on (010).

Phys. Acicular and fibrous (on b axis), no cleavage in suanite, perfect cleavage perpendicular to length in kurchatovite [1119].

Subdivision 2. With Additional OH Anions

I. With $[B_2O(OH)_6]^{2-}$ Radical (Paired $BO(OH)_3$ Tetrahedra)

1. PINNOITE GROUP. Tetr., $C_4^3 - P4_2$ or $C_{4h}^2 - P4_2/m$, $Z = 4$

		a	*c*	ρ	H
Pinnoite	$Mg[B_2O(OH)_6]$	7.62	8.19	2.27	3.75

Str. The elements are paired $BO(OH)_3$ tetrahedra and $Mg(OH)_6$ octahedra, the OH groups being common to the Mg and B polyhedra.

Octahedra joined to tetrahedra extend along the c axis and form a tubular backbone. Interatomic distances: $Mg-(OH)_6 = 2.06$ (2), 2.04 (2), and 2.12 (2); $B-O(OH)_3 = 1.46$, 1.54, 1.42, and 1.56 (Paton and McDonald, 1957 [278]). Krogh-Moe (1967 [851]) gives space group $C_{4h}^4 - P4_2/n$.

Chem. Composition constant.

Phys. Columnar to acicular and fibrous, no cleavage.

2. NIFONTOVITE GROUP. Mon.

		a	*b*	*c*	β	ρ	H	Cl.
Nifontovite	$Ca[B_2O(OH)_6]$ (?)	13.09	9.49	13.53	119°30′	2.36	3.5—4	Imperf. in 1 dir.

Str. Not known; formula needs fresh data (Malinko and Lisitsyn, 1961 [280]).

II. With $[B_2O_5]^{4-}$ Radical

1. WISERITE GROUP. Tetr., s.g. not det., $Z = 4$

		a	*c*	ρ	H
Wiserite	$Mn_4[B_2O_5](OH)_4$	14.30	3.32	3.4	(5)

Str. Not known.

Chem. Mn replaced by Ca (3.2%) and Mg (3.0%). OH replaced by Cl (3%).

Phys. Acicular to fibrous (on c axis), perfect cleavage perpendicular to length.

III. With $[B_2O_4OH]^{3-}$ Radical (Paired BO_3 and BO_2OH Triangles)

1. SZAIBELYITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, $Z = 4$

		a	*b*	*c*	β	ρ	H
Szaibelyite	$Mg_2[B_2O_4OH]OH$	12.50	10.42	3.14	95°40′	2.62	5—5.5
Sussexite	$Mn_2[B_2O_4OH]OH$	12.77	10.70	3.25	?	3.3	4.5—5

Str. Known for szaibelyite; paired BO_3 triangles (as in suanite), but with one O replaced by OH. Mg has an octahedral environment of O and OH; the $Mg(O, OH)_6$ octahedra are joined via common edges into columns along the c axis, and these are linked via the B radicals (Peng Chih-chung, Wu Ch'eng-yüe, and Chang P'i-hsing, 1963 [279]).

Chem. Variable, Mn replaced to a considerable extent by Mg (up to Mg:Mn = 2.2:1), but with considerable gap in the Mg region (Palache et al., 1951 [154]), so these species cannot be combined into one. Then Mg in szaibelyite is replaced by Mn (≤23.5%) and Fe (≤1.5%), while Mn in sussexite is replaced by Mg (≤16.3%), Zn (≤3.9%), and Ca (≤2%).

Var. Mn-szaibelyite, Mg-sussexite, Zn-sussexite, Ca-sussexite.

Phys. Columnar, acicular, elongated on c axis; (110) cleavage perfect, (100), (010), and (001) imperfect. Hardness of fibrous szaibelyite 3.5–4; hardness of individual crystals about 5.5.

2. ROWEITE GROUP. Orth., s.g. not det., $Z = 4$

		a	*b*	*c*	ρ	H
Roweite	$CaMn[B_2O_4OH]OH$	8.29	9.03	6.63	2.92	4.5—5
Sibirskite	$Ca_2[B_2O_4OH]OH$	—	—	—	(2.7)	(4.5)

Str. Not known; formulas written by analogy with szájbelyite.

Chem. Mn in roweite replaced by Zn (≤3.2%) and Mg (≤1.7%); sibirskite contains a little Mg (?) [281].

Phys. Roweite forms laths (elongated on c axis), (101) cleavage imperfect. Sibirskite not examined.

IV. With $[B_2O_2(OH)_4]^{2-}$ and $[B_2O_3(OH)_3]^{3-}$ Radicals

(Groups of $B(O,OH)_4$ Tetrahedra)

1. URALBORITE GROUP. Mon.

			a	*b*	*c*	β	*Z*	ρ	H
Uralborite	$Ca[B_2O_2(OH)_4]$	$C_{2h}^5 - P2_1/n$	6.92	12.35	9.80	83°	8	2.60	4
Borcarite	$Ca_4Mg[B_2O_3(OH)_3]_2[CO_3]_2$	$C_{2h}^3 - C2/m$	17.81	8.36	4.46	102°	2	2.77	(4.5—5)

Str. In uralborite B(O,OH) tetrahedra are connected by O vertices in $B_4O_4(OH)_8$ groups, which are joined with Ca polyhedra (CN = 8), forming layers. The interatomic distances: $B-(O,OH)_4$ = 1.41-1.51; $Ca-(O,OH)_8$ = 2.38-2.68 (Shashkin et al., 1969 [1133]). In borcarite the B atoms in four-fold coordination give rings of $B_4O_6(OH)_6$ composition which are connected with Mg octahedra, Ca polyhedra (CN = 7), and CO_3 triangles. The interatomic distances: $Ca-(O,OH)_7$ = 2.36-2.51; $Mg-O_6$ = 1.99(2), 2.11(4); $B-(O,OH)_4$ = 1.48; $C-O_3$ = 1.27 and 1.29(2) (Bakakin and Solov'eva, 1968 [1134]).

Chem. Composition constant.

Phys. Uralborite without cleavage; perfect (100) and (110) cleavage in borcarite.

Subdivision 3. With Additional Radicals and H_2O Molecules

I. With $[B_2O_5]^{4-}$ *Radical*

1. CARBOBORITE GROUP. Mon., s.g. not det., $Z = 4$

		a	b	c	β	ρ	H
Corboborite	$Ca_2Mg(H_2O)_{10}[B_2O_5][CO_3]$	11.32	6.68	18.59	89°	2.12	2

Str. Not known.

Chem. Composition constant, Ca replaced by Na (0.3%) [1391].

Phys. Isometric, no cleavage.

II. With $[B_2O(OH)_4]$ *Radical (Paired* $BO(OH)_2$ *Triangles)*

1. LUNEBURGITE GROUP. Mon. (pseudohex.), $C_{2h}^3 - A2/m$ or $C_2^3 - A2$, $Z = 2$

		a	b	c	β	ρ	H
Luneburgite	$Mg_3(H_2O)_6[PO_4]_2[B_2O(OH)_4]$	9.81	7.62	10.10	97°24′	2.05	—

Str. Not known; the $[BO_2(OH)_4]$ radical requires confirmation (Braitsch, 1961 [850]). According to the infrared absorption spectra data, the formula $Mg_3(H_2O)_5[B_2O(OH)_6][P_2O_7]$ [1135] is possible.

Chem. Composition constant; traces of Ca and F.

Phys. Platy to tabular, imperfect cleavage on (011) and $(01\bar{1})$.

DIVISION C. WITH COMPLEX $[B_mB_nO_p(OH)_q]$ RADICALS

I. With $[B_2BO_3(OH)_5]^{2-}$ Radical (2□ and 1△)

1. INDERITE GROUP. Mon., $Z = 4$

	S.g	*a*	*b*	*c*	β	ρ	H
Inderite $Mg(H_2O)_5[B_2BO_3(OH)_5]$	$C_{2h}^5 - P2_1/a$	12.12	13.18	6.83	104°49′	1.80	3.5
Inderborite $CaMg(H_2O)_6[B_2BO_3(OH)_5]_2$	$C_{2h}^6 - C2/c$	12.15	7.46	19.05	90°45′	1.93	3—3.5
Inyoite $Ca(H_2O)_4[B_2BO_3(OH)_5]$	$C_{2h}^5 - P2_1/a$	10.63	12.06	8.41	114°02′	1.88	2.5—3

Str. Studied as follows: inderite (Rumanova and Ashirov, 1963 [260]), inyoite (Clark, 1959 [852]), and inderborite (Kurkutova et al., 1965 [853]). Complex radicals consisting of two $BO_2(OH)_2$ tetrahedra and one BO_2OH triangle (Fig. 51f), which are linked via Mg or Ca and hydroxyl-hydrogen bonds (d = 2.61-2.96). The Mg in inderite is surrounded by two OH and four H_2O, with additional buffer water (Fig. 219). Mg has four OH and two H_2O in inderborite, while Ca has CN = 8 (Thomson cube with pseudosquare ends), the vertices being two O + four OH + two H_2O. Columns parallel to the c axis consist of alternating Mg octahedra and Ca polyhedra linked by insular $[B_2BO_3(OH)_5]^{2-}$ radicals (Fig. 220a). To both sides of each column project B triangles, whose free OH vertices link to Ca polyhedra in adjacent columns to form a layer parallel to (100) (Fig. 220b). These layers are linked along the a axis only by hydroxyl-hydrogen bonds and via buffer water molecules (Fig. 220a). The Ca in

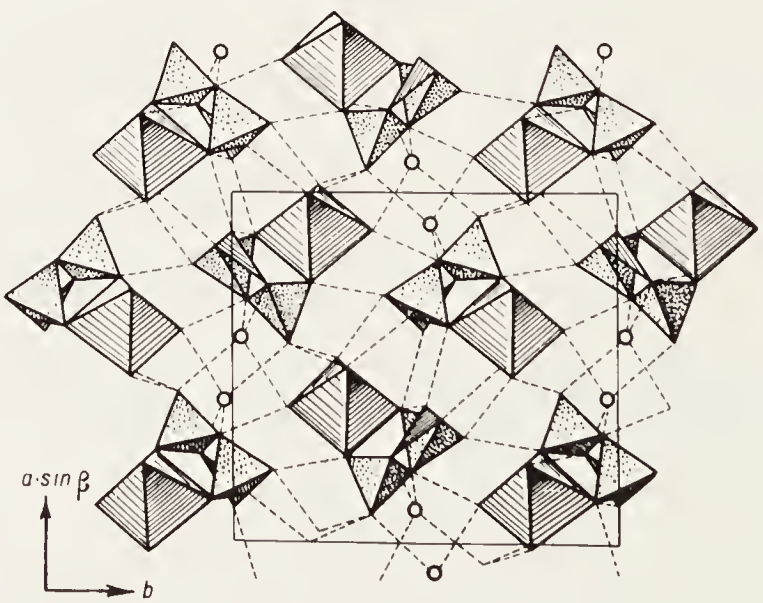


Fig. 219. Structure of inderite in projection on (001), buffer water shown by open circles.

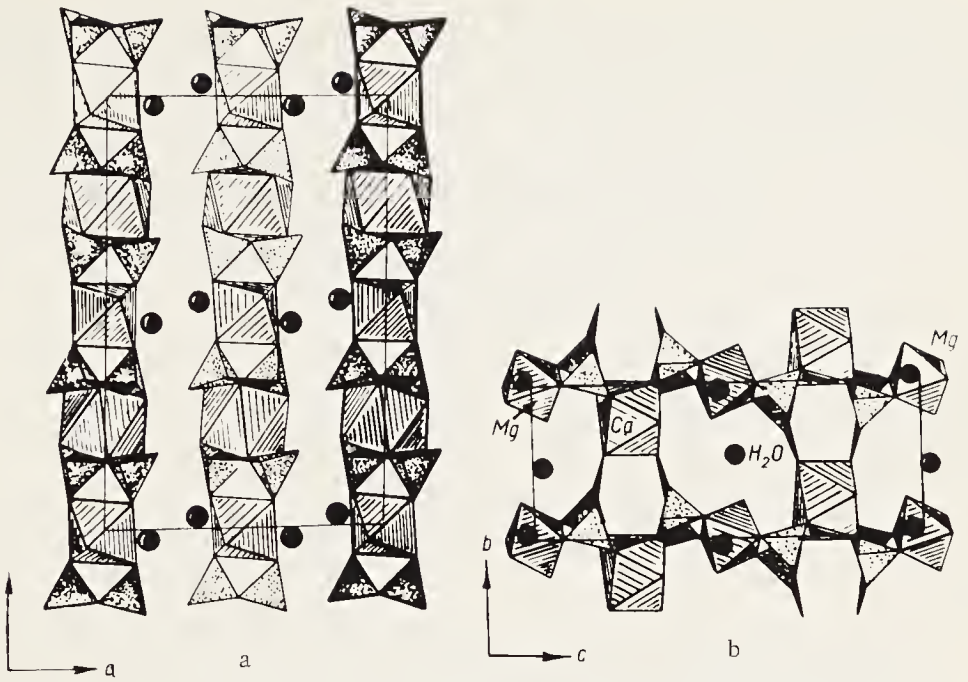


Fig. 220. Structure of inderborite: a) projection on (010) showing mode of linking of polyhedra into columns, b) projection on (100) showing layer of polyhedra, the columns being linked together by BO_3 triangles. Circles show the buffer water molecules.

inyoite has two O + three OH + three H_2O. Mean interatomic distances in inderite: $B-O_2OH = 1.37$; $B-O_2(OH)_2 = 1.48$; $Mg-(OH)_2(H_2O)_4 = 2.08$; in inderborite: $B-O_2OH = 1.38$; $B-O_2(OH)_2 = 1.475$; $Mg-(OH)_4(H_2O)_2 = 2.06$; $Ca-(O, OH, H_2O)_8 = 2.53$; in inyoite: $B-O_2(OH)_2 = 1.47$; $Ca-(O, OH, H_2O)_8 = 2.47$.

Phys. Nearly isometric (short columns to thick plates). Inderite has imperfect (010) cleavage; inderborite has perfect (100) cleavage, and inyoite has perfect (001).

2. KURNAKOVITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 2$

		a	b	c	ρ	H
Kurnakovite	$Mg(H_2O)_5[B_2BO_3(OH)_5]$	8.14	10.47	6.33	1.86	3.5
	$\alpha = 96^\circ 56.5'$	$\beta = 106^\circ 28'$		$\gamma = 106^\circ 03'$		
Meyerhofferite	$Ca(H_2O)[B_2BO_3(OH)_5]$	6.61	8.35	6.49	2.12	3
	$\alpha = 90^\circ 41'$	$\beta = 101^\circ 51'$		$\gamma = 86^\circ 44'$		

Str. The radical is as above, consisting of two $BO_2(OH)_2$ tetrahedra and a BO_2OH triangle. Meyerhofferite has been studied in detail (Christ and Clark, 1956 [854]); Ca has CN = 7 (six O and one OH). Mean interatomic distances: $B-O_2OH = 1.38$; $B-O_2(OH)_2 = 1.49$; $Ca-O_6H_2O = 2.40$. Hydroxyl-hydrogen bonds link these radicals into pseudochains along the c axis. Kurnakovite as a dimorph of inderite differs from the latter in the arrangement of identical B(O,OH) radicals [1313].

Phys. Columnar to platy, flattened on (100) and elongated along the c axis. Perfect cleavage on (010) and (1$\bar{1}$0) in kurnakovite, on (010) in meyerhofferite.

II. With $[B_2B_2O_5(OH)_4]^{2-}$ Radical (2□ and 2△)

1. HALURGITE GROUP. Mon.→tricl.

		S.g	*a*	*b*	*c*	*Z*	*ρ*	H
Halurgite (magnahydrabarite)	$Mg_2(H_2O)[B_2B_2O_5(OH)_4]_2$	$C_{2h}^4 - P2/c$	13.25	7.60	13.20	4	2.19	3—3.5
				$\beta = 92°09'$				
Haungchaoite	$Mg(H_2O)_7[B_2B_2O_5(OH)_4]$	Nat det.	—	—	—	—	1.72	2—2.5

Str. Not known. Parameters of halurgite from Kondrat'eva (1964) [855].

Chem. Composition constant (Lobanova, 1962 [856]).

Phys. Halurgite is platy, cleavage not observed. Huangchaoite has not been examined [1392].

2. BORAX GROUP. Trig.→mon.

		S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Tincalconite	$Na_2(H_2O)_3[B_2B_2O_5(OH)_4]$	$D_3^7 - R32$	11.3	—	20.9	9	1.88	(3)
Borax (natrahydraborite)	$Na_2(H_2O)_8[B_2B_2O_5(OH)_4]$	$C_{2h}^6 - C2/c$	11.84	10.63	12.32	4	1.72	2.5—3
				$\beta = 106°35'$				

Str. Fully known for borax (Morimoto, 1956 [258]). The radical consists of two BO_3OH tetrahedra and two BO_2OH triangles (Fig. 51g);

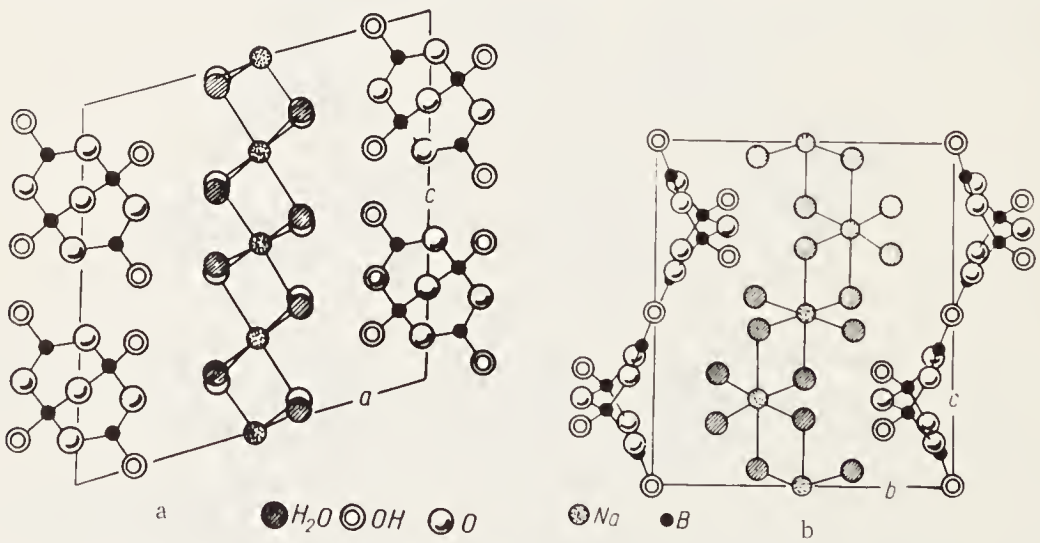


Fig. 221. Structure of borax in two projections with the c axis vertical: a) on (010), b) on (100). The insular $[B_2B_5O_5(OH)_4]$ complexes are seen.

these radicals are linked via hydroxyl-hydrogen bonds to Na, which has sixfold coordination to H_2O molecules (Fig. 221, a and b). These $Na(H_2O)_6$ octahedra are linked via common edges into slightly zigzag columns along the c axis. Mean interatomic distances: $Na-(H_2O)_6$ = 2.36; $B-O_3OH$ = 1.48; $B-O_2OH$ = 1.36 (SR XI, 431) [553].

Phys. Nearly isometric; borax has perfect (100) and (110) cleavage.

III. With $[B_2B_3O_6(OH)_5]^{2-}$ Radical (2□ and 3△)

1. BIRINGUCCITE GROUP. Mon.

		a	*b*	*c*	β	*ρ*	H
Biringuccite	$Na_2[B_2B_3O_6(OH)_5]$ (?)	—	—	—	—	—	—
Nasinite	$Na_2(H_2O)[B_2B_3O_6(OH)_5]$	—	—	—	—	—	—

Str. Not known, formulas require verification. Synthesized (Cipriani, 1959 [857]).

Phys. Tabular on (001), physical properties not studied.

IV. With $[BB_4O_6(OH)_4]^{1-}$ Radical (1□ and 4△)

1. LARDERELLITE GROUP. Mon. →orth.

		S.g.	*a*	*b*	*c*	β	*Z*	*ρ*	H
Larderellite	$NH_4[BB_4O_6(OH)_4]$	$C_{2h}^5 - P2_1/a$	11.65	7.63	9.47	97° 05′	4	1.91	—
Ammoniaborite	$NH_4(H_2O)[BB_4O_6(OH)_4]$	$C_{2h}^6 - C2/c$	25.27	9.65	11.56	94° 17′	12	1.77	—
Sbargite	$Na(H_2O)_3[BB_4O_6(OH)_4]$	$C_{2h}^6 - C2/c$	11.10	16.35	13.59	113°10′	4	1.71	2.5
Santite	$K(H_2O)_2[BB_4O_6(OH)_4]$	$C_{2v}^{17} - Aba2$	11.10	11.18	9.08	—	4	1.74	3

Str. Larderellite and the other minerals of this group are close to the structure of synthetic $K(H_2O)_2[BB_4O_6(OH)_4]$ (Zachariasen, 1938 [282]), in which the basic unit is a complex radical consisting of a BO_4 tetrahedron and four BO_2OH triangles (Fig. 51h). The interatomic distances in larderellite: $NH_4-(O,OH)_{10}$ = 2.86-3.35; $B-(O,OH)_4$ = 1.45-1.50; $B-(O,OH)_3$ = 1.33-1.41 [1309].

Phys. Tabular, cleavage in two directions.

V. With Complex (Heterogeneous) Radicals

1. GINORITE GROUP. Mon., $C_{2h}^5 - P2_1/a$, $Z = 4$

		a	*b*	*c*	β	ρ	H
Ginorite	$Ca_2(H_2O)_2[B_4O_5(OH)_4][B_5O_6(OH)_4]_2$	12.74	14.36	12.82	100° 46′	2.09	3.75
Strontium ginorite	$Sr_2(H_2O)_2[B_4O_5(OH)_4][B_5O_6(OH)_4]_2$	12.85	14.48	12.85	101° 35′	2.25	3.5

Str. Not known, formulas doubtful (Christ, 1960 [254]; Tennyson, 1963 [257]). New data has $SrCa(H_2O)_5[B_6B_8O_{20}(OH)_6]$ for strontium ginorite [1393].

Chem. Ca in ginorite replaced by Sr ($\leq 1.1\%$); strontium ginorite has about 1/3 Ca (Braitsch, 1959 [858]).

Phys. Thick tablets, perfect cleavage on (010) and (001).

Subclass 3. Chain

DIVISION A. WITH SIMPLE CHAINS

I. With $[B_2O_2(OH)_4]_\infty^{2n-}$ Chains (of $B(O,OH)_4$ Tetrahedra)

1. VIMSITE GROUP. Mon., C_{2h}^6—$C2/c$, $Z = 4$

		a	*b*	*c*	β	ρ	H
Vimsite	$Ca[B_2O_2(OH)_4]_\infty^1$	10.02	9.71	4.44	92°	2.54	(3.5—4)

Str. The chains of B(O,OH) tetrahedra are closely bound with columns consisting of slightly distorted cubes of CaO_8 joined at the edges: both run along the c axis. The mean interatomic distances: $Ca-(O,OH)_8 = 2.54$; $B-(O,OH)_4 = 1.48$ (Shashkin et al., 1968 [1314]).

Phys. Crystals elongated along c axis, cleavage on (100) perfect.

II. With $[B_2O_4]_\infty^{2n-}$ Chains (of BO_3 Triangles)

1. CALCIBORITE GROUP. Orth., $D_{2h}^{14} - Pbcn$, $Z = 4;8$

		a	*b*	*c*	ρ	H
Colciborite-I	$Ca[B_2O_4]_\infty^1$	6.21	11.60	4.29	2.70	3.5—4.5
Colciborite-II	$Ca[BBO_4]_\infty^1$	8.38	13.87	5.01	2.88	(4.5—5)

Str. Calciborite-I consists of $[B_2O_4]_\infty^1$ chains along the c axis (Fig. 222), which are linked by Ca atoms in irregular CaO_8 polyhedra. Interatomic distances: $B-O_3 = 1.33$, 1.39, and 1.40; $Ca-O_8 = 2.35$ (2), 2.40 (2),

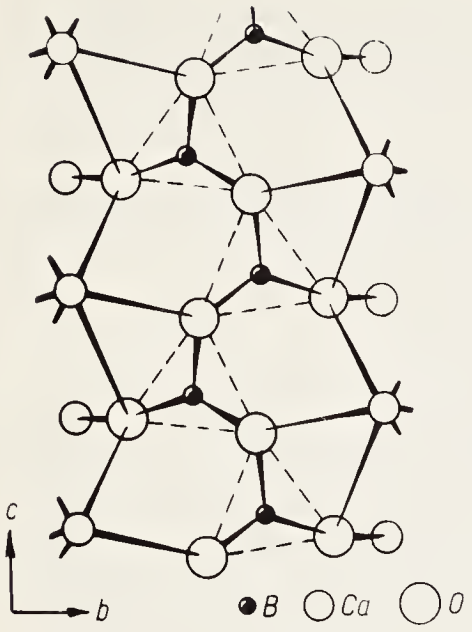


Fig. 222. Structure of calciborite in projection on (100).

2.55 (2), and 2.73 (2) (Marezio, Plettinger, and Zachariasen, 1963 [874]) for synthetic $Ca[B_2O_4]$. Calciborite-II (known in nature as a mineral) contains more complex chains of B polyhedra. These chains consist of BO_4 tetrahedra and BO_3 triangles; the latter join by vertices with the former. Ca atoms in eightfold coordination fasten these chains together. The mean interatomic distances: $Ca-O_8$ = 2.44; $B-O_4$ = 1.49; $B-O_3$ = 1.39 [1315].

Chem. Calciborite-I is of constant composition.

Phys. Calciborite-II is columnar to acicular, with perfect cleavage.

DIVISION B. WITH COMPLEX CHAINS

I. With $[B_2BO_4(OH)_3]_\infty^{2n-}$ Chains (2▨ and 1△)

1. HYDROBORACITE GROUP. Mon.,. $C_{2h}^4 - P2/c$, $Z = 2$

		a	*b*	*c*	β	ρ	H
Hydroboracite	$CaMg(H_2O)_3[B_2BO_4(OH)_3]_2\,\frac{1}{\infty}$	11.71	6.69	8.20	102° 40′	2.17	3.5—4.5

Str. $[B_2BO_4(OH)_3]_\infty^1$ chains along c axis consisting of three types of links (two B tetrahedra and one B triangle, Fig. 223). Each chain has on one side Mg atoms with CN = 6, which are linked via vertices into chains

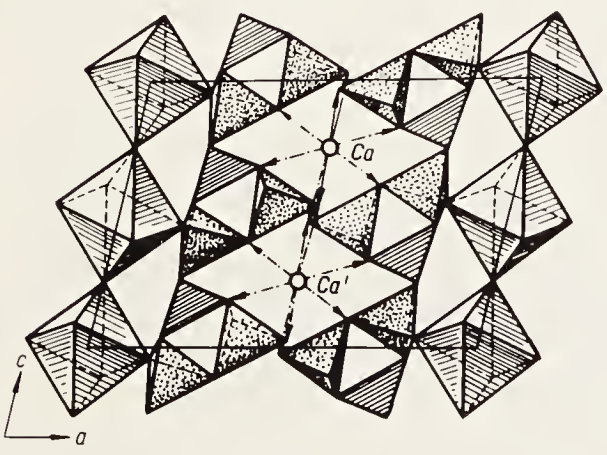


Fig. 223. Structure of hydroboracite in projection on (010).

parallel to the c axis, and on the other side Ca atoms with k = 8, which link the entire structure together (Rumanova and Ashirov, 1963 [260]). Mean interatomic distances: B−(O, OH)$_4$ = 1.48; B−O$_3$ = 1.38; Mg−(OH)$_2$(H$_2$O)$_4$ = 2.09; Ca−O$_4$(OH)$_4$ = 2.45.

Phys. Needles to fibers (on c axis), perfect (010) and (100) cleavage.

2. COLEMANITE GROUP. Mon., $C_{2h}^5 - P2_1/a$, $Z = 4$

		a	b	c	β	ρ	H
Colemanite	$Ca(H_2O)[B_2BO_4(OH)_3]\,\frac{1}{\infty}$	8.74	11.26	6.10	110° 07′	2.42	4.5—5

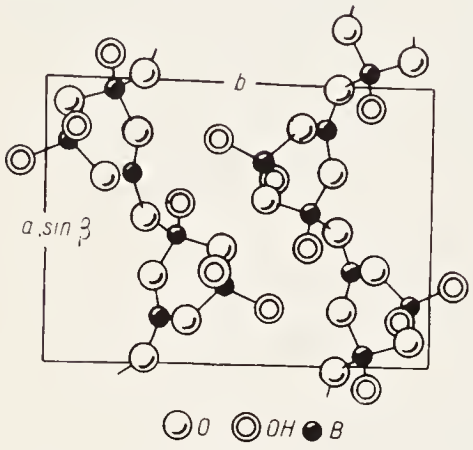


Fig. 224. Structure of colemanite in projection on (001).

Str. Also three-link chains consisting of two B tetrahedra and one B triangle, but with a different coupling of the links (Fig. 52, b and c), and with the chains running along the a axis (Fig. 224). The Ca atoms and buffer H_2O molecules link the chains together. Ca is surrounded by three (or four) O, three OH, and one H_2O. Mean interatomic distances: B−(O, OH)$_4$ = 1.48; B−O$_3$ = 1.37; Ca−(O, OH)$_6$HEO = 2.45 (Christ et al., 1958 [259]).

Phys. Short columns to isometric (chain pattern on the a axis), which is a consequence of the neutralization of the effects of the B−O chains by the chains of Ca polyhedra perpendicular to them. Cleavage on (010) moderate.

II. With $[B_2B_2O_6(OH)_2]_\infty^{2n-}$ Chains (2□ and 2△)

1. KERNITE GROUP. Mon., $C_{2h}^4 - P2/a$, $Z = 4$

		a	b	c	β	ρ	H
Kernite	$Na_2(H_2O)_3[B_2B_2O_6(OH)_2]\,\frac{1}{\infty}$	15.68	9.09	7.02	108°52′	1.90	3

Str. The chain radical, discovered by Christ (1969 [254]), was then confirmed by Giese (1966 [1137]) and Cialdi et al. (1967 [1138]). The chains, which are run along the b axis, consist of BO$_4$ tetrahedra, bound at the vertices (as in the pyroxenes), while vacant vertices of neighboring tetrahedra are connected by BO$_3$ triangles. These complex chains are joined with each other by Na atoms (CN = 5) and by hydroxyl−hydrogen bonds. The interatomic distances are: Na−(O,OH)$_5$ = 2.28-2.49; B−O$_4$ = 1.43-1.59; B−(O,OH)$_3$ = 1.35-1.38 [1138].

Phys. In the cleavable aggregates with a fibrous structure; cleavage in the monocrystals on (100) and (001) perfect.

III. With $[BB_2O_4(OH)_2]^{n-}$ Chains (1□ and 2△)$^1_\infty$

1. AKSAITE GROUP. Orth. → mon.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Aksaite	$Mg(H_2O)_3[BB_2O_4(OH)_2]_2{}^1_\infty$	D^{15}_{2h} — *Pbca*	12.54	24.32	7.48	—	8	2.29	~3 (?)
Gowerite	$Ca(H_2O)_3[BB_2O_4(OH)_2]_2{}^1_\infty$	C^5_{2h} — $P2_1/a$	12.93	16.40	6.58	121°30′	4	2.00	3.5
Ameghinite	$Na_2(H_2O)_2[BB_2O_4(OH)_2]_2{}^1_\infty$	C^6_{2h}—$C2/c$	18.45	9.89	6.32	104°20′	4	2.03	3

Str. Not known; formulas derived from composition, morphology, and cleavage.

Phys. Columnar (on c axis), with (100) and (010) cleavages.

2. TERUGGITE GROUP. Mon., C^5_{2h}—$P2_1/a$, $Z = 2$

		a	*b*	*c*	β	ρ	H
Teruggite	$Ca_4Mg(H_2O)_4[BB_2O_4(OH)_2]_4[AsO_4]_2{}^1_\infty$	15.68	19.90	6.25	100°05′	2.15	3

Str. Not known (Aristarain and Hurlbut, 1968 [1316]).

Chem. Composition constant.

Phys. Crystals are greatly elongated on the c axis; cleavage (110) perfect and (001) less so.

IV. With $[B_4BO_7(OH)_5]^{4n-}$ Chains (4□ and 1△)

1. TERTSCHITE GROUP. Mon. (?)

		a	*b*	*c*	β	ρ	H
Pandermite	$Ca_2(H_2O)[B_4BO_7(OH)_5]{}^1_\infty$	—	—	—	—	2.42	3.5—4
Tertschite	$Ca_2(H_2O)_7[B_4BO_7(OH)_5]{}^1_\infty$	—	—	—	—	—	—

Str. Not known; formulas and patterns doubtful, derived from morphology and crystallochemical considerations.

Phys. Pandermite is cryptocrystalline. Tertschite is acicular to fibrous (as ulexite), usually as fibrous masses.

V. With $[B_3B_2O_7(OH)_4]^{3n-}_{\infty}$ Chains (3▨ and 2△)

1. PREOBRAZHENSKITE GROUP. Orth., D^{14}_{2h} — *Pbcn*, $Z = 4$

		a	*b*	*c*	*ρ*	H
Preobrazhenskite	$Mg_3(H_2O)[B_3B_2O_7(OH)_4]_2{}^{1}_{\infty}$	16.33	9.16	10.59	2.45	5—5.5

Str. Not known, formula derived from composition and morphology [862]. New data [1394] has $Mg_3[B_7B_4O_{41}(OH)_8HO_2]$ as the formula.

Phys. Laths (elongated on c axis and flattened on a axis), no cleavage observed.

2. PROBERTITE GROUP. Mon. → tricl., $Z = 4 \rightarrow 2$

		S.g.	*a*	*b*	*c*	β	*ρ*	H
Probertite	$NaCa(H_2O)_3[B_2B_2O_7(OH)_4]{}^{1}_{\infty}$	C^5_{2h} — $P2_1/n$	13.43	12.57	6.59	100° 15′	2.14	3.5—4
Ulexite	$NaCa(H_2O)_5[B_3B_2O_7(OH)_4]{}^{1}_{\infty}$	C^1_i — $P\bar{1}$	8.81	12.86	6.68	109° 07′	1.96	3—3.5
		$\alpha = 90°\ 15'$	$\gamma = 105°\ 06'$					

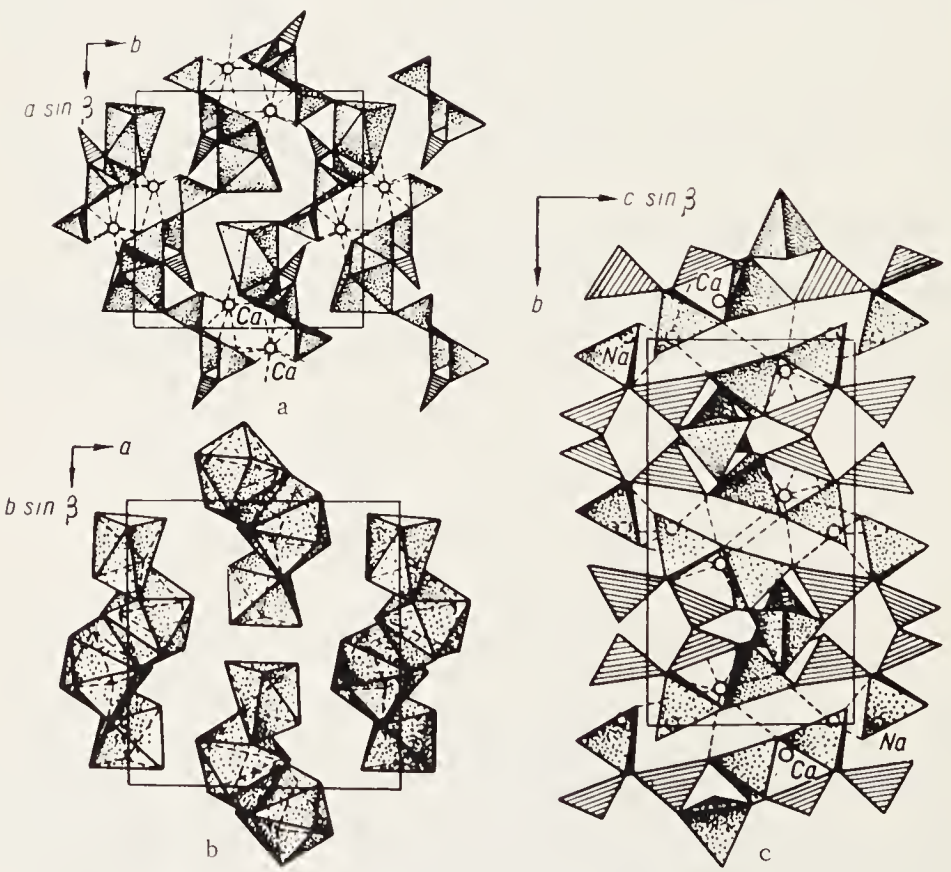


Fig. 225. Structure of probertite: a) and b) in projection on (001) showing respectively the B—O radicals and the Na and Ca polyhedra, c) projection on (100) showing $[B_3B_2O_7(OH)_4]^{1}_{\infty}$ chains along the c axis.

Str. Known for probertite (Kurbanov et al., 1963 [261]). $[B_3B_2O_7(OH)_4]^1_\infty$ chains along c axis, links composed of three $B(O, OH)_4$ tetrahedra and two $B(O, OH)_3$ triangles (Figs. 52d and 225c). Between the chains lie Na atoms with CN = 6 (deformed octahedra) and Ca with CN = 9, which are linked via common edges into groups with two Na and two Ca polyhedra (Fig. 225, a and b). Hydroxyl hydrogen bonds assist the ionic bonds in linking these groups and B –O chains into a single whole. Mean interatomic distances: $B-(O, OH)_4 = 1.47$; $B-(O, OH)_3 = 1.37$; $Na-O(OH)_2(H_2O)_3 \approx 2.45$; $Ca-O_5(OH)_3H_2O \approx 2.50$. Structure of ulexite may be found in [1395].

Phys. Laths to needles (probertite) and fibrous (ulexite); perfect cleavage on (110) in probertite and on (010) and $(1\bar{1}0)$ in ulexite.

VI. With $[B_2B_3O_7(OH)_3]^{2n-}_\infty$ Chains (2□ and 3△)

1. EZCURRITE GROUP. Tricl., C_i^1–$P\bar{1}$, $Z = 2$

		a	*b*	*c*	*α*	*β*	*γ*	*ρ*	H
Ezcurrite	$Na_2(H_2O)_2[B_2B_3O_7(OH)_3]^1_\infty$	8.60	9.57	6.58	102°45′	107°30′	71°31′	2.05	3.5—3.75

Str. Not known; formula deduced from crystallochemical arguments in conjunction with morphology and cleavage.

Chem. Composition constant, Na replaced by K up to 0.2%. The synthetic product has the same composition (Hurlbut and Aristarain, 1967 [873]).

Phys. Columnar to acicular. Highly perfect cleavage on (110), perfect on (010) and (100), imperfect on $(1\bar{1}0)$.

VII. With $[B_3B_3O_8(OH)_5]^{3n-}$ Chains (3□ and 3△)

1. KALIBORITE GROUP. Mon. C_{2h}^6–$C2/c$, $Z = 4$

		a	*b*	*c*	*β*	*ρ*	H
Kaliborite	$KHMg_2(H_2O)_4[B_3B_3O_8(OH)_5]_2$	18.53	8.43	14.67	100°13′	2.12	4–4.5

Str. Spiral $[B_3B_3O_8(OH)_5]^1_\infty$ chains, the unit being composed of three B tetrahedra and three B triangles. These extend along the b axis (Fig. 226a). The units lie perpendicular to the general trend of the chain and are linked via one oxygen atom, to which converge a B tetrahedron from one unit and a B triangle from the other. Mg has almost regular octahedral surroundings of O, OH, and H_2O, while K has CN = 8 (cube slightly flattened along a axis). Both of these lie in holes between the spiral chains and link the latter together; they are also linked via H_2O edges.

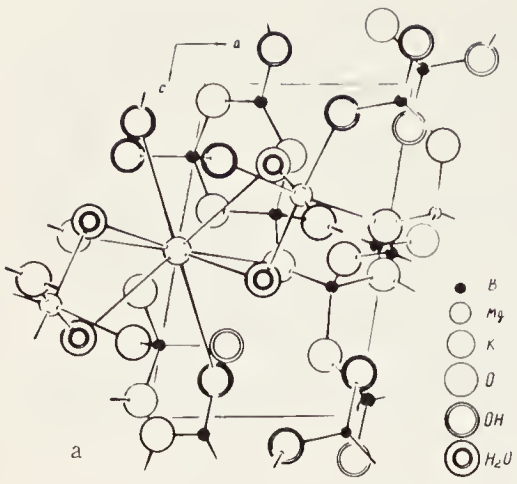


Fig. 226. Structure of kaliborite and sassolite: a) kaliborite in projection on (010), b) projection of a layer of sassolite on the (001) pseudohexagonal basal plane.

There is also a clear hydrogen bond with the proton half-way between two O atoms separated by 2.41. Interatomic distances: $K-O_2(OH)_2(H_2O)_4$= 2.91 (2); 2.92 (2); 2.95 (2); 2.98 (2); $Mg-O_2(OH)_2(H_2O)_2$ = 2.09 and 2.13; 2.06 and 2.07; 2.05 and 2.07; $B-O_2(OH)_2$ = 1.46; $B-O_4$ = 1.47; $B-(O,OH)_3$= 1.36; $H-O_2$ = 1.206 (Corazza and Sabelli, 1966 [864]).

Phys. Isometric, perfect cleavage on (100), (001), and $(\bar{1}01)$.

Subclass 4. Layer

DIVISION A. WITH LAYERS OF $[B(O,OH)_3]$ TETRAHEDRA

1. GARRELSITE GROUP. Mon., $C_{2h}^6 - A2/a$, $Z = 8$

		a	b	c	β	ρ	H
Garrelsite	$Ba_2[B_3SiO_7(OH)_3]\overset{2}{\infty}$	13.43	8.45	14.61	114° 19′	(4.4)	(4.5)

Str. Not known; assigned to the layer type from the analogy with the datolite group (Milton et al., 1955 [283]; Christ, 1959 [284]), although the cell parameters are substantially different.

Chem. Much of the Ba replaced by Ca (up to 2:1).

Phys. Data inadequate; nearly isometric habit, cleavage not observed.

DIVISION B. WITH LAYERS OF $[BO_3]$ TRIANGLES

1. SASSOLITE GROUP. Tricl. (pseudohex.), $C_i^1 - P\bar{1}$, $Z = 4$

		a	b	c	α	β	γ	ρ	H
Sassolite	$H_3[BO_3]\overset{2}{\infty}$	7.01	7.05	6.58	92° 35′	101° 10′	119° 50′	1.48	1

Str. Planar layers of $B(OH)_3$ composition (Fig. 226b), between which are residual bonds (distance 3.19). B in the layer is surrounded by three O, while O is surrounded by two H and one B. The oxygen atoms belonging to different BO_3 groups are joined via H atoms, which lie (Zachariasen, 1954 [865]) at different distances in two planar adjacent bonds directed from each O atom; one O–H = 0.88, the other O–H = 1.89, the O–O distance being 2.72.

Chem. Composition constant.

Phys. Tabular and platy crystals, pseudohexagonal, highly perfect cleavage on (001).

DIVISION C. WITH LAYERS OF $[B(O,OH)_4]$ TETRAHEDRA AND $[B(O,OH)_3]$ TRIANGLES

1. FABIANITE GROUP. Mon. C_{2h}^5—$P2_1/a$, $Z = 4$

		b	c	β	ρ	H
Fabianite	$Ca[B_2BO_5(OH)]$ ∞	6.59	10.49	6.37	113°23′	2.78	6.5

The layers, consisting of BO_4 tetrahedra and BO_3 triangles, are connected with each other by Ca atoms in eightfold coordination and by hydrogen bonds (Erd et al., 1969 [1321]).

Phys. Thick tablets, moderate cleavage on (110).

2. TUNELLITE GROUP. Mon.→trig.

	S.g.	a	b	c	β	Z	ρ	H
Nableite $Ca(H_2O)_3[B_3B_3O_9(OH)_2]$ ∞	$C_{2h}^5 - P2_1/a$	14.56	8.02	9.84	111° 45′	4	2.09	3.5
Tunellite $Sr(H_2O)_3[B_3B_3O_9(OH)_2]$ ∞	$C_{2h}^5 - P2_1/a$	14.39	8.21	9.93	114° 02′	4	2.40	3
Macallisterite $Mg(H_2O)_6[B_3B_3O_9(OH)_2]$ ∞	$D_{3d}^6 - R\bar{3}c$	11.55	—	35.56	—	12	1.87	3
Valkavskite $Ca(H_2O)_2[B_3B_3O_9(OH)_2]$ ∞	$C_2^2 - P2_1$	6.57	48.30	6.51	119°05′	8	2.34	(3.75)
Rivadavite $Na_6Mg(H_2O)_{16}[B_3B_3O_9(OH)_2]_4$ ∞	C_{2h}^2—$P2_1/m$	14.78	8.01	11.13	105°57′	1	1.91	3.5
Braitschite $Ca_6TR_2[B_6O_9(OH)_3]_4$ ∞ (?)	Not det.	12.16	—	7.38	—	1	2.90	—
Satimalite $KNa_2(H_2O)_4[B_3B_3O_6(OH)_6][Al(OH)_3]_4Cl_3$ ∞	Not det.	12.62	18.64	6.97	—	2	1.70	—

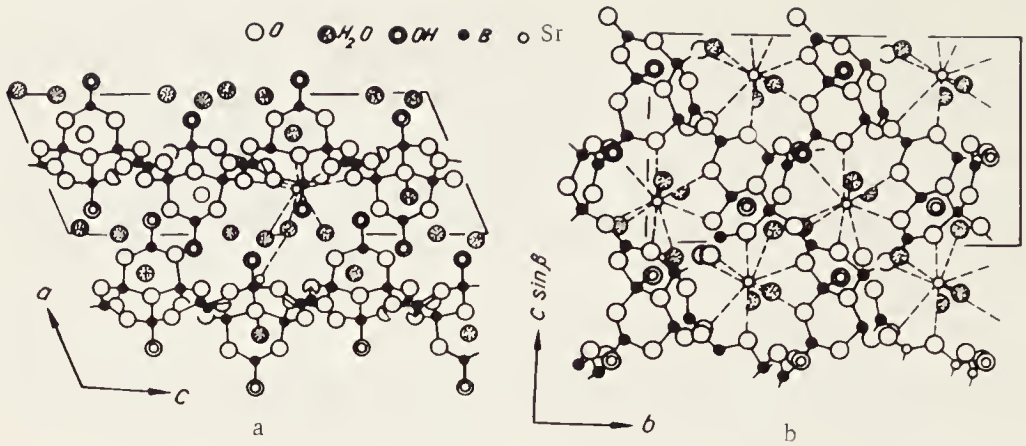


Fig. 227. Structure of tunellite: a) projected on (010), showing layers parallel to (100), b) projected on (100), showing the tenfold corrdination of the Sr atoms.

Str. Known for tunellite (Clark, 1964 [262]); the layer pattern is produced by a polyion composed of three B tetrahedra and three B triangles (Fig. 227b), the three tetrahedra converging on a single O atom. Sr has CN = 10 (six O + four H_2O) and lies in a hole within the layer. Hydroxyl-hydrogen bonds of water molecules bind the layers together (Fig. 227a). Mean interatomic distances: $Sr-O_6(H_2O)_4 = 2.74$; $B-O_3 = 1.36$; $B-O_4 = 1.47$. Macallisterite has been assigned here from the composition (Schaller et al., 1965 [866]; Kondrat'eva et al., 1966 [867]). The so-called strontioborite is similar in parameters to tunellite (Lobanova and Kondrat'eva, 1965 [875]).

Phys. Tabular, perfect cleavage on (100), but no cleavage observed for macallisterite. Volkovskite is platy, perfect (010) cleavage, moderate (001). Rivadavite is elongated on the b axis and flattened on (100); perfect cleavage on (100) and ($\bar{1}$01) (Hurlbut and Aristarain, 1967 [868]). Braitschite forms the smallest tabular hexagonal crystals [1317]; satimolite isometric or tabular [1318]; cleavage not observed.

3. HILGARDITE GROUP. Mon.→tricl.

		S.g.	a	b	c	Z	ρ	H
Hilgardite	$Ca_2[B_3B_2O_8(OH)_2]Cl\,{}^{2}_{\infty}$	C_s^4-Cc	6.31	11.33	11.44	4	2.71	5.5
					$\beta = 90°\,00'$			
Parahilgardite (triclinohilgardite)	$Ca_2[B_3B_2O_8(OH)_2]Cl\,{}^{2}_{\infty}$	C_1^1-P1	6.31	6.48	17.50	3	2.71	5.5
			$\alpha = 84°\,00'$		$\beta = 79°\,36'$	$\gamma = 60°\,54'$		
Strantiohilgardite	$SrCa[B_3B_2O_8(OH)_2]Cl\,{}^{2}_{\infty}$	C_1^1-P1	6.38	6.48	6.61	1	3.00	5.5—7
			$\alpha = 75°\,24'$		$\beta = 61°\,12'$	$\gamma = 60°\,30'$		
Tyretskite	$Ca_2[B_3B_2O_8(OH)_2]OH\,{}^{2}_{\infty}$	C_1^1-P1	6.41	6.44	6.45	1	2.55	(5.5)
			$\alpha = 73°30'$		$\beta = 61°46'$	$\gamma = 60°15'$		
Heidarnite	$Na_2Ca_3[B_3B_2O_8(OH)_2][SO_4]_2Cl\,{}^{2}_{\infty}$	C_{2h}^6-C2/c	10.21	7.84	18.79	4	2.75	4.5—5.5
					$\beta = 93°\,30'$			

Str. Not generally known, formulas doubtful, derived from general crystallochemical considerations (Christ, 1960 [254]; Tennyson, 1963 [257]). It has recently been shown for heidornite that $[B_3B_2O_8(OH)_2]$ layers parallel to (001) alternate with layers of Cl and SO_4 anions, the latter being separated from the B–O layers by Ca and Na atoms, which have CN of 8 and 7 respectively. Interatomic distances: $Na-O_6Cl$ = 2.53 (6) 3.02; $Ca-O_8$ = 2.52; $Ca-O_7Cl$ = 2.49 (7); 2.83; $B-O_4$ = 1.49; $B-O_3$ = 1.38; $S-O_4$ = 1.48 (Burzlaff, 1967 [869]).

Chem. In tyretskite Ca is replaced by Sr (≤2%), and OH by Cl (≤1.5%) (Kondrat'eva, 1969 [1319]; Davies and Machin, 1968 [1320]).

Phys. The hilgardites are tabular, perfect (010) and (001) cleavage. Heidornite occurs as wedge-shaped forms with perfect (001) cleavage.

1. VEATCHITE GROUP. Mon. $Z = 4; 2$

	S. g.	a	b	c	β	ρ	H
Veatchite $Sr_2(H_2O)[B_2B_3O_8(OH)]_2[B(OH)_3]$ ∞	C_s^4—Aa	20.81	11.74	6.64	92°02′	2.86	2—2.5
Paraveatchite $Sr_2(H_2O)[B_2B_3O_8(OH)]_2[B(OH)_3]$ ∞	C_2^2—$P2_1$	6.70	20.80	6.60	119°15′	2.69	2—2.5

Str. The layers stretching perpendicular to the b axis consist of two nets of BO_4 tetrahedra and BO_3 triangles (their ratio is 2:3), which give the general formula of each net $[B_2B_3O_8OH]$. Inside the layer these nets are joined by bound BO_2OH triangles, by free $B(OH)_3$ triangles, and by H_2O molecules. Between layers the bonds are caused by Sr atoms, which are placed in the centers of the large rings in the nets in 10- and 11-fold coordination (Gandymov et al., 1968 [860]; Kondrat'eva, 1964 [861]).

Chem. Sr is replaced by Ca (≤5%).

Phys. Tabular to laths; veatchite has perfect (100) cleavage, paraveatchite, perfect (010).

5. HOWLITE GROUP. Mon., C_{2h}^5—$P2_1/c$, $Z = 4$

		a	b	c	β	ρ	H
Howlite	$Ca_2[B_4BSiO_9(OH)_5]$ ∞	12.78	9.33	8.60	104°50′	2.56	3.5—4

Str. Complicated structure, in which are combined colemanite-like chains (two BO_4 and one BO_3) and borosilicate spirals consisting of four BO_4 and two SiO_4 tetrahedra. The chains and the spirals through common O atoms are connected to uneven layers parallel to (010). The Ca atoms in eightfold coordination are placed in holes between layers joining them together. The mean interatomic distances: $Ca-(O,OH)_8$ = 2.47; $B-(O,OH)_4$ =

1.47; $B{-}O_3$ = 1.36; $Si{-}O_4$ = 1.62 (Finney et al., 1970 [859]. Crystallographic arrangement by Murdoch (1957 [870]).

Chem. Composition (from six analyses) strictly constant.

Phys. Tabular to platy, on (100), no cleavage observed.

DIVISION D. WITH LAYERS OF $B(OH)_4$ TETRAHEDRA AND OTHER ATOMS

1. BANDYLITE GROUP. Tetr., $Z = 2$

		S.g.	a	c	ρ	H
Bandylite	$Cu[B(OH)_4]Cl$ ♂	C^3_{4h}—$P4/n$	6.19	5.61	2.81	3
Teepleite	$Na_2[B(OH)_4]Cl$ ♂	D^7_{4h}—$P4/nmm$	7.28	4.84	2.08	3.5—4

Str. Layers of firmly linked $Cu(OH)_4Cl_2$ octahedra and $B(OH)_4$ tetrahedra forming a corrugated surface in the (001) plane (Fig. 228a). Between layers there are weaker Cu–Cl bonds (distance 2.8). Interatomic distances $B{-}(OH)_4$ = 1.42; $Cu{-}(OH)_4Cl_2$ = 1.98 (4) and 2.80 (2) (Collin, 1951 [872]). Teepleite has layers of $B(OH)_4$ tetrahedra and $Na(OH)_4Cl_2$ octahedra (Fig. 228b), but there is no great difference in the strengths of the bonds within layers and between them, which (since the surfaces are uneven) prevents any cleavage. Interatomic distances: $B{-}(OH)_4$ = 1.41; $Na{-}(OH)_4Cl_2$ = 2.51 (Fornaseri, 1949 [871]).

Phys. Thick tabular to platy; bandylite has perfect (001) cleavage, teepleite has no cleavage.

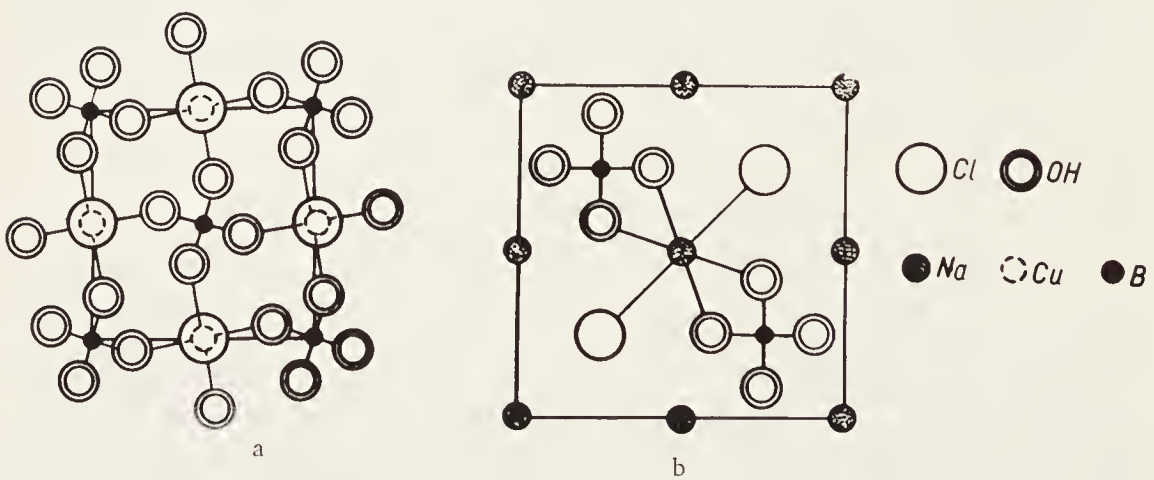


Fig. 228. Structure in projection on the basal plane for: a) bandylite, b) teepleite.

Inadequately Characterized and Doubtful

Aldzhanite (hydrate chloroborate Ca and Mn)
Balavinskite $Sr_2B_6O_{11} \cdot 4H_2O$
Chelcarite $Ca_3Mg_4B_6O_{16}Cl_5 \cdot 19H_2O$ (?)
Hydrochloroborite $Ca_4B_8O_{15}Cl_2 \cdot 22H_2O$
Hydroxylascharite $Mg_2B_{2-x}H_{3x}O_5 \cdot H_2O$
Ivanovite (hydrate chloroborate of K and Ca?)
Korzhinskite $CaB_2O_4 \cdot H_2O$ (?)
Olshanskyite $Ca_3[B(OH)_4]_4(OH)_2$(?)
Priceite $Ca_5B_{12}O_{23} \cdot 9H_2O$ (?)
Strontioborite $Sr_3CaMg_2B_{24}O_{42} \cdot 9H_2O$ (?)
Wardsmithite $Ca_5MgB_{24}O_{42} \cdot 30H_2O$

CLASS 5. VANADATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds Class 5. Vanadates																H 43	
2																O 47		
3	Na 5	Mg 2											Al 7		P 3		Cl 1	
4	K 2	Ca 16			V 47		Mn 5	Fe 5			Cu 5	Zn 1						
5		Sr 2	Y 1															
6		Ba 3												Pb 7	Bi 1			
7					U 12													

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						10	8	9	10	19	1

Subclass 1. Insular

I. Orthovanadates (with VO_4 Radical)

Division A. Without Water and Additional Anions

1. Wakefieldite $Y[VO_4]$ group

Division B. With Additional Anions

Subdivision 1. Simple

1. Vanadinite $Pb_2Pb_3[VO_4]_3Cl$

Subdivision 2. Complex

1. Deseloizite $Pb(Zn, Cu)[VO_4]OH$ group
2. Vesignieite $BaCu_3[VO_4]_2(OH)_2$ group

Division C. Hydrated

1. Steigerite $Al(H_2O)_3[VO_4]$ group
2. Sehoderite $Al_2(H_2O)_8[VO_4][PO_4]$ group
3. Santafeite $Na_2Ca_3Mn_3Mn_3^{4+}(H_2O)_4[VO_4]_6(OH)_8$ group
4. Brackebusehite $Pb_2(Mn, Fe)(H_2O)[VO_4]_2$ group

II. Diorthovanadates (with V_2O_7 Radical)

Division A. Without Water and Additional Anions

1. Chervetite $Pb_2[V_2O_7]$ group

Division B. With Water and Additional Anions

1. Volborthite $Cu_3(H_2O)_2[V_2O_7](OH)_2$ group

Subclass 2. Chain

Division A. Without Water and Additional Anions

1. Pucherite $Bi[VO_4]^1_\infty$ group

Division B. With Water or Additional Anions

1. Metarossite $Ca(H_2O)_2[VO_3]^1_{2\infty}$ group
2. Hendersonite $Ca_2V^{4+}(H_2O)_8[VO_3]^1_{8\infty}$ group
3. Metahewettite $Ca(H_2O)_3[V_6O_{16}]^1_\infty$ group
4. Melanovanadite $Ca_2V^{4+}_4[V_6O_{16}](OH)^1_{18\infty}$ group
5. Pascoite $Ca_3(H_2O)_{16}[V_{10}O_{28}]^1_\infty$ group

Subclass 3. Layer

1. Carnotite-tyuyamuyunite $K_2\{(UO_2)_2[V_2O_8]\}\cdot 3H_2O-Ca\{(UO_2)_2[V_2O_8]\}\cdot 8H_2O^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Insular

I. Orthovanadates (with VO_4 Radical)

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. WAKEFIELDITE GROUP. Tetr., D^{19}_{4h}—$I4_1/amd$, $Z = 4$

		a	c	ρ	H
Wakefieldite	$Y[VO_4]$	7.10	6.30	4.3	(5 5.5)

Str. Zircon-type structure (Fig. 166), Y has CN = 8 (Hogarth and Miles, 1969 [1288]).

Chem. There are some admixtures of Fe, Si, and U, some of them probably in the form of mechanical impurities.

DIVISION B. WITH ADDITIONAL ANIONS

Subdivision 1. Simple

1. VANADINITE GROUP. Hex., $C_{6h}^2 - P6_3/m$, $Z = 2$

		a	c	ρ	H
Vanadinite	$Pb_2Pb_3[VO_4]_3Cl$	10.33	7.34	6.9	3.25—3.5

Str. Apatite type (Fig. 243), two types of Pb differing in coordination: Pb_I with nine O, Pb_{II} with six O + Cl. Identical with the chlorapatite type. The Cl atoms lie within regular octahedra of Pb_{II}. Interatomic distances: Pb_I-O_9 = 2.47 (3), 2.57 (3), and 2.76 (3); $Pb_{II}-O_6Cl$ = 2.52 (2), 2.54, 2.89 (2), 3.17; $Cl-Pb_6$ = 3.17; $V-O_4$ = 1.72 (2) and 1.76 (2) (Trotter and Barnes, 1958 [288]).

Chem. Composition varies within comparatively narrow limits; Pb replaced by Ca (≤3.3%), and V^{5+} by As^{5+} (≤13.5%) and P^{5+} (≤2.9%).

Var. Ca-vanadinite, AsO_4-vanadinite, PO_4-vanadinite.

Subdivision 2. Complex

1. DESCLOIZITE GROUP. Orth., $D_2^4 - P2_12_12_1$, $Z = 4$

		a	b	c	ρ	H
Tangeite	$CaCu[VO_4]OH$	5.90	9.24	7.44	3.8	3.75
Descloizite	$Pb(Zn, Cu)[VO_4]OH$	6.06—5.87	9.41—9.54	7.58—7.54	6.2—5.9	3.5—3.75
Pyrobelanite	$PbMn[VO_4]OH$	6.23	9.59	7.76	5.8	3.5

Str. Almost the same for all species. Deseloizite has (Qurashi and Barnes, 1964 [289]) the following polyhedra: distorted VO_4 tetrahedra, $ZnO_4(OH)_2$ tetragonal bipyramids, and square $PbO_7(OH)$ antiprisms (Fig. 229). The mean interatomic distances are respectively 1.71, 2.11, and 2.70. The $ZnO_4(OH)_2$ bipyramids, with four short distances, [$Zn-(O, OH)_4$ = 2.03], are favorable for perfect Zn—Cu isomorphism. Pyrobelonite has (Donaldson and Barnes, 1955 [290]) V and Mn in tetrahedral and bipyramidal coordination respectively ($V-O_4$ = 1.75, $Mn-(O, OH)_6$ = 2.15), whereas Pb has very distorted sevenfold coordination, the Pb—O distances ranging from 2.28 to 2.89 (next two O at a distance of 3.28).

Chem. Deseloizite has perfect Zn—Cu isomorphism, so we have the subspecies zincdeseloizite and eupridesloizite. The Zn(Cu) is also replaced by Mn (≤4.6%) and Fe (≤1%); V^{5+} is replaced by As (≤7.1%). Tangeite has isomorphous (?) U^{6+}, Fe^{3+}, Ba, Mn, and Mg. Pyrobelonite

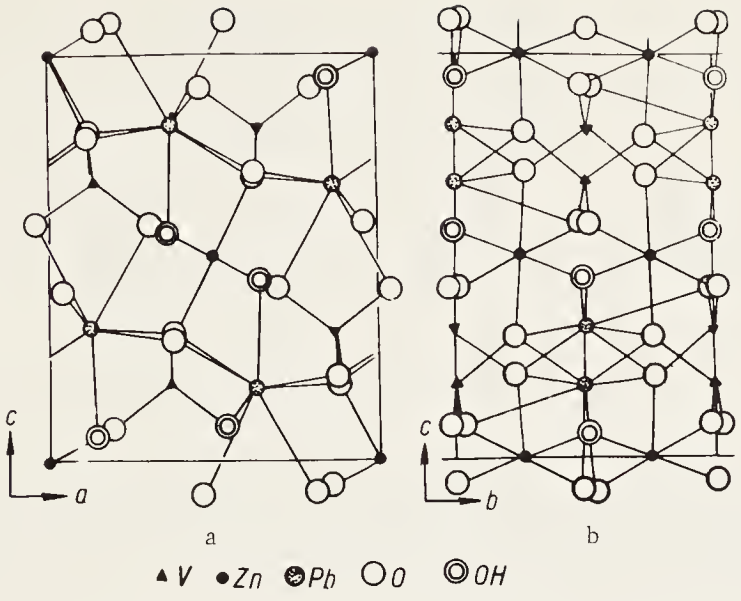


Fig. 229. Structure of descloizite in projection on: a) (010), b) (100).

has a variable Mn:Pb ratio, evidently from isomorphous replacement of Pb by Mn (up to Pb:Mn ≈ 5:3).

Var. Mn-descloizite, As-descloizite, Fe-descloizite, U-tangeite, Mn-pyrobelonite.

Phys. Descloizite varies from thick tablets to short columns; pyrobelonite forms laths and needles. Cleavage reported only for tangeite, on (001) and (010) (Guillemin, 1956 [880]).

2. VESIGNIEITE GROUP. Mon. →tricl.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Vesignieite	$BaCu_3[VO_4]_2(OH)_2$	Not det.	—	—	—	—	—	4.1	3 5—4
Mounanaite	$PbFe_2[VO_4]_2(OH)_2$	C_i^1—$P\bar{1}$	5.57	7.66	5.56	112°07′	1	4.9	(3.5)
			$\alpha = 111°01'$			$\gamma = 94°09'$			

Str. Not known, probably of the same type as bayldonite $PbCu_3 \cdot [AsO_4]_2(OH)_2$ (analogous powder patterns). In pseudomonoclinic arrangement the mounanaite cell parameters are close to those of brackebuschite $Pb_2(Mn, Fe)(H_2O)[VO_4]_2$ (Cesbron and Fritsche, 1969 [1289]).

Chem. Data for vesigneite inadequate; the composition corresponds to certain specimens of 'tangeite' from Thuringia, most 'volborthite' from the Urals, and a specimen of 'kolovratite' from Uzbekistan (Guillemin, 1955 [876]).

Phys. Platy, perfect cleavage parallel to plate faces.

DIVISION C. HYDRATED

1. STEIGERITE GROUP. Mon. →tricl.

		S.g.	a	b	c	β	Z	ρ	H
Steigerite	$Al(H_2O)_3[VO_4]$	Not det.	11.86	12.50	11.06	111°08′	4	2.52	3—3.5
Alvanite	$Al_5(H_2O)_5[VO_4]_2(OH)_9$(?)	Not det.	8.83	5.11	17.74	92°00′	1	2.41	3.5—3.75
Schubnelite	$Fe(H_2O)[VO_4]$	C_i^1—$P\bar{1}$	6.59	5.43	6.62	104°	2	3.3	(3.5)
			α = 125°		γ = 84°43′				

Str. Not known. Alvanites are probably layer and may be hydroxides [1131].

Chem. Data inadequate, but steigerite has Al replaced by Cr (≤8%) and Fe^{3+} (≤2%), and V by P (≤4.9%), while alvanite has V^{5+} replaced by V^{4+} (≤3.7%) and Al by Ni (≤2.7%?). In schubnelite part of V^{5+} is replaced by V^{4+} [1290].

Var. Cr-steigerite, PO_4-steigerite, Ni-alvanite.

Phys. Platy (steigerite crystals about 1 μ in size; Ross, 1959 [877]); alvanite has perfect (001) cleavage.

2. SCHODERITE GROUP. Mon., $C_{2h}^1 - P2/m$ (?), $Z = 4$

		a	b	c	β	ρ	H
Schoderite	$Al_2(H_2O)_8[VO_4][PO_4]$	11.4	15.8	9.2	79°	1.88	2—2.5
Metaschoderite	$Al_2(H_2O)_6[VO_4][PO_4]$	11.4	14.9	9.2	79°	—	—
Gutsevichite	$Al_3(H_2O)_8[VO_4][PO_4](OH)_3$ (?)	—	—	—	—	2.0	3

Str. Not known.

Chem. Data inadequate. V:P ratio appears to be constant; Al replaced by Fe^{3+} Schoderite loses two H_2O in dry air, but regains it in moist air (Hausen, 1962 [878]).

Phys. Tabular on (010), laths elongated on c axis. Gutsevichite not examined (Ankinovich, 1959 [879]).

3. SANTAFEITE GROUP. Orth., $D_2^5 - C222_1$, $Z = 2$ (?)

		a	b	c	ρ	H
Santafeite	$Na_2Ca_3Mn_3Mn_3^{4+}(H_2O)_4[VO_4]_6(OH)_8$	9.25	30.00	6.33	3.4 (?)	(3.5)

Str. Not known, but the habit and cleavage indicate a chain structure.

Chem. A single analysis indicates that Ca (and Na) are replaced

by Sr (6%) and V is replaced by As (2.2%); also Fe^{3+} (0.9%), Cu (0.5%), and U^{6+} (0.3%).

Phys. Needles elongated on c axis and flattened on b axis; (010) cleavage perfect, (110) moderate.

4. BRACKEBUSCHITE GROUP. Mon., $C_{2h}^2 - P2_1/m$ (?), $Z = 2$

		a	b	c	β	ρ	H
Brackebuschite	$Pb_2(Mn, Fe)(H_2O)[VO_4]_2$	8.88	6.16	7.68	111° 50′	6.1	4.5 (?)
Gamagarite	$Ba_2(Mn, Fe)(H_2O)[VO_4]_2$ (?)	—	—	—	—	4.6	5—5.5

Str. Known for brackebuschite (Donaldson and Barnes, 1955 [290]), fairly close to that of pyrobelonite. VO_4 radicals link (Mn, Fe) polyhedra, which have a distorted tetragonal-bipyramidal form, the base being nearly square [(Mn, Fe)—O = 1.9-2.0] and formed by O atoms belonging to four different VO_4 tetrahedra (Fig. 230, a and b). Fairly strong zigzag units along b axis, so the structure is of subchain type. H_2O molecules lie at the vertices of the dipyramid (Fig. 230a). The Pb atoms are of two types: CN = 8 (Pb—O_8 = 2.54-2.95) and CN = 10 (Pb—O_{10} = 2.58-3.02). These polyhedra are linked by edges to VO_4 radicals and so bind the whole structure together. Gamagarite is probably homostructural with brackebuschite.

Chem. Data inadequate. Brackebuschite has perfect Mn—Fe isomorphism that gives subspecies manganobrackebuschite and ferrobrackebuschite. Fe and Mn are replaced by Zn (1.3%) and Cu (0.4%), and V by P (0.2%).

Phys. Brackebuschite forms needles (on b axis), cleavage not observed.

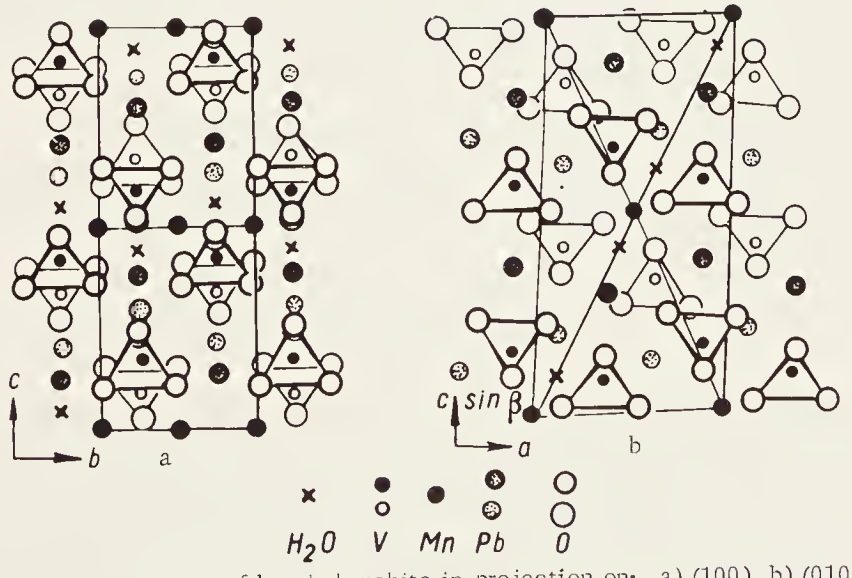


Fig. 230. Structure of brackebuschite in projection on: a) (100), b) (010).

II. Diorthovanadates (with V_2O_7 Radical)

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. CHERVETITE GROUP. Mon., $C_{2h}^5 - P2_1/a$, $Z = 4$

		a	*b*	*c*	β	ρ	H
Chervetite (plumdivanite)	$Pb_2[V_2O_7]$	13.30	7.14	7.08	106° 00′	6.5	3—3.5

Str. Paired V tetrahedra form V_2O_7 groups linked into a single insular structure by Pb atoms (CN of 8 and 9). The VO_4 tetrahedra are appreciably distorted (V—O distances 1.65-1.88). The PbO_8 and PbO_9 polyhedra also have very variable Pb—O distances; the first has three short and five long bonds, while the second has four short and five longer bonds. Interatomic distances: V_1-O_4 = 1.71-1.88 (d_m = 1.78); V_2-O_4 = 1.65-1.82 (d_m = 1.71); $Pb-O_8$ = 2.41-3.17 (d_m = 2.74); $Pb-O_9$ = 2.24-3.20 (d_m = 2.71) (Kawahara, 1967 [884]).

Chem. Composition variations not known (Bariand et al., 1963 [885]).

Phys. Short columns, imperfect cleavage on (100) and (010).

DIVISION B. WITH WATER AND ADDITIONAL ANIONS

1. VOLBORTHITE GROUP. Mon. $C_{2h}^3 - C2/m$, $Z = 2$

		a	*b*	*c*	β	ρ	H
Volborthite	$Cu_3(H_2O)_2[V_2O_7](OH)_2$	10.60	5.86	7.21	95°05′	3.5	3.5—4

Str. Preliminary investigations show that the basis of the structure is V_2O_7 groups which are connected with Cu octahedra, forming layers (Kashaev and Bakakin, 1968 [1132]).

Chem. Data inadequate; traces of Ca, Ba and Fe^{3+}.

Phys. Platy, perfect (001) cleavage, moderate (010) (Guillemin, 1956 [880]).

Subclass 2. Chain

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. PUCHERITE GROUP. Orth., $D_{2h}^{14} - Pnca$, $Z = 4$

		a	*b*	*c*	ρ	H
Pucherite (bisvanite)	$Bi[VO_4]^1_\infty$	5.33	5.06	12.02	6.6	4

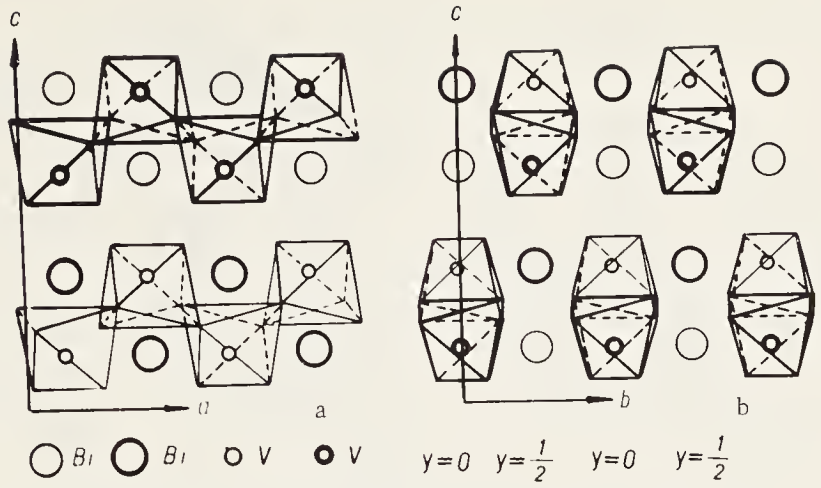


Fig. 231. Structure of pucherite in two projections; zigzag chains of VO_6 octahedra link the Bi atoms at different levels.

Str. Zigzag chains of VO_4 octahedra linked by their edges run along the a axis (Fig. 231, a and b). Bi^{3+} has CN = 8 (distorted); the atoms are linked into chains, which gives a fiarly strong structure (hardness 4). The weakest bonds lie perpendicular to (001). Interatomic distances: $V-O_6$ = 1.76 (2), 1.94 (2), and 2.69 (2); $Bi-O_8$ = 2.19 (2), 2.31 (2), 2.53 (2), and 2.73 (2) (Fischer et al., 1958 [287]).

Chem. Composition fairly constant; V replaced by P and As (≤3.7%).

Phys. Tabular to laths, flattened on (001) and elongated on (100). Perfect (001) cleavage, moderate (210).

DIVISION B. WITH WATER OR ADDITIONAL ANIONS

1. METAROSSITE GROUP. Tricl. →mon.

		S.g.	a	b	c	β	Z	ρ	H
Rossite	$Ca(H_2O)_4[VO_3]_2{}^1_\infty$	$C_i^1-P\bar{1}$	8.53	7.02	8.56	103° 23′	2	2.45	2.5—3.5
			α = 78° 28′		γ = 65° 02′				
Metarossite	$Ca(H_2O)_2[VO_3]_2{}^1_\infty$	$C_i^1-P\bar{1}$	6.22	7.07	7.77	96° 38′	2	—	—
			α = 92° 58′		γ = 105° 47′				
Delrioite	$SrCa(H_2O)_3[VO_3]_2(OH)_2{}^1_\infty$	C_{2h}^6-I2/a	17.17	7.08	14.64	102°25′	8	3.2	2.5
Metadelrioite	$SrCa[VO_3]_2(OH)_2{}^1_\infty$	C_i^1-P1	7.34	8.38	5.12	90°16′	2	4.3	(3.5)
			α = 111°39′		γ = 102°49′				

Str. Known for metarossite (Kelsey and Barnes, 1957 [292]) and rossite (Ahmed and Barnes, 1963 [881]), the two being similar. Paired chains of four V polyhedra along b axis (Fig. 232). The V polyhedron is a trigonal bipyramid; the polyhedra are linked by common edges to give the infinite radical $[VO_3]^{n-}_n$. The chains are linked by Ca (CN = 8, five O + three H_2O, square antiprism); edges and vertices in common

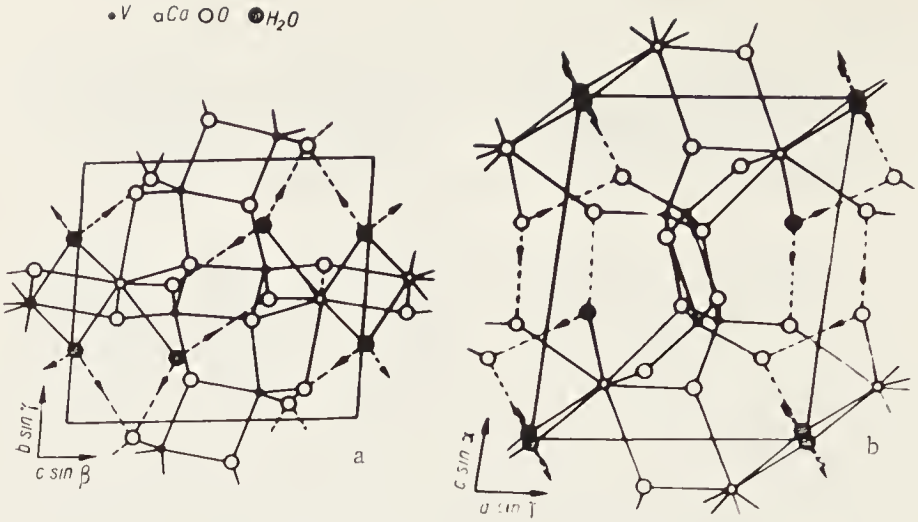


Fig. 232. Structure of metarossite; double chains of V bipyramids along b axis.

with the V polyhedra. The V and Ca polyhedra are substantially distorted, especially the $V-O_5$ one, where the distances range from 1.62 to 2.12. Mean interatomic distances: $V-O_5 = 1.83$, $Ca-O_5(H_2O)_3 = 2.47$. Delrioite and metadelrioite have been assigned to this group from cell parameters and morphology (Smith, 1970 [1291].

Chem. Composition constant, but data inadequate; the general lines of the structure are probably largely unaltered by reduction in water content.

Phys. Rossite forms short columns, perfect cleavage on (010); physical properties and morphology of metarossite not known. Delrioite and metadelrioite form needles and fibrous aggregates.

2. HENDERSONITE GROUP. Orth., $D_{2h}^{16} - Pnma$ (?), $Z = 4$

		a	*b*	*c*	β	ρ	H
Hendersonite	$Ca_2V^{4+}(H_2O)_8[VO_3]_8{}^1_\infty$	12.40	10.77	18.92	—	2.78	~3
Fervanite	$Fe^{3+}[VO_3](OH)_2{}^1_\infty$ (?)	9.02	?	6.65	103° 20′	—	—

Str. Not known, assigned from composition and morphology.

Chem. Ca in hendersonite replaced by Sr (≤1.3%).

Phys. Fibrous to acicular; perfect (100) cleavage in hendersonite.

3. METAHEWETTITE GROUP. Mon.→orth. (?)

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Hewettite	$Ca(H_2O)_9[V_6O_{16}]{}^1_\infty$	$C_{2h}^1 - P2/m$	12.56	3.61	11.47	97°	1	2.62	—
Metahewettite	$Ca(H_2O)_3[V_6O_{16}]{}^1_\infty$	$C_{2h}^3 - A2/m$	12.25	3.61	18.54	118°	2	2.94	—
Barnesite	$Na_2(H_2O)_3[V_6O_{16}]{}^1_\infty$	$C_2^1 - P2$	12.18	3.61	7.80	95°	1	3.2	—
Uvanite	$(UO_2)_2(H_2O)_{15}[V_6O_{17}]{}^1_\infty$	Orth. (?)	—	—	—	—	—	—	—

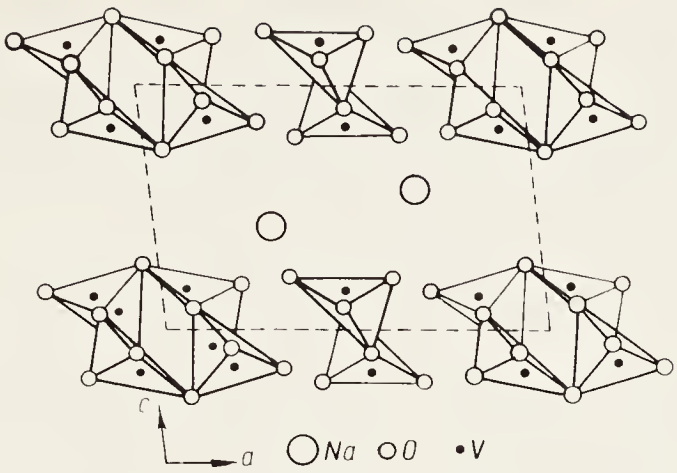


Fig. 233. Structure of metahewettite in projection on (010), which is perpendicular to the direction of the single and paired chains of V bipyramids.

Str. Metahewettite-barnesite has (Bachmann and Barnes, 1962 [293]) two types of zigzag chain composed of VO_5 bipyramids along the b axis. Single chains alternate with paired ones, which are linked by vertices into spiral tubes, giving the chain radical the composition $[V_6O_{16}]_n^{2n-}$ (Fig. 233). Between the chains lie Na(Ca) atoms and H_2O molecules. The mean interatomic distances in the $V-O_5$ bipyramids (three types) range from 1.92 to 1.99. Na in barnesite has four O + two H_2O as nearest neighbors; $Na-(O, H_2O)_6 = 2.38$. Metahewettite has an entirely analogous structure, as does the more hydrated hewettite. Uvanite has not been studied, but it is similar in some properties.

Chem. Composition-variation data inadequate. The V^{5+} in hewettite is replaced by Mo^{6+} (≤1.6%) and V^{4+} (≤1.2%). The Ca in metahewettite is replaced by Na (≤3.7%). Hewettite readily loses water in dry air.

Var. Na-metahewettite, Mo-hewettite.

Phys. Needles on b axis, very much flattened on (001), cleavage not indicated. Uvanite has cleavage in two directions.

4. MELANOVANADITE GROUP. Tricl.→tetr.

		S.g.	a	b	c	Z	ρ	H
Melonovanadite	$Ca_2V_4^{4+}[V_6O_{16}](OH)_{18}\,^1_\infty$	C_1^1-P1	7.97	16.86	9.81	2	3.5	3
		$\alpha = 87°\,55'$ $\beta = 90°\,45'$ $\gamma = 92°\,30'$						
Sherwoodite	$Ca_3V_2^{4+}(H_2O)_9[V_6O_{16}](OH)_{12}\,^1_\infty$	$D_{4h}^{19}-I4_1/amd$	27.8	—	13.8	16		2—2.5

Str. Not known; assigned from composition, morphology, and general crystallochemical arguments on the coordination of V^{5+} and V^{4+}.

Chem. Fairly constant composition; V^{4+} partly replaced by Fe and Al, and Ca by Mg.

Phys. Melanovanadite occurs as radiated masses and columnar crystals with perfect (010) cleavage along the length. Sherwoodite forms isometric crystals (?).

5. PASCOITE GROUP. Mon. → tricl.

	S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Pascoite	$C_2^3 - I2$	16.83	10.16	10.92	2	1.87	3
$Ca_3(H_2O)_{17}[V_{10}O_{28}]\frac{1}{\infty}$			$\beta = 93°\,08'$				
Hummerite	$C_i^1 - P\bar{1}$	10.81	11.01	8.85	1	—	—
$K_2Mg_2(H_2O)_{16}[V_{10}O_{28}]\frac{1}{\infty}$			$\alpha = 106°\,04'$	$\beta = 107°\,49'$		$\gamma = 65°\,40'$	
Huemulite	$C_i^1 - P1(?)$	11.77	11.84	9.02	1	2.40	2.5–3
$Na_4Mg(H_2O)_{24}[V_{10}O_{28}]\frac{1}{\infty}$			$\alpha = 107°13'$	$\beta = 112°10'$		$\gamma = 101°30'$	
Corvusite	Mon.	11.6—11.7	3.65—3.67	(?)	—	2.8	2.5–3
$(Na_2, Ca)V_2^{4+}(H_2O)_{14}[V_{10}O_{28}]O_2\frac{1}{\infty}$							
Grantsite	Mon.	17.54	3.60	12.45	1	2.94	—
$Na_4CaV_2^{4+}(H_2O)_8[V_{10}O_{28}]O_4\frac{1}{\infty}$			$\beta = 95°\,15'$				
Rauvite	—	—	—	—	—	—	—
$Ca(UO_2)_2(H_2O)_{16}[V_{10}O_{28}]\frac{1}{\infty}$							

Str. Known only for pascoite, in which $V_{10}O_{28}$ groups built up from V octahedra are linked into chains by $CaO_2(H_2O)_5$ polyhedra. Between the chains lie $Ca(H_2O)_7$ polyhedra, which link the chains in conjunction with hydroxyl-hydrogen bonds. Interatomic distances: $Ca-O_2(H_2O)_5$ = 2.45 (2), 2.39 (5); $Ca-(H_2O)_7$ = 2.35, 2.41 (4), 2.43 (2); V_1-O_6 = 1.62 (2), 1.90 (2), 2.14 (2); V_2-O_6 = 1.59, 1.82, 1.87 (2), 2.08, 2.31; V_3-O_6 = 1.62, 1.81 (2), 2.00 (2), 2.21 (Swallow et al., 1966 [882]).

Chem. Variation data inadequate. Corvusite has perfect Na–Ca isomorphism, subspecies natrocorvusite and calciocorvusite; V^{5+} is also replaced by V^{4+}, Fe^{3+} (≤12%), and Mo (≤1.6%), and Na and Ca are replaced by K (≤2%). Na:Ca and V^{4+}:V^{5+} in grantsite vary somewhat.

Phys. Mostly fibrous masses composed of needles, sometimes flattened; sometimes cleavage in one direction is observed.

Subclass 3. Layer

1. CARNOTITE-TYUYAMUYUNITE GROUP. Mon. → orth.

Carnotite subgroup. Mon.→tricl., $Z = 4;2$

		S.g.	a	b	c	ρ	H
Vanuralite (alurvanite)	$Al\{(UO_2)_2[V_2O_8]OH\} \cdot 11H_2O$	$C_{2h}^6 - A2/a$	10.55	8.44	24.52	3.6	2.5 (?)
		$\beta = 103°$					
Metavanuralite (metaalurvanite)	$Al\{(UO_2)_2[V_2O_8]OH\} \cdot 8H_2O$	$C_i^1 - P\bar{1}$ (?)	10.46	8.44	10.48	(3.8)	
		$\alpha = 75°53'$ $\beta = 102°50'$ $\gamma = 90°$					
Sengierite	$Cu\{(UO_2)_2[V_2O_8]\} \cdot 9H_2O$	$C_{2h}^5 - P2_1/a$	10.62	8.10	10.11	4.0	3
		$\beta = 103° 40'$					
Carnotite	$K_2\{(UO_2)_2[V_2O_8]\} \cdot 3H_2O$	$C_{2h}^5 - P2_1/a$	10.47	8.41	6.91	(5.0)	2.5—3
		$\beta = 103° 40'$					

Tyuyamuyunite subgroup. Orth., $Z = 4$

	S.g.	a	b	c	ρ	H
Tyuyamuyunite (calcurvanite) $Ca\{(UO_2)_2[V_2O_8]\} \cdot 8H_2O$	Not det.	10.63	8.36	20.40	3.6	2—2.5
Metatyuyamuyunite (metacalcurvanite) $Ca\{(UO_2)_2[V_2O_8]\} \cdot 5H_2O$	$D_{2h}^{16} - Pnam$ (?)	10.63	8.36	16.96	3.9	2.5—3
Curienite (plumurvanite) $Pb\{(UO_2)_2[V_2O_8]\} \cdot 5H_2O$	$D_{2h}^{14} - Pcan$	10.40	5.45	16.34	4.9	(3)
Francevillite (baurvanite) $Ba\{(UO_2)_2[V_2O_8]\} \cdot 5H_2O$	$D_{2h}^{14} - Pcan$	10.41	8.51	16.76	4.6	3.5
Ferganite (urvanite) $\{(UO_2)_3[V_2O_8]\} \cdot 6H_2O$	—	—	—	—	3.3 (?)	~ 3
Vanuranylite (axurvanite) $(H_3O)_2\{(UO_2)_2[V_2O_8]\} \cdot 4H_2O$	Not det.	10.49	8.37	20.30	3.6	2—2.5

Str. Anhydrous carnotite (Fig. 55) shows that the layer pattern is produced by a strong bond between the V_2O_8 radical and the $(UO_2)O_5$ polyhedron, the layers being of composition $\{(UO_2)_2[V_2O_8]\}_n^{2n-}$ (Appleman and Evans, 1957 [295]). These layers (separation about 2.65) are held together by hydroxyl-hydrogen bonds to water molecules, and also by the K, Ca, Ba, Cu, and Al between the layers. The number of H_2O molecules is governed by the size of the atoms and by the external conditions. The (U, V) layers are of lower symmetry than the (U, P) ones because of the complicated form of the V_2O_8 group (two VO_5 trigonal bipyramids linked by a common edge) and also because of the fivefold equatorial coordination of the U^{6+}.

Chem. Fairly constant composition; carnotite, tyuyamuyunite, and francevillite have the largest amounts of isomorphous components. The K in carnotite is replaced by Ca (≤3.3%); the Ca in tyuyamuyunite is re-

placed by Mg (≤1%), K and Na (≤2.5% K + Na), and Cu (≤4.1%?); and the Ba in francevillite is replaced by Pb (≤7.4%). The H_3O in vanuranylite is replaced by Ba (3.2%), Ca (0.6%), and K (0.4%) (Bur'yanova et al., 1965 [883]); the Pb in curienite is replaced by Ba (~1%) (Cesbron and Morin, 1968 [1292]). Vanuralite changes to metavanuralite; this transformation from one to the other being reversibly dependent on the humidity of the atmosphere (Cesbron, 1970 [1293]).

Var. Ca-carnotite, K,Na-tyuyamuyunite, Pb-francevillite.

Phys. Tabular or platy in all cases; (001) basal cleavage perfect. Tyuyamuyunite also has moderate cleavage on (010) and (100), as does ferganite on (100). Francevillite has cleavage on (110).

Inadequately Characterized and Doubtful

Bokite $KAl_2Fe_6V_6^{4+}V_{20}^{5+}O_{76} \cdot 30H_2O$
Kolovratite (hydrated vanadate of Ni and Zn?)
Pintadoite $Ca_2(H_2O)_9[V_2O_7]$
Rusakovite $(Fe, Al)_5[(V, P)O_4]_2(OH)_9 \cdot 3H_2O$
Satpaevite $6Al_2O_3 \cdot V_2O_4 \cdot 3V_2O_5 \cdot 30H_2O$
Vanalite $NaAl_8V_{10}O_{38} \cdot 30H_2O$

CLASS 6. ARSENATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds Class 6. Arsenates																H 97	
2		Be 1														O 110	F 3	
3	Na 5	Mg 12											Al 11		P 2	S 5	Cl 6	
4	K 3	Ca 26		Ti 1			Mn 19	Fe 14	Co 4	Ni 3	Cu 26	Zn 9			As 110			
5		Sr 1	Y 3															
6		Ba 6												Pb 13	Bi 5			
7					U 16													

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
		5				30	36	7	6	22	4

Subclass 1. Framework

1. Pharmacosiderite $(K, H_3O)\{Fe_4[AsO_4]_3(OH)_4\} \cdot 6H_2O^3_\infty$ group
2. Scorodite $Fe(H_2O)_2[AsO_4]^3_\infty$ group

Subclass 2. Insular

Division A. Without Water and Additional Anions

Subdivision I. Simple

1. Rooseveltite $Bi[AsO_4]$ group
2. Xanthiosite $Ni_3[AsO_4]_2$ group

Subdivision II. Complex

1. Stranskiite $Zn_2Cu[AsO_4]_2$ group
2. Berzeliite $NaCa_2(Mg, Mn)_2[AsO_4]_3$ group

Division B. With Additional Anions

Subdivision I. Simple

1. Angelellite $Fe_4[AsO_4]_2O_3$ group
2. Olivenite $CuCu[AsO_4]OH$ group

3. Erinite $Cu_5[AsO_4]_2(OH)_4$ group
4. Clinoelase $Cu_3[AsO_4](OH)_3$ group
5. Allaetite $Mn_7[AsO_4]_2(OH)_8$ group
6. Mimetite $Pb_2Pb_3[(As, P)O_4]_3Cl$ group

Subdivision II. Complex

1. Beudantite $PbFe_3[AsO_4][SO_4](OH)_6$ group
2. Carminite $PbFe_2[AsO_4]_2(OH)_2$ group
3. Flinkite $Mn_2Mn[AsO_4](OH)_4$ group
4. Durangite $NaAl[AsO_4]F$ group
5. Duftite $PbCu[AsO_4]OH$ group
6. Retzian $Mn_2Y[AsO_4](OH)_4$ group

Division C. Hydrated Arsenates Without Additional Anions

1. Pieropharmaeolite $Ca_3(H_2O)_6[AsO_4]_2$ group
2. Lindaekerite $H_2Cu_5(H_2O)_9[AsO_4]_4$ group

Division D. Hydrated Arsenates with Additional Anions

Subdivision I. Simple

1. Euchroite $Cu_2(H_2O)_3[AsO_4]OH$ group
2. Legrandite $Zn_2(H_2O)[AsO_4]OH$ group
3. Hemafibrite $Mn_3(H_2O)[AsO_4](OH)_3$ group

Subdivision II. Complex

1. Arthurite $Cu_2Fe_4(H_2O)_6[AsO_4]_3(OH)_7$ group
2. Liroeonite $Cu_2Al(H_2O)_4[AsO_4](OH)_4$ group
3. Tyrolite $Ca_2Cu_9(H_2O)_{10}[AsO_4]_4(OH)_{10}$ group
4. Lavendulan $NaCaCu_5(H_2O)_5[AsO_4]_4Cl$ group

Subclass 3. Chain

Division A. Anhydrous

1. Weilite $Ca\{H[AsO_4]\}^1_\infty$ group

Division B. Hydrated

1. Mixite $Cu_{12}Bi(H_2O)_9[AsO_4]_6(OH)_9^1{}_\infty$ group
2. Bearsite $Be_2(H_2O)_4[AsO_4]OH^1_\infty$ group
3. Roselite $Ca_2Co(H_2O)_2[AsO_4]_2^1{}_\infty$ group
4. Vladimirite $H_2Ca_5(H_2O)_5[AsO_4]_4^1{}_\infty$ group

Subclass 4. Layer

Division A. Without Water and Additional Anions

1. Hallimondite $Pb_2[(UO_2)(AsO_4)_2]^2_\infty$ group
2. Sehultenite $HPb[AsO_4]^2_\infty$ group

Division B. Hydrated Without Additional Anions

1. Uranium-mica $R(H_2O)_n[UO_2(AsO_4)_2]^2_\infty$ group
2. Erythrite $(Co, Ni)_3(H_2O)_8[AsO_4]_2^2{}_\infty$ group
3. Pharmacolite $HCa(H_2O)_2[AsO_4]^2_\infty$ group

Division C. Hydrated With Additional Anions

1. Walpurgite $Bi_4(H_2O)_3[(UO_2)(AsO_4)_2O_4]^2_\infty$ group
2. Arsenuranylite $Ca(H_2O)_6[(UO_2)_4(AsO_4)_2(OH)_4]^2_\infty$ group
3. Chalcophyllite $\{Cu_6Al(H_2O)_3[AsO_4][SO_4](OH_{10})\}^1 \cdot 8H_2O^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Framework

1. PHARMACOSIDERITE GROUP. Cubic, →Tetr., $Z = 1$

		a	c	ρ	H
Pharmacosiderite	$T_d^1 - P\bar{4}3m$	7.98	—	2.90	3
$(K, H_3O)\{Fe_4[AsO_4]_3(OH)_4\} \cdot 6H_2O$ ∞					
Barium-alumapharmacosiderite	T_d^1—$P\bar{4}3m$	7.89	—	—	2 3
$Ba\{Al_4[AsO_4]_3(OH)_5\} \cdot 5H_2O$ ∞					
Barium-pharmacosiderite	D_{4h}^1—$P4/mmm$	7.97	8.10	3.0	2 3
$Ba\{Fe_4[AsO_4]_3(OH)_5\} \cdot 5H_2O$ ∞					

Str. Framework composed of groups of four $FeO_3(OH)_3$ octahedra (centers of the groups at the vertices of the cubic cell), which are linked to AsO_4 tetrahedra (at centers of edges of cell) (Fig. 234). The octahedra share edges with each other, and vertices with the tetrahedra. The large holes contain zeolitic water and K ions, which are easily replaced by oxonium, so we have continuous $K-H_3O$ isomorphism. Mean inter-

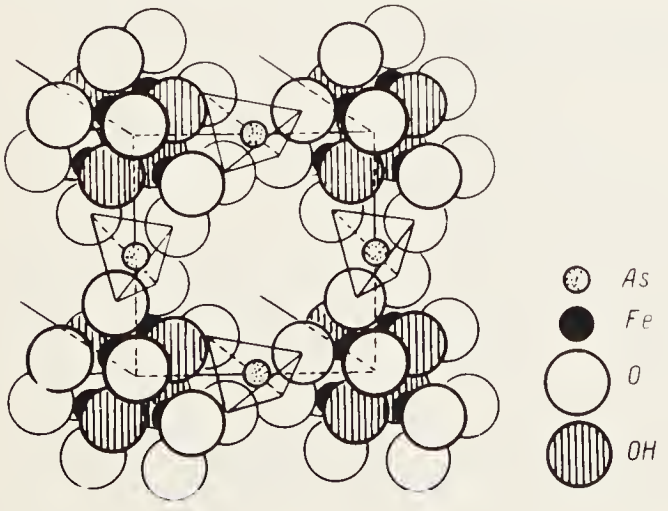


Fig. 234. Structure of pharmacosiderite, showing the linking in the framework.

atomic distances: $K-O_{12} = 3.3$ (?); $Fe-O_3(OH)_3 = 1.94$ (3), 2.11 (3); $As-O_4 = 1.71$; OH–OH and O–OH = 2.80; $H_2O-OH = 3.04$; $H_2O-O = 3.32$ (Zemann, 1948 [886]).

Chem. The perfect $K-H_3O$ isomorphism gives the subspecies kaliopharmacosiderite and oxoniopharmacosiderite. Also, the As is replaced by P (≤2.1%). Composition of barium-pharmacosiderite and barium-alumopharmacosiderite has only been studied by spectral analysis (Walenta, 1966 [1295]).

Phys. Imperfect cleavage on (100).

2. SCORODITE GROUP. Orth., $D_{2h}^{15} - Pcab$, $Z = 8$

		a	*b*	*c*	*ρ*	H
Mansfieldite	$Al(H_2O)_2[AsO_4]$	10.10	9.66	8.72	3.0	3.5—4
Scorodite	$Fe(H_2O)_2[AsO_4]$	10.28	10.00	8.90	3.3	3.5—4

Str. Known for scorodite; pairs of AsO_4 tetrahedra in two orientations and two types of $FeO_4(H_2O)_2$ octahedra, the latter being linked to the former via common O vertices into a framework, leaving two vertices free (with H_2O) in each octahedran. Mean interatomic distances: $Fe_I - O_4(H_2O)_2 = 1.94$ (4), 2.15 (2); $Fe_{II}-O_4(H_2O)_2 = 1.95$ (4), 2.19 (2); $As_I-O_4 = 1.68$; $As_{II}-O_4 = 1.69$ (Kiriyama and Sakurai, 1949 [887]).

Chem. Present data do not demonstrate perfect Al–Fe isomorphism, so the two species cannot be combined into one (Palache et al., 1951 [154]). Scorodite contains up to 5.8% Al; mansfieldite contains only a little Fe^{3+}. As in scorodite is replaced by P (≤16%).

Var. Al-scorodite, PO_4-scorodite.

Phys. Isometric to thick tablets; imperfect cleavage on (201), (001), and (100).

Subclass 2. Insular

DIVISION A. WITHOUT ADDITIONAL ANIONS

Subdivision I. Simple

1. ROOSEVELTITE GROUP. Tetr. → Mon., $Z = 4$

		S.g.	*a*	*b*	*c*	*β*	*ρ*	H
Chernovite	$Y[AsO_4]$	$D_{4h}^{19} - I4_1/amd$	7.04	—	6.27	—	4.9	4.5–5.5
Rooseveltite	$Bi[AsO_4]$	$C_{2h}^5 - P2_1/n$	6.87	7.15	6.73	104°30′	6.9	4–5

Str. Chernovite is of the zircon type (Fig. 166) (Goldin, 1967 [1294]); rooseveltite is analogous to the structure of monazite (Fig. 242)(Bedlivy et al., 1969 [1296]).

Chem. Chernovite contains admixtures of La, Ce, P, V, etc., rooseveltite has not been studied.

Phys. Chernovite has perfect (100) cleavage, moderate on (001) and (110).

2. XANTHIOSITE GROUP. Mon., $C_{2h}^5 - P2_1/a$, $Z = 4$

		a	b	c	β	ρ	H
Xanthiosite (trinicasite)	$Ni_3[AsO_4]_2$	10.17	9.55	5.77	92°59′	5.4	(5)

Str. Not known.

Chem. Ni replaced by Co (≤1.5%), Cu (≤0.7%), and Fe (≤0.7%).

Phys. Habit not reported; cleavage not observed.

Subdivision II. Complex

1. STRANSKIITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 1$

		a	b	c	ρ	H
Stranskiite	$Zn_2Cu[AsO_4]_2$	5.09	6.75	5.30	5.2	4
		$\alpha = 111°00'$		$\beta = 112°30'$		$\gamma = 86°00'$

Str. AsO_4 radicals linked via Cu and Zn polyhedra; Cu has CN = 4 (nearly square), while Zn is surrounded by five oxygen atoms, which form a trigonal bipyramid. Interatomic distances: $Cu-O_4$ = 2.01 (2), 2.07 (2); $Zn-O_5$ = 2.00-2.10 (d_m = 2.05); $As-O_4$ = 1.75-1.78 (d_m = 1.76) (Plieth and Sänger, 1967 [888]).

Chem. Zn replaced by Mg and Fe, and As by Si.

Phys. Perfect cleavage on (010), moderate on (100).

2. BERZELIITE GROUP. Cubic→mon.

		S.g.	a	b	c	Z	ρ	H
Berzeliite	$NaCa_2(Mg, Mn)_2[AsO_4]_3$	$O_h^{10} - Ia3d$	12.37—12.48	—	—	8	4.1—4.5	5.5—5
Caryinite	$NaCaMn_3[AsO_4]_3$	$C_{2h}^6 - C2/c$	12.42	13.17	6.87	4	4.3	4 (?)
				$\beta = 114°05'$				

Str. Berzeliite is isostructural with the garnets (Fig. 167); Na and

Ca have CN = 8, Mg and Mn have CN = 6. Caryinite is probably isostructural with hagendorfite (Strunz, 1957 [113]).

Chem. Berzeliite has perfect Mg−Mn isomorphism; subspecies magnesioberzeliite and manganoberzeliite. Mg(Mn) is also replaced by Fe (≤1%), and As by Sb (≤6.5%), Si (≤9%), and V (≤4.5%). Ca in caryinite is replaced by Pb (≤11.7%), Mn by Mg (≤4.7%).

Var. Na-berzeliite, Sb-berzeliite, SiO_4-berzeliite, Pb-caryinite, Mg-caryinite.

Phys. Berzeliite has no cleavage, caryinite has moderate (100) and (010) cleavage.

DIVISION B. WITH ADDITIONAL ANIONS

Subdivision I. Simple

1. ANGELELLITE GROUP. Tricl.→mon.

		S.g.	a	b	c	Z	ρ	H
Angelellite	$Fe_4[AsO_4]_2O_3$	$C_i^1 - P1$ (?)	5.03	6.49	7.11	1	4.9	5.5—6
		$\alpha = 114°24'$	$\beta = 116°24'$	$\gamma = 81°54'$				
Atelestite	$Bi_2[AsO_4]O(OH)$	$C_{2h}^2 - P2_1/m$	7.01	7.46	11.03	4	6.8	5—5.5
		$\beta = 109°57'$						

Str. Not known. A different formula has been proposed for atelestite: $Bi_8[AsO_4]_3O_5(OH)_5$, s.g. $C_{2h}^5 - P2_1/a$; $a = 10.88$, b = 7.42, c = 6.98, $\beta = 107°13'$, Z = 1 (Culver and Berry, 1963 [889]).

Chem. Data on composition variations inadequate.

Phys. Cleavage on (001) moderate to imperfect (atelestite).

2. OLIVENITE GROUP. Orth. → tricl. → mon.

		S.g.	a	b	c	Z	ρ	H
Olivenite	$CuCu[AsO_4]OH$	$D_{2h}^{13} - Pnmm$	8.64	8.22	5.95	4	4.6	3.5
Adamite	$ZnZn[AsO_4]OH$	$D_{2h}^{12} - Pnnm$	8.34	8.56	6.09	4	4.4	3.75
Eveite	$MnMn[AsO_4]OH$	$D_{2h}^{12} - Pnnm$	8.57	8.77	6.27	4	3.7	3.5—4
Paradamite (triclinoadamite)	$Zn_2[AsO_4]OH$	$C_i^1 - P\bar{1}$	5.81	6.67	5.63	2	4.5	(3.75)
			$\alpha = 104°15'$	$\beta = 87°52'$	$\gamma = 103°12'$			
Sarkinite	$Mn_2[AsO_4]OH$	$C_{2h}^5 - P2_1/a$	12.68	13.54	10.17	16	4.1	4 (?)
				$0 = 108°44'$				
Aerugite	$Ni_8[AsO_4]_2O_3$ (?)	$C_{2h}^6 - C2/c$ (?)	10.29	5.95	9.79	3	5.9	(4—4.5)
				$\beta = 110°19'$				

Str. Adamite is isostructural with andalusite, which is homostructural with olivenite; Cu and Zn have CN of 5 and 6. Interatomic dis-

tances: in adamite Zn—O_4OH = 1.84 (2), 1.99, 2.19, 1.91; Zn- $O_4(OH)_2$ = 2.08 (2), 2.29 (2), 2.08 (2); As—O_4 = 1.59 (2), 1.81 (2) (Kokkoros, 1937 [890]); in olivenite Cu—O_4OH = 1.92, 2.16 (2), 2.03 and 1.99; Cu—$O_4(OH)_2$ = 2.12 (2), 2.34 (2), and 1.96 (2); As—O_4 = 1.64 (Heritsch, 1938 [891]). Structures of paradamite and sarkinite not studied, but sarkinite is isostructural with triploidite (Strunz, 1957 [113]) and paradamite is the same with tarbuttite (Finney, 1966 [894]). The interatomic distances in eveite: Mn—O_6 = 2.14-2.29 (d_m = 2.19); Mn—O_5 = 2.10-2.16 (d_m = 2.12); As—O_4 = 1.65-1.73 (d_m = 1.69) (Moore, 1968 [1297]).

Chem. Variable. Cu in olivenite replaced by Zn (≤22.5%) and Fe (≤2.8%), As replaced by P (≤6%). Zn in adamite is replaced by Cu (≤23.5%), Co (≤5.2%), Fe (≤1.5%). Mn in sarkinite is replaced by Mg (≤6.1%), Fe (≤3.1%), and Ca (≤2.9%), and As by Sb (≤3%). Aerugite contains small amounts of Fe, Co, and Cu; its composition has also been described as $Ni_{18}[AsO_4]_5[AsO_3]O_9$, Z = 1 (Davis et al., 1965 [892]).

Var. Zn-olivenite, Fe-olivenite, PO_4-olivenite, Cu-adamite, Co-adamite, Fe-adamite, Mg-sarkinite, Fe-sarkinite, Ca-sarkinite.

3. ERINITE GROUP. Mon.→tricl.→orth.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Erinite	$Cu_5[AsO_4]_2(OH)_4$	$C_{2h}^5 - P2_1/a$	17.61	5.81	4.60	92° 15′	2	(4.7)	5
Cornubite (triclinoerinite)	$Cu_5[AsO_4]_2(OH)_4$	Not det.	—	—	—	—		4.6	(5)
Arsenoclosite	$Mn_5[AsO_4]_2(OH)_4$	D_2^4—$P2_12_12_1$	9.31	5.75	18.84	—	4	4.3	5,5—6

Str. Erinite is isostructural with pseudomalachite; sub-layered, consisting of linked chains of $Cu(O,OH)_6$ octahedra. Arsenoclasite has the new parameters from the data by Moore [1164]. Cornubite differs considerably in powder pattern from erinite.

Chem. Cu in erinite replaced by Zn (≤1%) and As by P (≤2.7%). Only minor components in arsenoclasite.

Var. PO_4-chalcophyllite.

Phys. Perfect (010) cleavage.

4. CLINOCLASE GROUP. Mon.. $C_{2h}^5 - P2_1/a$, $Z = 4$

		a	*b*	*c*	β	ρ	H
Clinoclose	$Cu_3[AsO_4](OH)_3$	12.38	6.46	7.24	99° 30′	4.4	3—3.5
Georglodesite	$Pb_3[AsO_4]Cl_3$	—	—	—	102° 34′	7.1	3.75
Sohlinite	$Pb_{14}[AsO_4]_2O_9Cl_4$	—	—	—	—	8.0	2.5—3.5

Str. Known for clinoclase; the other two species probably have little in common with this. Tetragonal $Cu(O, OH)_5$ pyramids occur singly and in pairs, the latter sharing a base edge, with the tops facing in op-

posite directions (as in carnotite, Fig. 55), to give $Cu_2O_4(OH)_4$ groups, whieh are linked by the single $Cu(O, OH)_5$ pyramids and AsO_4 tetrahedra into layers parallel to (001). But these layers are linked one to another by nearly as strong (O, OH) bonds, so the strueture is sublayered. Mean interatomie distanees: $Cu_I-O_3(OH)_2 = 2.08$; $Cu_{II}-O_2(OH)_3 = 2.14$; $Cu_{III}-O_3(OH)_2 = 2.09$; $As-O_4 = 1.71$ (Ghose et al., 1965 [893]). Georgiadesite and sahlinite may be layered.

Phys. Clinoelase is eolumnar to tabular; the others oeeur as thiek tablets (data seanty). Perfect eleavage on (001) in elinoelase and on (010) in sahlinite; no eleavage reported for georgiadesite.

5. ALLACTITE GROUP. Mon.→tricl. (pseudoorth.)

		S.g.	a	b	c	β	Z	ρ	H
Allactite	$Mn_7[AsO_4]_2(OH)_8$	$C_{2h}^5 - P2_1/a$	11.03	12.12	5.51	114° 04′	2	3.9	5
Synadelphite	$Mn_4[AsO_4](OH)_5$	Not det.	9.93	18.74	10.67	90°	10	3.6	5
			$\alpha = \gamma = 90°$						

Str. Allaetite eonsists of sub-layered MnO_6 octahedra which are eonnected with other Mn oetahedra and AsO_4 tetrahedra. The mean interatomic distanees are: $Mn_1-O_6 = 2.27$; $Mn_2-O_6 = 2.23$; $Mn_3-O_6 = 2.18$: $Mn_4-O_6 = 2.19$; $As-O_4 = 1.68$ (Moore, 1968 [1154]). Another formula of synadelphite may be found in [1407].

Chem. Allaetite eontains isomorphous Mg (≤2%), while Mn in synadelphite is replaced by Mg (≤6.2%), Pb (≤3.2%), and Ca (≤1.6%), and As is replaced by Si (≤1.5%).

Var. Mg-synadelphite, Pb-synadelphite, SiO_4-synadelphite.

Phys. Short eolumns to tabular, moderate to imperfeet eleavage on (001) in allaetite, on (010) in synadelphite.

6. MIMETITE GROUP. Hex., $C_{6h}^2 - P6_3/m$, $Z = 2$

		a	c	ρ	H	Cl.
Mimetite	$Pb_2Pb_3[(As, P)O_4]_3Cl$	10.38—9.97	7.54—7.33	7.3—7.1	3.5—4	$(10\bar{1}0)$ imperf.
Svabite	$Ca_2Ca_3[AsO_4]_3(OH, F)$	9.72	6.96	3.5	4.5—5.5	$(10\bar{1}0)$ imperf.

Str. Apatite type; Pb and Ca have CN of 7 and 9 (Fig. 243).

Chem. Perfect As−P isomorphism in mimetite, so pyromorphite is deleted as an independent speeies, there being instead the two subspeeies arsenomimetite and phosphoromimetite. The other isomorphous eomponents are Ca (≤15%), Ba (≤8.3%), and V^{5+} (≤4.1%). Svabite eon-

tains Mg (≤3.9%), Pb (≤4.5%), Mn (≤1.2%), and P^{5+} (≤12.5%). Perfect F−OH isomorphism, so we have hydroxylsvabite and fluorosvabite. Minute traces of Cl.

Var. Ca-phosphoromimetite, Ca-arsenomimetite, Ca,Ba-arsenomimetite, VO_4-mimetite, PO_4-svabite, Pb-svabite, Mg-svabite, Mn-svabite.

Subdivision II. Complex

1. BEUDANTITE GROUP. Trig., $D_{3d}^5 - R\bar{3}m$, $Z = 1; 3$

		a_{rh}	α	a_h	c_h	ρ	H
Hidalgoite	$PbAl_3[AsO_4][SO_4](OH)_6$	6.97	60° 40′	7.04	16.99	(4.3)	4.5—5
Beudantite	$PbFe_3[AsO_4][SO_4](OH)_6$	7.07	62°20′	7.32	17.02	4.4	3.75—4.5
Weilerite	$BaAl_3[AsO_4][SO_4](OH)_6$	7.02.	60°18′	7.05	17.16	(3.6)	(4.5—5)
Dussertite	$BaFe_3[AsO_4]_2(OH)_5(H_2O)$	7.23	61°37′	7.40	17.48	3.8	3.75—4
Kemmlitzite	$SrAl_3[AsO_4][SO_4](OH)_6$	6.84	61°51′	7.03	16.51	3.6	5—5.5

Str. Alunite type; Pb(Ba) CN = 12, Al(Fe) has CN = 6 (Fig. 258b). Lattice parameters for beilerite from data of Walenta (1966) [1020]).

Chem. Isomorphous components unimportant; data on weilerite and dussertite inadequate.

Phys. Usually massive cryptocrystalline aggregates.

2. CARMINITE GROUP. Orth.→mon.

		S.g.	a	b	c	β	Z	ρ	H
Carminite	$PbFe_2[AsO_4]_2(OH)_2$	$D_{2h}^{20} - Cccm$ (?)	12.29	16.59	7.58	—	8	5.2	(4.5—5)
Bayldanite	$PbCu_3[AsO_4]_2(OH)_2$	Not det.	5.03	5.97	6.93	103°	1	5.5	5
Plumcusulasite	$Pb_2Cu[AsO_4][SO_4]OH$	$C_{2h}^2 - P2_1/m$	8.85	5.92	7.84	112°36′	2	6.4	(4.5–5)

Str. Known only for carminite, which is closely related to brackebuschite $Pb_2(Mn, Fe)(H_2O)[VO_4]_2$ (Finney, 1963 [895]). There are two types of AsO_4 tetrahedra, whose mean As−O_4 distances are respectively 1.64 and 1.74. Fe has a nearly regular octahedral environment of four O plus two OH, distances 2.06 (4) and 1.95 (2). Pb (also two types) has CN = 8; mean Pb−O_8 distances 2.67 and 2.69. Plumcusulasite was named by me according to a rational system [896]. H. Strunz assigns to it the name "arsentsumebite" [1236].

Chem. Carminite has a constant composition; Cu in bayldonite is replaced by Fe (≤5.75%).

Var. Fe-bayldonite.

3. FLINKITE GROUP. Orth.→trig.→mon.→cubic

	S.g.	a	b	c	β	Z	ρ	H
Flinkite $Mn_2Mn[AsO_4](OH)_4$	D_{2h}^{16}—$Pnma$	9.55	13.11	5.25	—	4	(3.7)	5
Hematolite $Mn_4Al[AsO_4](OH)_8$	$C_{3i}^2 - R\bar{3}$	8.29	—	36.58	—	3	3.5	3.75
Chlorophoenicite $Mn_3Zn_2[AsO_4](OH)_7$	C_{2h}^3—$C2/m$	22.98	3.23	7.32	106°00′	2	3.5	3.75
Mogchlorophoenicite $Mg_3Mn_2[AsO_4](OH)_7$	Not det.	—	—	—	—	—	3.4	(3.5)
Holdenite $Mn_4Zn_2[AsO_4]O_2(OH)_5$	$D_{2h}^{21} - Bmam$	11.99	31.21	8.60	—	2	4.1	4
Coforsite $Ca_6Mn_2Fe_4Ti_3[AsO_4]_{12}(OH)_4$	T_h^2—$Ph3$	16.01	—	—	—	4	3.9	(5–5.5)

Str. Flinkite [1129] and chlorophoenicite have been studied [1161], in which the Mn polyhedra are layered with pyrochroite $Mn(OH)_2$ structure fragments, causing the subschistosity of these structures. Cafarsite placed here conditionally (Graeser, 1966 [1396]).

Chem. The following components occur: in flinkite Mg (1.7%), Fe^{3+} (1.5%), Sb^{5+} (2.5%); in hematolite Mg (7.1%), Fe^{3+} (1.5%); in chlorophoenicite Ca (3.4%), Mg (1.3%); in magchlorophoenicite Zn (8.9%), Fe^{3+} (3.85%), Si (3.4%); in holdenite Ca (3%), Fe (2%), Mg (1.6%).

Var. Sb-flinkite, Fe-flinkite, Mg-hematolite, Ca-chlorophoenicite, Zn-magchlorophoenicite, Fe-magchlorophoenicite, Ca-holdenite, Fe-holdenite.

4. DURANGITE GROUP. Mon., $C_{2h}^6 - C2/c$, $Z = 4$

		a	b	c	β	ρ	H
Durongite	$NaAl[AsO_4]F$	6.54	8.48	7.31	119° 22′	4	5.5
Tilosite	$CaMg[AsO_4]F$	6.67	8.97	7.58	121° 00′	3.8	5—5.5

Str. Isostructural with sphene $CaTi[SiO_4]O$; Na(Ca) has CN = 7, Al(Mg) has CN = 6. Sublayered.

Chem. Na in durangite replaced by Li (≤0.7%), and Al by Fe^{3+} (≤9.2%) and Mn^{3+} (≤2.1%); no major components in tilasite.

Var. Fe^{3+}-durangite.

Phys. Moderate cleavage in one direction.

5. DUFTITE GROUP. Orth., $D_2^4 - P2_12_12_1$; $Z = 4$

		a	b	c	ρ	H	Cl.
Duftite	$PbCu[AsO_4]OH$	5.91	9.14	7.52	6.4	4.5—5	None
Conichalcite	$CaCu[AsO_4]OH$	5.85	9.23	7.43	4.3	5	None
Austinite	$CaZn[AsO_4]OH$	5.91	9.02	7.44	4.4	5.5	(011) ·m
Adelite	$CaMg[AsO_4]OH$	5.89	8.87	7.44	3.8	5.5	None
Gobrielsanite	$PbFe[AsO_4]OH$	5.98	8.62	7.86	6.2	4.5	—

Str. Descloizite type (see Section IB of vanadates); Ca(Pb) has CN = 8, Cu(Zn, Mg) has CN = 6. Mean interatomic distances in conichalcite: Ca–O_7OH = 2.51; Cu–$O_4(OH)_2$ = 2.20 (4) and 1.95 (2); As–O_4 = 1.69 (Qurashi and Barnes, 1963 [897]).

Chem. Isomorphous components mostly minor. Conichalcite contains Zn (≤7.3%) and Mg (≤1.9%); As^{5+} replaced by P^{5+} (8.8%) and V^{5+} (2.1%). Austinite contains a little Cu. Adelite has Ca replaced by Pb (≤2.8%) and Mn (≤4.4%), As by P (≤3%), and OH by F (≤1.4%).

Var. Zn-conichalcite, PO_4-conichalcite, VO_4-conichalcite, Cu-austinite, Mn-adelite, Pb-adelite, PO_4-adelite, F-adelite.

6. RETZIAN GROUP. Orth. D_{2h}^4—*Pban*, $Z = 2$

		a	*b*	*c*	*ρ*	H
Retzian	$Mn_2Y[AsO_4](OH)_4$	5.67	12.03	4.86	4.2	4.5

Str. Sublayered similar to flinkite, built up on the basis of pyrochroite $Mn(OH)_2$ structure, in which part of the Mn positions are occupied by Y in eightfold coordination. Cation layers are connected by AsO_4 radicals. The interatomic distances are: Mn–O_6 = 2.32 (2), 2.10 (2), 2.12 (2); Y–O_8 = 2.52 (4), 2.50 (4); As–O_4 = 1.60 (Moore, 1967 [1129]).

Chem. One analysis only; a little Mg (2.7%) and Fe^{2+} (1.7%).

Phys. Thick tablets, no cleavage.

DIVISION C. HYDRATED ARSENATES WITHOUT ADDITIONAL ANIONS

1. PICROPHARMACOLITE GROUP. Tricl. → orth., S.g. not det., $Z = 1;4$

		a	*b*	*c*	*ρ*	H
Picropharmacolite	$H_2Ca_4Mg(H_2O)_{11}[AsO_4]_4$	13.55	13.56	6.74	2.62	—
		$\alpha = 99°38'$	$\beta = 96°07'$	$\gamma = 91°31'$		
Trichalcite	$Cu_3(H_2O)_5[AsO_4]_2$	26.95	5.58	10.36	(3.5)	3

Str. Not established, parameters of picropharmacolite based on the data of Abona et al., 1969 [898]. The rational name is to be preferred, as picropharmacolite can lead to misunderstanding.

Chem. Ca:Mg ratio is not constant (Dana, [154]); in trichalcite some As is replaced by P [154].

Phys. Needles, cleavage in one direction. Trichalcite is platy.

2. LINDACKERITE GROUP. Mon.→tricl.

		a	b	c	β	Z	ρ	H
Lindackerite	$H_2Cu_5(H_2O)_9[AsO_4]_4$	3.95	8.02	6.28	100° 30′	1	3.3	2.5—3.5
Rösslerite	$HMg(H_2O)_7[AsO_4]$	6.73	25.92	11.61	95° 23′	8	1.93	2.5—3.5
Chudöbaite	$NaHMg_2(H_2O)_4[AsO_4]_2$	7.69	11.37	6.59	95° 54′	2	2.91	3—3.5
			$\alpha = 115°\ 10'$		$\gamma = 94°\ 06'$			

Str. Not known; assigned to a group from composition. Space group of rösslerite C_{2h}^6–C2/c (Fischer, 1960 [899]).

Chem. Data inadequate. Cu in lindackerite replaced by Co (2.3%) and Ni (1.5%); Na in chudobaite replaced by K (2%) and Mg by Zn (11.5%) and Mn (2%).

Phys. Lindackerite tabular, rösselerite columnar, chudobaite isometric. Cleavage on (010) perfect, on (100) and (001) (lindackerite) moderate. Imperfect cleavage on (111) in rösslerite.

HYDRATED ARSENATES WITH ADDITIONAL ANIONS

Subdivision I. Simple

1. EUCHROITE GROUP. Orth. → mon.

		S.g.	a	b	c	Z	ρ	H
Euchroite	$Cu_2(H_2O)_3[AsO_4]OH$	$D_2^4-P2_12_12_1$	10.07	10.52	6.12	4	3.4	3.5—4
Strashimirite	$Cu_4(H_2O)_{2.5}[AsO_4]_2(OH)_2$	$C_{2h}^1-P2'm$	9.70	18.98	9.13	6	3.8	(4)
				$\beta = 97°15'$				

Str. Chains of distorted Cu octahedra along c axis linked by AsO_4 tetrahedra to form uneven layers parallel to (100). Interatomic distances: $Cu_I-O_2(OH)_2(H_2O)_2$ = 1.97 (2), 1.99 (2), 2.41 (2); $Cu_{II}-O_3(OH)(H_2O)_2$ = 2.11 (3), 2.01, 2.37 (2); $As-O_4$ = 1.67 (Finney, 1966 [900]).

Phys. Isometric, highly imperfect cleavage; strashimirite is scaly and fibrous [1301].

2. LEGRANDITE GROUP. Mon., $C_{2h}^5-P2_1/c$, $Z = 8$

		a	b	c	β	ρ	H
Legrandite	$Zn_2(H_2O)[AsO_4]OH$	12.80	7.94	10.22	104° 12′	4.0	(4,5—5)

Str. Not known; formula and space group recently revised (Finney, 1963 [901]; Desaultels and Clarke, 1963 [902]).

Chem. Zn replaced by Mn (1.7%) and Fe (1.4%).

Phys. Columnar, moderate (100) cleavage.

3. HEMAFIBRITE GROUP. Orth.→mon.

		S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Hemafibrite	$Mn_3(H_2O)[AsO_4](OH)_3$	D_{2h}^{16}—*Pbnm* (?)	9.87	10.73	18.84	12	3.7	3.5
Liskeardite	$Al_3(H_2O)_5[AsO_4](OH)_6$		—	—	—	—	3.0	4
Arsenobismite	$Bi_4(H_2O)[AsO_4]_3(OH)_3$ (?)		—	—	—	—	5.1	3
Sarmientite	$Fe_2(H_2O)_5[AsO_4][SO_4]OH$	C_{2h}^5—$P2_1/c$	6.55	18.55	9.70	4	2.58	—
			$\beta = 97°39'$					

Str. Not known. Hemafibrite has columnar crystals, moderate (100) cleavage; the others occur as cryptocrystalline aggregates. The parameters of hemafibrite are given in [1164], those of sarmientite in [1397].

Subdivision II. Complex

1. ARTHURITE GROUP. Mon., s.g. not det., $Z = 1$

		a	*b*	*c*	β	*ρ*	H
Arthurite	$Cu_2Fe_4(H_2O)_8[AsO_4]_4(OH)_4$	10.09	9.62	5.55	92° 12′	3.1	—

Str. Not known. Occurs as cryptocrystalline masses and encrustations. The cell contents of arthurite have been redetermined by Davis and Hey [1299].

2. LIROCONITE GROUP. Mon., $C_{2h}^6 - I2/a$, $Z = 4$

		a	*b*	*c*	β	*ρ*	H
Liroconite	$Cu_2Al(H_2O)_4[AsO_4](OH)_4$	12.70	7.57	9.88	91° 23′	3.1	2.5—3
Cerulé́ite	$CuAl_4(H_2O)_4[AsO_4]_2(OH)_8$	—	—	—	—	2.80	(3.5)

Str. Known only for liroconite; AsO_4 tetrahedra alternate with $AlO_2(OH)_4$ octahedra to form chains linked by Cu in very distorted octahedral coordination to O, OH, and H_2O. Interatomic distances: $Cu-O_2(OH)_2(H_2O)_2$ = 1.98 (2), 1.98 (2), and 2.61 (2); $Al-O_2(OH)_4$ = 1.89 (2) and 1.92 (4); $As-O_4$ = 1.65 (Giuseppetti et al., 1962 [903]; Kolesova, 1967 [980]).

Chem. As in liroconite replaced by P (≤3.7%) and Al by Fe (≤1%).

Var. PO_4-liroconite.

Phys. Tabular to isometric, imperfect cleavage on (110) and (011)

3. TYROLITE GROUP. Orth.→mon.

		a	*b*	*c*	β	*Z*	ρ	H
Chenevixite	$Cu_2Fe_2(H_2O)[AsO_4]_2(OH)_4$	12.3	15.4	10.7	—	8	3.9	4
Tyrolite	$Ca_2Cu_9(H_2O)_{10}[AsO_4]_4(OH)_{10}$	10.50	54.71	5.59	—	4	3.3	2.–2.5
Akrochordite	$MgMn_4(H_2O)_4[AsO_4]_2(OH)_4$	5.70	17.60	6.75	99°48′	2	3.2	3.75

Str. Not known, assigned here only from composition. Space group of tyrolite D^5_{2h}–Pmn*a* (?); of akrochordite, C^5_{2h}–$P2_1/C$ [1164].

Chem. Fe in chenevixite replaced by Al (≤2.3%) and As by P (≤2.3%). As in tyrolite replaced by S (≤2.45%).

Var. PO_4-chenevixite, SO_4-tyrolite.

Phys. Chenevixite and tyrolite have platy to tabular crystals. Tyrolite has perfect (001) cleavage and low hardness; it may have a layered structure.

4. LAVENDULAN GROUP. Orth. →mon., s.g. not det., $Z = 8; 18$

		a	*b*	*c*	ρ	H
Lavendulon	$NaCaCu_5(H_2O)_5[AsO_4]_4Cl$	9.73	41.0	9.85	3.5	3.5–4
Zinklavendulon	$NaCaZn_5(H_2O)_5[AsO_4]_4Cl$	9.87	38.7	9.99	(3.6)	(4)
Shubnikovite	$KCaCu_5(H_2O)_5[AsO_4]_4Cl$	30.1	14.01	14.08	3.4	(3.5)
			$\beta = 90°$			

Str. Not studied, but isostructural with sampleite, a phosphate of analogous composition (Strunz, 1957 [113]). Zinklavendulan data after Strunz (1960 [1298]); shubnikovite was discovered by Nefedov [1306].

Phys. Occurs as platy aggregates, perfect (010) cleavage.

Subclass 3. Chain

DIVISION A. ANHYDROUS

1. WEILITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 2$

		a	*b*	*c*	α	β	γ	ρ	H
Weilite	$Ca\{H[AsO_4]\}\frac{1}{\infty}$	7.11	6.94	7.15	94° 19′	101° 35′	87° 22′	3.5	(3.5)

Str. Isostructural with monetite $CaHPO_4$. Morphology not known (occurs as pseudomorphs after pharmacolite). Artificial crystals tabular (Pierrot, 1964 [904]).

DIVISION B. HYDRATED

1. MIXITE GROUP. Hex., $C_{6h}^2 - P6_3/m$ or $C_6^6 - P6_3$, $Z = 2$

		a	c	ρ	H
Mixite	$Cu_6Bi(H_2O)_3[AsO_4]_3(OH)_6$	13.63	5.90	3.8	3—4
Chlorotile	$Cu_6(H_2O)_6[AsO_4]_3(OH)_3$	13.61	5.90	(4.0)	3—4
Agordite	$Cu_6Y(H_2O)_3[AsO_4]_3(OH)_6$	13.55	5.87	3.7	(4)

Str. Not known. It is very unusual for two minerals of substantially different composition to have almost identical structures (Walenta, 1960 [905]). Previously considered as identical (synonyms).

Chem. Mixite has Cu replaced by Zn (2.7%) and Fe (1.5%); agardite has Y replaced by Ca (2.6%) and TR (1.2%) (Dietrich et al., 1969 [1300]).

Phys. Thin needles to fibers, elongated on c axis with longitudinal striation. Imperfect cleavage on pyramid.

2. BEARSITE GROUP. Mon., $C_s^4 - Cc$ or $C_{2h}^6 - C2/c$, $Z = 12$

		a	b	c	β	ρ	H
Beorsite (behyosite)	$Be_2(H_2O)_4[AsO_4]OH$	8.55	36.90	7.13	97° 49′	2.20	(4)

Str. Not known, but isostructural with moraesite $Be_2(H_2O)_4[PO_4]OH$, whose parameters are precisely those of bearsite (Kopchenova and Sidorenko, 1962 [906]).

Phys. Acicular and fibrous (on c axis), aggregates of tangled fibers.

3. ROSELITE GROUP. Mon.→tricl., $Z = 2, 1$

	S.g	a	b	c	β	ρ	H
Roselite	$C_{2h}^5 - P2_1/c$	5.61	12.83	5.61	100° 45′	3.8	3.5—4
$Ca_2\{Co(H_2O)_2[AsO_4]_2\}$							
Brondtite	$C_{2h}^5 - P2_1/c$	5.66	12.83	5.66	99° 30′	3.7	3.5—4
$Ca_2\{Mn(H_2O)_2[AsO_4]_2\}$							
Triclinoroselite	Tricl.	—	—	—	—	3.7	3.5—4
$Ca_2\{Co(H_2O)_2[AsO_4]_2\}$							
Tolmessite	$C_i^1 - P\bar{1}$	5.89	7.69	5.56	70° 49′	3.4	3.5—4
$Ca_2\{Mg(H_2O)_2[AsO_4]_2\}$		$\alpha = 112°\,38'$		$\gamma = 119°\,25'$			

Str. Roselite and brandtite are isostructural with the chain mineral kröhnkite $Na_2\{Cu(H_2O)_2[SO_4]_2\}$. Triclinoroselite and talmessite are very similar to the first (see cell parameters). The chain pattern

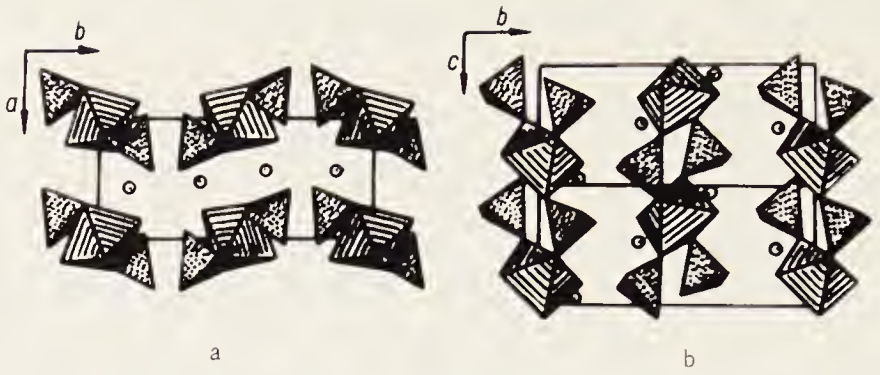


Fig. 235. Structure of roselite in two projections showing: a) the Co octahedra surrounded by two As tetrahedra, b) chains of Co octahedra and As tetrahedra. Ca atoms shown by circles.

is produced by Co(Mn, Mg)$-O_4(H_2O)_2$ octahedra, which are linked via common O vertices with AsO_4 tetrahedra into chains along the c axis (Fig. 235). These chains are linked together by Ca atoms (CN = 7) forming nets parallel to the *a* axis. Interatomic distances: in brandtite $Ca-O_6(H_2O)$ = 2.46 (6) and 2.37; $Mn-O_4(H_2O)_2$ = 2.19 (2), 2.27 (2), and 2.11 (2); $As-O_4$ = 1.67 (Dahlman, 1952 [296]); in roselite $Ca-O_6(H_2O)$ = 2.17-2.78; $Co-O_4(H_2O)_2$ = 2.03 (4), 2.12 (2); $As-O_4$ = 1.72 (Mustafaev et al., 1964 [297]).

Chem. Co in roselite replaced by Mg up to 1:1; brandtite contains Mg (1%) and Pb (1%); triclinoroselite has Co replaced by Ni (1.4%) and Mg (8.6%); talmessite has Ca replaced by Ba (3.2%).

Var. Mg-roselite, Mg-triclinoroselite, Ni-triclinoroselite, Ba-talmessite.

Phys. Short columns, also radially radiated aggregates; perfect (010) cleavage.

4. VLADIMIRITE GROUP. Mon.→tricl., $Z = 4$

		S.g.	*a*	*b*	*c*	β	ρ	H
Sainfeldite	$H_2Ca_5(H_2O)_4[AsO_4]_4\ {}^1_\infty$	$C^6_{2h}-C2/c$	18.64	9.81	10.12	97°	3.0	—
Vladimirite	$H_2Ca_5(H_2O)_5[AsO_4]_4\ {}^1_\infty$	$C^5_{2h}-P2_1/c$	5.81	10.19	22.75	112°41′	3.2	—
Guerinite	$H_2Ca_5(H_2O)_9[AsO_4]_4\ {}^1_\infty$	Not det.	—	—	—	—	2.68	—
Rauenthalite	$Ca_3(H_2O)_{10}[AsO_4]_2\ {}^1_\infty$	Tricl. (?)	—	—	—	—	2.36	—

Str. Not known; assigned to chain type from morphology and crystallochemical arguments. Cell parameters from Pierrot (1964 [904]).

Chem. Composition extremely constant.

Phys. Laths and needles, radially radiated spherical aggregates. Cleavage and hardness not reported.

Subclass 4. Layer

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. HALLIMONDITE GROUP. Tricl., $C_i^1 - P\bar{1}$, Z = 2.

		a	b	c	ρ	H
Hallimandite	$Pb_2[(UO_2)(AsO_4)]_2^2\infty$	7.12	10.47	6.84	6.4	3—3.5
		$\alpha = 100°34'$	$\beta = 94°48'$	$\gamma = 91°16'$		

Str. Not known; assigned from morphology and crystallochemical arguments.

Chem. Data inadequate; formula derived by comparison with synthetic material (Walenta, 1965 [907]).

Phys. Tabular to platy, cleavage not observed. Biaxial positive.

2. SCHULTENITE GROUP. Mon.. $C_{2h}^4 - P2/a$ ($C_s^2 - Pa$), Z = 2

		a	b	c	β	ρ	H
Schultenite	$HPb[AsO_4]_\infty^2$	5.83	6.76	4.85	95°24'	6.1	2.5—3

Str. Differs from monetite $CaH[PO_4]$ in having a preferred distribution of bonds parallel to (010); Pb has CN = 8. Mean interatomic distances: $Pb-O_8 = 2.72$; $As-O_4 = 1.76$ (SR XIII, p. 309 [908]).

Phys. Tabular on b axis, moderate (010) cleavage.

DIVISION B. HYDRATED WITHOUT ADDITIONAL ANIONS

1. URANIUM-MICA GROUP

There are three subgroups, which are differentiated on details of structure and water content, the water being partly zeolitic: zeunerite ($H_2O > 8$), metazeunerite ($8H_2O$), and abernathyite ($3H_2O$).

Zeunerite subgroup. Tetr., $D_{4h}^{17} - I4/mmm$ or $C_{4h}^4 - P4_2/n$, Z = 2

	a	c	ρ	H
Zeunerite $Cu(H_2O)_8[UO_2(AsO_4)]_2 \cdot nH_2O_\infty^2$	7.18	21.06	3.5	2—3
Maguraspyllite $Mg(H_2O)_8[UO_2(As, P)O_4]_2 \cdot nH_2O_\infty^2$	7.16—7.02	20.19—19.81	3.7—3.2	2—3
Heinrichite $Ba(H_2O)_7[UO_2(AsO_4)]_2 \cdot nH_2O_\infty^2$ (?)	7.13	20.56	—	2—3

Metazeunerite subgroup. Tetr.

	S.g.	a	c	Z	ρ	H
Metozeunerite $Cu(H_2O)_8[UO_2(AsO_4)]_2$	$C_{4h}^3 - P4/n$ (?)	7.12	17.45	2	3.8	2—3
Metakirchheimerite $Co(H_2O)_8[UO_2(AsO_4)]_2$	$D_{4h}^{17} - I4/mmm$	14.29	21.92	4	3.3	2—3
Kahlerite $Fe(H_2O)_8[UO_2(AsO_4)]_2$	$D_{4h}^{17} - I4/mmm$	14.30	21.97	4	—	2—3
Metanovočekite $Mg(H_2O)_4[UO_2(AsO_4)]_2$	$C_{4h}^3 - P4/n$	7.12	8.60	1	3.5	2—3
Uranospinite $Ca(H_2O)_8[UO_2(AsO_4)]_2$	$D_{4h}^7 - P4/nmm$	7.19	8.81	1	3.7	2—3

Abernathyite subgroup. Tetr.

	S.g.	a	c	Z	ρ	H
Metaheinrichite $Ba(H_2O)_7[UO_2(AsO_4)]_2$ (?)	$C_4^3 - P4_2$	7.07	17.74	2	4.1	2—3
Nauraspyllite $Na(H_2O)_3[UO_2(AsO_4)]$	Nat det.	7.12	8.61	2	3.8	2—3
Abernathyite $K(H_2O)_3[UO_2(AsO_4)]$	$D_{4h}^8 - P4/ncc$	7.18	9.08	2	3.6	2—3
Trögerite $H_3O(H_2O)_3[UO_2(AsO_4)]$	$D_{4h}^7 - P4/nmm$	7.16	8.80	2	3.6	2—3

Str. The layer pattern is due to strong bonds between the AsO_4 radicals and the $(UO_2)O_4$ polyhedra, which form corrugated tetragonal layers of composition $[UO_2(AsO_4)]_n^{n-}$ (Fig. 236) parallel to (001). These layers are connected mainly by hydroxyl-hydrogen bonds from water molecules in a square (Fig. 56b), the centers of half of the squares in the metazeunerite subgroup being filled by Cu(Mg, Ca) atoms, which are also linked to the O atoms of the uranyl groups. These centers remain empty in the abernathyite subgroup, while one H_2O is replaced by Na, K, or H_3O. Interatomic distances in metazeunerite: $Cu-(H_2O)_4O_2 = 2.14$ (4), 2.55, and 2.58; $U-O_2O_4 = 1.94$, 1.78, and 2.18 (4); $As-O_4 = 1.77$ (Hanić, 1960 [909]); in abernathyite $K-(H_2O)_3O = 2.80$ (3) and 3.25; $U-O_2O_4 = 1.81$, 1.71, and 2.35 (4); $As-O_4 = 1.68$ (Ross and Evans, 1964 [299]).

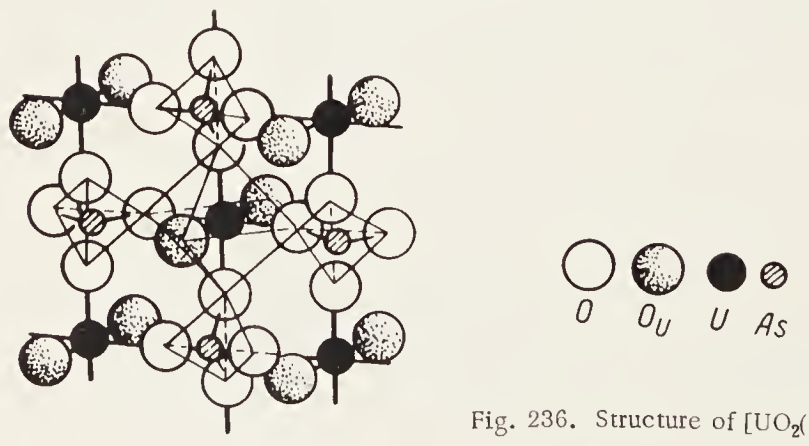


Fig. 236. Structure of $[UO_2(AsO_4)]_n^{n-}$ layer in zeunerite.

Chem. Composition varies only from As–P isomorphism, which is perfect for magurasphyllite, so the former novačekite and saleite become the subspecies arsenomagurasphyllite and phosphoromagurasphyllite. The P content of the other minerals does not exceed 3-5%. The water content in the zeunerite subgroup (n of 2-4) is dependent on the atmospheric humidity.

Var. Fe-zeunerite, PO_4-trögerite, PO_4-metaheinrichite.

Phys. Tabular and platy; perfect (001) cleavage, moderate to imperfect on (100) and (010).

2. ERYTHRITE GROUP. Mon.→tricl.

	S.g.	a	b	c	β	Z	ρ	H
Erythrite	$C_{2h}^3 - C2/m$	10.20—	13.37—	4.74—	105°01′—	2	3.18—	2—3
$(Co, Ni)_3 (H_2O)_8 [AsO_4]_2 \overset{2}{\infty}$		10.14	13.13	4.71	104°45′		3.23	
Köttigite	$C_{2h}^3 - C2/m$	10.13	13.34	4.71	103°51′	2	3.3	2—3
$Zn_3 (H_2O)_8 [AsO_4]_2 \overset{2}{\infty}$								
Clinosymplesite	$C_{2h}^3 - C2/m$	10.25	13.48	4.71	103°50′	2	3.1	2—3
$Fe_3 (H_2O)_8 [AsO_4]_2 \overset{2}{\infty}$								
Manganesehoernesite	$C_{2h}^5 - P2_1/c$	10.38	28.09	4.77	105°40′	4	2.90	2—3
$Mn_3 (H_2O)_8 [AsO_4]_2 \overset{2}{\infty}$								
Hoernesite	$C_{2h}^3 - C2/m$	10.26	13.44	4.74	104°54′	2	2.57	2—3
$Mg_3 (H_2O)_8 [AsO_4]_2 \overset{2}{\infty}$								
Symplesite	$C_i^1 - P\bar{1}$	7.87	9.41	4.72	97°23′	1	3.0	2—3
$Fe_3 (H_2O)_8 [AsO_4]_2 \overset{2}{\infty}$		$\alpha = 99°55'$		$\gamma = 105°58'$				

Str. Vivianite $Fe_3(H_2O)_8[PO_4]_2$ type, layer pattern parallel to (010) produced by strong bonds between $AsO_4(PO_4)$ tetrahedron and $Fe(O, H_2O)_6$ octahedra, which are linked via common O vertices (Fig. 249). Single and paired octahedra alternate in the layers, which are connected via hydroxyl-hydrogen bonds between water molecules coordinated to Fe. Interatomic distances in symplesite: $Fe-(O, H_2O)_6 = 2.01$; $As-O_4 = 1.65$ (Mori and Ito, 1950 [911]). Lattice parameters for hoernesite according to the data of Koritnig and Süsse (1966) [1115].

Chem. Perfect Co–Ni isomorphism in erythrite enables us to group the former species as the two subspecies cobalt erythrite and nickel-erythrite. The following isomorphous components also occur: in erythrite: Ca (≤9.3%), Zn (≤8.5%), Mg (≤6.2%), Fe (≤4%); in köttigite Co (6.9%) and Ni (2%); in symplesite the Fe^{2+} is replaced continuously by Fe^{3+} to give ferrisymplesite $Fe^{3+}(H_2O)_5[AsO_4]_2(OH)_3\overset{2}{\infty}$, as for the $Fe^{2+}-Fe^{3+}$ series of vivianite (the kerchenites). The details have not been examined.

Var. Ca-nickel erythrite, Zn-nickel erythrite, Mg-nickel erythrite, Fe-cobalt erythrite, Co-köttigite, Ni-köttigite, Fe^{3+}-symplesite.

Phys. Platy to tabular, perfect (010) cleavage.

3. PHARMACOLITE GROUP. Mon.→orth.

		S.g.	a	b	c	Z	ρ	H
Pharmacolite	$HCa(H_2O)_2[AsO_4]^2_\infty$	$C^6_{2h}-C2/c$ $\beta=114°43'$	6.01	15.58	6.32	4	2.70	2—3
Haidingerite	$HCa(H_2O)[AsO_4]^2_\infty$	$D^{14}_{2h}-Pcnb$	6.95	16.14	7.93	8	2.93	2—3

Str. Pharmacolite is homostructural with gypsum, the layer patterns in both being produced by a symmetrical distribution of the weak hydroxyl-hydrogen bonds perpendicular to (010). Haidingerite has AsO_4 tetrahedra connected into chains by hydrogen bonds, these forming (with Ca octahedra) layers parallel to (010), which are connected by H_2O, the H_2O—O distance being about 2.6. Interatomic distances: $Ca-O_5H_2O$ = 2.37-2.51 (mean 2.41), $As-O_4$ = 1.62-1.76 (mean 1.68) (Cassien et al., 1966 [912]).

Phys. Short columns to thick tablets, perfect (010) cleavage.

DIVISION C. HYDRATED WITH ADDITIONAL ANIONS

1. WALPURGITE GROUP. Tricl., $C_i^1-P\bar{1}$(?), Z = 1

		a	b	c	ρ	H
Walpurgite	$Bi_4(H_2O)_3[(UO_2)(AsO_4)_2O_4]^2_\infty$	7.13	10.44	5.49	6.7	3—3.5
		$\alpha=101°40'$	$\beta=110°49'$	$\gamma=88°17'$		

Str. Not known; assigned from properties and crystallochemical arguments.

Chem. As replaced by P (≤5.9%).

Phys. Tabular and platy, perfect (010) cleavage.

2. ARSENURANYLITE GROUP. Orth., $D^{17}_{2h}-Bmmb$ (?), Z = 6

	a	b	c	ρ	H
Arsenuranylite $Ca(H_2O)_8[(UO_2)_4(AsO_4)_2(OH)_4]^2_\infty$	15.40	17.40	13.77	(4.2)	(2—3)
Hügelite $Pb_2(H_2O)_3[(UO_2)_3(AsO_4)_2(OH)_4]^2_\infty$	Mon.	$\beta=119°48'$		5.1	3

Str. Not known. Arsenuranylite is isostructural with phosphuranylite, which is platy and has perfect (001) cleavage. Hügelite should be isostructural with dumontite (Hey, 1963 [323]); perfect (100) cleavage.

3. CHALCOPHYLLITE GROUP. Trig., $D_{3d}^5 - R\bar{3}m$, $Z = 3$

		a_h	c_h	ρ	H
Chalcophyllite	$\{Cu_6Al(H_2O)_3[AsO_4][SO_4](OH)_{10}\} \cdot 8H_2O$ $\frac{2}{\infty}$	10.77	57.51	2.67	2—2.5

Str. Not known; assigned from morphology and properties.

Chem. Some variations in Cu:Al and AsO_4:SO_4 ratios. Half of the H_2O is lost at 110°C but re-enters the lattice in moist air.

Phys. Tabular and platy, perfect (0001) cleavage.

Inadequately Characterized and Doubtful

Arseniopleite $(Ca,Mn)_4(Fe, Mn)_3[AsO_4]_4(OH)_5 \cdot 2H_2O$ (?)
Arseniosiderite $Ca_3Fe_4[AsO_4](OH)_4 \cdot 4H_2O$
Bukovskite $Fe_2[AsO_4][SO_4]OH \cdot 7H_2O$
Forbesite $H(Co, Ni)[AsO_4] \cdot 4H_2O$ (?)
Kerstenite $Fe_2[AsO_4](OH)_3 \cdot 4.5H_2O$ (?)
Pitticite $Fe_{20}^{3+}[AsO_4, PO_4, SO_4]_{13}(OH)_{24} \cdot 9H_2O$,
Smolyaninovite $(Fe, Al)_2(Co, Ni, Mg, Ca)_4[AsO_4]_4O \cdot 11H_2O$ (?)
Yukonite $Ca_3Fe_8(AsO_4]_5(OH)_{15} \cdot 12H_2O$ (?)

CLASS 7. PHOSPHATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds Class 7. Phosphates																H 154	
2	Li 7	Be 10												C 1	N 5	O 172	F 11	
3	Na 19	Mg 14											Al 49	Si 1	P 172	S 5	Cl 2	
4	K 5	Ca 49	Sc 1				Mn 32	Fe 51		Ni 1	Cu 12	Zn 10						
5		Sr 6	Y 2															
6		Ba 5												Pb 10	Bi 1			
7				Th 4	U 25	Ce 4												

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
		8	12			33	67	6	4	29	13

Subclass 1. Framework

Division A. Without Water and Additional Anions

1. Berlinite $Al[PO_4]^3_\infty$ group
2. Hurlbutite $Ca\{Be_2[PO_4]_2\}^3_\infty$ group
3. Beryllonite $Na\{Be[PO_4]\}^3_\infty$ group

Division B. With Additional Anions

1. Amblygonite $Li\{Al[PO_4](OH, F)\}^3_\infty$ group

Division C. Hydrated Without Additional Anions

1. Variscite $(Al, Fe)(H_2O)_2[PO_4]^3_\infty$ group
2. Kehoeite $CaZn_3[(H_3AlP)_8O_{48}] \cdot 16H_2O^3_\infty$ group
3. Hopeite $ZnZn_2(H_2O)_4[PO_4]_2^3{}_\infty$ group
4. Anapaite $Ca_2Fe(H_2O)_4[PO_4]_2^3{}_\infty$ group

Division D. Hydrated with Additional Anions

1. Eosphorite $(Mn, Fe)Al(H_2O)[PO_4](OH)_2^3{}_\infty$ group
2. Turquoise $Cu(Al, Fe)_6(H_2O)_4[PO_4]_4(OH)_8^3{}_\infty$ group

Subclass 2. Insular

Division A. Without Water and Additional Anions

Subdivision I. Simple

1. Heterosite (Mn; Fe)$[PO_4]$ group
2. Xenotime Y$[PO_4]$ group
3. Monazite Ce$[PO_4]$ group
4. Whitlockite $Ca_3[PO_4]_2$ group
5. Lithiophosphate $Li_3[PO_4]$ group

Subdivision II. Complex

1. Graftonite $CaMn_2Fe_3[PO_4]_4$ group
2. Arrojadite $Na_2(Mn, Fe)_5[PO_4]_4$ group
3. Hagendorfite $Na_2(Mn, Fe)_2Fe[PO_4]_3$ group
4. Triphylite Li(Mn, Fe)$[PO_4]$ group

Division B. With Additional Anions and Radicals

Subdivision I. Simple

1. Augelite $Al_2[PO_4](OH)_3$ group
2. Libethenite $CuCu[PO_4]OH$ group
3. Pseudomalachite $Cu_5[PO_4]_2(OH)_4$ group
4. Cornetite $Cu_3[PO_4](OH)_3$ group
5. Triplite $(Mn, Fe)_2[PO_4]F$ group
6. Apatite $Ca_2Ca_3[PO_4]_3(OH, F)$ group

Subdivision II. Complex

1. Crandallite $CaAl_3[PO_4]_2[(OH)_5H_2O]$ group
2. Dufrenite $Fe_3Fe_6[PO_4]_4(OH)_{12}$ group
3. Rockbridgeite $(Mn, Fe)Fe_4[PO_4]_3(OH)_5$ group
4. Lazulite $(Mg, Fe)Al_2[PO_4]_2(OH)_2$ group
5. Palermoite $SrAl_2[PO_4]_2(OH)_2$ group
6. Brazilianite $NaAl_3[PO_4]_2(OH)_4$ group
7. Griphite $Na_3CaMn_4Al_2[PO_4]_5(OH)_4$ group
8. Belovite $NaSr_3Ce[PO_4]OH$ group
9. Isokite $CaMg[PO_4]F$ group

Division C. Hydrated Phosphates without Additional Anions

1. Rhabdophane $Ce(H_2O)[PO_4]$ group
2. Phosphoferrite $(Mn, Fe)_3(H_2O)_3[PO_4]_2$ group
3. Hureaulite $H_2Mn_5(H_2O)_4[PO_4]_4$ group
4. Struvite $NH_4Mg(H_2O)_6[PO_4]$ group

Division D. Hydrated Phosphates with Additional Anions

Subdivision I. Simple

1. Beraunite $Fe_3(H_2O)_2[PO_4]_2(OH)_3$ group
2. Wavellite $Al_3(H_2O)_5[PO_4]_2(OH)_3$ group
3. Veszelyite $(Zn, Cu)_3(H_2O)_2[PO_4](OH)_3$ group

Subdivision II. Complex

1. Overite $Ca_3Al_8(H_2O)_{15}[PO_4]_8(OH)_6$ group
2. Morinite $Na_2Ca_4Al_4(H_2O)_5[PO_4]_4O_2F_6$ group
3. Wardite $NaAl_3(H_2O)_2[PO_4]_2(OH)_4$ group
4. Minyulite $KAl_2(H_2O)_4[PO_4]_2OH$ group
5. Roscherite $CaMnFeBe_3(H_2O)_2[PO_4]_3(OH)_3$ group

Subclass 3. Chain

Division A. Anhydrous

1. Väyrynenite $Mn\{Be[PO_4]OH\}^1_\infty$ group
2. Monetite $Ca\{H[PO_4]\}^1_\infty$ group

Division B. Hydrated

1. Moraesite $Be_2(H_2O)_4[PO_4]OH^1_\infty$ group
2. Ludlamite $Fe_2(H_2O)_2\{Fe(H_2O)_2[PO_4]_2\}^1_\infty$ group
3. Fairfieldite $Ca_2\{Mn, Fe)(H_2O)_2[PO_4]_2\}^1_\infty$ group

Subclass 4. Layer

Division A. Without Water and Additional Anions

1. Parsonsite $Pb[(UO_2)(PO_4)_2]^2_\infty$ group

Division B. Anhydrous with Additional Anions

1. Herderite $Ca\{Be[PO_4](OH, F)\}^2_\infty$ group

Division C. Hydrated without Additional Anions

1. Uranium mica $R(H_2O)_n[UO_2(PO_4)]_2^2{}_\infty$ group
2. Churchite $Y(H_2O)_2[PO_4]^2_\infty$ group
3. Vivianite $Fe^{2+}_{3-X}Fe^{3+}_X(H_2O)_{8-X}[PO_4]_2(OH)_X^2{}_\infty$ group
4. Taranakite $K_3H_6Al_5(H_2O)_8[PO_4]_8^2{}_\infty$ group

Division D. Hydrated with Additional Anions

1. Phosphuranylite $Ca(H_2O)_8[(UO_2)_4(PO_4)_2(OH)_4]^2_\infty$ group
2. Dumontite $Pb_2(H_2O)_3[(UO_2)_3(PO_4)_2(OH)_4]^2_\infty$ group
3. Metavauxite-laueite $Fe(H_2O)_4\{Al_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O\,{}^2_\infty$ group
   and $Mn(H_2O)_4\{Fe^{3+}(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Framework

(In part aluminophosphates and beryllophosphates)

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. BERLINITE GROUP. Trig., $D_3^4 - P3_121$, Z = 3

		a_h	c_h	ρ	H	Cl.
Berlinite (alphite)	$Al[PO_4]^3_\infty$	4.94	10.96	2.62	~6.75	None

Str. Homostructural with quartz (c_h doubled), with alternation of PO_4 and AlO_4 tetrahedra linked by vertices. The $P-O_4$ and $Al-O_4$ distances are close to standard, namely 1.52 and 1.74 respectively. Parameters and space group recently revised (Sharan and Dutta, 1964 [913]; Schwarzenbach, 1966 [914]).

Chem. Composition constant.

2. HURLBUTITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, Z = 4

		a	b	c	β	ρ	H
Hurlbutite (calcberyphite)	$Ca\{Be_2[PO_4]_2\}^3_\infty$	8.29	8.80	7.81	≈90°	2.88	6,5

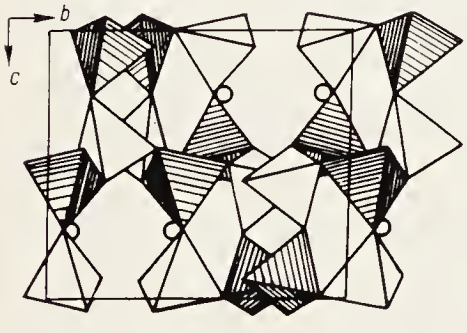


Fig. 237. Array of BeO_4 and PO_4 tetrahedra in the framework of hurlbutite.

Str. Of the type of paracelsian or danburite; framework formed by PO_4 and BeO_4 tetrahedra, each one being linked via vertices to four of the other type (Fig. 237). The tetrahedra form regular four-sided and elongated eight-sided rings in the xy plane. Ca has CN = 7 (a trigonal prism plus half an octahedron). Interatomic distances: $Ca-O_7 = 2.47$; $Be-O_4 = 1.61$; $P-O_4 = 1.54$ (Bakakin, 1963 [301]).

Chem. Composition constant.

Phys. Nearly isometric, no cleavage observed.

3. BERYLLONITE GROUP. Mon., $C_{2h}^5 - P2_1/n$, Z = 12

		a	b	c	β	ρ	H
Beryllonite	$Na\{Be[PO_4]\}^3_\infty$	8.16	7.79	14.08	90°	2.81	6--6.5

Str. Framework of somewhat distorted PO_4 and BeO_4 tetrahedra joined by vertices into six-sided rings; the Na atoms lie between these (k of 6 and 9), the Na polyhedra with CN = 9 being joined by edges into col-

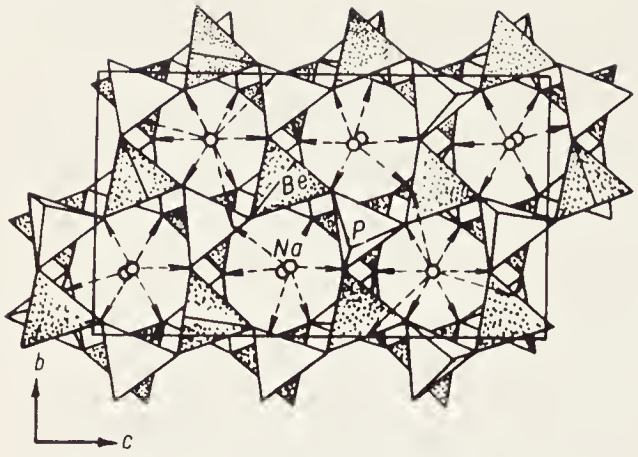


Fig. 238. Structure of beryllonite in projection on (100).

umns parallel to the c axis (Fig. 238). Pairs of coupled Na octahedra are oriented in the same direction. Interatomic distances: $Na-O_6$ = 2.68-2.22; $Na-O_9$ = 2.51-2.82; $Be-O_4$ = 1.58-1.66; $P-O_4$ = 1.48-1.56 (Golovastikov, 1961 [302]).

Chem. Na replaced by Ca (0.4%) and K (0.9%).

Phys. Nearly isometric, perfect (010) cleavage, moderate (100).

DIVISION B. WITH ADDITIONAL ANIONS

1. AMBLYGONITE GROUP. Tricl., $C_i^1 - P\bar{1}$, Z = 2

		a	b	c	ρ	H
Amblygonite	$Li\{Al[PO_4](OH, F)\}^3_\infty$	5,06	5,16	7.08	2,98—3,11	6—6,5
		α = 109°52′	β = 107°30′	γ = 97°54′		
Notromontebrosite	$Na\{Al[PO_4]OH\}^3_\infty$	—	—	—	3,1	6—6,5
Tovorite	$Li\{Fe[PO_4]OH\}^3_\infty$	—	—	—	3,3	(5,5—6)

Str. Framework pattern produced by vertex coupling of Al octahedra and PO_4 tetrahedra (Fig. 239a). There are no large holes, which is reflected in the relatively high density. Li has CN = 5 and lies in the small holes between the PO_4 tetrahedra and thd nearest Al octahedra (Fig. 239b), where two $Li(O; OH, F)_5$ polyhedra are joined by a common face to give a distorted octahedron, the probability of finding Li in either half being 1/2 (Simonov and Belov, 1958 [303]). Two types of chain may be distinguished: continuous ones along thc b axis composed of Al octahedra, and ones along the c axis composed of alternate Al octahedra and P tetrahedra. Interatomic distances: $Li-O_4(OH, F)$ = 2.1 (2), 2.3, 2.0 (2); $Al-O_4(OH, F)_2$ = 1.88; $P-O_4$ = 1.54.

Chem. Amblygonite has perfect F−OH isomorphism, which gives the subspecies fluoramblygonitc and hydroxylamblygonite. Li is replaced by Na to a limited extent (≤5.3%), and there is often some H_2O (up to two

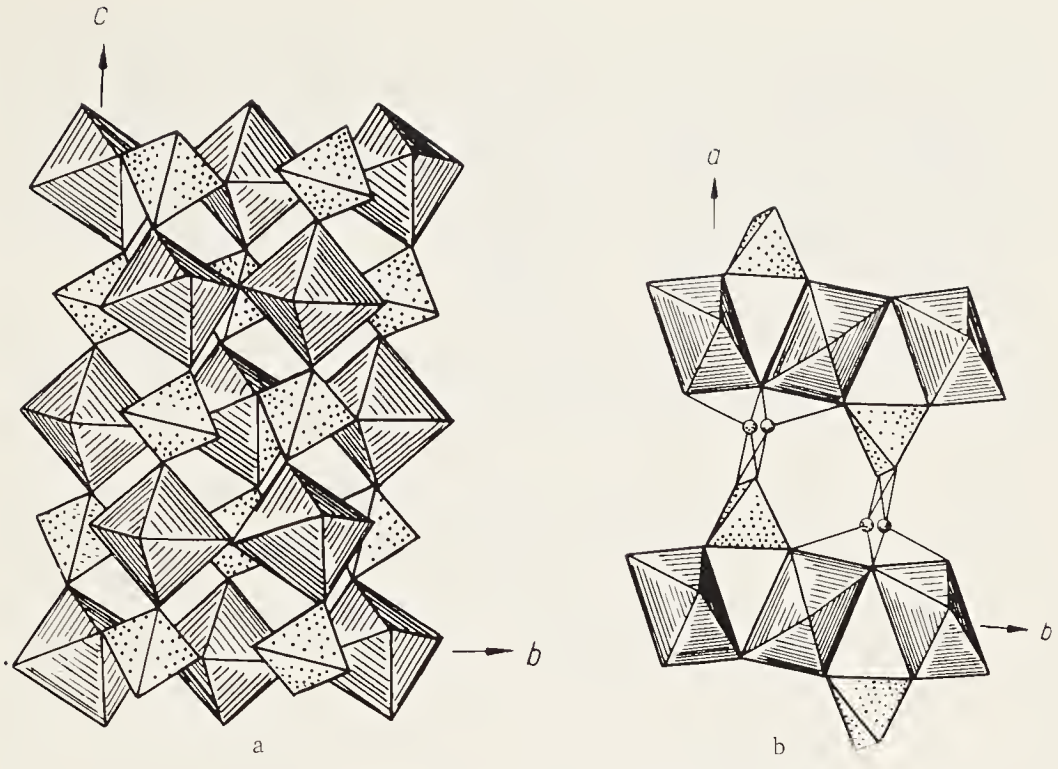


Fig. 239. Structure of amblygonite: a) framework of Al octahedra and P tetrahedra, b) chains of Al octahedra parallel to b axis.

molecules per unit cell). Natromontebrasite has Li replacing 1/3 of the Na. Tavorite has Fe^{3+} replaced by Fe^{2+} ($\leq$2.4%) and Mn ($\leq$1.5%).

Var. Na-fluoramblygonite, Li-natromontebrasite, Fe^{2+}-tavorite.

Phys. Isometric or short columns on b axis, perfect cleavage on (100) and (110), both of which planes do not intersect the P–O bonds, which are the strongest in the structure.

DIVISION C. HYDRATED WITHOUT ADDITIONAL ANIONS

1. VARISCITE GROUP. Orth., $D_{2h}^{15} - Pcab \rightarrow$ mon. $C_{2h}^{2} - P2_1/m$

			a	*b*	*c*	β	*Z*	ρ	H
Variscite	$(Al, Fe)(H_2O)_2[PO_4]^{3}_{\infty}$		9.85–10.05	9.55–9.80	8.50–8.65	—	8	2.57–2.87	5—4
Clinovariscite	$Al(H_2O)_2[PO_4]^{3}_{\infty}$		5.14	9.45	8.45	~90°	4	2.54	4—4.5
Clinostrengite	$Fe(H_2O)_2[PO_4]^{3}_{\infty}$		5.32	9.75	8.65	90°36′	4	2.76	3,75—4
Sterrettite	$Sc(H_2O)_2[PO_4]^{3}_{\infty}$		5.45	10.25	8.93	90°45′	4	2.35	5—5.5
Koninckite	$Fe(H_2O)_3[PO_4]^{3}_{\infty}$	Tetr.	11.95	—	14.52	—	16	2.30	3.75

Str. Isostructural with scorodite; Al and Fe have CN = 6 (four O, two H_2O). The four O of an (Al, Fe) octahedron are in common with four different P tetrahedra, the framework thus being heterogeneous (Kiriyama

and Sakurai, 1949 [887]; Moore, 1965 [915]). Clinovariscite is closely related to variscite; it and the others in the group (except possibly the last) differ from variscite in having a halved. The interatomic distances are for clinovariscite: $Al-O_4(H_2O)_2$ = 1.85-1.94 (d_m 1.90), $P-O_4$ = 1.50-1.55 (d_m 1.52); for clinostrengite: $Fe-O_4(H_2O)_2$ = 1.94-2.12 (d_m 2.01), $P-O_4$ = 1.49-1.53 (d_m 1.52) (Borensztain, 1966 [916]). The cell parameters of koninkite are after data by Van Tassel (1968 [1163]).

Chem. Variscite has perfect Al−Fe isomorphism, subspecies alumovariscite and ferrivariscite. Cr (≤0.7%) occurs as a minor component. Clinovariscite and clinostrengite appear not to have perfect Al−Fe isomorphism. Sterrettite contains ~9% Be and Si.

Var. Cr-variscite, Fe-clinovariscite, Al-clinovariscite, Be-sterrettite.

Phys. Short columns to thick tablets, (010) cleavage moderate.

2. KEHOEITE GROUP. Cubic, s.g. not det., $Z = 2$

		a	ρ	H
Kehoeite	$CaZn_3[(H_3AlP)_8O_{48}]\ 16H_2O\ ^3_\infty$	13.70	2.34	(3.5—4.5)
Viséite	$NaCa_5\{[(H_3)_6Al_{10}Si_3P_5]O_{48}\}\ 8H_2O\ ^3_\infty$	13.65	2.20	(3.5—4.5)

Str. Homostructural with analcime $Na[AlSi_2O_6]\cdot H_2O\ ^3_\infty$, having identical parameters and density. McConnell (1952 [917] and 1964 [306]) assumes that PO_4 and AlO_4 are replaced by H_3O_4 tetrahedra (in place of H_4O_4 in insular structures), which give $[H_3O_2]^-$ tetrahedra on linking via common vertices.

Chem. Only minor isomorphous components.

Phys. Occurs as continuous masses.

3. HOPEITE GROUP. Orth.→mon.→tricl.

		S.g.	a	b	c	β	Z	ρ	H
Hopeite	$ZnZn_2(H_2O)_4[PO_4]_2\ ^3_\infty$	D^{16}_{2h} — *Pnma*	10.64	18.36	5.04	—	4	3.1	3.5—3.75
Phosphophyllite	$FeZn_2(H_2O)_4[PO_4]_2\ ^3_\infty$	C^5_{2h} — $P2_1/c$	10.23	5.08	10.49	120°15′	2	3.1	3.5—3.75
Parahopeite (triclinohopeite)	$ZnZn_2(H_2O)_4[PO_4]_2\ ^3_\infty$	C^1_i — $P\bar{1}$	5.77	7.55	5.30	91°55′	1	3.3	4
		α = 93° 18′ γ = 91° 19′							

Str. Hopeite (Gamidov et al., 1963 [304]) and phosphophyllite (Kleber et al., 1961 [918]) have two Zn atoms with CN = 4 and one Zn atom (Fe in phosphophyllite) with CN = 6, two O + four H_2O (Fig. 240a). Each O atom around Zn_I belongs to a different PO_4 tetrahedron. At two vertices of ZnO_4 there are also two ZnO_4 tetrahedra, which together give rise to $[Zn_2O_6]^1_\infty$ chains along the c axis (Fig. 240b). The two-layer close packing produces a similarity to the diaspore-goethite structure. Zn_{II} (Fe in

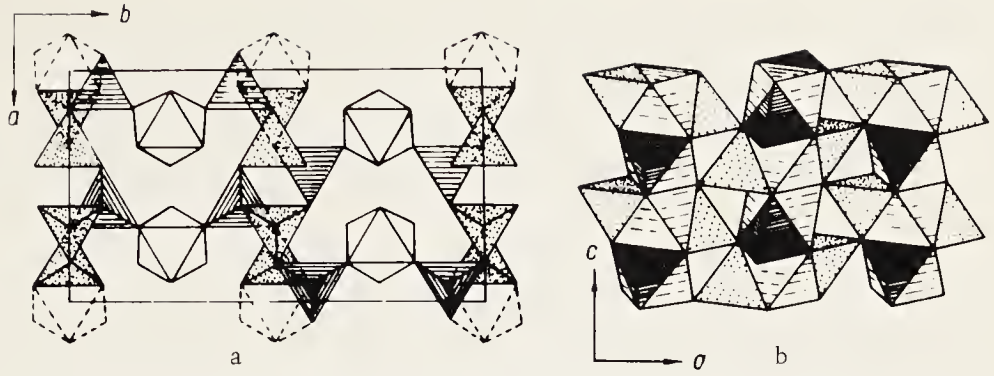


Fig. 240. Structure of hopeite: a) framework of Zn polyhedra and P tetrahedra; b) polar $[Zn_2O_6]^1_\infty$ chains surrounded by P tetrahedra (hatched).

phosphyllite) is linked via two oxygen vertices to PO_4 tetrahedra to give a framework, 70% of which is made up by two-vertex linking of polyhedra. There is a very close relation between hopeite and phosphophyllite; hopeite can be considered as microtwinned phosphophyllite, because its b parameter is $\sqrt{3}$ times the a parameter of phosphophyllite. The mean interatomic distances are close to standard: $Zn-O_4 \approx 1.96$; $Zn-O_2(H_2O)_4 \approx 2.15$; $P-O_4 \approx 1.54$. In parahopeite: $Zn-O_4 = 1.95$; $Zn-O_2(H_2O)_4 = 2.11$; $P-O_4 = 1.55$ [1302].

Chem. Composition mainly constant; Fe in phosphophyllite replaced by Mn (≤5%).

Var. Mn-phosphophyllite.

Phys. Hopeite and parahopeite occur as laths elongated on the c axis and flattened on the b axis (a axis for parahopeite); phosphophyllite is tabular on the a axis. Parahopeite and hopeite have perfect cleavage on (010), as does phosphophyllite on (100); the latter two also have moderate cleavage on (100) and (010) respectively.

4. ANAPAITE GROUP. Tricl., $C_i^1 - P\bar{1}$, Z = 1

		a	b	c	α	β	γ	ρ	H
Anapaite	$Ca_2Fe(H_2O)_4[PO_4]_2\frac{3}{\infty}$	6.42	6.89	5.87	101° 35′	104° 06′	71° 04′	2.81	3.75

Str. Ca has CN = 7, while Fe has CN = 6; all the Fe octahedra and P tetrahedra are linked via vertices, while the Ca polyhedra are paired via a common edge; 88% of the links are two-vertex ones, so the structure is close to a true framework type (compare the density of 2.81). The pairs of Ca polyhedra are joined with the Fe octahedra into layers parallel to (010), which are linked together via PO_4 tetrahedra (sublayer pattern). Interatomic distances: $Ca-O_5(H_2O)_2 = 2.42$ (5) and 2.51 (2); $Fe-O_2(H_2O)_4 = 2.00$ (2), 2.21 (2), and 2.31 (2); $P-O_4 = 1.55$ (Rumanova and Znamenskaya, 1960 [919]).

Chem. Constant, with Mg and Fe^{3+} constituting less than 1%.

Phys. Tabular, perfect (001) cleavage, moderate (010).

DIVISION D. HYDRATED WITH ADDITIONAL ANIONS

1. EOSPHORITE GROUP. Orth., D_{2h}^{18} — *Bbam* (?), Z = 8

			a	*b*	*c*	ρ	H
Eosphorite	(Mn, Fe) Al (H_2O) $[PO_4]$ $(OH)_2$	$\frac{3}{\infty}$	10.45—10.38	13.49—13.36	6.93—6.91	3.1—3.2	5.5—5

Str. Transitional between the heterogeneous-framework and chain types, because tetrahedra occur together with octahedra and also because the large (Mn, Fe) octahedra are linked together via edges into chains (Fig. 241a). The $AlO_2(OH)_2(H_2O)_2$ octahedra are linked to one another via H_2O vertices, to (Mn, Fe) octahedra via OH vertices, and to PO_4 tetrahedra via oxygen vertices. In all, 68% of the bonds are via common vertices, so eosphorite can be assigned to the framework subclass. Interatomic distances: (Mn, Fe)$-O_4(OH)_2$ = 2.25 (2), 2.23 (2), 2.24 (2); Al$-O_2(OH)_2(H_2O)_2$ = 1.87 (2), 1.97 (2), 1.90 (2); P$-O_4$ = 1.55 (Hanson, 1960 [305]).

Chem. Perfect Mn$-$Fe isomorphism allows us to combine eosphorite and childrenite as one species, with subspecies manganoeosphorite and ferroeosphorite. Fe^{2+} and Mn^{2+} can be replaced by Fe^{3+} (≤18.5%) and Mn^{3+} (≤8.7%), with simultaneous OH → O replacement.

Var. Fe^{3+}-ferroeosphorite, Mn^{3+}-manganoeosphorite.

Phys. Short columns, imperfect (100) cleavage.

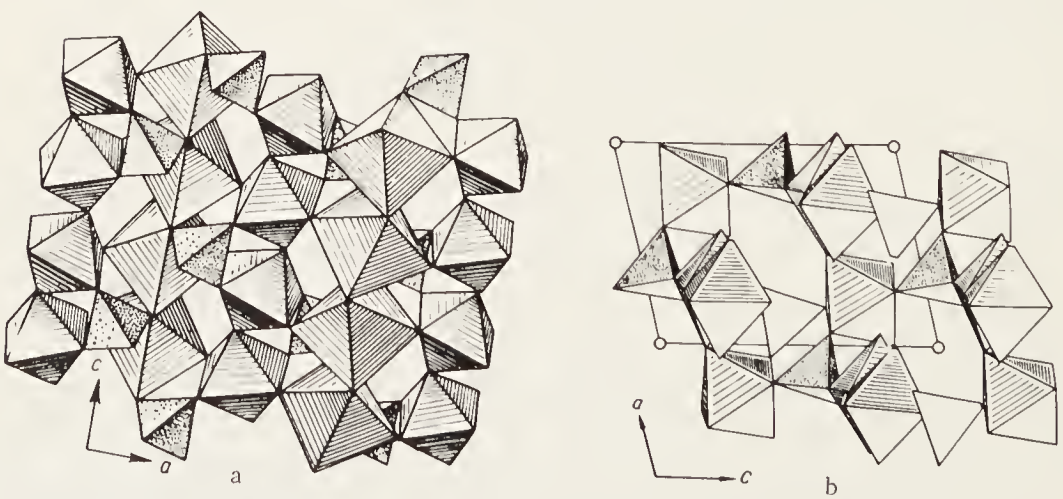


Fig. 241. Structures of eosphorite and turquoise represented in polyhedra: a) eosphorite in projection on (010), b) turquoise in projection on (010), the circles indicating Cu atoms at inversion centers.

2. TURQUOISE GROUP. Tricl., $C_i^1 - P\bar{1}$, Z = 1

		a	*b*	*c*	*ρ*	H
Turquoise (cualferhyphite)	7.42—7.68	7.63—7.82	9.91—10.21	2.8—3.2	6—5
$Cu(Al, Fe)_6(H_2O)_4[PO_4]_4(OH)_8 \cdot \frac{3}{\infty}$	$\alpha = 68°37'—67°30'$	$\beta = 69°43'—69°06'$	$\gamma = 65°04'—64°48'$		
Faustite	—	—	—	2.92	6
$ZnAl_6(H_2O)_4[PO_4]_4(OH)_8 \cdot \frac{3}{\infty}$					

Str. Framework of PO_4 tetrahedra and (Al, Fe) octahedra linked by common vertices, one-third of the octahedra being single and the others paired via OH edges (Fig. 241b). The fairly large holes in this heterogeneous framework contain Cu(Zn) atoms at centers of symmetry, with four OH and two H_2O around each. Interatomic distances in alumocualferhyphite: $Cu-(OH)_4(H_2O)_2$ = 1.92 (2), 2.11 (2), and 2.42 (2); $Al_I-O_2(OH)_3H_2O$ = 1.81, 1.82, 1.86, 1.96, 2.01, and 1.94; $Al_{II}-O_2(OH)_3H_2O$ = 1.81, 1.83, 1.84, 1.90, 1.96, and 2.08; $Al_{III}-O_4(OH)_2$ = 1.88, 1.89, 1.90 (2), 1.91 and 2.16; P_I-O_4 = 1.54; $P_{II}-O_4$ = 1.54 (Cid-Dresdner, 1965 [920]).

Chem. Perfect $Al-Fe^{3+}$ isomorphism in cualferhyphite has led me to replace the two former species by one (with this new name), the old species becoming the subspecies alumocualferhyphite and ferricualferhyphite. The Zn in faustite is replaced by Cu (1.6%) and Al by Fe^{3+} (1.7%).

Phys. Short columns, perfect (010) cleavage, moderate (001).

Subclass 2. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

Subdivision I. Simple

1. HETEROSITE GROUP. Orth. $D_{2h}^{16} - Pbmn$, Z = 4

		a	*b*	*c*	*ρ*	H
Heterosite	(Mn; Fe)$[PO_4]$	4.77	9.77	5.83	3.3	4.5—5

Str. Close to that of olivine, probably defective, because the mineral is formed by oxidation of triphylite and sicklerite (with loss of Li), while retaining nearly the same lattice parameters.

Chem. Narrow variations due to Mn—Fe isomorphism; Mn:Fe ranges from 1:2 to 2:1. H_2O always present because the structure is defective.

Var. Mn-heterosite, Fe-heterosite.

Phys. Moderate (010) cleavage, imperfect (001).

2. XENOTIME GROUP. Tetr., $D_{4h}^{19} - I4_1/amd$, $Z = 4$

		a	c	ρ	H
Xenotime (yphite)	$Y[PO_4]$	6.89	6.04	4.25	5.25—6

Str. Isostructural with $Ca[CrO_4]$ and zircon (Fig. 166); Y has CN = 8 Interatomic distances: $Y-O_8$ = 2.27 (4), 2.56 (4); $P-O_4$ = 1.50 (Krstanović, 1965 [921]).

Chem. Y in xenotime is replaced by TR of the yttrium group (Yb, Dy, Er, Ho, Lu, Sm), Ce, and La (≤3-4%), U (≤4.1%), Th (≤2.8%), Zr (≤2.7%), Al (≤4.8%); replacement of Y by U, Th, or Zr is accompanied by P−Si replacement (≤4.3%).

Var. Yb-xenotime, Dy-xenotime, Er-xenotime (and other TR-xenotimes), Ce-xenotime, Zr-xenotime, U-xenotime, Th-xenotime, Al-xenotime, SiO_4-xenotime.

Phys. Short columns to isometric, moderate (100) cleavage.

3. MONAZITE GROUP. Mon., $C_{2h}^5 - P2_1/n$, $Z = 4$

		a	b	c	β	ρ	H
Monazite (cephite)	$Ce[PO_4]$	6.76	7.00	6.44	103° 38′	5.2	5—5.75

Str. Ce has CN = 9, linking six PO_4 tetrahedra (Fig. 242). Interatomic distances: $Ce-O_9$ = 2.60; $P-O_4$ = 1.52 (Kokkoros, 1942 [922]); Mooney (1948) [923] gives 2.55 and 1.56 while Ueda (1953) [924] gives 2.53 and 1.64. Isostructural with crocoite and huttonite.

Chem. Variable; lanthanides (La > Nd > Pr > Sm > Gd) always present as isomorphous components, up to 1:1, with substantial amounts also of Th (≤32%), Si (≤6.1%), Y (≤5.1%), U (≤6.6%), Ca (≤3%). Th and U replace Ce via ThCa → 2Ce and ThSi → CeP.

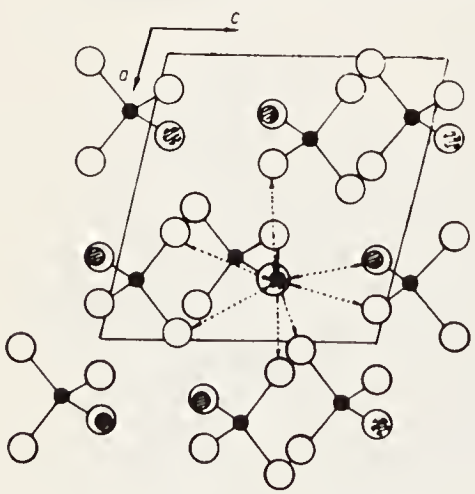


Fig. 242. Structure of monazite in projection on (010). Filled circles are p atoms, open ones are O, and hatched ones are Ce.

Var. La-monazite, Th-monazite, U-monazite, Y-monazite, Ca, Th, U-monazite, SO_4-monozite.

Phys. Isomorphous subsitution affects the cell parameters and the density. Thick tablets (on a axis), moderate (100) cleavage, imperfect (010).

4. WHITLOCKITE GROUP. Trig., $D^5_{3d} - R\bar{3}m$, Z = 7; 21

		a_{rh}	α	a_h	c_h	ρ	H
Whitlockite	$Ca_3[PO_4]_2$	13.65	44° 21′	10.34	36.9	3.2	5.5

Str. Probably close to that of palmierite (Strunz, 1942 [925]); also said (Keppler, 1963 [926]) to be related to rockbridgeite.

Chem. Ca replaced by Mg (≤3.5%) and Fe (≤2.3%).

Phys. Isometric to tabular on c axis, no cleavage.

5. LITHIOPHOSPHATE GROUP. Orth., $D^{16}_{2h} - Pbnm$, Z = 4

		a	b	c	ρ	H
Lithiophosphote (liphite)	$Li_3[PO_4]$	4.93	10.53	6.12	2.46	4—4.5

Str. The parameters indicate some similarity to olivine, while the mode of coupling of the LiO_4 and PO_4 tetrahedra is close to that in enargite. Mean interatomic distances: Li—O_4 = 1.97; P—O_4 = 1.55 (Zemann, 1960 [927]). The cell parameters are for artificial material [1398].

Phys. Moderate cleavage in two directions.

Subdivision II. Complex

1. GRAFTONITE GROUP. Mon., Z = 2; 4

		S.g.	a	b	c	β	ρ	H
Sarcopside	$MnFe_2[PO_4]_2$	$C^5_{2h} - P2_1/a$	10.46	4.80	6.05	90° 30′	3.7	(5.5—6)
Groftonite	$CaMn_2Fe_3[PO_4]_4$	$C^5_{2h} - P2_1/c$	8.91	11.57	6.24	98°54′	3.8	5.5
Beusite	$Mn_2Fe[PO_4]_2$	$C^5_{2h} - P2_1/c$	8.78	11.52	6.15	99°25′	3.7	5.5—6

Str. Sarcopside probably closely resembles olivine (see cell parameters), but graftonite does not [1155].

Chem. Mn in sarcopside replaced by Ca (≤5%) and Fe^{2+} by Fe^{3+} (≤9%) and Mg (≤3.4%). The ratios of Ca, Mn, and Fe in graftonite vary somewhat, on account of isomorphism. Mn in beusite is replaced by Ca (4.6%), and Fe^{2+} by Mg (2.6%) [625].

Var. Ca-sarcopside, Mg-sarcopside.

Phys. Short columns, cleavage of sarcopside on (100) and (001) perfect, on (010) imperfect; cleavage of graftonite and beusite on (010) and (100) moderate.

2. ARROJADITE GROUP. Mon.→trig., $Z = 12; 24$

	S.g.	a	b	c	β	ρ	H
Arrojadite $Na_2(Mn,Fe)_5[PO_4]_4$	$C_{2h}^3 - C2/m$ (?)	16.68— 16.51	10.11— 10.05	24.89— 24.78	105°41′— 105°41′(?)	3.4— 3.5	5—5.5
Fillowite $Na_2Mn_5[PO_4]_4$ (?)	$C_3^4 - R3$ or $C_{3i}^2 - R\bar{3}$	15.25	—	43.32	—	3.4	5

Str. Not known; parameters of arrojadite and trigonal fillowite from Fischer (1965 [928]), who gives for the rhombohedral cell of the latter $a_{rh} = 16.91$, $\alpha = 53°36'$.

Chem. The similar parameters of arrojadite and dickinsonite have led to the two being combined as one species with perfect Fe–Mn isomorphism, but this requires confirmation, since the space groups and angles β are different. Na in arrojadite is replaced by K (≤1.8%), and Fe and Mn by Mg (≤2%) and Ca (≤5.7%). Fillowite contains Ca (≤4.1%) and Fe (≤9.7%). Subspecies: manganoarrojadite and ferroarrojadite.

Var. Ca-arrojadite, Fe-fillowite, Ca-fillowite.

Phys. Perfect (001) cleavage.

3. HAGENDORFITE GROUP. Mon., $C_{2h}^6 - I2/a$, $Z=4$

		a	b	c	β	ρ	H
Hagendorfite	$Na_2(Mn, Fe)_2Fe[PO_4]_3$	10.93	12.59	6.52	97° 59′	3.5—3.6	5—5.5
Alluaudite	$Na_2(Mn, Fe^{3+})_3[PO_4]_2$	11.03	12.53	6.40	97° 34′	3.5—3.6	5—5.5

Str. Not known, but appears to differ appreciably from that of graftonite or arrojadite. The parameters given are for the ferroan subvarieties; the formula of alluaudite has been simplified.

Chem. Mn–Fe isomorphism in hagendorfite and Mn–Fe^{3+} in alluaudite give us the subspecies manganohagendorfite, ferrohagendorfite, manganoaluaudite, and ferrialluaudite. Other important isomorphous components are for hagendorfite Ca (≤9.7%), Mg (≤2.6%) and Li (≤1.7%), for alluaudite Ca (≤4.6%) and Fe^{2+} (≤3.2%).

Var. Ca-ferrohagendorfite, Mg-ferrohagendorfite, Ca-manganoalluaudite, and Fe^{2+}-alluaudite.

4. TRIPHYLITE GROUP. Orth., $D_{2h}^{16} - Pbnm$, $Z = 4$

		a	b	c	ρ	H
Triphylite	$Li(Mn, Fe)[PO_4]$	4.74—4.68	10.46—10.36	6.10—6.01	3.3—3.6	4.5—5.5
Natrophilite	$NaMn[PO_4]$	4.98	10.54	6.33	3.5	5—5.5
Sicklerite	$Li_{1-x}(Mn_{1-x}, Fe_x^{3+})[PO_4]$	4.78—4.80	10.24—10.11	6.01—5.95	3.2—3.4	(4.5—5)

Str. Close to that of olivine (Fig. 168); Li(Na) and (Mn, Fe) have octahedral coordination, the octahedra being linked via edges into zigzag chains connected via PO_4 tetrahedra. Interatomic distances in triphylite $Li-O_6 = 2.10$ (2), 2.16 (2), 2.20 (2); $Fe-O_6 = 2.08$ (2), 2.16 (2), 2.28 (2); $P-O_4 = 1.54$ (Destenay, 1950 [929]), in natrophilite $(Na, Mn)_I-O_6 = 2.26$ (4), 2.27 (2); $(Na, Mn)_{II}-O_6 = 2.17$ (2), 2.23 (2), 2.31 (2); $P_I-O_4 = 1.64$, $P_{II}-O_4 = 1.59$ (2), 1.66 (2) (Byström, 1943 [930]). In the latter the Na and Mn atoms are randomly distributed over the octahedral positions. Sicklerite is an intermediate product in the oxidation of triphylite (with x not exceeding 2/3) and also appears to have a random distribution over the octahedral positions, some of which become vacant and allow H_2O to enter as the Fe^{3+} content increases.

Chem. Perfect Mn–Fe isomorphism (somewhat restricted for sicklerite) gives us the subspecies manganotriphylite, ferrotriphylite, manganosicklerite, and ferrisicklerite. The other main isomorphous components are in triphylite Ca (≤9.7%), Mg (≤7.4%), and Na (≤2.7%), in natrophilite Fe (≤3.1%), and in sicklerite Ca (≤3.4%), Mg (≤1.7%), and Na (≤1.2%).

Var. Ca-triphylite, Mg-triphylite, etc.

Phys. All have moderate (010) cleavage and imperfect (001).

DIVISION B. WITH ADDITIONAL ANIONS AND RADICALS

Subdivision I. Simple

1. AUGETITE GROUP. Mon., $C_{2h}^3 - C2/m$, $Z = 4$

		a	b	c	β	ρ	H
Augelite	$Al_2[PO_4](OH)_3$	13.13	7.98	5.07	112° 27′	2.70	5—5.5
Trolleite	$Al_{5.33}[PO_4]_4(OH)_4$	—	—	—	—	3.1	6—6.5

Str. Al has two different coordinations in its structure; one is coordinated to four OH and two O and the other to three OH and two O. Four Al polyhedra, two of each type, are linked together by sharing OH–OH edges. These groups are connected by P tetrahedra. The interatomic distances are: $Al-O_2(OH)_4 = 1.83$ (2), 1.98 (2), 1.86 (2); $Al-O_2(OH)_3 = 1.75$, 1.80, 1.78 (2), 2.05; $P-O_4 = 1.52$ (2) and 1.53 (2) [1162].

Chem. Only minor isomorphous components; the formula given for the synthetic material is $Al_{5.33}[PO_4]_4(OH)_4$ (Sclar, 1964 [931]).

Phys. Augelite thick plates, (110) cleavage perfect, $(\bar{2}01)$ moderate. Trolleite has cleavage in two directions at about 111°.

2. LIBETHENITE GROUP. Orth.→tricl.

		S.g.	a	b	c	Z	ρ	H
Libethenite	$CuCu[PO_4]OH$	$D_{2h}^{12} - Pmnm$	8.45	8.10	5.91	4	3.9	4
Tarbuttite	$Zn_2[PO]_4OH$	$C_i^1 - P\bar{1}$	5.50	5.65	6.46	2	4.1	4
			$\alpha = 102°51'$	$\beta = 102°46'$	$\gamma = 86°50'$			

Str. Libcthenite is isostructural with andalusite and adamite; Cu has CN of 5 and 6. The $CuO_4(OH)_2$ octahedra are linked by edges into columns along the c axis and are connected by PO_4 tetrahedra and CuO_4OH polyhedra. Interatomic distances $Cu-O_4OH = 2.07$ (3), 1.99, 1.96; $Cu-O_4(OH)_2 = 2.06$ (2), 2.01 (2), 2.39 (2); $P-O_4 = 1.61$, 1.58, 1.49 (2) (Walitzi, 1963 [932]). The structure of tarbuttite is very different; there are two types of Zn atom (CN = 5, trigonal dipyramid) linked by edges into chains and pairs connected by PO_4 tetrahedra. Mean interatomic distances: $Zn_1-O_3(OH)_2 = 2.04$; $Zn_2-O_4OH = 2.03$; $P-O_4 = 1.54$ (Cocco et al., 1966 [933]).

Chem. P in libethenite partly replaced by As ($\leq$2.3%).

Var. AsO_4-libethenite.

Phys. Short columns to isometric. Libethenite has imperfect cleavage on (100) and (010); tarbuttite has perfect cleavage on (001).

3. PSEUDOMALACHITE GROUP. Mon., $C_{2h}^5 - P2_1/a$. $Z = 2$

		a	b	c	β	ρ	H
Pseudomalachite	$Cu_5[PO_4]_2(OH)_4$	17.08	5.75	4.47	91° 07′	4.4	5—5.5

Str. PO_4 tetrahedra and two types of distorted Cu octahedra; the latter are linked by edges into two types of parallel chain along the b axis. The types of chain occur alternately and are connected by common edges into layers parallel to (001), the layers being connected by PO_4 tetrahedra, so the mineral is only sublayered and does not show cleavage on (001). Interatomic distances: $Cu_I-O_4(OH)_2 = 1.94$ (2), 2.69 (2) and 2.02 (2); $Cu_{II}-O_3(OH)_3 = 1.91$, 2.39, 2.70, 2.00 (3); $Cu_{III}-O_4(OH)_2 = 1.94$, 2.00, 2.36, 2.51, and 1.96 (2); $P-O_4 = 1.55$ (Ghose, 1963 [308]).

Phys. Short columns, moderate (010) cleavage.

4. CORNETITE GROUP. Orth., $D_{2h}^{15} - Pbca$, $Z = 8$

		a	b	c	ρ	H
Cornetite	$Cu_3[PO_4](OH)_3$	10.88	14.08	7.12	4.1	5

Str. Substantially different from that of clinoclase, although the formulas are identical. A preliminary study (Fehlman et al., 1964 [934]) shows that there are chains of distorted Cu octahedra (Cu dimer links) connected as in euchroite into a framework.

Chem. Composition constant (specimens from Katanga contain isomorphous Co).

Phys. Short columns, no cleavage.

5. TRIPLITE GROUP. Mon., $C_{2h}^3 - I2/m$, $C_{2h}^5 - P2_1/a$

	a	b	c	β	Z	ρ	H
Triplite $(Mn, Fe)_2[PO_4]F$	12.05—12.02	6.47—6.45	10.05—10.01	105°42′—~108°	8	3.8—3.9	5.5—6
Triplaidite $(Mn, Fe)_2[PO_4]OH$	12.26—12.12	13.38—13.16	9.90—9.73	108°04′—108°18′	16	3.7—3.8	5—5.5
Wagnerite $Mg_2[PO_4]F$	11.92	12.53	9.65	108°07′	16	3.2	5.5—6

Str. The structures of these minerals are very similar; they are composed of isolated PO_4 tetrahedra joined by vertices to distorted MO_4F_2 or $MO_4(OH)_2$ octahedra. These octahedra are linked into two chains by shared edges, which are parallel to *a* and b axes. Interatomic distances in triplite: $(Mn, Fe)_1-(O,F)_6 = 2.14$; $(Mn, Fe)_2-(O,F)_6 = 2.10$; $P-O_4 = 1.53$ (Waldrop, 1969 [1303]); in triploidite: $(Mn, Fe)-(O,OH)_6 = 2.18$-2.23 and 2.10-2.15; $P-O_4 = 1.53$-1.54 (Waldrop, 1970 [1304]).

Chem. Perfect Mn−Fe isomorphism in triplite and triploidite, so the subspecies are manganotriplite, ferrotriplite, manganotriploidite, and ferrotriploidite. The main other isomorphous components are in triplite Mg (≤17.4%), Ca (≤14.9%), OH (≤3%), in triploidite Mg (≤4.7%), Fe^{3+} (≤7.8%), Ca (≤2%), F (≤0.9%), and in wagnerite Ca (≤13.5%?), Fe (≤4.3%).

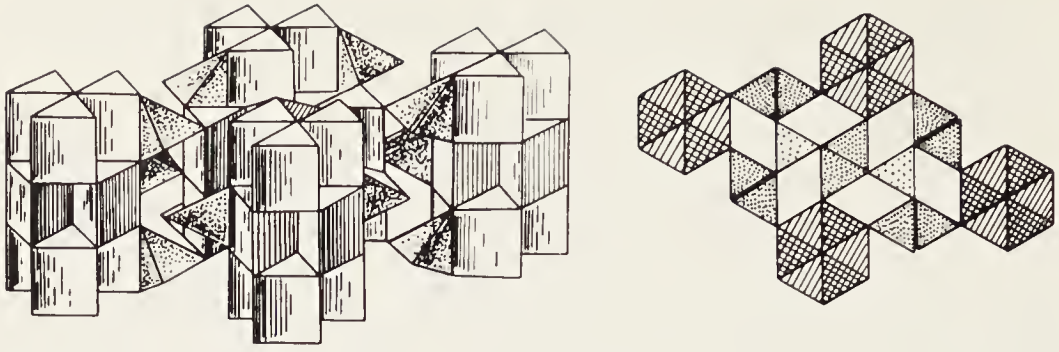
Var. Mg-triplite, Ca-triplite, OH-triplite, Mg-triploidite, Fe^{3+}-triploidite, Ca-wagnerite.

Phys. Short columns to isometric. Triplite has moderate (001) and (010) cleavage, imperfect (100); triploidite and wagnerite have (100) and (120) cleavages moderate (triploidite) to imperfect (wagnerite).

6. APATITE GROUP. Hex., $C_{6h}^2 - P6_3/m$, $Z = 2$ (1)

		a	c	ρ	H
Apatite	$Ca_2Ca_3[PO_4]_3(OH, F)$	9.43—9.38	6.88—6.86	3.1—3.2	5.5—6
Chlorapatite	$Ca_2Ca_3[PO_4]_3Cl$	9.54	6.86	3.2	5.25—5.75
Voelckerite	$Ca_4Ca_6[PO_4]_6O$	9.40	6.94	3.2	(5.5)
Dahllite	$Ca_4Ca_6[PO_4]_6CO_3$	9.36	6.90	3.1	(5.5)
Fermarite (stronapatite)	$Sr_3Ca_2[PO_4]_3F$	9.63	7.22	3.8	(5—5.5)
Lead hydroxyapatite (plumapatite)	$Pb_2Pb_3[PO_4]_3OH$	(9.83)	(7.42)	(7.1)	(5)

Str. Ca_I in apatite lies on threefold axes, while Ca_{II} lies in mirror planes (Fig. 243). Ca_I is surrounded by six O + three O, and Ca_{II} by six O plus one F (or six O + one Cl); Ca_I:$Ca_{II} = 2:3$. The Ca_I polyhedron is a somewhat twisted trigonal prism with centered faces (the latter three distances are appreciably larger than the others), one standing on an-



a b

Fig. 243. Structure of apatite in polyhedra: a) general view, b) projection on (0001).

other (Fig. 243a). The six nearest atoms (five O + one F) in the Ca_{II} polyhedron also lie at the vertices of a trigonal prism as triplets (Fig. 243, a and b), being linked via edges into columns along the c axis. These columns of two types of prism are connected via PO_4 tetrahedra. The F, OH, Cl, and O lie at the axes of the prisms. The Sr and Ca in fermorite are ordered with respect to the two cation positions, which reduces the stresses, gives the formula as (Sr, Ca)$(Sr_2Ca)[PO_4]F$, and reduces the symmetry to $C_6^6-P6_3$ (Borisov and Klevtsova, 1963 [935]). Interatomic distances in hydroxylapatite Ca_I-O_9 = 2.42 (3), 2.45 (3), and 2.80 (3); $Ca_{II}-O_6OH$ = 2.37 (2), 2.51 (2), 2.36, 2.71, and 2.35; $P-O_4$ = 1.52 (Posner et al., 1958 [936]); in fermorite $Sr-O_9$ = 2.59 (3), 2.48 (3), and 2.69 (3); $Ca-O_9$ = 2.39 (3), 2.41 (3) and 3.03 (3); $Sr-O_6F$ = 2.64 (6) and 2.39; $P-O_4$ = 1.56 (Klevtsova, 1964 [937]).

Chem. Only OH and F certainly show perfect isomorphism in apatite, which gives the subspecies hydroxylapatite and fluorapatite. Isomorphous components are numerous and varied, occurring in the cation and anion positions, which is due to the two different Ca positions and the possibility of removal or replacement of F, OH, and Cl or their replacement by oxygen atoms. The isomorphous components in fluorapatite are TR (≤12%), Sr (≤11.5%), Y (≤10.6%), Mn (≤10%), Cl (≤2%), S^{6+} (≤12%), As^{5+} (≤25%), Si (≤11%); those in hydroxylapatite are Mn (≤7.5%), Na (≤7.1%), K (≤3.7%), Al (≤3.7%); and those in chlorapatite are Mn (≤1.5%) and F (≤1.2%). TR and Sr often enter the Ca_{II} positions instead of Ca_I (Borisov and Klevtsova, 1963 [935]). PO_4 may be replaced not only by the tetrahedral radicals AsO_4, SO_4, SiO_4 but also by CO_3 or by CO_3 + F(OH), though with the latter in structurally different positions (Winand, 1963 [938]). The PO_4:SiO_4 ratio can attain 1:1 with corresponding replacement of Ca by Ce (Lindberg and Ingram, 1964 [939]).

Var. TR-fluorapatite, Sr-fluorapatite, Y-fluorapatite, Mn-fluorapatite, SO_4-fluorapatite, AsO_4-fluorapatite, SiO_4-fluorapatite, Mn-hydroxylapatite, Na-hydroxylapatite, K-hydroxylapatite, etc.

Phys. Short columns, (0001) and $(10\bar{1}0)$, cleavages imperfect.

Subdivision II. Complex

1. CRANDALLITE GROUP. Trig., $D^5_{3d} - R\bar{3}m$, $Z = 1; 3$

Plumbogummite subgroup

		a_{rh}	α	a_h	c_h	ρ	H
Florencite	$CeAl_3[PO_4]_2(OH)_6$	—	—	6.76	16.55	3.7	6—6.5
Woylandite	$BiAl_3[PO_4]_2(OH)_6$	—	—	6.96	16.26	3.9	5—5.5
Plumbogummite	$PbAl_3[PO_4]_2(OH)_5 H_2O$	—	—	—	—	4.1	5—5.5
Crandollite	$CaAl_3[PO_4]_2(OH)_5 H_2O$	6.72	62° 40′	6.99	16.13	2.9	5.5—6
Goyazite	$SrAl_3[PO_4]_2(OH)_5 H_2O$	6.83	61° 28′	6.98	16.54	3.3	5—5.5
Gorceixite	$BaAl_3[PO_4]_2(OH)_5 H_2O$	—	—	7.03	17.03	3.2?	5
Lusungite	$SrFe_3[PO_4]_2(OH)_5 H_2O$	6.92	61° 12′	7.04	16.80	—	(4.5—5)

Woodhouseite subgroup

Hinsdalite	$PbAl_3[PO_4][SO_4](OH)_6$	—	89° 40′	—	—	3.7	4.5—5
Woodhouseite	$CaAl_3[PO_4][SO_4](OH)_6$	6.76	62° 04′	6.97	16.30	3.0	5—5.5
Svonbergite	$SrAl_3[PO_4][SO_4](OH)_6$	6.90	60° 38′	6.97	16.80	3.2	5
Corkite	$PbFe_3[PO_4][SO_4](OH)_6$	—	91° 16′	—	—	4.3	4—4.5

Str. Alunite type (Fig. 258), CN of 12 and 6. The plumbogummite subgroup has 1/6 of the OH replaced by H_2O. Crandallite has space group C^5_{3V}–R3m. Some of the minerals occur in colloidal form and so have not been fully studied. Interatomic distances given for svanbergite and woodhouseite are Sr–(O, OH)$_{12}$ = 2.90; Al–(O, OH)$_6$ = 1.71 and 1.90; P–O$_4$ = 1.57; S–O$_4$ = 1.51; Ca–(O, OH)$_{12}$ = 2.74; Al–(O, OH)$_6$ = 1.88 and 1.93; P–O$_4$ = 1.55; S–O$_4$ = 1.53 (Pabst, 1947 [940]).

Chem. Fairly prominent isomorphous components: in fluorencite La (2–3%) and Sr (≤9%); in waylandite Si (4.7%) and Ca (3%); in crandallite Sr (≤2.2%); in goyazite Ce (≤14%), Ba (≤4%), and F (≤1.9%); in gorceixite Ce (≤7%) and Ca (≤3.6%); in lusungite Pb (≤3.5%); in hinsdalite Sr (≤3.1%); in woodhouseite Ba (≤1%); in svanbergite Ca (≤3.3%); in corkite Cu (2.5%).

Var. Sr-florencite, SiO_4-waylindite, Ce-goyazite, Ce-gorceixite, Pb-lusungite, Sr-hinsdalite, Cu-corkite.

Phys. Thick tablets to isometric, perfect (0001) cleavage.

2. DUFRENITE GROUP. Mon. →orth., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Dufrenite	$Fe_3Fe_6[PO_4]_4(OH)_{12}$	$C^5_{2h} - P2_1/n$	24.6	5.14	13.87	100° 25′	3.2	4—5
Andrewsite	$(Fe; Cu)_3 Fe_6[PO_4]_4(OH)_{12}$	D^5_2—$B22_12$	14.16	16.83	5.18	—	3.5	4

Str. Not known.

Chem. Composition of dufrenite varies from oxidation of Fe^{2+}; andrewsite has Fe:Cu fairly constant at about 1:1.

Phys. Radially radiated aggregates, cleavage in two directions.

3. ROCKBRIDGEITE GROUP. Orth., $D_2^5 - B22_12\,(?)$, $Z = 4$

		a	b	c	ρ	H
Rockbridgeite	$(Mn, Fe)\,Fe_4[PO_4]_3\,(OH)_5$	13.89—13.76	17.01—16.94	5.21—5.19	3.3—3.5	4.5—5
Zinc-rockbridgeite	$ZnFe_4\,[PO_4]_3\,(OH)_5$	13.97	16.88	5.19	3.5	4.5—5

Str. Not known. Similarity to whitlockite reported (Keppler, 1963 [926]).

Chem. Rockbridgeite has perfect Mn—Fe isomorphism, subspecies manganorockbridgeite and ferrorockbridgeite. Only minor amounts of other isomorphous components, e.g., Mg (≤2.2%). Zinc-rockbridgeite has Zn replaced by Mn and Fe (2-3% each).

Phys. Perfect to moderate cleavage on three pinakoids.

4. LAZULITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, $Z = 2$

	a	b	c	β	ρ	H
Lazulite $(Mg, Fe)\,Al_2\,[PO_4]_2\,(OH)_2$	7.16—7.15	7.26—7.31	7.24—7.25	120°40′—120°35′	3.1—3.4	6.5—6
Barbosalite $FeFe_2\,[PO_4]_2\,(OH)_2$	7.25	7.46	7.49	120°15′	3.6	(5.5)

Str. The (Mg, Fe) octahedra are linked via common edges and faces to Al(Fe) octahedra to give groups, which are linked by vertices one to another and to PO_4 tetrahedra. Mean interatomic distances: $Mg-(O, OH)_6 = 2.03$; $Fe-(O, OH)_6 = 2.09$; $Al-(O, OH)_6 = 1.95$; $P-O_4 = 1.55$ (Katz and Lipscomb, 1951 [941]; Lindberg and Christ, 1959 [942]).

Chem. Perfect Mg—Fe isomorphism in lazulite gives the subspecies magnesiolazulite and ferrolazulite. The isomorphous components include Ca (≤3.5%) and (in barbosalite) Mn (2.8%).

Var. Ca-lazulite, Mn-barbosalite.

Phys. Thick tablets to isometric (dipyramidal habit), moderate (110) cleavage.

5. PALERMOITE GROUP. Orth., D_{2h}^{25}-Immm, $Z = 4$

		a	b	c	ρ	H
Cirrolite	$Ca_3Al_2[PO_4]_3\,(OH)_3$	—	—	—	3.1	5.5–6.5
Attacolite	$CaAl_2[PO_4]_2\,(OH)_2$	11.46	15.71	7.28	3.2	6.5
Bertossaite	$Li_2CaAl_4[PO_4]_4\,(OH)_4$	11.48	15.73	7.23	3.1	6-6.5
Palermoite	$Li_2SrAl_4\,[PO_4]_4\,(OH)_4$	11.53	15.79	7.31	3.2	6

Str. Attacolite is isostructural with carminite, although the space groups are different. Ca has CN = 8, Al has CN = 6 (four O + two OH). Half of the Ca(Sr) in bertossaite and palermoite is replaced by twice the num-

ber of Li atoms, which may have CN = 5 (as in amblygonite) and lie in a cubic polyhedron. Cirrolite has not been examined.

Chem. Cirrolite contains Mn (2.2%); attacolite has Ca replaced by Mn (≤7.1%) and Sr (≤3.3%), Al by Fe^{2+} (≤1.3%), and P by Si (≤9.4%); bertossaite contains isomorphous Na, Mn, and F; and palermoite has Li replaced by Na (≤1.6%) and Sr by Ca (≤1.4%).

Var. Mn-attacolite, Sr-attacolite, SiO_4-attacolite, Na-bertossaite, Mn-bertossaite, Ca-palermoite.

Phys. Palermoite columnar; all minerals except cirrolite have perfect (100) cleavage.

6. BRAZILIANITE GROUP. Mon., $Z = 2$

		S.g.	a	b	c	β	ρ	H
Brazilianite	$NaAl_3[PO_4]_2(OH)_4$	$C_{2h}^5 - P2_1/n$	11.19	10.08	7.06	97° 22′	3.0	6
Lacroixite	$Na_4Ca_3MnAl_3[PO_4]_3(OH)_6F_2$	—	—	—	—	—	3.1	5
Tsumebite	$Pb_2Cu[PO_4][SO_4]OH$	$C_{2h}^2 - P2_1/m$	8.70	5.80	7.85	111°30′	6.0	4

Str. Not known.

Phys. Columnar, cleavage in one direction perfect to moderate (no cleavage for tsumebite) (Nichols, 1966 [1121]).

7. GRIPHITE GROUP. Cubic, $O_h^{10} - Ia3d$, $Z = 4$

		a	ρ	H	Cl.
Griphite	$Na_3CaMn_4Al_2[PO_4]_5(OH)_4$	12.28	3.4	6	None

Str. Homostructural with garnet, or rather hibschite $Ca_3Al_2[(SiO_4)_2 \cdot (OH)_4]$ (McConnell, 1942 [943]) about 1/6 of the PO_4 tetrahedra being replaced by $(OH)_4$. Only half of the Mn has CN = 8, the other half having CN = 6 and lying in positions equivalent to those for Al. The garnet-type formula for griphite is then $(Na; Ca; Mn)_3(Mn; Al)_2[(PO_4); (OH)_4]_3$.

Chem. Mn^{2+} replaced by Fe^{2+} (≤11%) and Al by Fe^{3+} (≤7%); OH replaced by F (≤3%).

Var. Fe^{2+}-griphite, Fe^{3+}-griphite, F-griphite.

8. BELOVITE GROUP. Trig., $C_{3i}^1 - P\bar{3}$, $Z = 2$

		a_h	c_h	ρ	H	Cl.
Belovite (nastroncephite)	$NaSr_3Ce[PO_4]_3OH$	9.63	7.22	4.2	5.5	$(10\bar{1}0)$ imperf.

Str. The main features are as for apatite, but there are differences in coordination and symmetry, the latter being reduced by the ordered distribution of the various species of atom over the different positions. Na has CN = 6 (trigonal prism), Sr has CN = 7, and Ce has CN = 9. The NaO_6 and CeO_9 polyhedra alternate regularly in the vertical columns. Interatomic distances: $Na-O_6 = 2.48$ (3) and 2.56 (3); $Sr-O_6OH = 2.41$ (2), 2.62 (2), 2.73, 2.80, and 2.39 (eighth distance 2.92); $Ce-O_9 = 2.35$ (3), 2.52 (3), and 2.60 (3); $P-O_4 = 1.56$ (1.50-1.62) (Klevtsova and Borisov, 1964 [944]).

Chem. Narrow variations due to a variety of possibilities for isomorphism. Na and Sr are replaced by Ca (≤5.2%), K and Mg (0.2-0.3%); Sr by Ba (≤1%), Ce by Th (≤1%) and P by S (≤1.2%).

Var. Ca-belovite, SO_4-belovite.

9. ISOKITE GROUP. Mon., $C_{2h}^6 - C2/c$, $Z = 4$

		a	b	c	β	ρ	H
Isokite	$CaMg[PO_4]F$	6,52	8,75	7,51	121° 28′	3,2	5,5—6

Str. Isostructural with sphene $CaTi[SiO_4]O$; CN of 7 and 6 for Ca and Mg respectively. Sublayered structure.

Chem. Ca replaced by Sr (1.65%), Ba (0.2%), and TR (0.2%); Mg by Fe (0.5%) and Mn (0.2%), and F by OH (0.5%).

DIVISION C. HYDRATED PHOSPHATES WITHOUT ADDITIONAL ANIONS

1. RHABDOPHANE GROUP. Hex.→orth., $Z = 3, 6$

		S.g.	a	b	c	ρ	H
Rhabdophone	$Ce(H_2O)[PO_4]$	$D_6^1 - P6_222$	7.06	—	6.44	4.0	(4.5—5)
Brockite	$(Ca; Th)(H_2O)[PO_4]$	$D_6^1 - P6_222$	6.98	—	6.40	4.0	(5—5.5)
Ningyoite	$(Ca; U)(H_2O)[PO_4]$	$D_2^1 - P222$	6.73	12.13	6.36	(4.1)	(5—5.5)
Smirnovskite	$Th_3(H_2O)_4[PO_4]_4(?)$	Tetr.	—	—	—	4.6	~5.5

Str. Ce in rhabdophane has CN = 8 (Fig. 244), the Ce polyhedra being linked to PO_4 tetrahedra to leave open channels parallel to the e axis, which contain the H_2O molecules. Interatomic distances in rhabdophane: $Ce-O_8 = 2.34$ (4) and 2.65 (4); $H_2O-O_8 = 2.93$ (4), 3.05 (4); $P-O_4 = 1.56$ (Mooney, 1950 [945]). The parameters of ningyoite are for synthetic material (Seeliger and Strunz, 1965 [946]).

Chem. Ce in rhabdophane is replaced by La (≤30%), Nd (≤20%), Y (≤8%), Ca (≤4%), and Th (≤4.4%), while P is replaced by Si (5-10%)

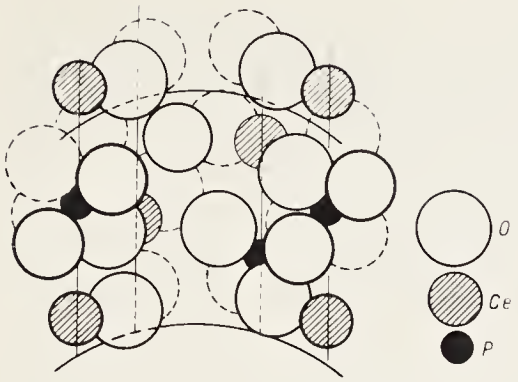


Fig. 244. Structure of rhabdophane.

and C (≤3.6%). The Ca in brockite is replaced by U, and Th by Ce and Nd (TR = 6.6%). The TR content of ningyoite is 1.7%. The Th in smirnovskite is replaced by TR (7.9%) and Ca (3.9%), and P by Si (6.5%). The composition thus tends to be very variable.

Var. La-rhabdophane, Nd, La-rhabdophane, Y-rhabdophane, Th-rhabdophane, SiO_4-rhabdophane, SiO_4-smirnovskite.

2. PHOSPHOFERRITE GROUP. Orth. →mon.

	Sg.	a	b	c	Z	ρ	H
Scholzite $CaZn_2(H_2O)_2[PO_4]_2$	D^5_{2h}—*Pbmm*	17.14	22.19	6.61	12	(3.1)	(4)
Phosphoferrite $(Mn, Fe)_3(H_2O)_3[PO_4]_2$	D^7_{2h} — *Pcnm*	8.71—8.66	10.08—10.02	9.49—9.41	4	3.0—3.2	3.5—3.75
Switzerite $Mn_3(H_2O)_4[PO_4]_2$	C^4_{2h}—*P2/a*	17.10	12.69	8.28	8	3.0	3
			$\beta = 95°55'$				

Str. Scholzite has not been examined. The Mn(Fe) in phosphoferrite has CN = 6 (four O + two H_2O), the four atoms belonging to four different PO_4 tetrahedra. These (Mn, Fe) octahedra are linked partly by edges and partly by vertices (subframework structure). Mean interatomic distances: $Fe-O_4(H_2O)_2$ = 2.24 (4) and 2.20 (2); $P-O_4$ = 1.57 (Flachsbart, 1963 [947]). Cell parameters of switzerite in [1399].

Chem. Composition variations not known for scholzite. The perfect Mn—Fe isomorphism in phosphoferrite gives us the subspecies manganophosphoferrite and ferrophosphoferrite. Other components are unimportant, apart from Fe^{3+}, which is produced by oxidation of part of the Fe^{2+} in manganophosphoferrite, but without producing defects, because one of the two H_2O linked to Fe is replaced by OH, which balances the charge increase. The formula of this manganophosphoferrite (formerly called landesite) is $[Mn^{2+}_{1-x}(Fe^{3+}OH)_x]_3(H_2O)_{3-3x}[PO_4]_2$ (Moore, 1964 [948]).

Var. Fe^{3+}-manganophosphoferrite.

Phys. Isometric, imperfect cleavage on (010).

3. HUREAULITE GROUP. Mon., C^6_{2h}—*C2/c*, Z = 4

		a	b	c	β	ρ	H
Hureaulite	$H_2Mn_5(H_2O)_4[PO_4]_4$	17.42	9.12	9.50	96° 40′	3.2	3.75
Ca-hureaulite (calchureaulite)	$CaMn_5(H_2O)_4[PO_4]_4$	—	—	—	—	—	(4)

Str. Not known.

Chem. H replaced by Li (≤2.1%) and Mn by Fe^{2+} (≤11%) and Fe^{3+} (≤10%), in the latter case with simultaneous loss of H.

Var. Li-hureaulite, Fe^{2+}-hureaulite, Fe^{3+}-heureaulite.

Phys. Short columns, moderate (100) cleavage.

4. STRUVITE GROUP. Orth.→mon.→tricl.

		S.g.	a	b	c	Z	ρ	H
Newberyite	$HMg(H_2O)_3[PO_4]$	$D_{2h}^{15} - Pbca$	10.06	10.56	9.83	8	2.12	3.5—3.75
Phosphorrösslerite	$HMg(H_2O)_7[PO_4]$	$C_{2h}^{6} - C2/c$	6.61	25.41	11.37	8	1.73	3
					$\beta = 94°\,56'$			
Struvite	$NH_4Mg(H_2O)_6[PO_4]$	$C_{2v}^{2} - Pmc\,2_1$	6.98	6.10	11.20	2	1.71	2—3
Schertelite	$(NH_4)_2H_2Mg(H_2O)_4[PO_4]_2$	$D_{2h}^{15} - Pbca$	11.47	23.63	8.62	8	1.83	(2.5—3)
Stercorite	$NH_4NaH(H_2O)_8[PO_4]$	Not det.	—	—	—	—	1.57	2
					$\beta = 99°\,18'$			
Hannayite	$(NH_4)_2H_4Mg_3(H_2O)_8[PO_4]_4$	$C_i^1 - P\bar{1}$	7.70	11.51	6.70	1	2.03	(2.5)
			$\alpha = 76°\,00'$		$\beta = 99°\,08'$		$\gamma = 115°\,08'$	

Str. Known only for newberyite, in which each Mg octahedron is linked via three oxygen vertices of PO_4 tetrahedra in a framework structure, which deviates somewhat from the true framework type because the three H_2O molecules at the other vertices of the Mg octahedron are linked by hydrogen bonds of length 2.45-2.55 to O atoms in PO_4 radicals. The Mg atoms and PO_4 radicals lie in planes parallel to (010), between which are only hydrogen bonds, which is responsible for the cleavage. Interatomic distances: Mg–$O_3(H_2O)_3$ = 2.05 (3); 2.12 (3); P–O_4 = 1.50-1.59 (d_m = 1.54) (Sutor, 1967 [949]).

Chem. Composition mainly constant. Mg in struvite is replaced by Fe (≤3.1%) and Mn (≤2%).

Phys. Short columns to isometric or thick tabular. No cleavage in phosphorrösslerite, schertelite, and stercorite; struvite and hannayite have moderate cleavage on (001), and newberyite has perfect cleavage on (010).

DIVISION D. HYDRATED PHOSPHATES WITH ADDITIONAL ANIONS

Subdivision I. Simple

1. BERAUNITE GROUP. Mon.→hex.

		S.g.	a	b	c	β	Z	ρ	H
Beraunite	$Fe_3(H_2O)_2[PO_4]_2(OH)_3 \cdot H_2O$	$C_{2h}^{6} - C2/c$	20.69	5.13	19.21	93°37	8	3.0	3.5—4
Cacoxenite	$Fe_4(H_2O)_{12}[PO_4]_3(OH)_3$	Not det.	27.·67	—	10.66	—	12	2.26	3—3.5
Tinticite	$Fe_3(H_2O)_3[PO_4]_2(OH)_3$	Orth. (?)	—	—	—	—	—	~2.8	(3—3.5)

Str. Known for beraunite, which is of subframework type, since many of the links of the Fe polyhedra and PO_4 tetrahedra are via common vertices. The channels contain 1/3 of the H_2O. There are four different octahedral environments for Fe^{2+}: five O + OH, four O + two OH, three O + two OH + H_2O, two O + two OH + two H_2O. Interatomic distances: $Fe-O_5OH$ = 1.93 (3); 2.17 (2); 2.08; $Fe-O_4(OH)_2$ = 2.02; $Fe-O_3(OH)_2H_2O$ = 1.97 (3); 1.99 (2); 2.12; $Fe-O_2(OH)_2(H_2O)_2$ = 1.94 (2); 1.93 (2); 2.04 (2); $P-O_4$ = 1.54 (Fanfani and Zanazzi, 1967 [950]). Cell parameters of cacoxenite in [1400].

Chem. Fe^{3+} replaced by Al (≤3-5%), and in beraunite also by Fe^{2+} (≤10%). Perhaps the formula of the latter should be written $Fe^{2+}Fe_5^{3+} \cdot (H_2O)_4[PO_4]_4(OH)_5 \cdot 2H_2O$, as follows from analyses and structural data.

Phys. Beraunite is tabular, while cacoxenite is acicular. Cleavage of beraunite on (100) moderate; cacoxenite has no cleavage.

2. WAVELLITE GROUP. Orth.

	S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Wovellite $Al_3(H_2O)_5[PO_4]_2(OH)_3$	D_{2h}^{16} — *Pcmn*	9.62	17.34	6.99	4	2.37	3.5—4
Fluellite $Al_2(H_2O)_7[PO_4](OH)F_2$	D_{2h}^{24} — *Fddd*	8.55	11.22	21.16	8	2.13	3.5
Coeruleoloctite $Al_3(H_2O)_4[PO_4]_2(OH]_3$	Not det.	—	—	—	—	2.57	4.5
Evonsite $Al_3(H_2O)_6[PO_4](OH)_6$	Not det.	—	—	—	—	2.2	3.5—4

Str. Probably heterogeneous frameworks, as is indicated by the recently discovered structure of fluellite, where the framework consists of chains of AlO_4F_2 octahedra linked to PO_4 tetrahedra via common vertices. Interatomic distances: $Al-O_4F_2$ = 1.86; $P-O_4$ = 1.53 (Guy and Geffrey, 1966 [951]). It would probably be better to assign these minerals to the first subclass.

Chem. Al in wavellite is replaced by Fe^{3+} (≤3.2%) and OH by F (≤2.8%). Minor components in colloidal coeruleolactite and evansite cannot for certain be taken as isomorphous. F in fluellite is replaced by OH (≤3.1%).

Phys. Wavellite is collumnar to acicular, perfect (110) cleavage, moderate (101) and (010).

3. VESZELYITE GROUP. Mon.

		S.g.	*a*	*b*	*c*	β	Z	*ρ*	H
Veszelyite	$(Zn;Cu)_3(H_2O)_2[PO_4](OH)_3$	C_{2h}^5 — $P2_1/a$	9.84	10.17	7.48	103° 25′	4	3.4	3.75
Togilite	$Cu_2(H_2O)[PO_4]OH$ (?)	Not det.	—	—	—	—	—	~3.5	3.5
Spencerite	$Zn_4(H_2O)_3[PO_4]_2(OH)_2$	C_{2h}^4—$P2/c$	10.54	5.33	11.3			3.1	3.5
Isoclosite	$Ca_2(H_2O)_2[PO_4]OH$	Not det.	—	—	—	—	—	2.92	(3)
Nissonite	$MgCu(H_2O)_{2.5}[PO_4]OH$	C_{2h}^6 — $C2/c$	22.58	5.03	10.54	99°20′	8	2.74	3

Str. Known for speneerite, whieh has an insular pattern consisting of Zn atoms in oetahedral and tetrahedral environments, whieh are linked together by PO_4 tetrahedra. Mean interatomie distances: $Zn-O_4(OH)_2$ = 2.06; $Zn-O_2(OH)(H_2O)$ = 1.84-2.01; $P-O_4$ = 1.58 (Hans-Hermann, 1966 [1124]).

Chem. The Zn:Cu ratio in veszelyite is fairly constant at 2:3; P is replaeed by As ($\leq$10%). The other minerals are of eonstant eomposition, exeept that nissonite contains a little V^{5+} and Fe^{3+} (Mrose et al., 1966 [952]).

Var. AsO_4-veszelyite.

Phys. Cleavage of veszelyite on (001) and (110) moderate, of speneerite on (100) perfeet, on (010) and (001) moderate, of isoelasite on (010) moderate, of nissonite on (100) perfect.

Subdivision II. Complex

1. OVERITE GROUP. Orth.→mon.

	S.g.	a	b	c	β	Z	ρ	H
Bermanite. $Mn\,Mn_2^{3+}(H_2O)_4\,[PO_4]_2(OH)_2$	$D_{2h}^5-C222_1$	6.20	8.92	19.20	—	4	2.85	3.75
Overite $Ca_3Al_8\,(H_2O)_{15}\,[PO_4]_8\,(OH)_6$	$D_{2h}^{21}-Bmam$	14.78	18.78	7.13	—	2	2.47	3.5—4
Mantgomeryite $Ca_4Al_5\,(H_2O)_{11}\,[PO_4]_6\,(OH)_5$	C_{2h}^6-C2/c	10.01	24.15	6.26	91° 28′	2	2.51	4
Calcioferrite $Ca_3Fe_3\,(H_2O)_8\,[PO_4]_4\,(OH)_3$	Hex. (?)	—	—	—	—	—	2.53	3
Xanthaxenite $Ca_2Fe\,(H_2O)\,[PO_4]_2\,OH$	Man. (?)	—	—	—	—	—	2.97	3

Str. Not known.

Chem. The following isomorphous eomponents are present: in bermanite Mg (2.4%) and Fe^{3+} (3%); in caleioferrite Mg (2.7%) and Al (2.9%); in xanthoxenite Mn (4.6%).

Phys. Bermanite is tabular on the c axis; the others are plates to laths elongated on e and flattened on b. Perfeet eleavage on (001) in bermanite, in the others on (010).

2. MORINITE GROUP. Mon. $C_{2h}^2-P2_1/m$ (?), Z = 1

		a	b	c	β	ρ	H
Morinite	$Na_2Ca_4Al_4\,(H_2O)_5\,[PO_4]_4O_2F_6$	9.46	10.69	5.45	105° 28′	2.94	4.5—5
Lehiite	$Na_2Ca_5Al_8\,(H_2O)_6\,[PO_4]_8\,(OH)_{12}$	—	—	—	—	2.89	5.5—6

Str. Not known.

Chem. Morinite has Ca replaced by Mn (2.4%); lehiite has Na replaced by K (2.3%).

Phys. Platy; morinite has perfect (100) cleavage.

3. WARDITE GROUP. Tetr.→mon.

		S.g.	a	c	Z	ρ	H
Avelinoite	$NaFe_3(H_2O)_2[PO_4]_2(OH)_4$	$D_4^4 - P4_12_12$	7.32	19.40	4	3.1	5—5.5
Wordite	$NaAl_3(H_2O)_2[PO_4]_2(OH)_4$	$D_4^4 - P4_12_12$	7.04	18.88	4	2.87	5.5—6
Pollite	$CaAl_3(H_2O)_2[PO_4]_2O(OH)_3$	Not det.	7.0	19.2	4	(3.0)	(5.5—6)
Souzolite	$Mg_3Al_4(H_2O)_2[PO_4]_4(OH)_6$	Mon. (?)	—	—	—	3.1	6—6.5

Str. Not known.

Chem. Fe in avelinoite is replaced by Al (1.4%); Na in wardite by Ca (≤7%); Mg in souzalite by Fe (≤11.6%) and Al by Fe^{3+} (≤2.7%).

Var. Ca-wardite, Fe-souzalite.

Phys. The first three are thick tablets on c, with perfect (001) cleavage; souzalite is platy with cleavage in two directions.

4. MINYULITE GROUP. Orth.→mon., $Z = 2; 4$

		S.g.	a	b	c	β	ρ	H
Minyulite	$KAl_2(H_2O)_4[PO_4]_2OH$	$C_{2v}^1 - Pmm2$	9.37	9.76	5.53	—	2.45	(4—4.5)
Leucophosphite	$KFe_2(H_2O)_2[PO_4]_2OH$	$C_{2h}^5 - P2_1/n$	9.76	9.65	9.70	102° 54′	2.92	(4.5)

Str. Not known; the parameters of leucophosphite are for synthetic material.

Chem. Minyulite is of constant composition; Fe in leucophosphite is replaced up to 12.7% by Al.

5. ROSCHERITE GROUP. Mon.→orth.

		S.g.	a	b	c	Z	ρ	H
Roscherite	$CaMnFeBe_3(H_2O)_2[PO_4]_3(OH)_3$	$C_{2h}^6 - C2/c$	15.95	11.95	6.62	4	2.92	5
				$\beta = 94° 50'$				
Sompleite	$NaCaCu_5(H_2O)_5[PO_4]_4Cl$	Not det.	9.72	38.48	9.67	8	3.3	4

Str. Not known.

Chem. The Ca:Mn:Fe ratio in roscherite varies substantially from isomorphous substitution. Na in sampleite is replaced by K (1.5%).

Phys. Tabular on c axis (roscherite) or b axis (sampleite); cleavage of roscherite on (001) and (010) moderate, of sampleite on (010) perfect and on (100) and (001) moderate.

Subclass 3. Chain

DIVISION A. ANHYDROUS

1. VÄYRYNENITE GROUP. Mon., $C_{2h}^5 - P2_{1/a}$, $Z = 4$

		a	b	c	β	ρ	H
Väyrynenite	$Mn\{Be[PO_4]OH\}\,^{1}_{\infty}$	5.41	14.49	4.73	102° 45′	3.2	5.5—6.5

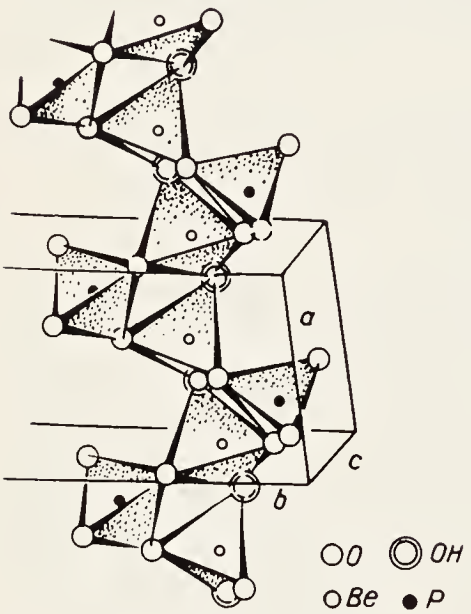


Fig. 245. Structure of vayrynenite, with chains of PO_4 and $BeO_2(OH)_2$ tetrahedra.

Str. Zigzag chains along a axis composed of $BeO_2(OH)_2$ and PO_4 tetrahedra linked by vertices (Fig. 245), composition $[Be(PO_4)OH]_n^{2n-}$, which are connected via Mn atoms (CN = 6), with two O and one OH belonging to one chain, while the other three O belong to three adjacent chains. The bonds within a chain are two or three times as strong as those between chains. Interatomic distances: $Mn-O_5OH$ = 2.17 (5) and 2.37; $Be-O_2(OH)_2 = 1.64$ (2) and 1.66 (2); $P-O_4 = 1.54$ (Mrose and Appleman, 1962 [309]).

Chem. Mn replaced by Fe (4.6%), Ca (1.8%), Na (1.4%), K (1.1%), and Al (2.5%).

Phys. Platy, moderate (001) cleavage.

2. MONETITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 4$

		a	b	c	α	β	γ	ρ	H
Monetite	$Ca\{H[PO_4]\}\,^{1}_{\infty}$	6.90	6.65	7.00	96° 21′	103° 54′	88° 44′	2.93	3.75

Str. Chain pattern produced by hydrogen bonds; the PO_4 tetrahedra are linked via H in the bent parts of discontinuous chains, which are connected by Ca (CN = 9). Interatomic distances: $Ca-O_9$ = 2.38-2.82; H—O = 2.44-2.66; $P-O_4 = 1.54$ (Jones and Cruickshank, 1961 [310]).

Phys. Thick tablets, imperfect cleavage.

DIVISION B. HYDRATED

1. MORAESITE GROUP. Hex.→mon.

		S.g.	a	b	c	Z	ρ	H
Faheyite	$MnBe_2Fe_2^{3+}(H_2O)_6[PO_4]_4 \frac{1}{\infty}$	$D_6^1 - P6_222(?)$	9.43	—	16.00	3	2.67	—
Moraesite	$Be_2(H_2O)_4[PO_4]OH \frac{1}{\infty}$	$C_{2/l}^6 - C2/c(?)$	8.55	36.90	7.13	12	1.81	(3)
					$\beta = 97°\,41'$			
Glucine	$CaBe_4[PO_4]_2(OH)_4 \frac{1}{\infty}$	Not det.	—	—	—	—	—	—
Uralolite	$CaBe_3(H_2O)_4[PO_4]_2(OH)_2 \frac{1}{\infty}$	Not det.	8.43	39.50	7.12	6	2.14	3
					$\beta = 94°\,58'$			

Str. Not known; assigned from morphology, properties, and general crystallochemical considerations. The minerals of the roscherite group are similar in composition but different in properties and have been considered in subclass 2 (division D, subdivision II).

Chem. Only minor isomorphous substitution.

Phys. Laths, needles, or fibers. Faheyite has perfect cleavage on $(10\bar{1}0)$ (?), while moraesite has perfect cleavage on (010) and (001) (?). Cleavage of glucine and uralolite not ascertained (Grigor'ev, 1963 [953] and 1964 [954]).

2. LUDLAMITE GROUP. Mon., $C_{2/l}^5 - P2_1/c$, $Z = 2$

		a	b	c	β	ρ	H
Ludlamite	$Fe_2(H_2O)_2\{Fe(H_2O)_2[PO_4]_2\} \frac{1}{\infty}$	9.25	4.65	10.45	100° 30′	3.2	3.75

Str. Two types of Fe octahedron: $FeO_4(H_2O)_2$ and $FeO_4(H_2O)_3$. The first type is linked by O–O edges to two PO_4 tetrahedra to form chains parallel to the b axis; between the chains lie the Fe_{II}. These and hydrogen bonds connect the chains together. Interatomic distances: Fe_I–$O_4(H_2O)_2$ = 1.99 (2), 2.06 (2), and 2.21 (2); Fe_{II}–$O_3(H_2O)_3$ = 2.03 (3) and 2.26 (3); P–O_4 = 1.51, 1.61, and 1.62 (2) (Ito and Mori, 1951 [311]).

Chem. Fe replaced by Mn (≤3.1%) and Mg (≤2.2%).

Phys. Thick tablets flattened on c axis and elongated on b axis. Perfect (001) cleavage, imperfect (100).

3. FAIRFIELDITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 1$

		a	b	c	ρ	H
Fairfieldite	$Ca_2\{(Mn,Fe)(H_2O)_2[PO_4]_2\} \frac{1}{\infty}$	5.78	6.57	5.48	3.0–3.1	3.75
		$\alpha = 102°\,05'$		$\beta = 109°\,42'$		$\gamma = 90°\,06'$
Callinsite	$Ca_2\{Mg(H_2O)_2[PO_4]_2\} \frac{1}{\infty}$	5.71	6.73	5.39	3.0	3.75
		$\alpha = 96°\,48'$		$\beta = 107°\,17'$		$\gamma = 104°\,32'$
Cassidyite (calcnihyphite)	$Ca_2\{Ni(H_2O)_2[PO_4]_2\} \frac{1}{\infty}$	5.71	6.73	5.41	3.2	3.75
		$\alpha = 96°49'$		$\beta = 107°21'$		$\gamma = 104°35'$

Str. Homostructural with roselite and kröhnkite, isostructural with trielinoroselite. The $\{(Mn, Fe)(H_2O)_2[PO_4]_2\}^1_\infty$ chains are linked by Ca with CN=7 (Fig. 235).

Chem. Perfect Mn–Fe isomorphism in fairfieldite, subspecies manganofairfieldite and ferrofairfieldite (the cell parameters related to the first); 1–2% Mg and Na. Collinsite has ≤7.3% Fe.

Var. Fe-collinsite.

Phys. Columns to laths, perfect (001) cleavage, moderate (010).

Subclass 4. Layer

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. PARSONSITE GROUP. Tricl. (?), s.g. not det., $Z = 2$

		a	b	c	ρ	H
Parsonsite	$Pb_2[(UO_2)(PO_4)_2]^2_\infty$	(6.8)	(10.4)	6.8	5.7	3—3.5

Str. Not known (isostructural with hallimondite). Assigned from morphology and crystallochemical considerations.

Chem. Data inadequate; formula derived from data of Bignand (1955) [955].

Phys. Tabular to platy, cleavage not observed. Biaxial negative.

DIVISION B. ANHYDROUS WITH ADDITIONAL ANIONS

1. HERDERITE GROUP. Mon.→orth. (pseudotetr.)

		S.g.	a	b	c	β	Z	ρ	H
Herderite	$Ca\{Be[PO_4](OH, F)\}^2_\infty$	$C^5_{2h} - P2_1/a$	9.82	7.70	4.81	90° 06′	4	3.0—3.1	5.5–6
Babefphite	$Ba\{Be[PO_4]F\}^2_\infty$	$C^{19}_{2v} - Fdd2$	6.93	16.74	6.93	–	2	4.3	5.5(?)

Str. Pseudotetragonal layers perpendicular to c axis and composed of PO_4 and $BeO_3(OH, F)$ tetrahedra differing in orientation (Fig. 246b), these tetrahedra forming four-sided and eight-sided rings. The layers are connected by Ca atoms (CN=8), which are also linked into layers made up of six-sided rings (Fig. 246a). Interatomic distances: $Ca–O_6F_2$ = 2.50 (6) and 2.65 (2); $Be–O_3F$ = 1.62 (3) and 1.67; $P–O_4$ = 1.53 (Pavlov and Belov, 1959 [802]). Babefphite has been placed in this group

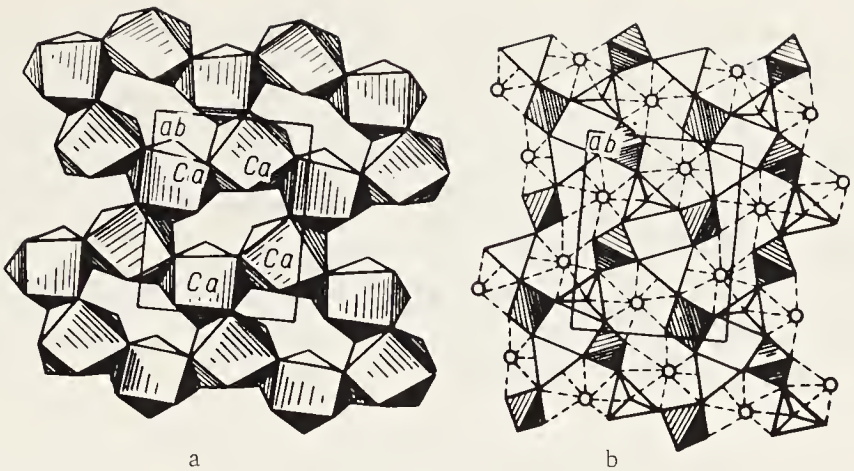


Fig. 246. Structure of herderite: a) layers of Ca polyhedra, b) layers of Be and P tetrahedra.

conditionally (Nazarova et al., 1966 [956]). Its symmetry and lattice parameters have recently been deduced based on an interpretation of its structure, for which a framework type has been postulated with the Be and P pseudotetrahedra joined at three apices. The fourth apex is free, with F ions having replaced the O ions. The interatomic distances are: (P, Be)$-O_4$ = 1.51, 1.53, 1.70, 1.61; Ba$-O_7$ = 2.75 (2), 2.79, 2.93 (2), 3.33 (2) (Shashkin et al., 1967 [1127]).

Chem. Perfect OH$-$F isomorphism, subspecies hydroxylherderite and fluoroherderite. Only minor components otherwise.

Phys. Short columns to thick tablets; herderite has imperfect (110) cleavage, with no (001) cleavage because the layers are uneven. Babefphite shows no cleavage.

DIVISION C. HYDRATED WITHOUT ADDITIONAL ANIONS

1. URANIUM-MICA GROUP

There are three main subgroups: torbernite ($H_2O > 8$), metatorbernite ($8H_2O$), and natroautunite ($3H_2O$), which differ in structure, some of the water also being zeolitic.

Torbernite subgroup. Tetr., $D_{4h}^{17} - I4/mmm$, $Z = 2$

		a	c	ρ	H
Torbernite	$Cu(H_2O)_8[UO_2(PO_4)]_2 \cdot nH_2O$ $\frac{2}{\infty}$	7.06	20.5	3.2	2—3
Autunite	$Ca(H_2O)_8[UO_2(PO_4)]_2 \cdot nH_2O$ $\frac{2}{\infty}$	7.00	20.67	3.1	2—3

Metatorbernite subgroup. Tetr.→pseudotetr. →orth.

		S.g.	a	c	Z	ρ	H
Sabugalite	$HAl(H_2O)_6[UO_2(PO_4)]_4\frac{2}{\infty}$	D_{4h}^{17} — $I4/mmm$	6.96	19.30	1	3.2	2—3
Metatarbernite	$Cu(H_2O)_8[UO_2(PO_4)]_2\frac{2}{\infty}$	C_{4h}^{3} — $P4/n$	6.97	17.31	2	3.7	2—3
Bassetite	$Fe(H_2O)_8[UO_2(PO_4)]_2\frac{2}{\infty}$	Pseudotetr.	7.0	17.07	2	3.6	2—3
Fritzscheite	$Mn(H_2O)_8[UO_2(PO_4)]_2\frac{2}{\infty}$	Tetr. (?)	—	—	—	3.5	2—3
Przhevalskite	$Pb(H_2O)_4[UO_2(PO_4)]_2\frac{2}{\infty}$	Orth.	—	—	—	—	2—3
Meta-autunite	$Ca(H_2O)_6[UO_2(PO_4)]_2\frac{2}{\infty}$	D_{4h}^{7} — $P4/nmm$	6.99	8.44	1	3.6	2—3
Uranacircite	$Ba(H_2O)_8[UO_2(PO_4)]_2\frac{2}{\infty}$	D_{4}^{5} — $P4_222$	6.98	16.85	2	4.1	2—3
Sincasite	$Ca(H_2O)_5[VO(PO_4)]_2\frac{2}{\infty}$	Tetr.	—	—	—	2.81	2—3

Natroautunite subgroup. Tetr. D_{4h}^{7} — $P4/nmm$, $Z = 1$

		a	c	ρ	H
Metauronocircite	$Ba(H_2O)_6[UO_2(PO_4)]_2\frac{2}{\infty}$	6.96	8.53	(4.4)	2—3
Natraautunite	$Na(H_2O)_3[UO_2(PO)_4]\frac{2}{\infty}$	6.97	8.69	3.9	2—3
Metaankoleite	$K(H_2O)_3[UO_2(PO_4)]\frac{2}{\infty}$	6.99	8.89	3.9	2—3
Uramphite (amurphosphyllite)	$NH_4(H_2O)_3[UO_2(PO)_4]\frac{2}{\infty}$	—	—	3.7	2—3
Hydragen autunite (axurphosphyllite)	$H_3O(H_2O)_3[UO_2(PO_4)]\frac{2}{\infty}$	—	—	3.8	2—3

Psuedoautunite subgroup. Man. (?), $Z = 2$

		a	b	c	β	ρ	H
Pseudoautunite	$(H_3O)_2Ca(H_2O)_3[UO_2(PO_4)_2]\frac{2}{\infty}$	6.96	6.96	12.90	—	3.3	2—3

Str. The PO_4 radicals and $(UO_2)O_4$ polyhedra are linked into tetragonal corrugated layers of composition $[UO_2(PO_4)]_n^{n-}$ parallel to (001) (Fig. 236). These layers are held together mainly via hydroxyl-hydrogen bonds to H_2O molecules forming squares between the layers at two levels. The centers of half of the squares are taken by Cu (and its analogs) in the metatorbernite subgroup, these being linked to the four H_2O and to two O atoms in uranyl groups (Fig. 247). The torbernite subgroup has additional H_2O (n of 2-4), which increases the c parameter. The centers of the H_2O squares remain empty in the natroautinite subgroup, while one of the water molecules is replaced by Ba, Na, K, or NH_4 and H_3O, which have low electronegativity and are mostly univalent. Interatomic distances in metatorbernite: $Cu-(H_2O)_4O_2$ = 1.91 (4), 2.40 and 2.66; $U-O_2O_4$ = 1.77, 1.82 and 2.33 (4); $P-O_4$ =

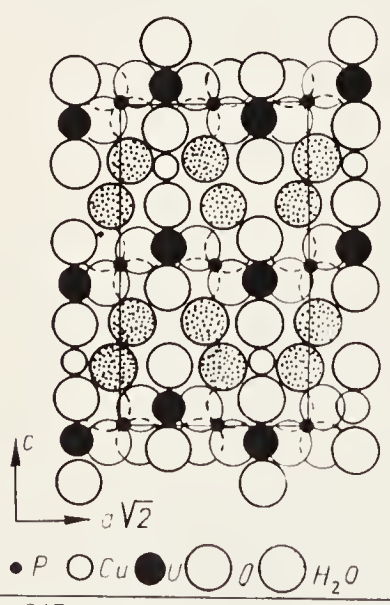


Fig. 247. Structure of metatorbernite, with Cu in spaces between layers.

1.52 (Ross et al., 1964 [957]); in meta-autunite Ca–$(H_2O)_4O_2$ = 2.27 (4) and 2.35 (2); U–O_2O_4 = 1.79, 1.99, and 2.32 (4); P–O_4 = 1.47 (Markarov and Ivanov, 1960 [958]). Pseudoautunite should be monoclinic or triclinic (Sergeev, 1964 [910]); the uranyl phosphate radical here is as in parsonsite.

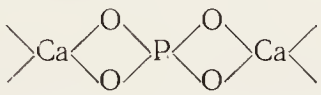
Chem. Compositions fairly constant, the main isomorphous component being As, which does not exceed 3-4%). Fritzscheite contains V^{5+}. More data are needed on pseudoautunite.

Phys. Tabular and platy, perfect (001) cleavage, moderate (100) and (010).

2. CHURCHITE GROUP. Mon.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Churchite	$Y(H_2O)_2[PO_4]$ $\frac{2}{\infty}$	$C_{2h}^6 - A2/a$	5.47	15.15	6.29	113° 24′	4	3.1	3—3.5
Brushite	$HCa(H_2O)_2[PO_4]$ $\frac{2}{\infty}$	$C_2^3 - A2$	5.89	15.18	6.38	117° 28′	4	2.26	2.5—3
Ardealite	$HCa_2(H_2O)_4[PO_4][SO_4]$ $\frac{2}{\infty}$	Not det.	5.68	14.67	6.29	~113°	2	2.30	(2.5)

Str. Churchite is isostructural with gypsum, while brushite and ardealite are homostructural with the latter. Brushite has corrugated $Ca[PO_4]$ layers perpendicular to the b axis, which consist of chains:



that lie at different levels and are firmly connected via Ca–O bonds (d = 2.35) (Fig. 248). The layers have projecting H_2O molecules which provide the hydroxyl-hydrogen bonds (broken lines in Fig. 248) that connect them together, these being the weakest bonds in the structure. Interatomic distances: Ca–$O_6(H_2O)_2$ = 2.35 (2), 2.44 (2), 2.82 (2), 2.54 (2); P–O_4 = 1.54; O–H_2O = 2.82; O–H–O = 2.63 (Beevers, 1958 [313]).

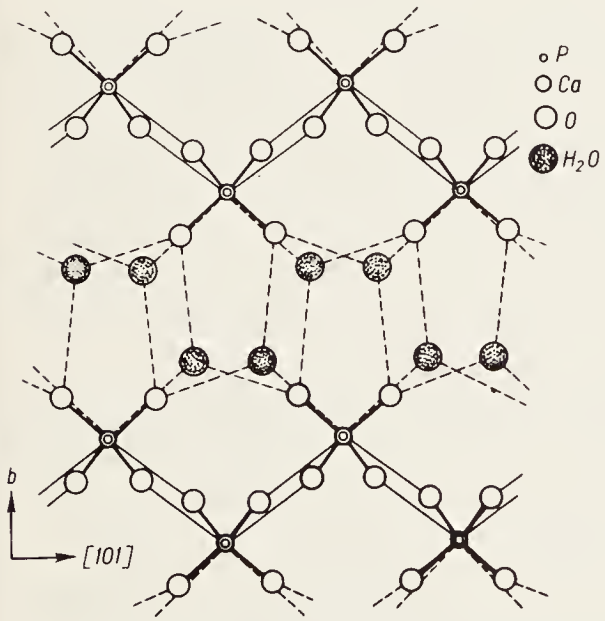


Fig. 248. Structure of brushite; the hydroxyl-hydrogen bonds to H_2O molecules are shown by broken lines.

Chem. Y in churchite is replaced by Ca (≤5.4%), and also by Dy, Er, Yb, Gd, etc. Brushite and ardealite are of constant composition.

Phys. Tabular on axis, laths elongated on c axis; highly perfect (010) cleavage, moderate (001), also moderate (100) in churchite.

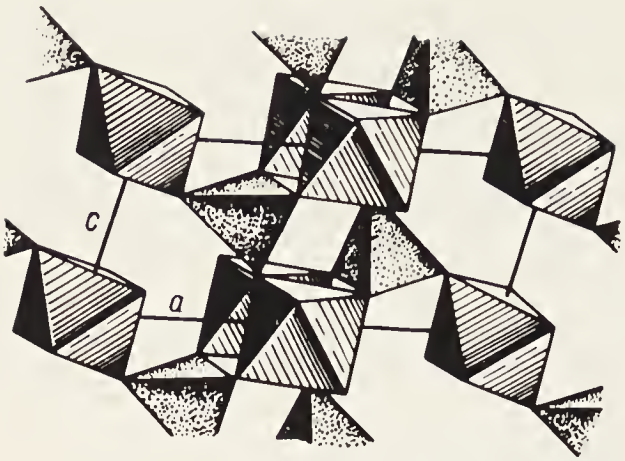


Fig. 249. Structure of vivianite, with $FeO_2(OH)_4$ and PO_4 polyhedra forming layers parallel to (010).

3. VIVIANITE GROUP. Mon.

		S.g.	a	b	c	Z	ρ	H
Vivianite	$(Fe^{2+}_{3-x}, Fe^{3+}_x)(H_2O)_{8-x}[PO_4]_2(OH)_x$ $\frac{2}{\infty}$	$C^3_{2h}-C2/m$	10.08	13.43	4.70	2	2.71	2—3
			$\beta = 104°30'$					
Bobierrite	$Mg_3(H_2O)_8[PO_4]_2$ $\frac{2}{\infty}$	$C^5_{2h}-P2_1/c$	9.97	27.71	4.65	4	2.17	2—3
			$\beta = 104°01'$					

Str. Two types of Fe octahedron: $FeO_2(H_2O)_4$ and $FeO_4(H_2O)_2$, the latter being paired via O—O edges (Fig. 249). The single and paired octahedra are linked via PO_4 tetrahedra into uneven layers parallel to (010), which are connected by weak H_2O-H_2O hydroxyl bonds. Interatomic distances: $Fe-O_2(H_2O)_4 = 2.00$ (2) and 2.01 (4); $Fe-O_4(H_2O)_2 = 2.02$ (2), 2.01 (2), and 2.02 (2); $P-O_4 = 1.64$; $H_2O-H_2O = 3.00$ (Mori and Ito, 1950 [911]). Bobierite has twice the b parameter of vivianite.

Chem. Oxidation causes a continuous composition change in vivianite, Fe^{2+} being isomorphously replaced by Fe^{3+}, valency compensation being provided by H_2O-OH replacement. All the oxidation products, the so-called kerchenites, have the same structure (Gamidov and Mamedov, 1960 [959]), so we have the subspecies ferrovivianite and ferrivivianite (parameters known only for the first). Isomorphous minor components are Mn (≤2.6%) and Mg (≤1.9%). The Mg in bobierite is replaced by Fe (≤15%) and Mn (≤3%).

Var. Mn-vivianite, Fe-bobierite, Mn-bobierite.

Phys. Platy to laths, elongated on c axis and flattened on b axis; perfect (010) cleavage.

4. TARANAKITE GROUP. Trig., $D^6_{3d}-R\bar{3}c$, $Z = 6$

		a_h	c_h	ρ	H
Taranakite	$K_3H_6Al_5(H_2O)_8[PO_4]_8$ $\frac{2}{\infty}$	8,71	96.1	2.09	(2—2.5)
Englishite	$K_2Ca_4Al_8(H_2O)_9[PO_4]_8(OH)_{10}$ $\frac{2}{\infty}$	—	—	~2.65	2.5—3

Str. Not known; assigned from morphology, properties, and crystallochemical considerations. The layers in taranakite presumably consist of Al and PO_4 tetrahedra, perhaps with K atoms, between which lie water molecules. There are probably six such layers in the unit cell (Smith and Brown, 1959 [960]).

Chem. K in taranakite replaced by NH_4 ($\leq$1%) and Ca ($\leq$1.5%), and Al by Fe ($\leq$1.2%); K in englishite is replaced by Na (1.6%).

Phys. Platy; englishite has perfect (001) cleavage.

DIVISION D. HYDRATED WITH ADDITIONAL ANIONS

1. PHOSPHURANYLITE GROUP. Orth., D^1_{2h} — $Bmmb$, $Z = 6$

		a	b	c	ρ	H
Kivuite	$Th(H_2O)_8[(UO_2)_4(PO_4)_2(OH)_6]\frac{2}{\infty}$	15.88	17.24	13.76	(4.5)	(2—3)
Renordite	$Pb(H_2O)_8[(UO_2)_4(PO_4)_2(OH)_4]\frac{2}{\infty}$	16.01	17.5	13.7	4.3	3—3.5
Phosphuronylite	$Ca(H_2O)_8[(UO_2)_4(PO_4)_2(OH)_4]\frac{2}{\infty}$	15.85	17.72	13.76	4.1	2—3
Bergenite	$Ba(H_2O)_8[(UO_2)_4(PO_4)_2(OH)_4]\frac{2}{\infty}$	16.2	17.7	13.9	4.2	(2—3)
Dewindtite	$Pb_2(H_2O)_7[(UO_2)_4(PO_4)_3(OH)_3]\frac{2}{\infty}$	16.00	17.62	13.66	5.0	(3—3.5)

Str. Not known, but the habit and cell parameters suggest a close relation to the uranium micas. The b parameter corresponds to c of the metatorbernite group, while a and c are similar and are twice the a of metatorbernite.

Phys. Tabular and platy, perfect (100) cleavage, moderate (010) (phosphuranylite).

2. DUMONTITE GROUP. Mon., C^2_{2h} — $P2_1/m$, $Z = 2$

		a	b	c	β	ρ	H
Dumontite	$Pb(H_2O)_3[(UO_2)_3(PO_4)_2(OH)_2]\frac{2}{\infty}$	8.16	16.73	7.02	110°	5.0	3.5
Coconinoite	$Al_2Fe^{3+}_2(H_2O)_{20}[(UO_2)_2(PO_4)_4(SO_4)(OH)_2]\frac{2}{\infty}$	—	—	—	—	2.70	(2.5)

Str. Dumontite has $[(UO_2)_3(PO_4)_2(OH)_2]^{2n-}_n$ layers parallel to (100), which are connected via Pb atoms; U takes two different positions, with CN of 7 and 8 (Piret-Meunier, et al., 1962 [961]). Kokoninoit not studied (Young et al., 1966 [1122]).

Chem. Data inadequate; the high Pb content of the earlier formulas for dumontite was an error.

Phys. Platy to laths elongated on c and flattened on a; moderate (100) cleavage in dumontite. No cleavage observed in coconinoit.

3. METAVAUXITE-LAUEITE GROUP. Mon. → tricl.

Here the minerals have been divided into subgroups by symmetry and proposed revised names are given. The species of the metavauxite (clinovauxite) subgroup have the a parameter twice that found in the laueite subgroup, so the unit cell is twinned on the a axis. This twinning is characteristic of the species in each subgroup; in strunzite it occurs on the b axis, while in vauxite (metavauxite) and stewartite (paralaueite) it occurs on the a axis. The latter two minerals have unit cells closely similar to those of metavauxite and pseudolaueite (clinolaueite), but with slight triclinic distortion, so the principle of classification requires us to assign them to the laueite subgroup.

Metavauxite subgroup. Mon.

	S.g.	a	b	c	β	Z	ρ	H
Metavauxite (clinovouxite)	$C_{2h}^5 - P2_1/c$	10.23	9.59	6.94	98° 02′	2	2.35	3.5
$Fe(H_2O)_4\{Al_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								
Pseudolaueite (clinalaueite)	Not det.	9.57	7.45	10.16	104° 40′	2	2,46	3.5
$Mn(H_2O)_4\{Fe_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								
Strunzite	$C_{2h}^6 - C2/c$	9.80	18,06	7.34	100° 10′	4	2.50	3.5
$Mn(H_2O)_4\{Fe_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								

Laueite subgroup Tricl. $C_i^1 - P\bar{1}$, $Z = 1; 2$

	a	b	c	α	β	γ	ρ	H
Sigloite	5.26	10.52	7.06	106° 58′	111° 30′	69° 30′	2.35	3.5
$Fe^{3+}(H_2O)_4\{Al_2(H_2O)_2[PO_4]_2O(OH)\} \cdot 2H_2O$ $^2_\infty$								
Paravauxite (vauxite)	5.24	10.54	6.97	107° 32′	110° 23′	72° 09′	2.38	3.5
$Fe(H_2O)_4\{Al_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								
Laueite	5.28	10.66	7.14	107° 55′	110° 59′	71° 07′	2.49	3.5
$Mn(H_2O)_4\{Fe_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								
Gardanite	5.26	10.51	6.98	109° 27′	110° 58′	71° 41′	2.23	3.75
$Mg_4(H_2O)_4\{Al_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								
Vauxite (metavauxite)	9.09	11.57	6.15	98° 52′	92° 22′	107° 43′	2.40	3.75
$Fe(H_2O)_4\{Al_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot H_2O$ $^2_\infty$								
Stewartite (paralaueite)	10.46	10.77	7.25	90° 35′	109° 58′	71° 21′	2.50	3.5
$Mn(H_2O)_4\{Fe_2(H_2O)_2[PO_4]_2(OH)_2\} \cdot 2H_2O$ $^2_\infty$								

Str. Studied in detail for laueite (Moore, 1965 [314]); chains parallel to the c axis consisting of Fe octahedra linked via common OH vertices and furtherlinked via O vertices to PO_4 tetrahedra (Fig. 250b). These chains are linked along the a axis by the same PO_4 tetrahedra into layers of composition $\{Fe_2(H_2O)_2[PO_4]_2(OH)_2\}^{2-}$ parallel to (010) (Fig. 250a), the layers being connected by Mn octahedra, which are connected via two opposite O vertices to four outer O vertices of P tetrahedra. These are the weakest bonds in the structure. The other four vertices of an Mn octahedron remain free and bear H_2O molecules. The further two H_2O mole-

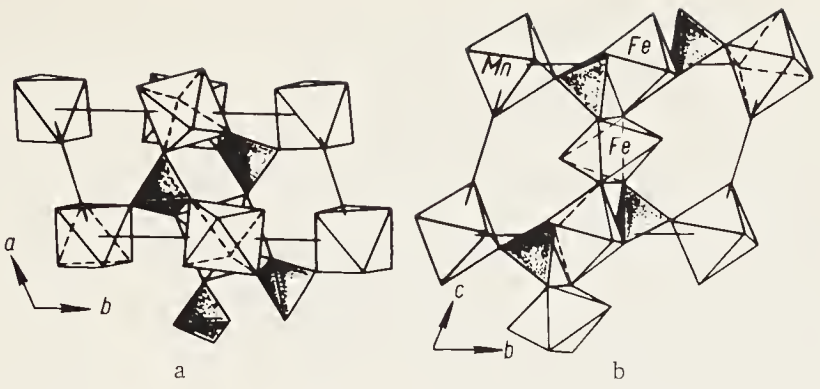


Fig. 250. Structure of laueite: a) projection on (001) showing layers of composition $[Fe_2(H_2O)_2(PO_4)_2(OH)_2]^{2-}$ parallel to (010); b) projection on (100) showing structure of chains of Fe octahedra and P tetrahedra in layers.

cules in the formula are of zeolite type and lie in holes in the structure. The (010) cleavage in most of the species is due to the layer pattern, while the habit is much influenced by the chains. The linking of the polyhedra would allow one to assign the structures to the framework type with zones of weaker bonds, as in the platy zeolites. Stereoisomerism with laueite has been proposed (Moore, 1965) for strunzite and stewartite. Interatomic distances: $Mn-O_2(H_2O)_4$ = 2.08 (2), 2.07 (2), 2.19 (2); $Fe-O_2(OH)_2(H_2O)_2$ = 1.98 (2), 1.95 (2), 2.10 (2); $P-O_4$ = 1.53. Recently the structures of metavauxite [1156] and vauxite [1157] have also been studied. For the latter interatomic distances are: $Fe-(O,OH,H_2O)_6$ = 2.16; $Al-(O,OH,H_2O)_6$ = 1.90; $P-O_4$ = 1.53.

Chem. Composition mainly constant. Almost all show small traces of isomorphous Mg and Ca (0.5-1%), and also heterovalent substitution of the type $R^{2+} \rightarrow R^{3+}$ and conversely. For instance, the Fe^{2+} in paravauxite is replaced by Fe^{3+} (≤1.5%) and in vauxite by Al (≤1%), whereas Al in metavauxite is replaced by Fe^{2+} (≤4%) and in gordonite by Mg (≤2%). Strunzite usually shows variations in Mn:Fe ratio from one locality to another (Frondel, 1957 [962]). Sigloite, which is formed from paravauxite, has half the OH replaced by O (Hurlbut and Honea, 1962 [963]), and it usually also has Fe_4^{2+} (2-3%).

Phys. Columnar to acicular, also laths. Cleavage observed only for sigloite, paravauxite, laueite, and gordonite on (010), perfect. The absence of cleavage in vauxite and stewartite causes these to approximate to the metavauxite subgroup (also without appreciable cleavage).

Inadequately Characterized and Doubtful

Azovskite $Fe_3^{3+}[PO_4](OH)_6$ (?)
Bolwarite $Al_2[PO_4](OH)_3 \cdot H_2O$ (?)

Borickite $CaFe_4[PO_4]_2(OH)_8 \cdot 3H_2O$ (?)
Delvauxite $Fe_2[PO_4](OH)_3 \cdot nH_2O$ (?)
Dittmarite $(NH_4)HMg_3(H_2O)_8[PO_4]_3$ (?)
Foucherite $Ca(Al, Fe)_4[PO_4]_2(OH)_8 \cdot 7H_2O$ (?)
Henwoodite $H_{10}CuAl_4[PO_4]_8 \cdot 6H_2O$ (?)
Kingite $Al_3[PO_4]_2(OH)_3 \cdot 9H_2O$ (?)
Kobokobite $(Mn, Fe)_2Fe^{3+}[PO_4]_3(OH)_4 \cdot nH_2O$ (?)
Kryzhanovskite $MnFe_2[PO_4]_2(OH)_2 \cdot H_2O$ (?)
Mitridatite $Ca_3Fe_4^{3+}[PO_4]_4(OH)_6 \cdot nH_2O$ (?)
Orpheite $Pb_2Al_4[PO_4]_2[SO_4](OH)_8 \cdot 4H_2O$ (?)
Richmondite $Al(H_2O)_4[PO_4]$ (?)
Richellite $Ca_3Fe_{10}[PO_4]_8(OH)_{12} \cdot nH_2O$ (?)
Rosieresite $(Pb, Cu)Al_5[PO_4]_2(OH)_{11} \cdot 10H_2O$ (?)
Sanjuanite $Al_2[PO_4][SO_4]OH \cdot 9H_2O$ (?)
Sodium hydrogen phosphate $Na_2H[PO_4] \cdot H_2O$ (?)
Sokolovite $(Sr, Ca)_2Al_8[PO_4]_2(OH)_{22}$ (?)
Spodiosite $Ca_2[PO_4]F$ (?)
Triclinocrandallite $Ca_2Al_7[PO_4]_3(OH)_{16} \cdot 3H_2O$ (?)

CLASS 8. TELLURITES AND SELENITES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds Class 8. Tellurites and selenites																H 12	
2																O 18		
3																S 1	Cl 1	
4		Ca 1					Mn 2	Fe 4	Co 1	Ni 1	Cu 4	Zn 2				Se 7		
5																Te 11		
6		Ba 1												Pb 3				
7					U 6													

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						10	3			4	1

Subclass 1. Insular

Division A. Without Water and Additional Anions

1. Molybdomenite $Pb[SeO_3]$ group
2. Denningite $CaMn[Te_2O_5]_2$ group

Divison B. Hydrated

1. Mackayite $Fe_2(H_2O)_2[TeO_3]_3$ group
2. Chalcomenite $Cu(H_2O)_2[SeO_3]$ group

Subclass 2. Layer

1. Moctezumite $Pb[UO_2(TeO_3)_2]^2_\infty$ group
2. Guilleminite $Ba[(UO_2)_3(SeO_3)_2(OH)_4] \cdot 3H_2O^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Insular

Here the simple tellurites and selenites are accompanied by diorthotellurites and orthodiorthotellurites. The $[TeO_3]$ and $[SeO_3]$ radicals are pyramidal, as for all subgroup b elements from group 4 onwards, from

incomplete use of the valency electrons (electron shell of 18 + 2 type). The subclass has anhydrous and hydrated divisions.

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. MOLYBDOMENITE GROUP. Mon., $C_2^2 - P2_1$ or $C_{2h}^2 - P2_1/m$, $Z = 2$

		a	b	c	β	ρ	H
Molybdomenite (plumseite)	$Pb[SeO_3]$	6.86	5.48	4.50	112° 45′	7.1	(2.5—3)

Str. Not known. Analogous parameters have been reported for synthetic material (Mandarino, 1965 [964]). Probably similar to structure of barytocalcite, but differing from latter in opposite disposition of the b and c axes (the b and c parameters must be interchanged).

Phys. Platy to laths, perfect (001) cleavage, moderate in another (h01) direction.

2. DENNINGITE GROUP. Cubic→tetr. → mon., $Z = 8;4$

		S.g.	a	b	c	β	ρ	H
Cliffordite	UTe_3O_8	$T_h^6 - Pa3$	11.37	—	—	—	6.8	4—4.5
Denningite	$CaMn[Te_2O_5]_2$	$D_{4h}^{11} - P4_2/nbc$	8.82	—	13.04	—	5.1	4
Spiroffite	$MnZn[Te_2O_5][TeO_3]$	$C_s^4 - Cc$ or $C_{2h}^6 - C2/c$	13.00	5.38	12.12	98°	5.0	3.75

Str. Known for denningite, a dimetatellurite. Ca has CN = 8, while Mn has CN = 6. The CaO_8 and MnO_6 polyhedra are linked by two common edges and alternate in columns parallel to the c axis (Fig. 251a), which are connected via TeO_3 pyramids in the form of pairs as Te_2O_5. Taking four O atoms around Te as coordinated (d = 2.36), we get the Te_2O_5 radicals linked into strips of Te polyhedra parallel to the c axis, which are

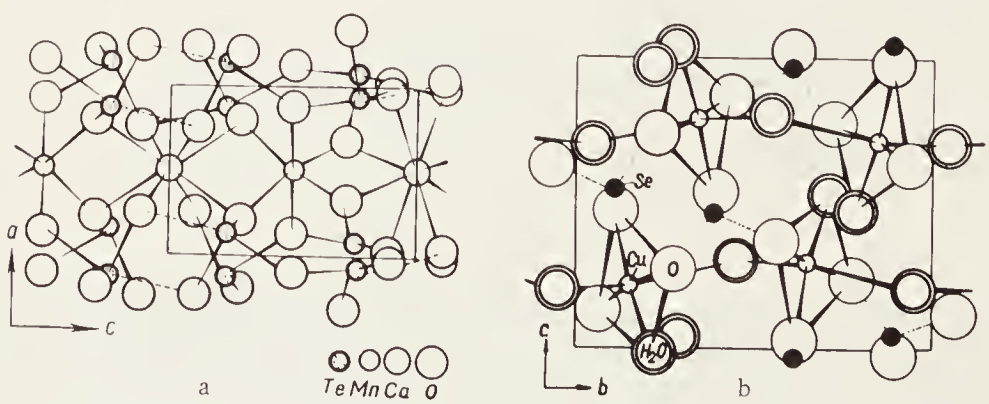


Fig. 251. Structure of : a) denningite in projection on (010), broken lines indicating the fourth Te—O coordination bond, b) chalcomenite in projection on (10Q).

responsible for the basal cleavage. Interatomic distances: $Ca-O_8$ = 2.42 (4) and 2.46 (4); $Mn-O_6$ = 2.04 (4) and 2.39 (2); $Te-O_{3+1}$ = 1.84, 1.87, 2.04, and 2.36 (Walitzi, 1964 [316]).

Chem. Part of the Ca in denningite is replaced by Mn, while the latter (in the octahedral positions) is itself isomorphously replaced by Zn (2.6%) and Mg (0.2%); Mn in spiroffite is replaced by Ca (0.2%). Clifordite has an admixture of Pb (≤3%) [1254].

Var. Zn-denningite.

Phys. Platy or thick tablets, perfect (001) cleavage only in denningite.

DIVISION B. HYDRATED

1. MACKAYITE GROUP. Hex.→tetr.→orth.→mon.→tricl.

		S.g.	a	b	c	β	Z	ρ	H
Zemonnite	$(H_{2-x}Na_x)Zn_2[TeO_3]_3 \cdot nH_2O$	C_{6h}^2—$P6_3/m$	9.41	—	7.64	—	2	4	(3—3.5)
Mackoyite	$Fe_2(H_2O)_5[TeO_3]_3$	D_{4h}^{20}—$I4_1/acd$	11.72	—	14.98	—	8	4.9	5
Poughite	$Fe_2(H_2O)_3[TeO_3]_2[SO_4]$	D_{2h}^{16}—$Pmnb$	9.66	14.20	7.86	—	4	3.8	3
Sonoroite	$Fe(H_2O)[TeO_3](OH)$	C_{2h}^5—$P2_1/c$	10.98	10.27	7.92	108°29′	8	4.2	3.5
Rodalquilorite	$H_3Fe_2[TeO_3]_4Cl$	C_i^1—$P1$	8.89	5.08	6.63	107°05′	1	5.1	2.5—3.5
			α = 103°10′		γ = 77°52′				

Str. For zemannite a zeolite-like structure with sodium—hydrogen (water) interchange in channels is assumed (Mandarino et al., 1969 [1263]). In the rodalquilarite structure, FeO_6 octahedra form chains which are joined by trigonal TeO_3 pyramids making dense planes which are connected by weak Te—Cl—Te bonds and by hydrogen bonds. Mean interatomic distances are: $Fe-O_6$ = 1.91-2.12 (d_m = 2.03); $Te-O_3$ = 1.86-1.91 (d_m = 1.89); Te—Cl = 3.06; O—H—O = 2.33-2.55 (Dusasoy and Protas, 1969 [1264]).

Chem. Mackayite has been fully analyzed by Gaines (1965 [1257]) and Pertlik (1968 [1258]). The formula corresponds to data [1257]; Pertlik analyzed an artificial product and proposes the formula $Fe[Te_2O_5]OH$.

Phys. Mackayite: short columns to isometric, no cleavage; poughite: perfect (010) and (101) cleavage [1256]. Rodalquilarite has moderate cleavage in one direction [1255].

2. CHALCOMENITE GROUP. Orth. → mon.

		S.g.	a	b	c	β	Z	ρ	H
Teineite	$Cu(H_2O)_2[TeO_3]$	D_2^4 — $P2_12_12_1$	6.63	9.61	7.43	—	4	3.8	3
Cholcomenite	$Cu(H_2O)_2[SeO_3]$	D_2^4 — $P2_12_12_1$	6.66	9.12	7.37	—	4	3.4	2.5—3
Ahlfeldite	$Ni(H_2O)_2[SeO_3]$	C_{2h}^5—$P2_1/n$	6.51	8.82	7.64	98°36′	4	3.4	(3)
Caboltomenite	$Co(H_2O)_2[SeO_3]$	C_{2h}^5—$P2_1/n$	6.46	8.75	7.55	99°00″	4	3.5	(3)

Str. Identical for teineite and chalcomenite. Cu in the latter has very distorted octahedral coordination, in which three O atoms and one H_2O molecule are arranged in a square around Cu (distances 1.94-1.98) with two further H_2O at 2.27 and 3.21 (Gattow, 1958 [317]). Se has three-fold pyramidal coordination, with Se—O of 1.72, 1.77, and 1.78, the three O atoms around Cu belonging to three different SeO_3 groups (Fig. 251b). The structure of teineite (Zemann and Zemann, 1962 [318]) is analogous, with distances of 1.81, 1.88, and 1.88 in the TeO_3 pyramid, while the distances in the CuO_3H_2O square are 1.79-1.98, the other two molecules being at 2.35 and 3.30. The bonds along [010] are somewhat weaker, on account of the position of the water molecules, which produces the corresponding cleavage. Ahlfeldite has not been examined in detail, but it appears similar to the previous, with a slight monoclinic distortion of the unit cell, as for synthetic selenite $Zn(H_2O)_2[SeO_3]$, whose space group is $C_{2h}^5-P2_1/n$; $a = 6.45$; b = 8.80; c = 7.65; $\beta = 82°$, Z = 4 (Gladkova and Kondrashev, 1963 [966]).

Chem. Te in teineite is replaced by S (up to 7% SO_3); chalcomenite is constant in composition. Ahlfeldite has considerable Co—Ni isomorphism (Gattow and Lieder, 1963 [319]).

Var. So_3-teineite, Co-ahlfeldite, Ni-cobaltomenite.

Phys. Teineite and chalcomenite are columnar but are not identical in habit (Dana [154]), perfect (010) cleavage (not reported for chalcomenite in works of reference). Ahlfeldite and cobaltomenite form very small prismatic crystals, no cleavage observed.

Subclass 2. Layer

Here the layer pattern (as in analogous subclasses of other classes) is determined by the coordination of U, which has its coordination bonds preferentially in one plane.

1. MOCTEZUMITE GROUP. Mon. → orth.

		S.g	*a*	*b*	*c*	β	*Z*	ρ	H
Moctezumite	$Pb[(UO_2)(TeO_3)_2]$ $^2_\infty$	$C_{2h}^5 - P2_1/c$	7.82	7.07	13.84	93° 38′	3	5.4	3.5
Schmitterite	$UO_2[TeO_3]$ $^2_\infty$	$D_{2h}^{11} - Pmab$	7.86	5.36	10.09	—	3	6.9	(2—3)

Str. Not known; assigned from morphology, cleavage, and crystallochemical arguments. Probably isostructural with pseudoautunite.

Chem. Data on composition variations inadequate (Gaines, 1965 [969]; Gaines, 1971 [1384]).

Phys. Platy to tabular, perfect (100) cleavage, biaxial negative.

2. GUILLEMINITE GROUP. Orth. → tricl.

	S.g.	*a*	*b*	*c*	*Z*	ρ	H
Guilleminite	$D_{2h}^{7} - Pncm$ (?)	7.25	16.84	7.08	2	4.9	(3—3.5)
$Ba[(UO_2)_3(SeO_3)_2(OH)_4] \cdot 3H_2O$ $\frac{2}{\infty}$							
Demesmaekerite	$C_i^1 - P\bar{1}$ or $C_1^1 - P1$	11.90	10.02	5.63	1	5.4	3.5—4
$Pb_2Cu_5[(UO_2)_2(SeO_3)_6(OH)_6] \cdot 2H_2O$ $\frac{2}{\infty}$		$\alpha = 89°\ 50'$	$\beta = 100°\ 20'$	$\gamma = 91°\ 25'$			
Marthozite	$D_{2h}^{16} - Pnma$	16.40	17.20	6.98	4	4.7	(3.5—4)
$Cu[(UO_2)_3(SeO_3)_3(OH)_2] \cdot 7H_2O$ $\frac{2}{\infty}$							

Str. Not known; assigned from morphology, physical properties, and crystallochemical data (uranyl-selenite layers form the basis of the structure) (Pierrot et al., 1965 [967]; Cesbron et al., 1965 [968]). Guilleminite is very close in structure to dumontite.

Chem. Data not complete.

Phys. Platy to tabular; guilleminite has perfect (100) cleavage, (010) moderate; demesmaekerite has no reported cleavage; marthozite has perfect (100) cleavage and flattened habit [1259].

Inadequately Characterized and Doubtful

Blakeite $Fe_2[TeO_3]_3$(?)
Dunhamite $Pb[TeO_3]$ (?)
Emmonsite $Fe_2(H_2O)_2[TeO_3]_3$
Ferrotellurite $FeTeO_4$ (?)
Magnolite $Hg_2[TeO_3]$ (?)

CLASS 9. TUNGSTATES AND MOLYBDATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds Class 9. Tungstates and molybdates																H 11	
2																O 17		
3		Mg 1											Al 1		P 1			
4		Ca 6						Fe 5			Cu 2				As 1			
5						Mo 10												
6			Ce 1			W 7								Pb 3				
7					U 4													

Coordinations		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						7	2			5	3

Subclass 1. Insular

Division A. Without Water and Additional Anions

1. Sedovite $U[MoO_4]_2$ group
2. Scheelite $Ca[WO_4]$ group
3. Raspite $Pb[WO_4]$ group

Division B. Hydrated

1. Ferritungstite $Ca_2Fe_2Fe_2^{3+}(H_2O)_9[WO_4]_7$ group
2. Betpakdalite $CaFe_2^{3+}(H_2O)_{14}[As_2Mo_5O_{24}]$ group

Subclass 2. Layer

1. Lindgrenite $Cu_3[MoO_4]_2(OH)_{2\infty}^2$ group
2. Iriginite $U(H_2O)_3[MoO_4]_2(OH)_{2\infty}^2$ group
3. Cousinite $Mg\{(UO_2)_2[MoO_4]_2(OH)_2\} \cdot 5H_2O_\infty^2$ group
4. Anthoinite $Al[WO_4]OH \cdot H_2O_\infty^2$ group

Inadequately Characterized and Doubtful

Subclass 1. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. SEDOVITE GROUP. Orth. (?), $Z = 1$

		a	b	c	ρ	H
Sedovite (urmolite)	$U[MoO_4]_2$	3.36	11.08	6.42	4.1	3.5

Str. Not known; parameters deduced from powder pattern. May be monoclinic (Skvortsova and Sidorenko, 1965 [970]).

Chem. Variations not known.

Phys. Needles, moderate cleavage along length.

2. SCHEELITE GROUP. Tetr., $C_{4h}^6 - I4_1/a$, $Z = 4$

		a	c	ρ	H
Scheelite	$Ca[WO_4]$	5.25	11.40	6.1	5
Powellite	$Ca[MoO_4]$	5.24	11.46	4.2	4
Stolzite	$Pb[WO_4]$	5.45	12.03	8.4	3—3.5
Wulfenite	$Pb[MoO_4]$	5.42	12.10	6.9	3—3.5

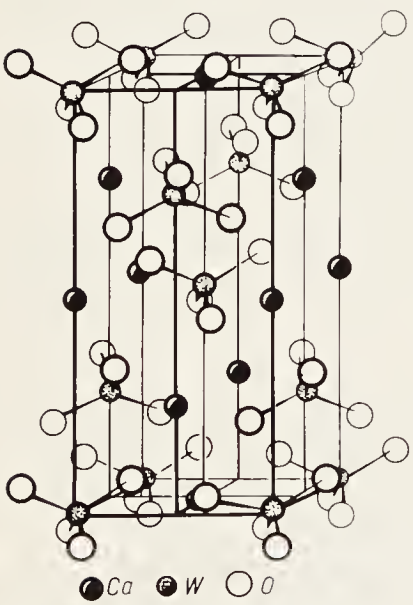


Fig. 252. Structure of scheelite, showing flattening of WO_4 tetrahedra along the c axis.

Str. Close to that of zircon and anhydrite, but differ from these in the mode of linking of the CaO_8 or PbO_8 polyhedra (Belov, 1947 [58]). The WO_4 and MoO_4 tetrahedra are somewhat flattened along the vertical axis (Fig. 252) and have edges in common with CaO_8 or PbO_8 (S. B. I [175]). The interatomic distances are not very precisely known, the values given for scheelite being $W-O_4 = 1.80$; $Ca-O_8 = 2.79$ p. 347 [175]. A later paper (Sillén and Nylander, 1943 [971]) gives standard $Ca-O = 2.40$ characteristic of sixfold oxygen coordination for Ca. Calculation of the hardness of scheelite (Povarennykh, 1963 [60]) indicates a normal distance $Ca-O_8 = 2.50$. The most probable values are $W-O_4 = 1.78$; $Ca-O_8 = 2.46$ (Burbank, 1965 [972]). The space group of wulfenite has been revised by Araki (1957) [973]; the interatomic distances for wulfenite are $Pb-O_8 = 2.61$ (4) and 2.63 (4); $Mo-O_4 = 1.77$ (Leciejwicz, 1965 [974]).

Chem. W—Mo isomorphism is the main cause of composition varia-

tion in scheelite and powellite. The Mo:W ratio in seheelite ranges up to 1:1.4 (24% MoO_3) and up to 9:1 in powellite (up to 10.3% WO_3). The Ca in scheelite is also partly replaced by Cu and TR. The Pb in wulfenite is replaced by Ca (≤6.9%; Ca:Pb = 1:1.7) and TR (≤2.2%), while Mo is replaced by W (up to 1:1), V (≤1.3%) and U (≤11.6%). The W in stolzite is replaeed by Mo (≤1.7%) and the Pb by Ca (≤1%).

Var. MoO_4-scheelite, Cu-schcelite, WO_4-powellite, U-wulfenite, WO_4-wulfenite, VO_4-wulfenite, Ca-wulfenite, (TR, WO_4)-wulfenite, MoO_4-stolzite, Ca-stolzite.

Phys. Isometric or occasionally tabular (wulfenite), imperfect cleavage in three directions.

3. RASPITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, $Z = 4$

		a	b	c	β	ρ	H
Raspite (plumwolite)	$Pb[WO_4]$	5.58	5.00	13.64	107° 33′	8.5	3—3.5

Str. Not known. The cell parameters and properties indicate a similarity to stolzite (pseudotetragonal).

Chem. Composition constant.

Phys. Thick tablets on (100), perfect (100) cleavage.

DIVISION B. HYDRATED

1. FERRITUNGSTITE GROUP. Tetr. → orth. (?)

		a	b	c	Z	ρ	H
Ferritungstite	$Ca_2Fe_2Fe_2^{3+}(H_2O)_9[WO_4]_7$ (?)	10.28	—	7.28	1	4.9	—
Ferrimolybdite	$Fe_2(H_2O)_8[MoO_4]_3$ (?)	—	—	—	—	3.1	1—2

Str. Not known; space group of ferritungstite not established, symmetry of ferrimolybdite not accurately known.

Chem. Data inadequate. Ferritungstite from different sources varies substantially in composition (Burnol et al., 1964 [975]).

Phys. Cryptocrystalline aggregates composed of very small crystals, which for ferritungstite are isometric (tetragonal dipyramids 0.01-0.02 mm in size). Ferrimolybdite sometimes forms radially radiated aggregates.

2. BETPAKDALITE GROUP. Mon., $C_{2h} - 2/m$ (?)

		a	b	c	β	Z	ρ	H
Betpakdalite	$CaFe_2^{3+}(H_2O)_{14}[As_2Mo_5O_{24}]$	11.22	19.25	17.73	92°30′	4	3.0	3.5

Str. Not known. Parameters after [1411].

Chem. Composition constant. Considered as a compound with a complex As–Mo radical (Ermilova and Senderova, 1961 [1261]).

Phys. Isometric crystals to short columns about 0.02 mm in size. No cleavage reported.

Subclass 2. Layer

1. LINDGRENITE GROUP. Mon., $C_{2h}^5 - P2_1/n$, $Z = 2$

		a	b	c	β	ρ	H
Lindgrenite	$Cu_3[MoO_4]_2(OH)_2$	5.61	14.06	5.40	98° 23′	4.3	5
Cuprotungstite	$Cu_2[WO_4](OH)_2$	—	—	—	—	(~5.6)	(5)

Str. Known for lindgrenite (Calvert and Barnes, 1957 [321]). There are two types of polyhedron: MoO_4 tetrahedra and $CuO_4(OH)_2$ octahedra. The latter are linked by edges into chains along the a axis (Fig. 253a), and the chains are connected via MoO_4 tetrahedra (which form common vertices with the Cu octahedra, Fig. 253b). The weakest bonds lie along the b axis, which is responsible for the layered structure parallel to (010). Interatomic distances: Mo–O_4 = 1.74; Cu_I–$O_4(OH)_2$ = 2.46 (2), 1.96 (2), and 1.98 (2); Cu_{II}–$O_4(OH)_2$ = 1.92, 2.36, 1.93, 2.45, 1.99, and 2.00.

Chem. Lindgrenite is of constant composition; cupritungstite contains Ca (≤4%) and Mg (≤0.7%).

Phys. Lindgrenite forms crystals tabular or platy on (010), perfect cleavage in that direction. Cupritungstite occurs as incrustations and aggregates.

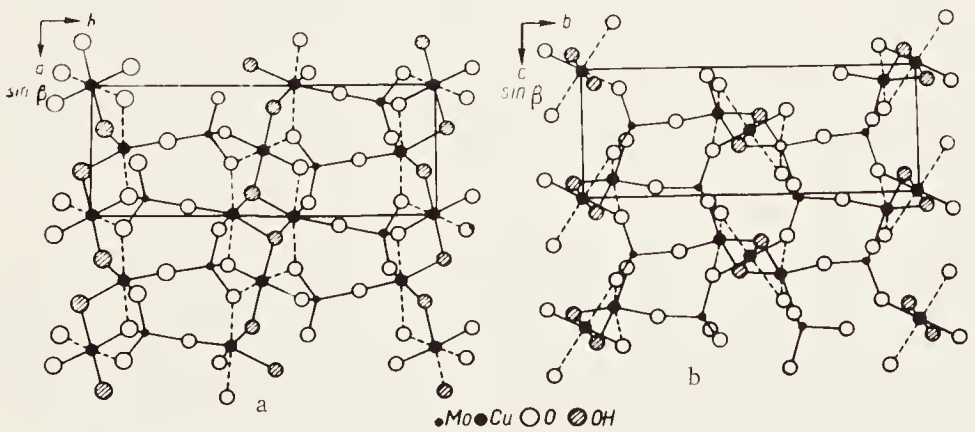


Fig. 253. Structure of lindgrenite: a) projection on (001), chains of Cu octahedra linked into layers by MoO_4 tetrahedra, b) projection on (100), layer pattern parallel to (010).

2. IRIGINITE GROUP. Mon., s.g. not det., $Z = 3$

		a	b	c	β	ρ	H
Iriginite	$U[MoO_4]_2(OH)_2 \cdot 3H_2O$ ☍	8.60	12.90	7.50	107° 40′	3.9	2.5—3

Str. Not known. The cell is pscudotetragonal, so it is supposed that the structure is close to that of lindgrenite, iriginite thus differing substantially from the uranium micas (Kazitsyn, 1961 [322]).

Chem. Data not complete; the water content varies somewhat (Stephenson, 1964 [976]).

Phys. Platy crystals with perfect cleavage on (010), moderate on (100), and imperfect on (101).

3. COUSINITE GROUP. Mon. (?)

		a	b	c	β	Z	ρ	H
Cousinite (magurmolite)	$Mg\{(UO_2)_2[MoO_4]_2(OH)_2\} \cdot 5H_2O$ ☍	6.37	33.46	15.0	90°	—	—	—
Calcurmolite	$Ca\{(UO_2)_3[MoO_4]_3(OH)_2\} \cdot 8H_2O$ ☍	—	—	—	—	—	—	—
Melkovite	$H_6CaFe[PO_4][MoO_4]_4 \cdot 6H_2O$ ☍	10.93	18.48	17.46	94°30′	4	2.97	3.5

Str. Not known; assigned from morphology and crystallochemical considerations. Formula of melkovite after Yegorov et al., 1969 [1385].

Chem. Data inadequate, especially for calcurmolite; H_2O content variable and dependent on external conditions.

Phys. Tabular or platy, perfect basal cleavage (?).

4. ANTHOINITE GROUP. Tricl.→mon.

		S.g.	a	b	c	β	Z	ρ	H
Anthoinite	$Al[WO_4]OH \cdot H_2O$ ☍	C_i^1—$P\bar{1}$(?)	9.51	9.23	13.05	120°	10	5.1	(3—4)
			$\alpha = 93°20'$		$\gamma = 88°20'$				
Cerotungstite	$Ce[WO_4]OH \cdot H_2O$ ☍(?)	C_2^2—$P2_1$	5.87	8.70	7.07	105°27′	2	5.3	(3.5)

Str. Not known.

Chem. Additional chemical analyses desirable. The formula $Ce(WO_3)_2(OH)_3$ for cerotungstite has been proposed (Sahama et al., 1970 [1260]).

Phys. Usually in colloidal-dispersed aggregates; crystals have bladed form with perfect cleavage (for anthoinite) in one direction.

Inadequately Characterized and Doubtful

Farallonite $2MgO \cdot W_2O_5 \cdot SiO_2 \cdot nH_2O$
Moluranite $3UO_3 \cdot 5MoO_3 \cdot nH_2O$ (?)
Mourite $UO_2 \cdot 5MoO_3 \cdot 5H_2O$ (?)
Pateraite $Co[MoO_4] \cdot nH_2O$ (?)
Thorotungstite (Th, Ce, Zn) $W_4O_8 \cdot nH_2O$ (?)
Yttrotungstite $YW_3O_9(OH)_3$(?)

CLASS 10. CHROMATES AND SELENATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds																H 2	
2	Class 10. Chromates and selemates															O 14	F 1	
3														Si 2	P 1	S 1		
4	K 2	Ca 1				Cr 11					Cu 3	Zn 1			As 1	Se 3		
5																		
6														Pb 11				
7																		

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						10	4				

Subclass 1. Insular

Division A. Without Water and Additional Anions

1. Crocoite $Pb[CrO_4]$ group
2. Tarapacaite $K_2[CrO_4]$ group
3. Lopezite $K_2[Cr_2O_7]$ group

Division B. With Additional Anions or Radicals

1. Vauquelinite $Pb_2Cu[PO_4][CrO_4]OH$ group
2. Bellite $Pb_2Pb_3[SiO_4](CrO_4)_2O$ group
3. Phoenicocroite $Pb_2[CrO_4]O$ group
4. Schmeiderite $PbCu[SeO_4](OH)_2$ group

Division C. Hydrated

1. Iranite $Pb(H_2O)[CrO_4]$ group

Inadequately Characterized and Doubtful

Subclass 1. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. CROCOITE GROUP. Tetr.→mon.→orth., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Chromatite	$Ca[CrO_4]$	$D_{4h}^{19} - I4_1/amd$	7.26	—	6.26	—	3.1	(3.75)
Crocoite	$Pb[CrO_4]$	$C_{2h}^5 - P2_1/n$	7.12	7.43	6.79	102° 27′	6.1	3—3.5
Kerstenite	$Pb[SeO_4]$	D_{2h}^{16}—$Pnma$	8.60	5.63	7.12	—	6.8	3.5
Olsacherite	$Pb_2[SeO_4][SO_4]$	D_2^2—$P22_12$	8.42	10.96	7.00	—	6.6	(3—3.5)

Str. Chromatite is isostructural with zircon (CN = 8 for Ca), while crocoite and kerstenite are isostructural with monazite $CePO_4$ (k = 9 for Pb). The cell parameters of kerstenite are for artificial $Pb[SeO_4]$ (Pistorius and Pistorius, 1962 [977]). Interatomic distances in crocoite: $Pb-O_9 = 2.53$-3.11 ($d_m = 2.79$); $Cr-O_4 = 1.61$-1.67 ($d_m = 1.65$) (Quareni and de Pieri, 1965 [1117]).

Chem. Chromatite has not been analyzed. Crocoite is of very constant composition; kerstenite has not been studied fully.

Phys. Crocoite and kerstenite are columnar, sometimes acicular. Crocoite has moderate cleavage on (110), kerstenite has imperfect cleavage along the length, and chromatite has no cleavage.

2. TARAPACAITE GROUP. Orth., $D_{2h}^{16} - Pmcn$, $Z = 4$

		a	b	c	ρ	H
Tarapacaite (kachrite)	$K_2[CrO_4]$	5.93	10.42	7.63	2.74	(2.5—3)

Str. Isostructural with mascagnite $(NH_4)_2[SO_4]$ (p. 446 [176]).

Chem. Data inadequate.

Phys. Thick tablets, moderate cleavage on (010) and (001).

3. LOPEZITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 4$

		a	b	c	α	β	γ	ρ	H
Lopezite (kadichrite)	$K_2[Cr_2O_7]$	7.52	13.43	7.39	98° 00′	90° 51′	96° 13′	2.69	2.5—3

Str. K and Cr lie in four independent positions. The CrO_4 tetrahedra are linked via vertices into pairs as Cr_2O_7 groups. K has four types of environment: two as KO_7 (trigonal prism and semioctahedron), one as octahedra, and one with CN = 8. The K polyhedra are linked together

in groups of four linked by edges and vertices, which are connected in the same way and also via Cr_2O_7 groups. Interatomic distances: K_1-O_7 = 2.67-2.78 (d_m = 2.73) and 2.97; K_2-O_7 = 2.78-3.00 (d_m = 2.91) and 2.69 (1); K_3-O_6 = 2.73-2.93 (d_m = 2.84); K_4-O_8 = 2.82-2.95 (d_m = 2.88) and 2.96 (1); $Cr-O_4$ = 1.52-1.65 (3); 1.73-1.85 (1) (Kuz'min et al., 1967 [978]).

Chem. Only microchemical data.

Phys. Spheroidal aggregates; artificial crystals are short columns on (001).

DIVISION B. WITH ADDITIONAL ANIONS OR RADICALS

1. VAUQUELINITE GROUP. Mon., Z = 4

		S.g.	a	b	c	β	ρ	H
Vauquelinite	$Pb_2Cu[PO_4][CrO_4]OH$	$C_{2h}^5 - P2_1/n$	13.68	5.83	9.53	93° 58′	5.8	3.5—3.75
Fornacite	$Pb_2Cu[AsO_4][CrO_4]OH$	$C_{2h}^5 - P2_1/c$	8.11	5.88	17.56	110° 00′	6.3	(3.5)

Str. Fornacite has CN = 9 for Pb and CN = 6 for Cu. Interatomic distances: $Pb-O_9$ = 2.35-3.03; $Cu-O_6$ = 1.97 (4), 2.36 and 2.47; $As-O_4$ = 1.61; $Cr-O_4$ = 1.63 (Cocco, 1966 [979]).

Chem. Both minerals have slightly variable Pb:Cu and PO_4:CrO_4 or AsO_4:CrO_4 ratios (Palache et al., [154]; Bariand and Herpin, 1962 [324]).

Phys. Vauquelinite occurs as small laths, while fornacite occurs as columnar crystals. No cleavage.

2. BELLITE GROUP. Hex.→tricl.

		S.g.	a	b	c	Z	ρ	H
Bellite	$Pb_2Pb_3[SiO_4][CrO_4]_2O$	$C_{6h}^2 - P6_3/m$	10.35	—	7.39	2	(6.6)	3.5
Hemihedrite	$Pb_4Pb_6Zn[SiO_4]_2[CrO_4]_6F_2$	$C_i^1 - P\bar{1}$	9.50	11.44	10.84	1	6.4	3.5

α = 120°30′ β = 92°06′ γ = 55°50′

Str. Apatite type, CN of 7 and 9 for Pb. Parameters quoted from Strunz (1958). The structure of hemihedrite is built of CrO_4 and SiO_4 tetrahedra, between which are placed Zn and Pb atoms in sixfold, eightfold, and ninefold coordinations. Interatomic distances are: $Pb-O_9$ = 2.29-3.34; $Pb-O_8$ = 2.32-3.11; $Zn-O_4F_2$ = 2.05-2.17; $Cr-O_4$ = 1.60-1.70; $Si-O_4$ = 1.62-1.65 (McLean and Anthony, 1970 [1265; 1266]).

Chem. More data needed on composition of bellite; Pb replaced by Ag and Cr^{6+} by As^{5+} (≤6.6%) (Palache et al., 1951 [154]).

3. PHOENICOCHROITE GROUP. Mon., $C_{2h}^3 - C2/m$, $Z = 4$

		a	b	c	β	ρ	H
Phoenicochroite	$Pb_2[CrO_4]O$	14.00	5.68	7.14	115°13′	6.5	3—3.5
Scheibeite	$Pb_8[CrO_4]_3O_5$	15.16	5.68	14.03	121°36′	6.7	3.5

Str. Phoenicochroite is isostructural with lanarkite $Pb_2[SO_4]O$. Structure contains independent chromate tetrahedra; Pb atoms in special position in mirror planes. The additional oxygen is associated with and tetrahedrally coordinated by the Pb atoms. Interatomic distances are: $Pb-O_5 = 2.78$; $Pb-O_4 = 2.60$; $Cr-O_4 = 1.67$ (Williams et al., 1970 [1270]).

Chem. Analyses of phoenicochroite inadequate; formula quoted from Bariand (1963) [325].

Phys. Tabular crystals, perfect cleavage in $(\bar{2}01)$; poorer cleavages are on (001), (010), and (011); for scheibeite perfect cleavage has been observed on (100) and distinct on (201) (Mücke, 1970 [1267]).

4. SCHMEIDERITE GROUP. Mon.

		a	b	c	β	ρ	H
Schmeiderite	$PbCu[SeO_4](OH)_2$ (?)	—	—	—	—	(5.6)	(2.5—3)

Str. Isostructural with linarite (Hey, 1963 [323]).

Chem. Data inadequate.

DIVISION C. HYDRATED

1. IRANITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 8$

		a	b	c	α	β	γ	ρ	H
Ironite	$Pb(H_2O)[CrO_4]$	10.02	9.54	9.89	104° 30′	66°	108° 30′	(5.8)	(2.5—3)

Str. Not known.

Chem. Composition determined by electron microprobe; full chemical analysis required [1387].

Phys. Small columnar crystals.

Inadequately Characterized and Doubtful

Berezovite $Pb_6[CrO_4]_3[CO_3]O_2$ (?).
Chrominium $Pb_2[CrO_4]O$
Khunite $(Pb, Zn, Cu)[CrO_4]O$

CLASS 11. SULFATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type III. Oxygen compounds Class 11. Sulfates																H 134	
2														C 5	N 6	O 162	F 3	
3	Na 32	Mg 22											Al 19			S 162	Cl 4	
4	K 30	Ca 18			V 1		Mn 8	Fe 64	Co 3	Ni 3	Cu 27	Zn 7		Ge 3				
5		Sr 2		Zr 1							Ag 1							
6		Ba 1										Hg 1		Pb 12				
7					U 5													

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
				4		66	77	6	2	5	2

Subclass 1. Insular

Division A. Without Water and Additional Anions

Subdivision I. Simple

1. Zinkosite $Zn[SO_4]$ group
2. Anhydrite $Ca[SO_4]$ group
3. Baryte $(Ba, Sr)[SO_4]$ group
4. Thenardite $Na_2[SO_4]$ group
5. Arcanite $K_2[SO_4]$ group

Subdivision II. Complex

1. Yavapaiite $KFe[SO_4]_2$ group
2. Langbeinite $K_2Mg_2[SO_4]_3$ group
3. Palmierite $K_2Pb[SO_4]_2$ group
4. Glauberite $Na_2Ca[SO_4]_2$ group

Division B. With Additional Anions

Subdivision I. Simple

1. Dolerophane $CuCu[SO_4]O$ group
2. Brochantite $Cu_4[SO_4](OH)_6$ group
3. Schuetteite $Hg_3[SO_4]O_2$ group

4. Lanarkite $Pb_2[SO_4]O$ group
5. Sulfohalite $Na_6[SO_4]_2ClF$ group

Subdivision II. Complex

1. Linarite $PbCu[SO_4](OH)_2$ group
2. Alunite-jarosite $NaAl_3[SO_4](OH)_6-KFe_3[SO_4](OH)_6$ group
3. Chlorothionite $K_2Cu[SO_4]Cl_2$ group
4. Sulfate-apatite $Na_3Ca_2[SO_4]_3Cl$ group

Division C. With Additional Radicals

1. Itoite $Pb_4[GeO_2(OH)_2][SO_4]_3$ group
2. Caledonite $Pb_5Cu_2[SO_4]_3[CO_3](OH)_6$ group
3. Burkeite $Na_6[SO_4]_2[CO_3]$ group

Division D. Hydrated Sulfates without Additional Anions

Subdivision I. Simple

1. Bassanite $Ca_2(H_2O)[SO_4]_2$ group
2. Kieserite $Mg(H_2O)[SO_4]$ group
3. Zircosulfate $Zr(H_2O)_4[SO_4]_2$ group
4. Chalcanthite $Cu(H_2O)_5[SO_4]$ group
5. Retgersite $Ni(H_2O)_6[SO_4]$ group
6. Epsomite-melanterite $Mg(H_2O)_7[SO_4]-Fe(H_2O)_7[SO_4]$ group
7. Coquimbite $Fe_2(H_2O)_9[SO_4]_3$ group
8. Mirabilite $Na_2(H_2O)_{10}[SO_4]$ group

Subdivision II. Complex

1. Syngenite $K_2Ca(H_2O)[SO_4]_2$ group
2. Leightonite $K_2Ca_2Cu(H_2O)_2[SO_4]_4$ group
3. Ferrinatrite $Na_3Fe(H_2O)_3[SO_4]_2$ group
4. Lecontite $NH_4Na(H_2O)_2[SO_4]$ group
5. Astrakhanite $Na_2Mg(H_2O)_4[SO_4]_2$ group
6. Voltaite $K_2Fe_5Fe_4^{3+}(H_2O)_{18}[SO_4]_{12}$ group
7. Picromerite $K_2Mg(H_2O)_6[SO_4]_2$ group
8. Tamarugite $NaAl(H_2O)_6[SO_4]_2$ group
9. Römerite $FeFe_2^{3+}(H_2O)_{14}[SO_4]_4$ group
10. Mendozite $NaAl(H_2O)_{11}[SO_4]_2$ group
11. Alum $KAl(H_2O)_{12}[SO_4]_2$ group
12. Halotrichite $(Mg, Fe)Al_2(H_2O)_{22}[SO_4]_4$ group

Division E. Hydrated Sulfates with Additional Anions

Subdivision I. Simple

1. Langite $Cu_4(H_2O)[SO_4]OH$ group
2. Butlerite $Fe(H_2O)_2[SO_4]OH$ group

3. Felsöbányite $Al_4(H_2O)_5[SO_4](OH)_{10}$ group
4. Minasragrite $V_2^{4+}(H_2O)_{15}[SO_4]_3(OH)_2$ group

Subdivision II. Complex

1. Fleischerite $Pb_3Ge(H_2O)_4[SO_4]_2(OH)_4$ group
2. Sideronatrite $Na_2Fe(H_2O)_3[SO_4]_2OH$ group
3. Metavoltine $K_5Fe_3(H_2O)_8[SO_4]_4(OH)_2$ group
4. Kainite $KMg(H_2O)_3[SO_4]Cl$ group
5. Ettringite $Ca_6Al_2(H_2O)_{24}[SO_4]_3(OH)_{12}$ group
6. Copiapite $(Mg, Fe)Fe_4^{3+}(H_2O)_{20}[SO_4]_6(OH)_2$ group

Subclass 2. Ring

1. Leonhardtite $Mg(H_2O)_4[SO_4]$ group

Subclass 3. Chain

1. Zippeite $(UO_2)_2[SO_4](OH)_2 \cdot 4H_2O^1_\infty$ group
2. Krausite $K\{Fe(H_2O)[SO_4]_2\}^1_\infty$ group
3. Kröhnkite $Na_2\{Cu(H_2O)_2[SO_4]_2\}^1_\infty$ group
4. Mercallite $K[HSO_4]^1_\infty$ group

Subclass 4. Layer

1. Johannite $Cu\{(UO_2)_2[SO_4]_2(OH)_2\} \cdot 6H_2O^2_\infty$ group
2. Rhomboclase $HFe[SO_4]_2 \cdot 4H_2O^2_\infty$ group
3. Natrochalcite $Na\{Cu_2(H_2O)[SO_4]_2OH\}^2_\infty$ group
4. Gypsum $Ca(H_2O)_2[SO_4]^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

Subdivision I. Simple

1. ZINKOSITE GROUP. Orth., $D_{2h}^{16} - Pnma$, $Z = 4$

		a	b	c	ρ	H	Cl.
Chalcocyanite (cuprisite)	$Cu[SO_4]$	8.39	6.69	4.83	3.7	3.75—4	None
Zinkosite	$Zn[SO_4]$	8.60	6.75	4.77	3.9	(4—4.5)	—

Str. The minerals are isostructural; chalcocyanite has nearly regular SO_4 tetrahedra linked via Cu atoms (CN = 6). Interatomic distances in

chalcocyanite Cu – O_6 = 1.87 (2), 2.15 (2), 2.36 (2); S–O_4 = 1.51; in zinkosite Zn–O_6 = 1.95 (2), 2.13 (2), 2.35 (2); S–O_4 = 1.48 (Kokkoros and Rentzeperis, 1958 [981]).

2. ANHYDRITE GROUP. Orth., D_{2h}^{17} — *Cmcm*, $Z = 4$

		a	*b*	*c*	*ρ*	H
Anhydrite	Ca [SO_4]	6.23	6.97	6.98	3.0	3.75

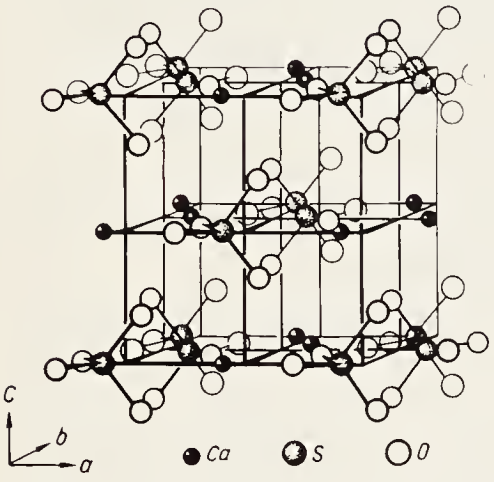


Fig. 254. Structure of anhydrite (general view); CN = 8 for Ca.

Str. Pseudotetragonal, composed of regular SO_4 tetrahedra linked by Ca (CN = 8, distorted; Fig. 254). Each SO_4 tetrahedron is linked to four Ca polyhedra by common vertices, and to fifth and sixth polyhedra by common edges. Interatomic distances: Ca–O_8 = 2.32 (2), 2.43 (2), 2.52 (2), 2.58 (2); S–O_4 = 1.47 (2) and 1.48 (2) (Höhne, 1962 [982]). Cheng and Zussman (1963) [983] give almost identical distances.

Phys. Perfect cleavage on three pinakoids.

3. BARYTE GROUP. Orth., D_{2h}^{16} — *Pnma*, $Z = 4$

		a	*b*	*c*	*ρ*	H
Anglesite	Pb [SO_4]	8.47	5.39	6.95	6.4	3—3.5
Baryte	(Ba, Sr) [SO_4]	8.87—8.38	5.44—5.35	7.15—6.87	4.5—4.0	3.5—3.75

Str. The minerals are identical in structure. The SO_4 tetrahedra are linked via Pb (or Ba or Sr) with CN = 7 in relation to SO_4 (Fig. 255a) or CN = 12 in relation to oxygen (Fig. 255b). The interatomic distances have only recently been determined more or less accurately; two of the 12 distances in the polyhedra are appreciably greater than the other 10.

These distances are as follows: in anglesite Pb–O_{12} = 2.63 (4), 2.77 (2), 2.93 (2), 3.05 (2), and 3.25 (2) (mean 2.88); S–O_4 = 1.42, 1.47, and 1.48 (2); in strontiobaryte Sr–O_{12} = 2.48, 2.58, 2.65 (2), 2.66 (2), 2.99 (2), and 3.25 (2) (mean 2.83); S–O_4 = 1.53, 1.55, and 1.50 (2); in bariobaryte Ba–O_{12} = 2.76, 2.78, 2.82 (2), 2.84 (2), 2.91 (2), 3.08 (2), and 3.30 (2) (mean 2.95); S–O_4 = 1.50, 1.52, 1.48 (2) (Sahl, 1963 [984]; Garske and Peacor, 1965 [985]).

Chem. Anglesite is of constant composition, with traces of Ba. Baryte has perfect Ba–Sr isomorphism (Palache et al., 1951 [154]), with

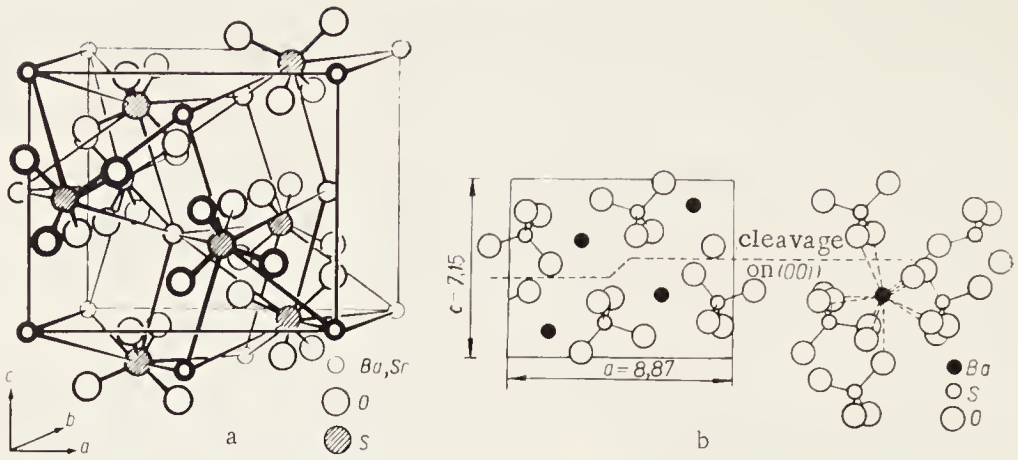


Fig. 255. Structure of baryte: a) general view, b) coordination of Ba and cleavage in bariobaryte.

the subspecies bariobaryte and strontiobaryte. Isomorphous components are Ca (≤1.9%) and (for bariobaryte) Pb (≤17.8%).

Var. Ba-anglesite, Ca-bariobaryte, Ca-strontiobaryte, Pb-bariobaryte.

Phys. Thick tablets on (001) and short columns; perfect cleavage on (001) and (210).

4. THENARDITE GROUP. Orth. → hex.

			S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Thenardite	(nasite)	$Na_2[SO_4]$	D_{2h}^{24} — *Fddd*	5.86	12.31	9.77	8	2.67	3—3.5
Metathenardite	(hexanasite)	$Na_2[SO_4]$	Not det.	5.40	—	7.59	2	2.57	(3—3.5)

Str. SO_4 tetrahedra linked via Na with CN = 6 (Fig. 256). Interatomic distances: Na—O_6 = 2.32 (2), 2.44 (2), and 2.48 (2); S—O_4 = 1.49 (Zachariasen and Ziegler, 1931 [986]). Metathenardite (stable above 240°C) has an unknown structure.

Phys. Isometric, (010) and (101) cleavages perfect.

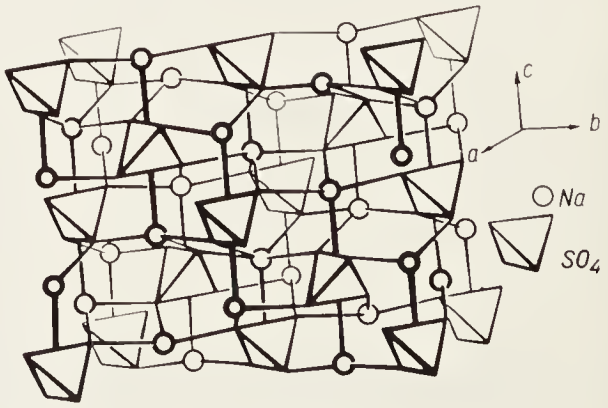


Fig. 256. Structure of thenardite.

5. ARCANITE GROUP. Orth., D_{2h}^{16} — $Pmcn$, $Z = 4$

		a	b	c	ρ	H	Cl.
Arcanite	$K_2[SO_4]$	5.77	10.07	7.47	2.70	(2.5—3)	(010) and (001) m
Mascagnite	$(NH_4)_2[SO_4]$	5.98	10.62	7.78	1.77	2.5—3	(001) m

Str. SO_4 tetrahedra linked via K atoms or NH_4 groups in two different positions (CN of 9 and 10). Interatomic distances: K—O_9 = 2.68, 2.71 (2), 2.77, 2.90 (2), 2.95, 3.07 (2); K—O_{10} = 2.72, 2.89 (4), 3.06, 3.07 (2), 3.11 (2); S—O_4 = 1.50 (p. 86 [176]).

Chem. K in arcanite replaced to a substantial extent by NH_4.

Var. NH_4-arcanite.

Subdivision II. Complex

1. YAVAPAIITE GROUP. Mon., C_{2h}^3 — $C2/m$. $Z = 4$

		a	b	c	β	ρ	H
Yavapaite (kaferrisite)	$KFe[SO_4]_2$	8.12	5.14	7.82	94° 24′	2.92	3—3.5

Str. Not known.

Phys. Thick tablets on c axis; (100) and (001) cleavages perfect, (110) moderate.

2. LANGBEINITE GROUP. Cubic, T^4 — $P2_13$, $Z = 4$

		a	ρ	H	Cl.
Langbeinite (kamagsite)	$K_2Mg_2[SO_4]_3$	9.98	2.83	3.5—4	None
Manganalangbeinite	$K_2Mn_2[SO_4]_3$	10.03	3.0	(3.5)	None

Str. SO_4 tetrahedra linked via K and Mg(Mn), with CN of 12 and 6 respectively. Interatomic distances in langbeinite: Mg—O_6 = 2.06; K—O_{12} = 2.78-3.25; S—O_4 = 1.48 (Zemann and Zemann, 1957 [987]).

3. PALMIERITE GROUP. Trig., D_{3d}^3 — $R\bar{3}ml$

		a_{rh}	α	a_h	c_h	Z	ρ	H
Palmierite	$K_2Pb[SO_4]_2$	7.56	42° 28′	5.58	20.67	1; 3	4.2	(3)
Kalistrantite (kastransite)	$K_2Sr[SO_4]_2$	—	—	5.46	20.70	3	3.3	(3—3.5)
Glaserite	$K_3Na[SO_4]_2$	—	—	5.66	7.30	1	2.72	3

Str. Palmierite and kalistrontite are probably isostructural; a preliminary study has been made for palmierite (Bellanca, 1946 [988]). The SO_4 groups (two types) are linked via Pb and K, the Pb lying at all vertices of the rhombohedron, the S atoms being on the threefold axis near the acute vertices, and the K atoms (two types) lying within the rhombo-

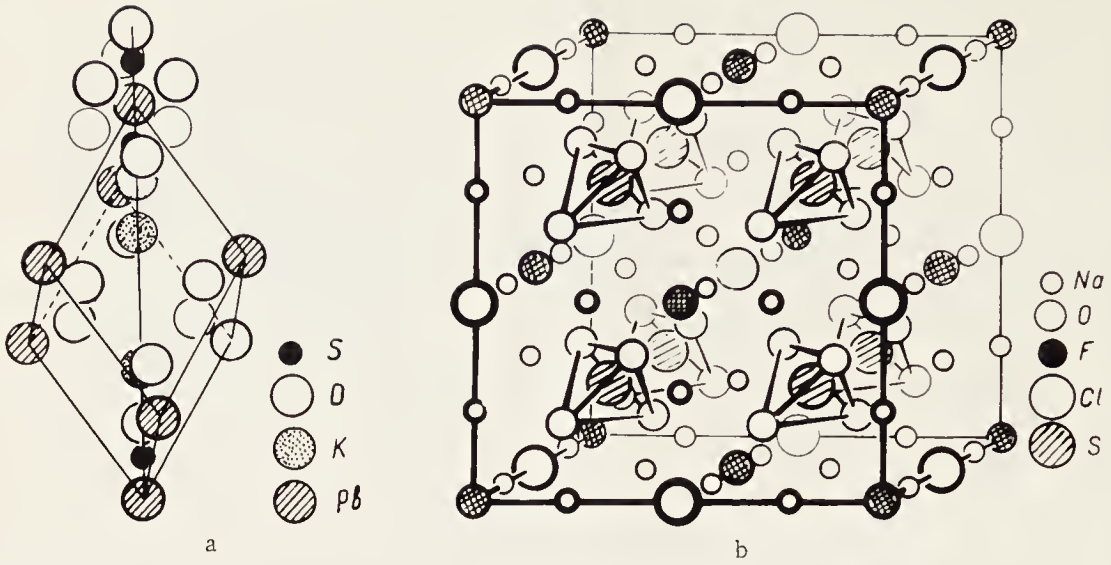


Fig. 257. Structure of palmierite and sulfohalite: a) rhombohedral cell of palmierite, b) sulfohalite.

hedron (Fig. 257a). Interatomic distances: $K_1-O_8 = 2.71$; $K_2-O_8 = 2.85$; $S_I-O_4 = 1.38$; $S_{II}-O_4 = 1.50$. The three O atoms nearest to Pb are at distances of 2.15. Glaserite has space group $D_{3d}^3-P\bar{3}ml$; Na has CN = 6, while K has CN = 10. Interatomic distances: $K-O_{10} = 2.78$, 2.69 (3), and 2.92 (6); $Na-O_6 = 2.44$; $S-O_4 = 1.41$ (3) and 1.60 (Bellanca, 1943 [989]).

Chem. K in palmierite partly replaced by Na (≤2.6%), while castronsite has traces of isomorphous (?) Na and Ca. Part of the K in glaserite is replaced by Na; other isomorphous components are NH_4 (≤5.7%), Pb (≤2.3%), and Cu (≤2.2%).

Var. Na-palmierite, Na-glaserite, NH_4-glaserite, Pb-glaserite, Cu-glaserite.

Phys. Tabular on (0001), perfect basal cleavage in palmierite and castronsite, moderate $(10\bar{1}0)$ cleavage in glaserite.

4. GLAUBERITE GROUP. Mon.

		S.g.	a	b	c	Z	ρ	H
Glauberite	$Na_2Ca[SO_4]_2$	$C_{2h}^6 - C2/c$	10.16	8.33 $\beta = 112°10'$	8.55	4	2.81	3—3.5
Vanthoffite	$Na_6Mg[SO_4]_4$	$C_{2h}^5 - P2_1/c$	9.80	9.22 $\beta = 113°30'$	8.20	2	2.69	3.5

Str. Glauberite has Ca polyhedra (CN = 8, irregular square antiprisms) and Na with CN = 7 (octahedron with one pyramidal centered face), which are linked by common edges and also via SO_4 tetrahedra. Interatomic distances: $Ca-O_8 = 2.36$ (2), 2.43 (2), 2.47 (2); and 2.74 (2); $Na-O_7 = 2.80$, 2.34, 2.55, 2.49, 2.35, 2.61, and 2.68; $S-O_4 = 1.47$, 1.49, 1.46, and 1.47 (Cocco et al., 1965 [990]).

Vanthoffite has Mg and one-third of the Na in octahedral coordination, the coordination of the other two-thirds of the Na being less regular (CN of 5 and 7). The SO_4 radicals are disposed in hexagonal close packing. Mean interatomic distances: $Na-O_5 = 2.41$; $Na-O_6 = 2.41$; $Na-O_7 = 2.53$; $Mg-O_6 = 2.08$; $S-O_4 = 1.48$ (Fischer and Hellner, 1964 [991]).

Chem. Compositions constant.

Phys. Glauberite is tabular to columnar; single crystals of vanthoffite have not been observed. Cleavage of glauberite on (001) perfect; no cleavage in vanthoffite.

DIVISION B. WITH ADDITIONAL ANIONS

Subdivision I. Simple

1. DOLEROPHANE GROUP. Mon., $C_{2h}^3 - C2/m$, $Z = 4$.

		a	b	c	β	ρ	H	Cl.
Dolerophane	$CuCu[SO_4]O$	9.36	6.31	7.63	122° 18′	4.2	3.5	(101) perf.

Str. Two types of Cu atom (CN of 5 and 6), the first represented by a CuO_5 trigonal dipyramid, and the second by a distorted $Cu^{[4+2]}O_6$ octahedron. The additional O atoms appear in Cu polyhedra as common to two trigonal Cu pyramids and one trigonal Cu octahedron. Interatomic distances: $Cu-O_5 = 1.87$, 1.91, 2.01, and 2.14 (2); $Cu-O_6 = 1.87$ (2), 2.07 (2), and 2.52 (2); $S-O_4 = 1.47$ (3) and 1.51 (Flügel-Kahler, 1963, 326]). Subchain structure (as in andalusite) from chains of Cu octahedra along the b axis, which is reflected in the columnar habit.

2. BROCHANTITE GROUP. Orth. → mon., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Antlerite	$Cu_3[SO_4](OH)_4$	$D_{2h}^{16} - Pnam$	8.23	11.98	6.05	—	3.9	3.75
Brochantite	$Cu_4[SO_4](OH)_6$	$C_{2h}^5 - P2_1/c$	13.08	9.85	6.02	103° 22′	4.1	3.75—4

Str. Antlerite has two types of Cu atom, both with octahedral coordination. One type of Cu is surrounded by four OH nearly forming a square, with an OH group and an O atom perpendicular to this; the other Cu has three OH in a plane with one O atom, the other two O atoms lying at the vertices of the octahedron. Interatomic distances: $Cu_1-(OH)_4(OH)O = 1.97$ (4), 2.32, and 2.56; $Cu_2-(OH)_3O_3 = 1.91$ (2), 2.03, 2.05, 2.37, and 2.41 (Finney and Araki, 1963 [327]).

Brochantite has octahedral coordination for Cu: four OH groups in a plane [$Cu-(OH)_4 = 2.0$] together with an O atom and another OH group

[Cu−O(OH) of 2.3·and 2.5]. The octahedra are linked by common edges and form a sublayered pattern parallel to (100) (Cocco and Mazzi, 1960 [328]).

Chem. Compositions constant.

Phys. Thick tabular to short columnar; perfect cleavage on (010) in antlerite, on (100) in brochantite.

3. SCHUETTITE GROUP. Hex., s.g. not det., $Z = 3$

		a	c	ρ	H	Cl.
Schuetteite	$Hg_3[SO_4]O_2$	7.07	10.05	8.4	~3.5	None (?)

Str. Not known. Composition and formula determined by comparison with the artificial compound.

4. LANARKITE GROUP. Mon., $C_{2h}^3 - C2/m$, $Z = 4$

		a	b	c	β	ρ	H	Cl.
Lanarkite	$Pb_2[SO_4]O$	13.76	5.69	7.08	115° 48′	7.0	2.5—3	$(\bar{2}01)$ perf.

Str. Not studied in full detail. Pb (CN = 3) in pyramidal coordination to O (as in minium) linked via SO_4 and additional O atoms, the last with tetrahedral surroundings of Pb (Binnie, 1951 [1269]). According to more precise data by Sahl [1286] the interatomic distances are: Pb_1-O_3 = 2.30(2), 2.55; Pb_2-O_3 = 2.31(2), 2.54; $S-O_4$ = 1.45, 1.47, and 1.49(2).

5. SULFOHALITE GROUP. Cubic → trig.

		S.g.	a	c	Z	ρ	H
Sulfohalite	$Na_6[SO_4]_2ClF$	$O_h^5 - Fm3m$	10.10	—	4	2.51	3.5
Galeite	$Na_3[SO_4]F$	$D_{3d}^1 - P\bar{3}lm$	12.17	13.94	15	2.61	3.75
Schairerite	$Na_3[SO_4]F$	$D_{3d}^1 - P\bar{3}lm$	12.17	19.29	21	2.63	3.75

Str. Sulfohalite can be derived from NaCl by replacing 1/6 of the Cl by F and 4/6 of the Cl by two SO_4 (Fig. 257b). Na has CN = 6, with one F atom, one Cl atom, and four O atoms. Interatomic distances: $Na-FO_4Cl$ = 2.28, 2.42 (4), and 2.76; $S-O_4$ = 1.51 (Pabst, 1934). The other two minerals have closely similar structures (Pabst et al., 1963 [992]); see also [1388].

Chem. Galeite and schairerite have F isomorphously replaced by Cl (≤3.9%) in galeite and 3.6% in schairerite).

Phys. No cleavage observed.

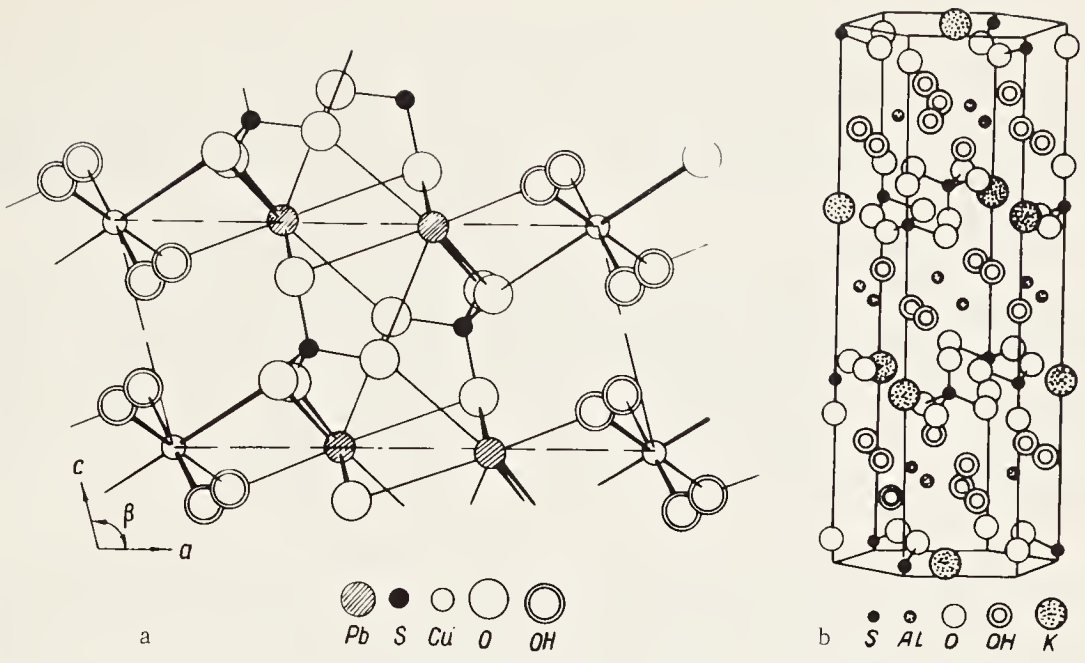


Fig. 258. Structure of: a) linarite in projection on (010), b) alunite (general view).

Subdivision II. Complex

1. LINARITE GROUP. Mon., C_{2h}^2—$P2_1/m$, $Z=2$

		a	b	c	β	ρ	H
Linarite	$PbCu[SO_4](OH)_2$	9.81	5.65	4.70	104°42′	5.3	3

Str. Pb has pyramidal coordination (two O and one OH), while Cu has four OH (nearly a square) and two O atoms (distorted octahedron, tetragonal dipyramid). The $Cu(OH)_4O_2$ octahedra are linked by OH edges into chains along the b axis (Fig. 258a). Interatomic distances: $Pb-O_2OH$ = 2.44 (2) and 2.38; $Cu-(OH)_4O_2$ = 1.93 (2), 1.98 (2), and 2.53 (2); $S-O_4$ = 1.48 (Bachmann and Zemann, 1961 [329]).

Chem. Composition constant; isomorphous Zn and Mg do not exceed 1%.

Phys. Columnar on b axis, perfect (100) cleavage.

2. ALUNITE-JAROSITE GROUP. Trig., $C_{3v}^5 - R3m$ (plumbojarosite $D_{3d}^5 - R\bar{3}m$)

Perfect Al—Fe isomorphism has not been demonstrated for this group (Brophy, Scott, and Snellgrove, 1962), so there are two composition subgroups.

Alunite subgroup

		a_{rh}	α	a_h	c_h	Z	ρ	H
Osarizowoite	$PbCuAl_2[SO_4]_2(OH)_6$	7.05	60°03′	7.05	17.25	1; 3	4.1	(4.5—5)
Alunite	$KAl_3[SO_4]_2(OH)_6$	7.05	59°14′	7.01	17.38	1; 3	2.8	3.75—4.5
Natroalunite	$NaAl_3[SO_4]_2(OH)_6$	—	—	6.98	16.70	3	(2.8)	(4—4.5)

Jarosite subgroup

Plumbojarosite	$PbFe_6[SO_4]_4(OH)_{12}$	11.97	35°05′	7.31	33.76	1; 3	3.7	(4—4.5)
Beaverite	$PbCuFe_2[SO_4]_2(OH)_6$	7.01	61°49′	7.20	16.94	1; 3	4.3	(4—4.5)
Argentojarosite	$AgFe_3[SO_4]_2(OH)_6$	6.88	63°21′	7.23	16.43	1; 3	3.8	(4.5)
Natrojarosite	$NaFe_3[SO_4]_2(OH)_6$	6.85	63°23′	7.19	16.33	1; 3	3.3	3.5—4
Jarosite	$KFe_3[SO_4]_2(OH)_6$	7.35	61°38′	7.21	17.03	1; 3	3.3	3—3.75
Ammoniojarosite	$(NH_4)Fe_3[SO_4]_2(OH)_6$	7.04	61°38′	7.21	17.03	1; 3	3.1	(3—3.5)
Carphosiderite (oxjarosite)	$(H_3O)Fe_3[SO_4]_2(OH)_6$	7.00	61°39′	7.35	17.01	1; 3	3.2	(3—3.75)

Str. The large atoms (Na, K, Ag, Pb) have CN = 12 (six O and six OH), while Al and Fe(Cu) have CN = 6, four OH and two O. Figure 258b shows the hexagonal cell of alunite, which shows that the K atoms lie at the vertices of a rhombohedron. Mean interatomic distances: $K-O_6(OH)_6$ = 2.82 (6), 2.87 (6); $Al-(OH)_4O_2$ = 1.86 (4), 1.96 (2); $S-O_4$ = 1.46 (Rong Wang et al., 1965 [993]). Plumbojarosite has only half the K positions taken by Pb, but this has little effect on the cell parameters. The distribution of the OH groups produces sublayering parallel to the basal plane.

Chem. Variable, from isomorphism. Osarizawaite has Al replaced by Fe (4.4%); alunite has Al replaced by Fe (≤8%) and K by Na (≤4.6%, which constitutes over 50% of K + Na). Plumbojarosite has less than 1% of such components. Beaverite has Fe replaced by Al (4%); natrojarosite has some K (≤2.3%). Jarosite has Fe replaced by Al (≤18.9%) and K by Ca (≤6%) and Na (≤1.7%); ammoniojarosite has 1.6% K. The H_3O in carphosiderite is partly replaced by K and Na.

Var. Fe-osarizawaite, Fe-alunite, Na-alunite, Al-beaverite, K-natrojarosite, Al-jarosite, Ca-jarosite, Na-jarosite, K-ammoniojarosite.

Phys. Isometric to thick tabular, moderate (0001) cleavage.

3. CHLOROTHIONITE GROUP. Orth., D_{2h}^{16}—*Pcmn* (?), $Z = 4$

		a	b	c	ρ	H
Chlorothionite	$K_2Cu[SO_4]Cl_2$	6.12	7.71	16.15	2.67	3

Str. Not known, parameters determined on artificial crystals. Orientation of the space group not determined exactly.

Chem. Composition constant.

Phys. Habit and cleavage not established.

4. SULFATE-APATITE GROUP. Hex., $C_{6h}^2 - P6_3/m$ (?), $Z=2$

		a	c	ρ	H
Sulfate-apalite (nacalcchlarsite)	$Na_3Ca_2[SO_4]_3Cl$	9.56	6.77	(2.93)	(4—4.5)
Caracalite (naplumchlarsite)	$Na_3Pb_2[SO_4]_3Cl$	9.81	7.14	5.0	4.5

Str. Apatite type, with 3/5 of the Cu(Pb) positions taken by Na (CN = 7), which is balanced by the charge difference between $[SO_4]$ and $[PO_4]$. The Ca(Pb) probably has CN = 9 (Seeliger and Berdesinski, 1956 [994]). The parameters of caracolite are from Schneider (1965) [995].

DIVISION C. WITH ADDITIONAL RADICALS

1. ITOITE GROUP. Orth., D_{2h}^{16}—$Pnma$ (?), $Z = 1$

		a	b	c	ρ	H
Itaite	$Pb_4[GeO_2(OH)_2][SO_4]_3$	8.47	5.38	6.94	6.6	(3.5)

Str. Isostructural with anglesite, $[GeO_2(OH)_2]$ tetrahedra replacing SO_4 in the ratio $[SO_4]:[GeO_2(OH)_2] = 3:1$, not 2:1 (Frondel and Strunz, 1960 [996]), since the latter does not agree with Z if integers are used in the formula.

Chem. No quantitative analysis.

Phys. Microcrystals laths to needles, cleavage not observed.

2. CALEDONITE GROUP. Orth.→mon.

		S.g.	a	b	c	Z	ρ	H
Caledonite	$Pb_5Cu_2[SO_4]_3[CO_3](OH)_6$	C_{2v}^7—$Pmn2_1$	21.10	7.15	6.56	2	5.7	3—3.5
Wherryite	$Pb_4Cu[SO_4]_2[CO_3]O(OH)$	C_{2h}^3—$C2/m$	20.82	5.79	9.17	4	6.4	(3—3.5)

Str. In caledonite Pb polyhedra, SO_4 tetrahedra, and CO_3 triangles form layers parallel to ac, which are connected with each other by chains consisting of Cu pseudooctahedra and by additional SO_4 groups (Giacovezz et al., 1970 [1287]). Wherryite is similar to leadhillite [1268].

Phys. Short columns and needle-like (for wherryite); caledonite has perfect (100) cleavage.

3. BURKEITE GROUP. Orth. → hex.

		S.g.	a	b	c	Z	ρ	H
Burkeite	$Na_6[SO_4]_2CO_3$	D_{2h}^{13}—$Pmnm$	5.17	27.26	21.18	12	2.57	3.75
Hanksite	$KNa_{22}[SO_4]_9[CO_3]_2Cl$	C_{6h}^2—$P6_3/m$	10.48	—	21.22	2	2.57	3.5—3.75

Str. Not known; hanksite may have a structure similar to that of apatite.

DIVISION D. HYDRATED SULFATES WITHOUT ADDITIONAL ANIONS

Subdivision I. Simple

1. BASSANITE GROUP. Mon., s.g. not det., $Z = 6$

		a	b	c	β	ρ	H
Bossonite	$Ca_2(H_2O)[SO_4]_2$	6.85	11.88	12.60	~90°	2.73	—

Str. Not known. The acicular habit may imply a chain sulfate. The symmetry and parameters are from Gay (1965) [997]).

2. KIESERITE GROUP. Mon., $C_{2h}^6 - A2/a$, $Z = 4$

		a	b	c	β	ρ	H
Poitevinite	$Cu(H_2O)[SO_4]$	7.64	7.43	7.18	116° 09′	3.2	3.5—3.75
Gunningite	$Zn(H_2O)[SO_4]$	7.57	7.59	6.95	115° 56′	3.3	(3.75—4)
Kieserite	$Mg(H_2O)[SO_4]$	7.52	7.69	6.89	116° 06′	2.57	3.75
Szomolnokite	$Fe(H_2O)[SO_4]$	7.62	7.47	7.12	115° 52′	3.1	3—3.5
Szmikite	$Mn(H_2O)[SO_4]$	—	—	—	—	3.1	(2.5—3)
Sonderite	$Mg(H_2O)_2[SO_4]$	—	—	—	—	—	(3.5)
Bonottite	$Cu(H_2O)_3[SO_4]$	5.59	13.03	7.37	97° 06′	2.68	(3—3.5)

Str. Known for kieserite and bonattite. Mg has CN = 6 (four O and two H_2O). Interatomic distances in kieserite: $Mg-O_4(H_2O)_2 = 2.08$; $S-O_4 = 1.49$ (Leonhardt and Weiss, 1957 [998]). The Cu in bonattite has distorted octahedral coordination, three O and three H_2O. The mean of the four distances in a square is 1.96, the other two being 2.39 and 2.45; $S-O_4 = 1.47$ (Zahrobsky and Baur, 1965 [999]).

Chem. Poitevinite has Cu replaced by Fe (18%) and Zn (3.7%); gunninghite has Zn replaced by Mn (3%), and szomolnokite has Fe replaced by Cu (≤20%) and Mg (≤10.5%).

Var. Fe-poitevinite, Mn-gunningite, Cu-szomolnokite, Mg-szomolnokite.

Phys. Isometric; cleavage observed only for kieserite, (110) and (111) perfect.

3. ZIRCONIUM SULFATE GROUP. Orth., $D_{2h}^{24} - Fddd$, $Z = 1$

		a	b	c	ρ	H
Zircosulfate (zirtetrohysite)	$Zr(H_2O)_4[SO_4]_2$	25.92	11.62	5.53	2.83	3—3.5

Str. Not known; parameters given for the analogous artificial compound (Kapustin, 1965 [1000]).

Chem. Composition constant.

Phys. Isometric, cleavage not observed.

4. CHALCANTHITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 2$

		a	b	c	α	β	γ	ρ	H
Chalcanthite	$Cu(H_2O)_5[SO_4]$	6.12	10.69	5.96	97° 35′	107° 10′	77° 33′	2.28	3
Pentahydrite (magpentahysite)	$Mg(H_2O)_5[SO_4]$	6.34	10.55	6.08	99°10′	109°53′	75°00′	1.72	(3)
Sideratil	$Fe(H_2O)_5[SO_4]$	6.26	10.59	6.05	92° 08′	110° 10′	77° 05′	2.20	2.5—3

Str. All are isostructural; known for chalcanthite, in which Cu is surrounded by four H_2O and two O. The fifth H_2O acts as a buffer, being tetrahedrally linked to two H_2O in a Cu octahedron and two O from different SO_4 radicals. Mean interatomic distances: $Cu-(H_2O)_4O_2$ = 1.96 (4), 2.41 (2); $S-O_4$ = 1.48 (Bacon and Curry, 1962 [1001]). The parameters of siderotil are for material containing about 14% CuO (Jambor and Trail, 1963 [1002]).

Chem. Pentahydrite has Mg replaced by Cu (≤12.4%), Zn (≤5.6%), and Mn (≤1.4%); siderotil has Fe replaced by Cu (14%).

Var. Cu-pentahydrite, Zn-pentahydrite, Mn-pentahydrite, Cu-siderotil.

5. RETGERSITE GROUP. Tetr. → mon.

	S.g.	a	b	c	β	Z	ρ	H
Retgersite $Ni(H_2O)_6[SO_4]$	$D_4^4 - P4_12_12$	6.79	—	18.28	—	4	2.07	3
Zinc hexahydrite (zinhexahysite) $Zn(H_2O)_6[SO_4]$	$C_{2h}^6 - C2/c$	—	—	—	98° 30′	—	2.07	3
Maarhauseite (cabhexahysite) $Co(H_2O)_6[SO_4]$	$C_{2h}^6 - C2/c$	10.03	7.23	24.26	98° 22′	8	2.01	(2.5—3)
Ferrahexahydrite (ferhexahysite) $Fe(H_2O)_6[SO_4]$	$C_{2h}^6 - C2/c$	—	—	—	—	—	—	(2.5—3)
Hexahydrite (maghexahysite) $Mg(H_2O)_6[SO_4]$	$C_{2h}^6 - C2/c$	10.11	7.21	24.41	98° 30′	8	1.72	(2.5—3)
Nickel hexahydrite (nickhexahysite) $Ni(H_2O)_6[SO_4]$	$C_{2h}^6 - C2/c$	9.84	7.17	24.0	97°30′	8	(2.00)	(2.5—3)

Str. These minerals differ in symmetry, but the divalent elements have octahedral surroundings of H_2O molecules, which are attached to SO_4

by hydroxyl-hydrogen bonds. Interatomic distances: in hexahydrite $Mg-(H_2O)_6$ = 2.06; $S-O_4$ = 1.49 (Zalkin et al., 1964 [330]); in retgersite $Ni-(H_2O)_6$ = 2.04; $S-O_4$ = 1.52 (p. 43 [176]); in moorhausite $Co-(H_2O)_6$ = 2.11; $S-O_4$ = 1.46; O−H...O = 2.79 (Zalkin et al., 1962 [1003]).

Chem. Ni in retgersite is replaced by Fe (≤3.5%) and Mg (≤2.8%); Zn in zinc hexahydrite is replaced by Fe (≤8.8%). Ferrohexahydrite almost free from impurities occurs in terrigenous deposits of Tataria (Vlasov and Kuznetsov, 1962). Ni in nickel hexahydrite is replaced by Mg (≤3.9%), Fe (≤6.4%), and Cu (≤2.1%).

Var. Fe,Mg-retgersite, Fe-zinc hexahydrite, Fe,Mg-zinc hexahydrite, Ni,Mn-moorhouseite, Mg,Fe-nickel hexahydrite.

6. EPSOMITE-MELANTERITE GROUP. Orth. → man.

Epsomite subgroup. Orth., $D_2^4 - P2_12_12_1$, $Z = 4$

		a	*b*	*c*	ρ	H
Morenosite	$Ni(H_2O)_7[SO_4]$	11.8	12.0	6.81	1.95	2.5
Goslarite	$Zn(H_2O)_7[SO_4]$	11.87	12.11	6.84	1.98	2.5
Epsomite	$Mg(H_2O)_7[SO_4]$	11.87	12.00	6.86	1.68	2.5
Tauriscite	$Fe(H_2O)_7[SO_4]$	—	—	—	(1.88)	(2.5)
Fauserite	$Mn(H_2O)_7[SO_4]$	—	—	—	(1.85)	(2.5)

Str. The $R^{2+}(H_2O)_6$ octahedra are accompanied by buffer H_2O molecules, each of which is linked to three H_2O in octahedra and O in an SO_4 radical. Mean interatomic distances in morenosite: $Ni-(H_2O)_6$ = 2.03; $S-O_4$ = 1.52 (Beevers and Schwartz, 1935 [1004]); in epsomite: $Mg-(H_2O)_6$ = 2.07; $S-O_4$ = 1.47 (Baur, 1964 [331]).

Chem. Isomorphism produces composition variations as follows: morenosite has Mg (≤7.65%); goslarite has Cu (≤6.7%), Mg (≤6.9%), Fe (≤6.4%), and Mn (≤6.5%); epsomite has Ni (≤12%), Mn (≤4.3%), Fe (≤7.8%), Zn (≤2.8%), and Co (≤1.1%); and fauserite has Mg (≤5.2%) and Zn (≤5.1%).

Var. Mg-morenosite, Cu-goslarite, Mg-goslarite, Fe-goslarite, Mn-goslarite, Ni-epsomite, Fe-epsomite, Mn-epsomite, Zn-epsomite, Co-epsomite, Zn-fauserite, Mg-fauserite.

Melanterite subgroup. Mon., ... $C_{2_1}^5 - P2_1/c$, $Z = 4$

		a	*b*	*c*	β	ρ	H
Bieberite	$Co(H_2O)_7[SO_4]$	14.13	6.55	11.00	105° 05′	1.96	2.5
Melanterite	$Fe(H_2O)_7[SO_4]$	14.07	6.50	11.04	105° 35′	1.90	2.5
Mallardite	$Mn(H_2O)_7[SO_4]$	—	—	—	104° 51′	1.85	2.5
Boothite	$Cu(H_2O)_7[SO_4]$	—	—	—	105° 36′	~2.10	2.5

Str. In principle, analogous to that of the orthorhombic heptahydrates, except that (in melanterite, for example) there are two types of $Fe(H_2O)_6$ octahedron with somewhat different sizes, the molecules of buffer water being linked to only one of these. Mean interatomic distances in melanterite: $Fe_I-(H_2O)_6 = 2.12$; $Fe_{II}-(H_2O)_6 = 2.13$; $S-O_4 = 1.47$ (Baur, 1964 [332]).

Chem. Bieberite has Mg (≤3.9%); melanterite has Cu (≤18.8%), Zn (≤8.9%), Mg (≤7.45%), and Mn (≤1.9%); mallardite has Ca (0.7%).

Var. Mg-bieberite, Cu-melanterite, Zn-melanterite, Mg-melanterite, Mn-melanterite, Cu,Mg-melanterite, Ca-mallardite.

7. COQUIMBITE GROUP. Mon. → trig. → tricl.

		S.g.	a	b	c	β	Z	ρ	H
Lausenite	$Fe_2(H_2O)_6[SO_4]_3$	Mon.	—	—	—	—	—	—	—
Kornelite	$Fe_4(H_2O)_{15}[SO_4]_6$	$C_{2h}^5-P2_1/n$	14.29	20.10	5.45	97° 01′	2	2.30	(3)
Coquimbite	$Fe_2(H_2O)_9[SO_4]_3$	$D_{3d}^2-P\bar{3}1c$	10.92	—	17.08	—	4	2.14	3
Paracoquimbite	$Fe_2(H_2O)_9[SO_4]_3$	Trig.	10.92	—	51.25	—	12	2.11	3
Quenstedtite	$Fe_2(H_2O)_{10}[SO_4]_3$	C_i^1-P1	6.15	23.77	6.56	101° 45′	2	2 15	3
			$\alpha = 94°\ 10'$		$\gamma = 96°\ 19'$				
Alunogen	$Al_2(H_2O)_{18}[SO_4]_3$	Tricl.	—	—	—	97° 26′	—	1.77	2
			$\alpha = 89°\ 58'$		$\gamma = 91°\ 52'$				

Str. The structure of coquimbite is subchain; chains composed of alternating Fe octahedra and SO_4 tetrahedra range parallel to the c axis. The Fe segments of the chains are linked through hydrogen bonds. In the holes ("channels") between the chains are placed water molecules also linked to the chains by hydrogen bonds. Mean interatomic distances are: $Fe_1-O_6 = 2.01$; $Fe_2-O_3(H_2O)_3 = 1.97$ (3) and 2.01 (3); (Al; Fe)$-(H_2O)_6 = 1.89$; $S-O_4 = 1.47$ (Fang and Robinson, 1970 [1271]). Paracoquimbite is the rhombohedral polytype of coquimbite (Ungemach, 1935 [1125]).

Chem. The Fe minerals contain a little Al; Al in alunogen is replaced by Fe^{3+} (≤ 7%), and SO_4 by PO_3OH (Strunz, 1957 [113]).

Var. Al-coquimbite, Fe^{3+}-alunogen, PO_4-alunogen.

8. MIRABILITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, $Z = 4$

		a	b	c	β	ρ	H
Mirabilite	$Na_2(H_2O)_{10}[SO_4]$	11.48	10.35	12.82	107° 40′	1.49	1.5—2

Str. The $Na(H_2O)_6$ octahedra are linked into zigzag chains, which are connected to SO_4 and two buffer H_2O by hydroxyl-hydrogen bonds (Cocco, 1962 [1272]).

Subdivision II. Complex

1. SYNGENITE GROUP. Mon., $C_{2h}^2 - P2_1/m$, $Z = 2$

		a	b	c	β	ρ	H	Cl.
Syngenite	$K_2Ca(H_2O)[SO_4]_2$	9.72	7.16	6.21	104° 05′	2.60	3	Perf. in 3 dir.
Koktoite	$(NH_4)_2Ca(H_2O)[SO_4]_2$	10.17	7.15	6.34	102° 45′	2.09	(2.5)	None

Str. Irregular KO_8, KO_9, and CaO_9 polyhedra. The K polyhedra are joined by faces, edges, and vertices into layers parallel to (100), which are connected by Ca polyhedra and SO_4 tetrahedra. Interatomic distances: $K-O_8$ = 2.69-2.98; $Ca-O_9$ = 2.40-2.74; $S-O_4$ = 1.47 (Corazza and Sabelli, 1966 [1005]; Gorogotskaya, 1966 [1006]).

2. LEIGHTONITE GROUP. Orth. → tricl. →mon.

		S.g.	a	b	c	γ	Z	ρ	H
Leightonite	$K_2Ca_5Cu(H_2O)_2[SO_4]_4$	$D_{2h}^{23} - Fmmm$	11.67	16.52	7.49	—	4	2.95	3.5
Polyholite	$K_2Ca_2Mg(H_2O)_2[SO_4]_4$	$C_i^1 - P\bar{1}$	6.96	6.74	8.96	101° 5′	1	2.78	3.75
			$\alpha = 104°\ 05'$	$\gamma = 113°\ 09'$					
Görgeyite	$K_2Ca_5(H_2O)[SO_4]_6$	$C_{2h}^6 - C2/c$	17.51	6.82	18.21	113° 16′	4	2.91	3.75

Str. The structure of polyhalite consists of octahedrally coordinated Mg, 8-coordinated Ca, and 11-coordinated K, which are linked by sulphate groups and hydroxyl–hydrogen bonds [1273]. Triclinic polyhalite (Braitsch, 1961 [1007]) differs structurally from orthorhombic leightonite (Van Loan, 1962 [1008]), in spite of its analogous formula. Görgeyite has precisely the structure of the synthetic compound (Smith et al., 1964 [1009]).

Chem. Compositions constant.

Phys. The first two are nearly isometric; leightonite has no cleavage, while polyhalite has perfect $(10\bar{1})$ cleavage.

3. FERRINATRITE GROUP. Trig., $C_{3i}^1 - P\bar{3}$, $Z = 6;3$

		a	c	ρ	H	Cl
Ferrinotrite	$Na_3Fe(H_2O)_3[SO_4]_3$	15.57	8.67	2.55	3	(1010) perf.
Löweite	$Na_{12}Mg_7(H_2O)_{15}[SO_4]_{13}$	18.96	13.47	2.37	3—3.5	None
		a_{rh} = 11.77	α = 106°30′			

Str. The structure of löweite is subframework. The Mg octahedra- and SO_4 tetrahedra are linked at the corners. The Na atoms are in sevenfold coordination. The interatomic distances are: $Na_1-O_6(H_2O)$ = 2.35-2.87 (d_m = 2.52); $Na_2-O_6(H_2O)$ = 2.31-2.62 (d_m = 2.47); $Mg-O_4(H_2O)_2$ = 2.05 (4) and 2.11 (2); $Mg-O_6$ = 2.09; $S-O_4$ = 1.47 (Fang and Robinson, 1970 [1274]). Parameters and space group of ferrinatrite from Cesbron (1964) [1010].

Chem. Na in löweite replaced by K (≤2.9%) (K-löweite).

4. LECONTITE GROUP. Orth., $D_2^4 - P2_12_12_1$, $Z = 4$

		a	b	c	ρ	H
Lecontite	$NH_4Na(H_2O)_2[SO_4]$	8.22	12.85	6.23	1.74	2.5—3

Str. Na (CN = 6) and NH_4 (CN = 7) are linked to SO_4 radicals; the $Na(O, H_2O)_6$ octahedra are linked by their ends into chains along the c axis. These are coupled to NH_4 and SO_4 by hydrogen bonds of H_2O molecules. Interatomic distances: $Na-O_4(H_2O)_2$ = 2.40 (4); 2.43 (2); NH_4-O_7 = 2.94 (5); 3.30 (2); $S-O_4$ = 1.49 (Corazza et al., 1967 [1011]).

Chem. NH_4 replaced by K (≤2.8%) (K-lecontite).

5. ASTRAKHANITE GROUP. Mon.

		S.g.	a	b	c	β	Z	ρ	H
Astrokhonite	$Na_2Mg(H_2O)_4[SO_4]_2$	$C_{2h}^5 - P2_1/a$	11.03	8.14	5.49	100° 40′	2	2.27	3—3.5
Leonite	$K_2Mg(H_2O)_4[SO_4]_2$	$C_{2h}^5 - C2/m$	11.78	9.53	9.88	95° 04′	4	2.20	3—3.5
Goldichite	$KFe(H_2O)_4[SO_4]_2$	$C_{2h}^5 - P2_1/c$	10.45	10.53	9.15	101° 49′	4	2.42	3

Str. Known for astrakhanite (Rumanova and Malitskaya, 1959 [1012]) and leonite (Schneider, 1961 [1013]); in the first Mg and Na have CN = 6, composed of H_2O and O, while in the second Mg has the same CN, and K has CN = 9. Interatomic distances in astrakhanite: $Mg-(H_2O)_4O_2$ = 2.04; $Na-(H_2O)_2O_4$ = 2.55 (2) and 2.35 (4); $S-O_4$ = 1.46.

Chem. Compositions constant.

6. VOLTAITE GROUP. Cubic, $O_h^8 - Fd3c$, $Z = 16$

		a	ρ	H	Cl.
Voltoite	$K_2Fe_5^{2+}Fe_4^{3+}(H_2O)_{18}[SO_4]_{12}$	27.38	2.7	3.5	None

Str. Not known.

Chem. Variable; K replaced by Na (≤1.6%), Fe^{2+} by Mg (≤7.35%), and Fe^{3+} by Al (≤6.1%).

7. PICROMERITE GROUP. Mon., $C_{2h}^5 - P2_1/a$, $Z = 2$

		a	b	c	β	ρ	H
Cyanochroite	$K_2Cu(H_2O)_6[SO_4]_2$	—	—	—	104° 28′	2.22	(3)
Picromerite	$K_2Mg(H_2O)_6[SO_4]_2$	9.06	12.26	6.11	104° 48′	2.03	3
Boussingoultite	$(NH_4)_2Mg(H_2O)_6[SO_4]_2$	9.32	12.60	6.21	107° 14′	1.72	2.5
Mohrite	$(NH_4)_2Fe(H_2O)_6[SO_4]_2$	9.29	12.61	6.24	106° 53′	1.87	(2.5)

Str. Known for picromerite and boussingaultite. Mg (CN = 6) is surrounded by H_2O, while NH_4(K) has 6 + 1 coordination, the 1 representing

H_2O and the 6 representing five O + H_2O. All the polyhedra are linked by hydroxyl-hydrogen bonds. Mean interatomic distances in boussingaultite: $Mg-(H_2O)_6$ = 2.07; $NH_4-O_5(H_2O)_2$ = 2.84-3.27; $S-O_4$ = 1.49 (Margulis and Templeton, 1962 [335]); in picromeritc $Mg-(H_2O)_6$ = 2.10; $K-O_5(H_2O)_2$ = 2.94 (6), 3.19; $S-O_4$ = 1.48 (Kannan and Viswamitra, 1965 [1014]).

8. TAMARUGITE GROUP. Mon., $C_{2h}^5-P2_1/a$, $Z = 4$

		a	b	c	β	ρ	H
Tamarugite	$NaAl(H_2O)_6[SO_4]_2$	7.35	25.22	6.10	94° 50′	2.07	3.5
Amarillite	$NaFe(H_2O)_6[SO_4]_2$	—	—	—	95° 37′	2.19	3—3.5

Str. The structure of tamarugite is subchain, in which NaO_6 octahedra and SO_4 tetrahedra form infinite chains parallel to the c axis. The Al atoms have sixfold coordination of H_2O and are joined with Na octahedra and S tetrahedra by hydroxyl–hydrogen bonds. The interatomic distances are: $Na-O_6$ = 2.26-2.51 (d_m = 2.42); $Al-(H_2O)_6$ = 1.85-1.92 (d_m = 1.88); $S_{1,2}-O_4$ = 1.47-1.52 (d_m = 1.48-1.49) (Robinson and Fang, 1970 [1275]).

Phys. Tamarugite has perfect (010) cleavage.

9. ROMERITE GROUP. Mon. → tricl.

		S.g.	a	b	c	β	Z	ρ	H
Ransomite	$CuFe_2^{3+}(H_2O)_6[SO_4]_4$	$C_{2h}^5-P2_1/c$	4.81	16.22	10.43	93°01′	2	2.63	3.5
Römerite	$FeFe_2^{3+}(H_2O)_{14}[SO_4]_4$	$C_1^1-P\bar{1}$	6.46	15.31	6.34	101°05′	1	2.17	3—3.5
			α = 90°32′		γ = 85°44′				

Str. In ransomite the Fe and Cu atoms are linked by SO_4 tetrahedra in layers parallel to (010), which are joined by hydroxyl–hydrogen bonds (O–H–O = 2.63-2.91). The interatomic distances are: $Cu-(O, OH)_6$ = 1.96 (2), 2.01 (2), and 2.44 (2); $Fe-(O, OH)_6$ = 1.95-2.02 (d_m = 1.98); Si_1-O_4 = 1.41-1.51 (d_m = 1.47); Si_2-O_4 = 1.45-1.49 (d_m = 1.48) (Wood, 1970 [1276]). The structure of roemerite consists of two types of isolated groups: $Fe(H_2O)_6$ and $Fe(H_2O)_4(SO_4)_2$. These groups are weakly connected to each other by hydroxyl–hydrogen bonds. The interatomic distances are: $Fe-(H_2O)_6$ = 2.08-2.14; $Fe-O_2(H_2O)_4$ = 1.94 (2) and 2.03 (4); $S-O_4$ = 1.47 (Fanfani et al., 1970 [1277]).

Chem. Composition varies; Fe^{3+} in ransomite replaced by Al (≤1.5%); Fe^2 in römerite replaced by Zn (≤3.1%) and Fe^{3+} by Al (≤2.6%).

Var. Al-ransomite, Zn-römerite, Al-römerite.

Phys. Ransomite has perfect (010) cleavage.

10. MENDOZITE GROUP. Mon. C_{2h}^6—$C2/c$, $Z = 4$

		a	b	c	β	ρ	H
Mendozite	$NaAl(H_2O)_{11}[SO_4]_2$	21.75	9.11	8.30	92°28′	1.78	~3
Kalinite	$KAl(H_2O)_{11}[SO_4]_2$	—	—	—	—	~1.8	(2.5—3)

Str. Not known. Occurs as fibrous aggregates.

11. ALUM GROUP. Cubic., $T_h^6 - Pa3$, $Z = 4$.

		a	ρ	H	Cl
Sodalumite (nalhysite)	$NaAl(H_2O)_{12}[SO_4]_2$	12.21	1.67	2.5—3	None
Alum (kalhysite)	$KAl(H_2O)_{12}[SO_4]_2$	12.15	1.75	2—2.5	None
Tschermigite (amalhysite)	$NH_4Al(H_2O)_{12}[SO_4]_2$	12.23	1.64	2	None

Str. Na(K) and Al have octahedral coordination to H_2O (Fig. 259), and the water is linked via hydroxyl-hydrogen bonds to SO_4 in a symmetrical structure. Interatomic distances: in sodalumite $Na-(H_2O)_6 = 2.45$; $Al-(H_2O)_6 = 1.88$; $S-O_4 = 1.48$ (Cromer, et al., 1967 [1015]); in alum

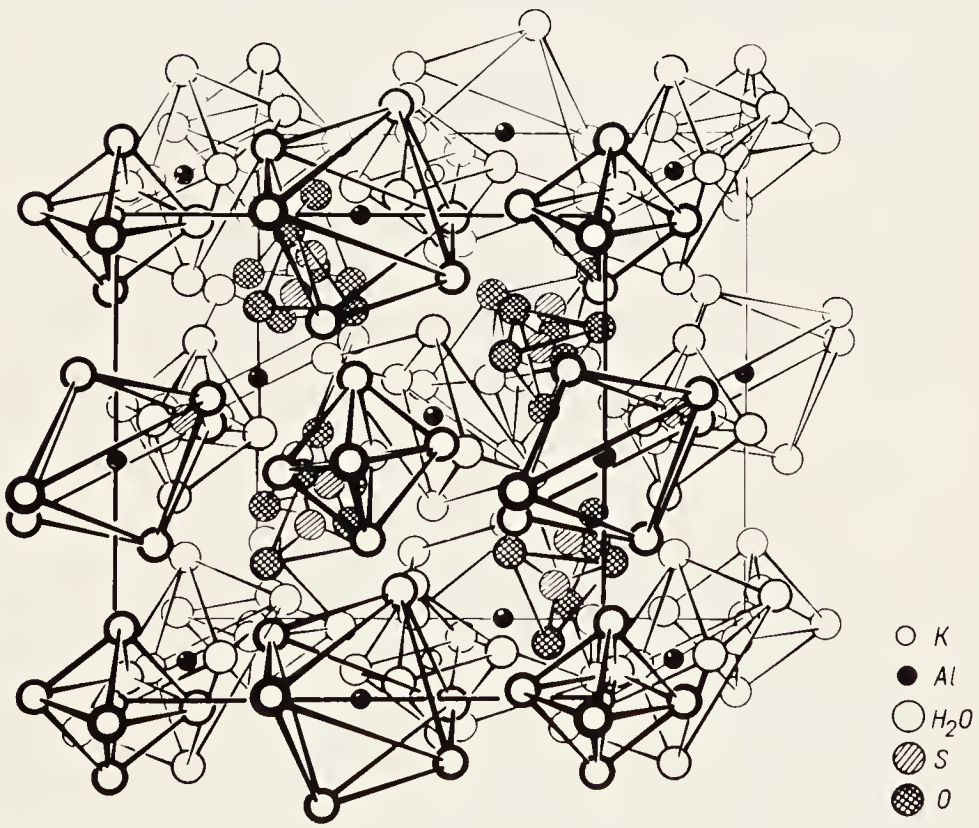


Fig. 259. Structure of potash alum in spheres and polyhedra.

$K-(H_2O)_6$ = 2.98; $Al-(H_2O)_6$ = 1.91; $S-O_4$ = 1.46; in tschermigite $NH_4-(H_2O)_6$ = 3.05, $Al-(H_2O)_6$ = 1.92; $S-O_4$ = 1.45 (Larson and Cromer, 1967 [1016]).

Chem. Composition variations not fully known; K in alum replaced by Na (1.4%) and NH_4 (2.4%).

12. HALOTRICHITE GROUP. Mon., $C_2^1 - P2$, $Z = 4$

	a	*b*	*c*	β	ρ	H
Holotrichite $(Mg, Fe)Al_2(H_2O)_{22}[SO_4]_4$	20.8—20.5	24.2—24.3	6.18	96° 34′— 100° 06′	1.84—1.95	1.5—2
Dietrichite $ZnAl_2(H_2O)_{22}[SO_4]_4$	—	—	—	—	(1.9)	1.5—2
Apjohnite $Mn\,Al_2(H_2O)_{22}[SO_4]_4$	—	—	—	—	1.78	1.5—2
Bilinite $FeFe_2^{3+}(H_2O)_{22}[SO_4]_4$	—	—	—	—	1.88	1.5—2

Str. Not known.

Chem. Halotrichite has perfect $Mg-Fe^{2+}$ isomorphism, subspecies magnesiohalotrichite and ferrohalotrichite; there are also the following isomorphous components: Zn (≤3.7%), Mn (≤2.6%), Co (≤1%), Cr (≤7.5%), Fe^{3+} (≤4%).

Var. Zn-ferrohalotrichite, Mn-magnesiohalotrichite, Mn,Co-ferrohalotrichite, Cr-ferrohalotrichite, Fe^{3+}-halotrichite, Mn-dietrichite, Fe-dietrichite.

Phys. Columnar to acicular and fibrous; imperfect (010) cleavage.

DIVISION E. HYDRATED SULFATES WITH ADDITIONAL ANIONS

Subdivision I. Simple

1. LANGITE GROUP. Orth. → mon.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Langite	$Cu_4(H_2O)[SO_4](OH)_6$	$D_{2h}^5 - Pmma$	6.02	11.2	7.12	—	2	3.5	3—3.5
Ktenasite	$Cu_5(H_2O)_2[SO_4](OH)_4$	$C_{2h}^5 - P2_1/c$	11.16	6.11	23.74	95° 24′	8	2.97	2.5—3
Poznyokite	$Cu_4(H_2O)[SO_4](OH)_6(?)$	Mon.	9.80	6.32	7.85	107°	2	3.3	2.5—3

Str. Not known; the unit cell of langite is from Pierrot and Sainfield (1958) [1017], while that of poznyakite is from Komkov and Nefedov (1967) [1018].

Chem. Cu in ktenasite replaced by Zn nearly up to Cu:Zn = 1:1.

Phys. Perfect cleavage of langite on (010) and (001), of poznyakite on (010) and $(10\bar{1})$.

2. BUTLERITE GROUP. Mon. → orth. → tricl. → mon. →trig.

		S.g.	a	b	c	β	Z	ρ	H
Butlerite	$Fe(H_2O)_2[SO_4]OH$	$C_{2h}^2 - P2_1/m$	6.44	7.31	5.87	108° 28′	2	2.55	3
Parabutlerite	$Fe(H_2O)_2[SO_4]OH$	$D_{2h}^{16} - Pmnb$	7.38	20.13	7.22	—	8	2.55	3
Amarantite	$Fe(H_2O)_3[SO_4]OH$	$C_i^1 - P\bar{1}$	8.90	11.56	6.64	90° 31′	4	2.29	3
			$\alpha = 95°\ 33'$		$\gamma = 97°\ 25'$				
Hohmannite	$Fe_2(H_2O)_7[SO_4]_2(OH)_2$	$C_i^1 - P\bar{1}$	9.05	10.88	7.17	91°10′	2	2.28	3
			$\alpha = 90°10'$		$\gamma = 101°13'$				
Fibroferrite	$Fe(H_2O)_5[SO_4]OH$	Mon.	7.45	12.10	7.65	110°07′	4	1.97	2.5—3
Slavikite	$Fe(H_2O)_8[SO_4]OH$	Trig.	12.22	—	34.86	—	32	1.90	(2.5)

Str. Not known; cell parameters from Cesbron (1964) [1010]). For slavikite another formula $MgFe_3^{3+}(H_2O)_{18}[SO_4]_4(OH)_3$ and an orthorhombic system are also proposed [1145]. The structure of amarantite was determined by Süsse [1146].

3. FELSOBANYITE GROUP. Orth.→hex.→mon. (?)

		S.g.	a	b	c	β	Z	ρ	H
Felsöbanyite	$Al_4(H_2O)_5[SO_4](OH)_{10}$	Not det.	—	—	—	—	—	2.33	(2,5—3)
Hexafelsobanyite	$Al_4(H_2O)_5[SO_4](OH)_{10}$	Not det.	22.56	—	18.72	—	24	2.12	(2,5—3)
Aluminite	$Al_2(H_2O)_7[SO_4](OH)_4$	Not det.	—	—	—	—	—	1.82	(2—2.5)
Metaaluminite	$Al_2(H_2O)_5[SO_4](OH)_4$	Not det.	—	—	—	—	—	1.85	(2.5)

Str. Not known. Chemical compositions need to be checked.

4. MINASRAGRITE GROUP. Mon.

		a	b	c	β	ρ	H
Minasragrite	$V_2^{4+}(H_2O)_{15}[SO_4]_3(OH)_2$	—	—	—	110° 57′	—	—

Str. Not known; properties not studied.

Subdivision II. Complex

1. FLEISCHERITE GROUP. Hex., $D_{6h}^4 - P6_3/mmc$, $Z = 2$

		a	c	ρ	H	Cl
Fleischerite	$Pb_3Ge^{4+}(H_2O)_3[SO_4]_2(OH)_6$	8.89	10.86	4,6	(3)	None
Schaurteite	$Ca_3Ge^{4+}(H_2O)_3[SO_4]_2(OH)_6$	8.52	10.80	2.65	(3.5)	None
Despujalsite	$Ca_3Mn^{4+}(H_2O)_3[SO_4]_2(OH)_6$	8.56	10.76	2.25	3	None

Str. Not known. Needles up to 2 mm in size (Frondel and Strunz, 1960 [996]; Strunz and Tennyson, 1967 [1019]).

2. SIDERONATRITE GROUP. Orth., $D_{2h}^{16} - Pbnm$, $Z = 4$

		a	b	c	ρ	H
Sideronotrite	$Na_2Fe(H_2O)_3[SO_4]_2OH$	7.27	20.50	7.15	2.28	2.5—3
Metasideranatrite	$Na_4Fe_2(H_2O)_3[SO_4]_4(OH)_2$	—	—	—	2.46	3

Str. Not known; parameters of sideronatrite from Cesbron (1964) [1010]. Habit laths to acicular.

3. METAVOLTINE GROUP. Hex.→trig.→mon.

		S.g.	a	b	c	Z	ρ	H
Metavaltine	$K_5Fe_3(H_2O)_8[SO_4]_4(OH)_2$	$C_{6h}^1 - P6/m$ (?)	19.47	—	18.64	8	2.40	3
Ungemochite	$K_3Na_9Fe(H_2O)_9[SO_4]_6(OH)_3$	$C_{3i}^2 - R\bar{3}$	10.86	—	24.87	3	2.29	3
Clinoungemachite	$K_3Na_9Fe(H_2O)_9[SO_4]_6(OH)_3$	Not det.	—	—	—	—	(2.3)	(3)
			$\beta = 110°40'$					
Humberstanite	$K_3Na_7Mg_2(H_2O)_6[SO_4]_6[NO_3]_2$	$C_{3i}^2 - R\bar{3}$	10.90	—	24.41	3	2.25	(3.5)
			$a_{rh} = 10°29'$		$\alpha = 64°00'$			

Str. Not known.

Chem. K in metavoltine replaced by Na ($\leq 8.9\%$) and Fe^{3+} by Fe^{2+} ($\leq 2.9\%$) (?). Humberstonite has constant composition [1389].

Phys. Ungemachite and humberstonite have perfect (0001) cleavage.

4. KAINITE GROUP. Mon.→orth.

	S.g.	a	b	c	β	Z	ρ	H
Uklanskovite (namagdihyahsite) $NaMg(H_2O)_2[SO_4]OH$	$C_{2h}^2 - P2_1/m$	7.20	7.19	5.72	113° 55′	2	2.50	(3,5)
Kainite $KMg(H_2O)_3[SO_4]Cl$	$C_{2h}^3 - C2/m$	19.76	16.26	9.57	94° 56′	16	2.24	3—3.5
Tutarskite $Ca_3Mg(H_2O)_3[SO_4][CO_3](OH)_2Cl_2$	Not det.	—	—	—	—	—	2.34	3

Str. Known for uklonskovite. Na has CN = 8, while Mg has CN = 6 (surroundings O, OH, and H_2O). The Na polyhedra are linked via SO_4 groups into sublayers, while the Mg octahedra are linked by vertices into chains (Borisov, 1964 [1021]). Interatomic distances: $Na-O_5OH(H_2O)_2$ = 2.62 (2), 3.06 (2), 2.33, 2.29, 2.36 (2); $Mg-O_2(OH)_2(H_2O)_2$ = 2.13 (2), 1.94 (2), 2.13 (2); $S-O_4$ = 1.43, 1.48 (3).

5. ETTRINGITE GROUP. Hex. → mon. (?)

		S.g.	a	b	c	Z	ρ	H
Ettringite	$Ca_6Al_2(H_2O)_{24}[SO_4]_3(OH)_{12}\cdot 2H_2O$	$D_{6h}^4 - P6_3/mmc$	11.26	—	21.49	2	1.75	2.5—3
Jouravskite	$Ca_6Mn_2^{4+}(H_2O)_{24}[SO_4]_2[CO_3]_2(OH)_{12}$	$C_{6h}^2 - P6_3/m$ (?)	11.06	—	10.50	1	1.95	3
Kašparite	$MgAl_2(H_2O)_{28}[SO_4]_5OH$	Mon. (?)	—	—	—	—	1.78	(3)

Str. Ettringite has corrugated layers of Ca and Al octahedra linked by SO_4 and two buffer H_2O. Interatomic distances: $Ca-(OH)_3(H_2O)_3$ = 2.38-2.44; $Al-(OH)_3(H_2O)_3$ = 1.90-1.94; H−O = 2.70-2.74 (Bezjak and Jelenić, 1966 [1022]). If the SiO_4 in thaumasite is replaced by MnO_4 and AlO_4, all the formulas become analogous: thaumasite $H_4Ca_6(H_2O)_{26}[(SiO_4)_2(SO_4)_2(CO_3)_2]$, jouravskite $H_4Ca_6(H_2O)_{28}[(MnO_4)_2(SO_4)_2(CO_3)_2]$, and ettringite $H_4Ca_6(H_2O)_{30}[(AlO_4)_2(SO_4)_3]$ (Gaudefroy and Permingeat, 1965 [1023]). It is very probable that Si in thaumasite has sixfold coordination (O and OH).

Chem. Ettringite has SO_4 replaced by SiO_4 and (to a smaller extent) by BO_3 and CO_3. The composition of jouravskite is not fully known. The Mg in kasparite is replaced by Co (≤ 1.5%).

Phys. Isometric and thick tabular, perfect $(10\bar{1}0)$ cleavage. Kasparite has not been studied.

6. COPIAPITE GROUP. Mon. → tricl.

	S.g.	a	b	c	Z	ρ	H
Zincobotryogen $ZnFe(H_2O)_7[SO_4]_2OH$	$C_{2h}^5 - P2_1/n$	10.49	17.82	7.19	4	2.20	3
		$\beta = 100°50'$					
Botryogen $MgFe(H_2O)_7[SO_4]_2OH$	$C_{2h}^5 - P2_1/n$	10.47	17.83	7.11	4	2.14	3
		$\beta = 100°20'$					
Guildite $CuFe(H_2O)_4[SO_4]_2OH$	$C_{2h}^2 - P2_1/m$	9.79	7.13	7.26	2	2.72	3
		$\beta = 105°47'$					
Zincocopiopite $ZnFe_4^{3+}(H_2O)_{20}[SO_4]_6(OH)_2$	$C_i^1 - P1$	7.35	18.16	7.28	1	2.18	(3.5)
		$\alpha = 93°50'$	$\beta = 101°30'$	$\gamma = 99°22'$			
Cuprocopiopite $CuFe_4(H_2O)_{20}[SO_4]_6(OH)_2$	$C_i^1 - P\bar{1}$	—	—	—	—	(2.22)	(3—3.5)
Copiopite $(Mg, Fe)Fe_4(H_2O)_{20}[SO_4]_6(OH)_2$	$C_i^1 - P\bar{1}$	7.34	18.19	7.28	1	2.08—2.17	3—3.5
		$\alpha = 93°50'$	$\beta = 101°30'$	$\gamma = 99°23'$			
Colcocopiopite $CaFe_4(H_2O)_{20}[SO_4]_6(OH)_2$	Not det.	—	—	—	—	(2.1)	(3)

Str. In magnesiocopiapite the Fe^{3+} octahedra and SO_4 tetrahedra are connected to form chains along (101), while Mg octahedra lie isolated between the chains and are joined to them by hydroxyl−hydrogen bonds. The interatomic distances are: $Mg-(O, H_2O)_6$ = 2.08; $Fe_1-(O, OH, H_2O)_6$ = 1.92-2.05 (d_m = 2.01); $Fe_2-(O, OH, H_2O)_6$ = 1.98-2.06 (d_m = 2.02); $S-O_4$ = 1.48 (Süsse, 1970 [1278]).

Chem. Perfect Mg−Fe isomorphism in copiapite gives the subspecies magnesiocopiapite and ferrocopiapite. Other isomorphous components are Al (≤4.65%), Zn (≤2.5%), and Cu (≤1%). Little is known about cuprocopiapite and calcocopiapite. Some specimens of ferrocopiapite have Fe^{2+} completely oxidized to Fe^{3+}, so we may speak of ferricopiapite as an independent species.

Var. Al-copiapite, Zn-copiapite, Fe^{3+}-copiapite.

Subclass 2. Ring

1. LEONHARDTITE GROUP. Mon., ... $C_{2h}^5 - P2_1/n$, $Z = 4$

		a	b	c	β	ρ	H
Aplowite (cabtetrahysite)	$Co(H_2O)_4[SO_4]$	5.94	13.66	7.90	90°30′	2.36	(3)
Razenite (ferrotetrahysite)	$Fe(H_2O)_4[SO_4]$	5.97	13.64	7.98	90°26′	2.28	(3)
Ilesite (mantetrahysite)	$Mn(H_2O)_4[SO_4]$	5.94	13.76	8.01	90°47′	2.26	(3)
Leonhardtite (magtetrahysite)	$Mg(H_2O)_4[SO_4]$	5.92	13.60	7.90	90.51′	2.01	(3—3.5)

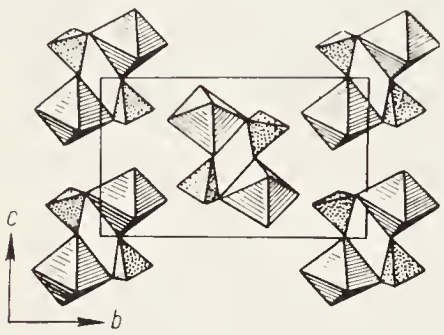


Fig. 260. Structure of leonhardtite, with $Mg_2(H_2O)_8[SO_4]_2$ rings connected by hydroxyl-hydrogen bonds.

Str. Known for leonhardtite and rozenite (Baur, 1962 [337] and 1964 [338]). Mg (Fe) has surroundings of four H_2O and two O. Two Mg (Fe) octahedra are linked via oxygen vertices to two SO_4 tetrahedra in a centered ring (Fig. 260), the rings being connected by hydroxyl-hydrogen bonds. Mean interatomic distances in leonhardtite $Mg-O_2$ $(H_2O)_4 = 2.08$; $S-O_4 = 1.47$; in rozenite $Fe-O_2$ $(H_2O)_4 = 2.12$; $S-O_4 = 1.49$.

Var. Mn,Ni-aplowite, Zn-ilesite, Fe-ilesite.

Subclass 3. Chain

1. ZIPPEITE GROUP. Orth.→mon. (C_{2h}^3—$C2/m$)

	a	b	c	β	Z	ρ	H
Zippeite $(UO_2)_2[SO_4](OH)_2 \cdot 4H_2O\ {}^1_\infty$	17.34	7.14	4.43	—	2	(3.9)	(3—3.5)
Clinazippeite $(UO_2)_3[SO_4]_2(OH)_2 \cdot 8H_2O\ {}^1_\infty$	8.81	14.13	8.85	114°15′	2	3.7	(3)
Uranapilite $(UO_2)_6[SO_4](OH)_{10} \cdot 12H_2O\ {}^1_\infty$	—	—	8.91	—	—	4.0	(2.5—3)
Metauranapilite $(UO_2)_6[SO_4](OH)_{10} \cdot 5H_2O\ {}^1_\infty$	—	—	—	—	—	—	(3)

Str. Not known. The acicular to fibrous habit is very characteristic, so a chain structure is very probable, as has been demonstrated for $U[SO_4](OH)_2$ (Lundgren, 1952 [1024]). Clinozippeite has been distinguished on the basis of chemical analysis (Frondel, 1958 [1025]) and corresponds to an artificial compound of analogous composition (Traill, 1952 [1026]). The parameters of zippeite are related to those of clinozip-

peite as follows: $a_Z = 2a_{kz}$, $b_Z = \frac{1}{2} b_{kz}$, $c_Z = \frac{1}{2} c_{kz}$ (Strunz, 1957 [113]). The parameter c = 8.91 (Traill, 1952 [1026]; Strunz, 1957 [113]) has been determined for uranopilite; this is parallel to the fiber axis and allows us to consider it (or rather the c of zippeite) as the characteristic parameter. The chemical compositions would allow uranopilite and metauranopilite to be assigned to the hydroxides.

Chem. Data inadequate; appreciable amounts of Ca, Cu, and Fe^{3+} revealed by analysis probably represent mechanical impurities of other hypergene minerals (e.g., gypsum and goethite).

Phys. Zippeite and uranopilite are elongated on the c axis and slightly flattened on the b axis; perfect (010) cleavage.

2. KRAUSITE GROUP. Mon., $C_{2h}^2 - P2_1/m$. $Z = 2$

		a	b	c	β	ρ	H
Krausite	$K\{Fe(H_2O)[SO_4]_2\}\frac{1}{\infty}$	7.91	5.15	8.99	102°45′	2.84	3

Str. Fe octahedra and SO_4 tetrahedra are firmly linked in chains of composition $[Fe_2(H_2O)_2(SO_4)_4]^{2-}$, which run along the b axis and which are cross linked via K atoms. Fe^{3+} has octahedral coordination, while K has CN=10. Mean interatomic distances: $K-O_{10}$ = 2.92; $Fe-O_5(H_2O)$ = 1.99; $S-O_4$ = 1.47 (Graeber et al., 1965 [341]).

Chem. Compositions constant.

Phys. Short columns, perfect cleavage on (100) and (001).

3. KRÖHNKITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, $Z = 2$

		a	b	c	β	ρ	H
Krohnkite	$Na_2\{Cu(H_2O)_2[SO_4]_2\}\frac{1}{\infty}$	5.79	12.60	5.49	108°30′	2.95	3—3.5

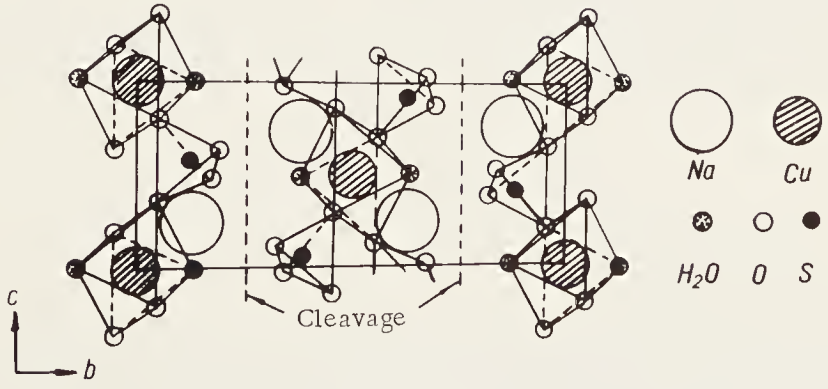


Fig. 261. Structure of kröhnkite in projection on (100), with heterogeneous chains parallel to the c axis.

Str. Isostructural with brandtite $Ca_2\{Mn(H_2O)_2[AsO_4]\}_2$. Cu is surrounded by two H_2O and four O, being linked via common O with SO_4 tetrahedra into chains along the c axis (Fig. 261). Each Na has six O and one H_2O; the Na atoms cross-link the chains. Interatomic distances: Na–O_6H_2O = 2.46 (6), 2.31; Cu–$O_4(H_2O)_2$ = 2.20 (4), 1.92 (2); S–O_4 = 1.48 (Dahlman, 1952 [296]; Rao, 1961 [339]).

Phys. Isometric to acicular, perfect (010) cleavage.

4. MERCALLITE GROUP. Orth. → mon.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Mercollite	$K\{H[SO_4]\}^1_\infty$	D^{15}_{2h} — *Pbca*	9.79	18.93	8.40	—	16	2.31	—
Misenite	$K_8\{H_6[SO_4]_7\}^1_\infty$	Mon.	—	—	—	102°05′	—	2.32	—

Str. Known for mercallite. The chain pattern is produced by hydrogen bonds between SO_4 tetrahedra: ...SO_4–H–SO_4...(dO–H...O = 2.67), these chains running along the c axis and being cross-linked by K (CN = 9). Mean interatomic distances: K–O_9 = 2.85; S–O_4 = 1.52 (Loopstra and MacGillarpy, 1958 [340]); S–O(OH) = 1.56 (Cruickshank, 1964 [1123]).

Phys. Laths to needles, sometimes tabular, elongated on *a* axis and flattened on c. Perfect (010) cleavage in misenite only.

Subclass 4. Layer

1. JOHANNITE GROUP. Tricl., $C_i^1 - P\bar{1}$, $Z = 4$

		a	*b*	*c*	ρ	H
Johannite	$Cu\{(UO_2)_2[SO_4]_2(OH)_2\} \cdot 6H_2O\,^2_\infty$	16.54	6.84	18.02	3.3	2—3
		α = 90°54′	β = 110°37′	γ = 90°38′		

Str. Not known, but evidently a general structure close to that of the torbernite-autunite uranium micas.

Phys. Laths (on c axis), thick tablets (on *a* axis), perfect (100) cleavage.

2. RHOMBOCLASE GROUP. Orth. → mon.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Rhomboclase	$HFe^{3+}[SO_4]_2 \cdot 4H_2O\,^2_\infty$	D^{16}_{2h}—*Pnma* (?)	21.75	9.11	8.30	92°28′	4	2.23	2
Letovicite	$(NH_4)_3H[SO_4]_2\,^2_\infty$		—	—	—	102°06′	—	1.83	—

Str. Not known; assigned from morphology and properties.

Phys. Tabular and platy on c axis, perfect (001) cleavage, also (110) moderate in rhomboclase.

3. NATROCHALCITE GROUP. Mon.

	S.g.	a	b	c	Z	ρ	H
Natrochalcite (nacuprihysite) $Na\{Cu_2(H_2O)[SO_4]_2OH\}\,^2_\infty$	$C^3_{2h}-C2/m$	8.76	6.16	6.54	2	3.5	(2.5—3)
			$\beta = 118°43'$				
Devilline $Ca\{Cu_4(H_2O)_3[SO_4]_2(OH)_6\}\,^2_\infty$	$C^5_{2h}-P2_1/a$	22.38	6.09	20.88	8	3.1	3
			$\beta = 102°30'$				
Serpierite (paradevilline) $Ca\{Cu_4(H_2O)_3[SO_4]_2(OH)_6\}\,^2_\infty$	$C^6_{2h}-C2/c$	22.19	6.25	21.85	8	(3.1)	(3)
				$113°22'$			

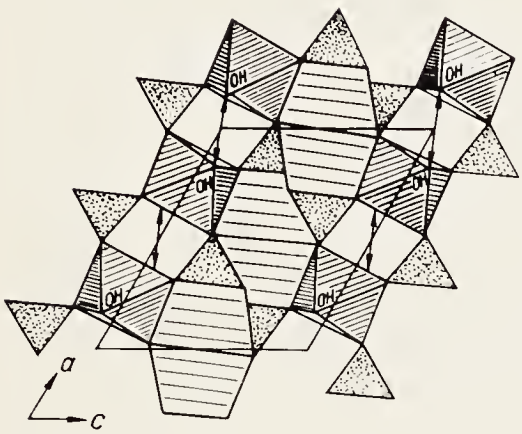


Fig. 262. Structure of natrochalcite in projection on (010), with layers of Cu octahedra and SO_4 tetrahedra parallel to this.

Str. Known for natrochalcite. Cu has an octahedron of four O, one OH, and one H_2O, the octahedra being linked by common (O, OH) edges into columns along the b axis, which are connected via SO_4 groups into layers perpendicular to the c axis (Fig. 262). Between layers at centers of symmetry lie Na atoms surrounded by eight O atoms. Interatomic distances: Na—O_8 = 2.59; Cu—O_4 (OH)H_2O = 2.30 (2), 2.02 (2), 1.94 (2). The OH—H_2O distance (shown by arrows in Fig. 262) is 2.42, which points to a hydrogen bond (Rumanova and Volodina, 1958 [343]).

Chem. Natrochalcite and devilline are of constant composition; Cu is serpierite is replaced by Zn (≤15.5%).

Var. Zn-serpierite.

Phys. Natrochalcite is columnar (dipyramidal), the reverse of the distribution of the strongest bonds. The hardness quoted 4.5 (Palache et al., [154]) is clearly exaggerated; it should not exceed 3. Perfect (001) cleavage. Devilline and serpierite form plates and laths flattened on c. The density of 2.52 given for serpierite in works of reference is erroneous.

4. GYPSUM GROUP. Mon., $C^6_{2h}-A2/a$, $Z = 4$

		a	b	c	β	ρ	H
Gypsum	$Ca(H_2O)_2[SO_4]\,^2_\infty$	5.68	15.18	6.29	113°50′	2.32	1.5—2.5

Str. Isostructural with brushite, pharmacolite, and churchite. Layer pattern produced by distribution of water molecules (coordinated to Ca), between which are relatively weak (d = 2.78) hydroxyl-hydrogen bonds (Fig. 263). The Ca scalenohedra are linked within a layer via edges along

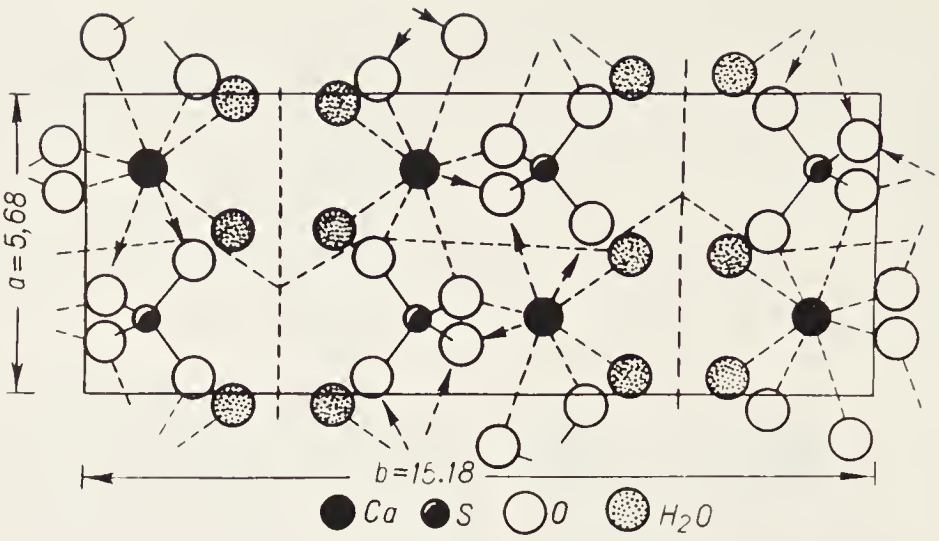


Fig. 263. Structure of gypsum in projection on (001), layers shown by broken lines.

the c axis and via SO_4 tetrahedra along the *a* axis. Interatomic distances: $Ca-O_6(H_2O)_2$ = 2.59 (2), 2.38 (2), 2.57 (2), 2.44 (2); $S-O_4$ = 1.49 (Wooster, 1936 [342]).

Phys. Tabular and platy on b axis, highly perfect (010) cleavage.

Inadequately Characterized and Doubtful

Anhydrokainite $KMg[SO_4]Cl$ (?)
Aromite $Mg_6Al_2[SO_4]_9 \cdot 54H_2O$ (?)
Dumreicherite $Mg_4Al_2[SO_4]_7 \cdot 36H_2O$ (?)
Euchlorine, sulfate of K, Na, and Cu (?)
Honessite, hydrated sulfate of Ni and Fe
Hydrobasaluminite $Al_4[SO_4]_3(OH)_{10} \cdot 36H_2O$ (?)
Hydroglauberite $Na_{10}Ca_3[SO_4]_8 \cdot 6H_2O$
Matteuccite $NaH[SO_4] \cdot H_2O$
Metaalunogen $Al_2[SO_4]_3 \cdot 13.5H_2O$ (?)
Metahohmannite $Fe_2[SO_4]_3(OH)_2 \cdot 3H_2O$ (?)
Monsmedite $K_2O \cdot Tl_2O_3 \cdot 8SO_3 \cdot 15H_2O$
Phillipite $CuFe_2^{3+}[SO_4]_4 \cdot 12H_2O$ (?)
Planoferrite $Fe_2[SO_4](OH)_2 \cdot 13H_2O$ (?)
Rubrite $MgFe_2^{3+}[SO_4]_4 \cdot 18H_2O$
Sonomaite $Mg_3Al_2[SO_4]_6 \cdot 33H_2O$ (?)
Udokanite $Cu_8[SO_4]_3(OH)_{10} \cdot H_2O$ (?)
Winebergite $Al_4(H_2O)_7[SO_4](OH)_{10}$ (?)

CLASS 12. CARBONATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1																	H 52	
2														C 92	N 1	O 92	F 9	
3	Na 20	Mg 18											Al 4			S 4	Cl 2	
4	K 1	Ca 37					Mn 3	Fe 3	Co 1	Ni 3	Cu 8	Zn 6						
5		Sr 5	Y 3	Zr 1								Cd 1						
6		Ba 10	La 6											Pb 7	Bi 3			
7				Th 1	U 10	Ce 11												

Type III. Oxygen compounds
Class 12. Carbonates

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						30	35	2	7	12	6

Subclass 1. Insular

Division A. Without Water and Additional Anions

Subdivision I. Simple

1. Calcite $Ca[CO_3]$ group
2. Aragonite $Ca[CO_3]$ group
3. Vaterite $Ca[CO_3]$ group

Subdivision II. Complex

1. Sahamalite $Mg(La; Ce)_2[CO_3]_4$ group
2. Dolomite-norsethite $CaMg[CO_3]_2$–$BaMg[CO_3]_2$ group
3. Barytocalcite $BaCa[CO_3]_2$ group
4. Eitelite $Na_2Mg[CO_3]_2$ group

Division B. With Additional Anions or Radicals

Subdivision I. Simple

1. Bastnäsite $Ce[CO_3](OH, F)$ group
2. Malachite $CuCu[CO_3](OH)_2$ group
3. Azurite $Cu_2Cu[CO_3]_2(OH)_2$ group

Subdivision II. Complex

1. Parisite $CaCe_2[CO_3]_3F_2$ group
2. Aurichalcite $Zn_3Cu_2[CO_3]_2(OH)_6$ group
3. Northupite $Na_3Mg[CO_3]_2Cl$ group

Division C. Hydrated without Additional Anions

Subdivision I. Simple

1. Tengerite $Y_2(H_2O)_3[CO_3]_3$ group
2. Lansfordite $Mg(H_2O)_5[CO_3]$ group
3. Monohydrocalcite $Ca(H_2O)[CO_3]$ group
4. Thermonatrite $Na_2(H_2O)[CO_3]$ group

Subdivision II. Complex

1. Lanthanite $LaCe(H_2O)_8[CO_3]_3$ group
2. Andersonite $Na_2Ca(UO_2)(H_2O)_6[CO_3]_3$ group
3. Pirssonite $Na_2Ca(H_2O)_2[CO_3]_2$ group

Division D. Hydrated with Additional Anions or Radicals

Subdivision I. Simple

1. Zaratite $Ni_3(H_2O)_4[CO_3](OH)_4$ group
2. Artinite $Mg_2(H_2O)_3[CO_3](OH)_2$ group

Subdivision II. Complex

1. Ancylite $(Sr, Ca)_2LaCe(H_2O)_2[CO_3]_4(OH)_2$ group
2. Callaghanite $Mg_2Cu_2(H_2O)_2[CO_3](OH)_6$ group

Subclass 2. Chain

1. Alumohydrocalcite $CaAl_2(H_2O)_3[CO_3]_2(OH)^1_{4\infty}$ group
2. Dawsonite $NaAl[CO_3](OH)^1_{2\infty}$ group
3. Nahcolite $Na[HCO_3]^1_\infty$ group

Subclass 3. Layer

Division A. Anhydrous

1. Rutherfordite $UO_2[CO_3]^2_\infty$ group
2. Bismutite $Bi_2[CO_3]O^2_{2\infty}$ group
3. Hydrocerussite $Pb_3[CO_3]_2(OH)^2_{2\infty}$ group
4. Phosgenite $Pb_2[CO_3]Cl^2_{2\infty}$ group

Division B. Hydrated

1. Liebigite $Ca_2\{UO_2[CO_3]_3\} \cdot 10H_2O^2_\infty$ group
2. Schröckingerite $NaCa_3\{UO_2[SO_4][CO_3]_3\}F \cdot 10H_2O^2_\infty$ group

3. Trona $Na_3(H_2O)_2\{H[CO_3]_2\}^2_\infty$ group

Inadequately Characterized and Doubtful

Subclass 1. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

Subdivision I. Simple

1. CALCITE GROUP. Trig. $D^6_{3d} - R\bar{3}c$, $Z = 2$; 6

	a_{rh}	α	a_h	c_h	d	ρ	H
Gaspeite $Ni[CO_3]$	5.58	48°39.7′	4.60	14.72	(2.12)	4.4	4.5–5
Smithsonite $Zn[CO_3]$	5 68	48°19.6′	4.65	15.03	2.15	4.3	4.25—5
Cobaltocalcite $Co[CO_3]$	5.67	48°33,1′	4.66	14.96	(2.16)	4.1	~4.5
Manfercite $(Mn, Fe)[CO_3]$	5 91— 5.80	47°43,3′— ?	4.78— 4.69	15.66—15.37	2.25—2.18	3.7—4.0	4.5–3.5
Magfercite $(Mg, Fe)[CO_3]$	5.61— 5.80	48°11′— 47°43,3′	4.63— 4.69	15.02—15.37	2.14—2.18	3,0—4.0	4.75–3.5
Otavite (cadmacite) $Cd[CO_3]$	6.13	47°19,2′	4.92	16.30	(2.35)	5.0	3.5—4
Calcite $Ca[CO_3]$	6.37	46°04,6′	4.99	17.06	2.37	2.71	3.25—3.75

Str. Calcite type, which may be derived from NaCl type by replacing Na by R^{2+} and Cl by CO_3, the cubic lattice being compressed along the threefold axis. CO_3 is perpendicular to this axis (Fig. 58); Ca is surrounded by six O (from CO_3). Lattice parameters from Graf (1961) [1027] and Kohls and Rodda (1966) [1028].

Chem. Marked variations from isomorphous substitution; perfect Mg–Fe and Mn–Fe isomorphism, so the former three species give us the two new ones magfercite and manfercite, the subspecies being magnesiomagfercite, ferromagfercite, manganomanfercite, and ferromanfercite (Fig. 59). All species contain substantial amounts of other components: in gaspeite Mg (≤16%) and Fe (≤5.7%); in smithsonite Fe (≤33%), Ca (≤12.7%), Co (≤10.3%), Mn (≤9.3%), Mg (≤7.2%), Cu (≤6.1%), Cd (≤2.3%), Pb (≤1%); in cobaltocalcite Ca (≤3.1%), Fe (≤3%), Cu (≤2.9%), Ni (≤1.2%); in magfercite Ni (≤30%), Ca (≤11.7%), Mn (≤7.5%) (magnesian subspecies), Co (≤9.1%), Zn (≤2%) (ferroan subspecies); in manfercite (Ca 19.4%), Zn (≤31%), Mg (≤13%) (manganian subspecies), Co and Cd (≤1%); in calcite Mn (≤16%), Fe (≤13.1%), Mg (≤7.3%), Pb (≤6%), Zn (≤4%), Sr and Ba (3-4%?), Co (≤2%), TR (Ce or Y) (1-2%).

Var. Mg-gaspeite, Mg,Fe-gaspeite, Fe-smithsonite, Ca-smithsonite, Co-smithsonite, Mn-smithsonite, Mg-smithsonite, Cu-smithsonite, Cd-

smithsonite, Ca-cobaltocalcite, Fe-cobaltocalcite, Cu-cobaltocalcite, Ni-cobaltocalcite, Ca-magfercite, Ni-magnesiomagfercite, Mn-magnesiomagfercite, Co-magfercite, Zn-ferromagfercite, Ca-manganomanfercite, Zn-manganomanfercite, Mg-manganomanfercite, Co-manfercite, Cd-manfercite, Mn-calcite, Fe-calcite, Mg-calcite, Pb-calcite, Zn-calcite, Sr-calcite, Ba-calcite, Co-calcite, TR-calcite (Ce or Y).

Phys. Habit varies (especially for calcite) from columnar to laths and platy or tabular, and even to foliated (papierspath). The last reveals the sublayered structure produced by the orientation of the CO_3 radicals. Perfect $(10\bar{1}1)$ cleavage, parting on $(01\bar{1}2)$ and (0001).

2. ARAGONITE GROUP. Orth., $D_{2h}^{16} - Pmcn$, $Z = 4$

		a	*b*	*c*	*d*	*ρ*	H
Aragonite	$Ca[CO_3]$	4.95	7.96	5.73	2.53	2.95	3.5—4.25
Strontianite	$Sr[CO_3]$	5.13	8.42	6.09	2.64	3.8	3.75
Witherite	$Ba[CO_3]$	5.26	8.85	6.55	2.81	4.3	3.5—3.75
Cerussite	$Pb[CO_3]$	5.15	8.47	6.11	2.71	6.6	3.5—3.75

Str. The aragonite type (Fig. 60) differs from the calcite type in having a hexagonal distribution of the R^{2+} polyhedra (Belov, 1947 [58]), which gives us a relation to the NiAs type (p. 295 [175]). The large R—O distances raise CN from 6 to 9 (very distorted cube-octahedron). The CO_3 groups are perpendicular to the c axis (Fig. 264). The interatomic distances in strontianite: $Sr-O_9 = 2.56\,(1)$, $2.58\,(2)$, $2.64\,(2)$, $2.65\,(2)$, and $2.73\,(2)$ ($d_m = 2.64$); $C-O_3 = 1.30$ and $1.29\,(2)$ [1281]; see also [1390].

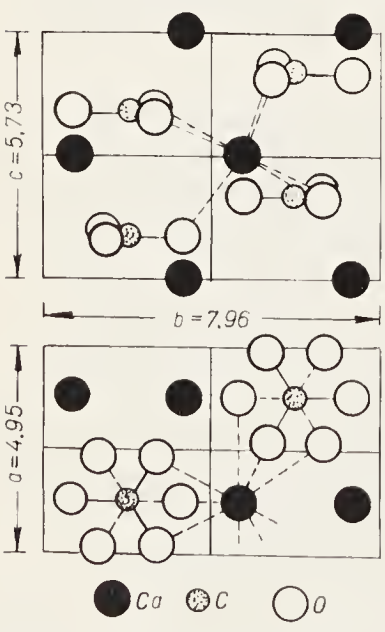


Fig. 264. Structure of aragonite showing coordination of Ca.

Chem. Much less variable than in the preceding group. Ca in aragonite is replaced by Pb (≤15%), Zn (≤10%?), Sr (≤3.9%), and TR (about 1%); strontianite contains Ca (≤10.6%) and Ba (2-3%); and cerussite contains Sr (3.2%), Zn (≤3.4%?) and Ca (≤0.5%).

Var. Pb-aragonite, Zn-aragonite (?), Sr-aragonite, TR-aragonite, Ca-strontianite, Ba-strontianite, Sr-cerussite, Zn-cerussite (?).

Phys. Habit ranges from short columns via laths to needles; cleavage varies. Aragonite and witherite have moderate (010) cleavage, while strontianite and cerussite have moderate (110). This is due to differences in atomic size and (to some extent) in disposition.

3. VATERITE GROUP. Hex., s.g. not det., $Z = 12$

		a	c	ρ	H
Vaterite	$Ca[CO_3]$	7.16	16.98	2.65	(3—3.5)

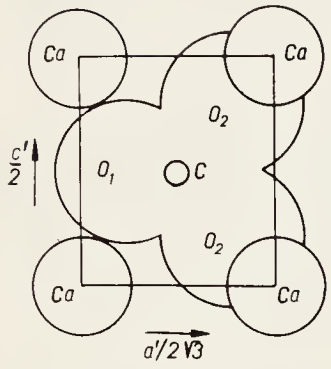


Fig. 265. Structure of vaterite showing orientation of CO_3.

Str. Close to that of bastnäsite; can be considered as an end-member of the bastnäsite-synchysite series (McConnell, 1960 [346]). Neglecting the weak superlattice reflections, we get a pseudocell with $a' = 4.13$, $c' = 8.49$, and space group $D_6^4 - P6_3/mmc$, $Z = 2$ (Kamhi, 1963 [1029]). The Ca atoms form a trigonal prism, in the center of which lies the C atom with the CO_3 radical v vertical (parallel to the c' axis, Fig. 265). Ca is surrounded by six O; mean $Ca-O_6 = 2.40$ (2.29 to 2.48). The next two O atoms (at 2.9) cannot be considered.

Chem. Composition constant.

Phys. Habit of artificial crystals tabular on (0001); also forms spherulites. Optically positive.

Subdivision II. Complex

1. SAHAMALITE GROUP. Mon.→orth.→hex.

		S.g.	a	b	c	β	Z	ρ	H
Sahamalite	$Mg(La; Ce)_2[CO_3]_4$	$C_{2h}^5 - P2_1/a$	5.92	16.21	4.63	106°45′	2	4.3	(5.5)
Carbocernaite	$NaSrCa(La; Ce)[CO_3]_4$	$C_{2v}^2 - Pb2_1m$	6.40	7.29	5.22	—	1	3.5	3.5—4
Burbankite	$(Na_2Ca)Sr_2Ca[CO_3]_5$	$C_{6v}^4 - P6_3mc$	10.52	—	6.51	—	2	3.5	3.5

Str. A preliminary study has been made for burbankite, in which the cations form two types of polyhedra (CN of 8 and 10), the first type containing the Na and some (probably half) of the Ca, and the second the Sr and the rest of the Ca. The polyhedra with CN = 10 are linked via common vertices in (0001) planes and are also attached to CO_3 groups lying parallel to (0001). The other 3/5 of the CO_3 triangles are inclined to the c axis, which is the reason for the low birefringence and poor cleavage (Voronkov et al., 1967 [1030]).

Chem. Sahamalite has La:Ce ≈ 1:1, Mg is replaced by Fe (≤2%). Carbocernaite has nearly the same La:Ce ratio, with Ca partly replaced by Y and Sr by Ba (5.9%). Burbankite has Sr replaced by Ba (≤13.6%) and Ca (and Sr) by TR (Ce predominant) via $NaTR \rightarrow 2Ca(Sr)$, with up to 15.1% TR.

Var. Ba-burbankite, Ce-burbankite.

Phys. Sahamalite and carbocernaite form tabular crystals; burbankite has short columns. Cleavage imperfect in all.

2. DOLOMITE-NORSETHITE GROUP

Dolomite subgroup. Trig., $C_{3i}^2 - R\bar{3}$

		a_{rh}	α	a_h	c_h	Z	ρ	H
Dolomite	$Ca(Mg, Fe)[CO_3]_2$	6.01—6.06	47°30′—46°58′	4.81	16.01	1; 3	2.85—3.2	4—3.75
Kutnahorite	$CaMn[CO_3]_2$	6.12	46°38′	4.88	16.37	1; 3	3.0	(3.75)

Str. Dolomite type, differing from calcite type in a regular sequence of layers of Ca octahedra and (Mg, Fe) or Mn octahedra. The mean distance $Ca(Mg, Fe)-O_6$ is about 2.30.

Chem. Dolomite has perfect Mg—Fe isomorphism (although pure $CaFe[CO_3]_2$ has not yet been observed), so the subspecies are magnesiodolomite and ferrodolomite. Ca is replaced by Mn (≤23%) and Pb, and also by Fe and Mg (transition to a disordered structure); Mg and Fe are replaced by Co (≤5.2%). Kutnahorite has Mn replaced by Mg (≤6.9%) and Fe (≤8.7%); Ca—Mn substitution also occurs.

Var. Mn-dolomite, Co-dolomite, Pb-dolomite, Mg-kutnahorite, Fe-kutnahorite.

Phys. Habit and cleavage as for the calcite group.

Norsethite subgroup. Trig.

		S.g.	a_{rh}	α	a_h	c_h	Z	ρ	H
Norsethite	$BaMg[CO_3]_2$	$D_3^7 - R32$	6.29	47°02	5.02	16.75	1 : 3	3.8	3.75
Benstonite	$Ba_6Ca_7[CO_3]_{13}$	$C_{3i}^2 - R\bar{3}(?)$	10.94	113°18′	18.28	8.67	1:3	3.6	3.5—4
Huntite	$CaMg_3[CO_3]_4$	$D_3^7 - R32$	6.08	102°56′	9.51	7.82	1;3	2.70	(4)

Str. Norsethite may have a structure of dolomite type (Strunz, 1966 [1031]), although its space group is as for huntite (Graf and Bradley, 1962 [1032]). Benstonite has a superlattice of calcite type with $a' = a\sqrt{3} = 5.07$ and $c' = 2c = 17.34$ (Lippmann, 1962 [1033]). According to the new data of Lippman, in norsethite the Ba atoms are surrounded by 12 oxygen atoms (ditrigonal prism). The mean interatomic distances are: $Ba-O_{12} = 2.72$ (6) and 3.18 (6); $Mg-O_6 = 2.09$; $C-O_3 = 1.28$ [1140].

Chem. Norsethite and huntite are of constant composition. The Ba in benstonite is replaced by Sr (4%) and the Ca by Mg (1.7%) and Mn (0.4%).

Phys. Cleavage on the rhombohedron in every case.

3. BARYTOCALCITE GROUP. Orth.→mon., →hex.

		S.g.	a	b	c	β	Z	ρ	H
Alstonite	$BaCa[CO_3]_2$	$D_{2h}^{16} - Pmcn(?)$	5.00	8.79	6.12	—	2	3.6	4—4.5
Barytocalcite	$BaCa[CO_3]_2$	$C_{2h}^{2} - P2_1/m$	8.17	5.23	6.59	106°08′	2	3.7	4
Ewaldite	$Ba_3Ca_2[CO_3]_5$	$C_{6v}^{4} - P6_3mc$	5.28	—	12.78	—	4	3.9	3.75—4

Str. Alstonite is of the aragonite type; Ba and Ca have CN of 9, and the distribution over the positions in the structure should be ordered. Ca in barytocalcite has CN = 6, and Ba has CN = 9. Mean distances: $Ca-O_6$ = 2.49; $Ba-O_9$ = 2.69 (Alm, 1960 [344]).

Chem. Compositions fairly constant. Alstonite contains isomorphous Sr (≤4.3%), and both contain Mn (≤0.2%).

Phys. Short columns to isometric; alstonite has imperfect (110) cleavage, while barytocalcite has (210) perfect and (001) imperfect.

4. EITELITE GROUP. Trig. → hex. → orth.

		S.g.	a	b	c	Z	ρ	H
Eitelite	$Na_2Mg[CO_3]_2$	$C_3^1 - P\bar{3}$	4.96	—	16.53	3	2.73	(3.75)
Nyerereite	$Na_2Ca[CO_3]_2$	Not det.	20.34	—	12.04	32	2.54	(3)
Shortite	$Na_2Ca_2[CO_3]_3$	$C_{2v}^{14} - C2mm$	7.11	10.99	4.99	2	2.60	3.5

Str. Known only for shortite (Wickman, 1950 [1034]); consists of Na and Ca distorted polyhedra (Na_I CN = 6, Na_{II} CN = 7, Ca CN = 9). The CO_3 groups have several orientations, about half lying in the (001) plane and the rest being perpendicular to that plane and almost mutually perpendicular in pairs, so that they lie in the (110) and ($\bar{1}10$) planes. Mean interatomic distances: $C-O_3$ = 1.31; $Na-O_6$ = 2.55; $Na-O_7$ = 2.64; $Ca-O_9$ = 2.53.

Phys. Shortite is columnar to tabular, moderate (010) cleavage. Nyerereite has perfect (0001) cleavage.

DIVISION B. WITH ADDITIONAL ANIONS OR RADICALS

Subdivision I. Simple

1. BASTNASITE GROUP. Hex., $D_{3h}^{4} - P\bar{6}2c$, $Z = 6$

		a	c	ρ	H
Bastnäsite	$Ce[CO_3](OH, F)$	7.05—7.23	9.79—9.88	5.1—4.9	5.5—6
Yttrobastnäsite	$Y[CO_3]F$	6.57	9.48	4.0	(6)

Str. Typical insular structure (Oftedal, 1931 [1035]), which Ce and F atoms and CO_3 radicals (Fig. 266). The last are all oriented along the

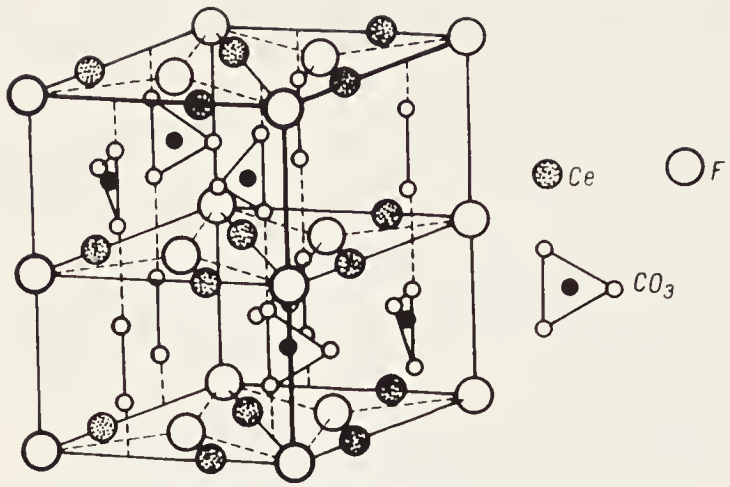


Fig. 266. Structure of bastnäsite.

principal axis, but their planes are turned around this axis and are nearly mutually perpendicular. Environment of Ce = 3F (d = 2.39) + 2O (2.4.9) + 6O (2.74). Mean distances: $C-O_3 = 1.27$; $Ce-(O, F)_{11} = 2.51$ (Donnay and Donnay, 1953 [1038]).

Chem. Ce often replaced by La, Nd, and Pr (≤45.8%), and also Th (≤3%) (Ce → Th + Ca) and Y (≤25%). F replaceable completely by OH (Aleksandrov et al., 1965 [1036]), so we have the subspecies hydroxylbastnäsite and fluorobastnäsite. In yttrobastnäsite Y is replaced by Ca (4.1%), Ce (7.1%), Nd (6.2%), Sm (5.3%), Gd (6.8%), Dy (11%), Er (7.5%), and Yb (5.3%) [1279].

Var. Y-bastnäsite, Th-bastnäsite, La-hydroxylbastnäsite, Ca-yttrobastnäsite, Ce-yttrobastnäsite, Dy-yttrobastnäsite, etc.

Phys. Tabular, imperfect $(10\bar{1}0)$ cleavage, distinct (0001) parting.

2. MALACHITE GROUP. Mon., $C_{2h}^5 - P2_1/a$, $Z = 4$

		a	b	c	β	ρ	H
Malachite	$CuCu[CO_3](OH)_2$	9.48	12.03	3.21	98°	4.0	3.5—4

Str. Two types of Cu, both with planar fourfold coordination of two O plus two OH (Fig. 267a); but the two next nearest neighbors, which give rise to a very distorted octahedron, are two O (too remote) for Cu_I and two OH for Cu_{II}. Interatomic distances: $Cu_I-(O, OH) = 1.91$ (2), 2.03 (2), and 2.58 (2); $Cu_{II}-(O, OH) = 2.08$ (2), 1.92 (2), and 2.36 (2); $C-O_3 = 1.29$ (Süsse, 1967 [1037]).

Chem. Cu replaced by Zn (≤12%).

Var. Zn-malachite.

Phys. Columnar, perfect (201) and (010) cleavages.

3. AZURITE GROUP. Mon., $Z = 2$

		S.g.	a	b	c	β	ρ	H
Azurite	$Cu_2Cu[CO_3]_2(OH)_2$	$C_{2h}^5 - P2_1/c$	4.97	5.84	10.29	92°24′	3.8	3.75—4
Hydrozincite	$Zn_3Zn_2[CO_3]_2(OH)_6$	$C_{2h}^3 - C2/m$	13.62	6.30	5.42	95°50′	4.0	4—4.5

Str. The two minerals are not identical. Azurite has two types of Cu: Cu_I is surrounded by two O + two OH (rectangle), while Cu_{II} has three O + two OH (tetragonal pyramid). These polyhedra are linked via common OH groups (Fig. 267b) and are mutually perpendicular in direction. The O atoms are in common with the CO_3 radicals, the three O atoms in each radical joining to three different Cu polyhedra. Mean interatomic distances: $Cu_I-(O, OH)_4 = 1.93$; $Cu_{II}-(O, OH)_5 = 2.07$; $C-O_3 = 1.27$ (Gattow and Zemann, 1958 [348]).

Hydrozincite has three Zn with octahedral (two O + four OH) surroundings, and two Zn with tetrahedral (O + three OH) surroundings. Mean interatomic distances: $Zn-(O, OH)_6 = 2.10$; $Zn-(O, OH)_4 = 1.95$; $C-O_3 = 1.35$ (Ghose, 1964). Sublayered structure.

Chem. Compositions constant.

Phys. Habit of azurite varies from columnar to tabular; perfect (011) and (100) cleavages. Hydrozincite has plates to laths elongated on (001) and flattened on (100), perfect (100) cleavage.

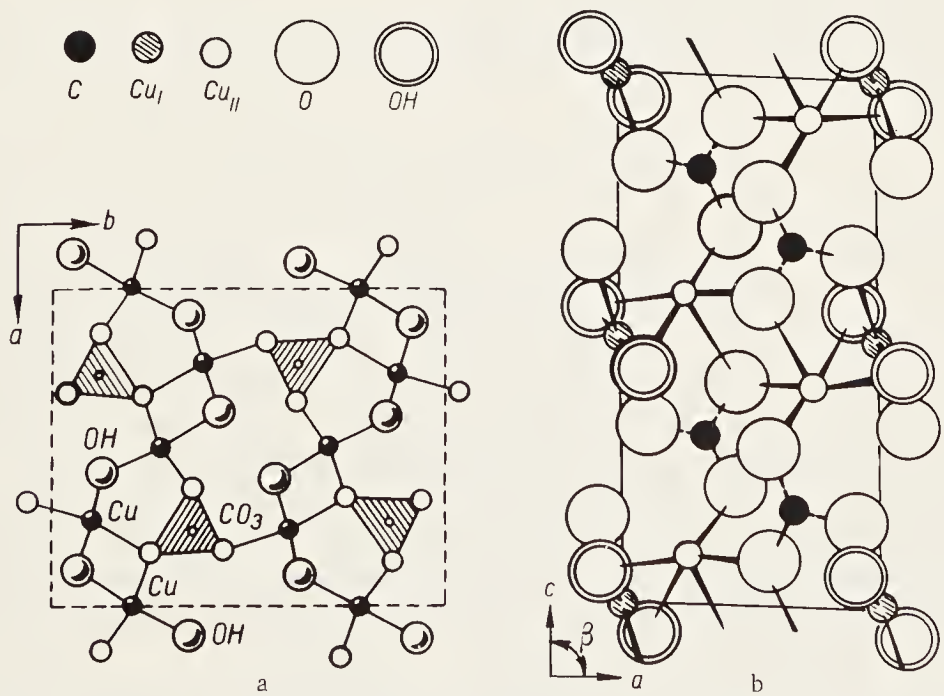


Fig. 267. Structure of: a) malachite in projection on (001), b) azurite in projection on (010).

Subdivision II. Complex

1. PARISITE GROUP. Trig.→orth. (pseudohex.)→hex.

		Syst.	S.g.	a	c	c'pseudo-repeot	Z	ρ	H
Parisite	$CaCe_2[CO_3]_3F_2$	Trig.	$C_3^1 - R3$	7.18	84.1	4.68	18	4.4	5—5.5
Röntgenite	$Ca_2Ce_3[CO_3]_5F_3$	Trig.	$C_3^1 - R3$	7.13	69.4	4.62	9	4.2	(5)
Synchysite	$CaCe[CO_3]_2F$	Orth.	(pseudohex.)	7.11	54.7	4.56	18	3.9	5
Cordylite	$BaCe_2[CO_3]_3F_2$	Hex.	$D_{6h}^1 - P6_3/mmc$	7.55	22.8	—	6	4.3	4.5—5
Huonghoite	$BaCe[CO_3]_2F$	Hex.	Not det.	5.11	19.6	—	3	4.7	4.5—5

Str. Analogous to that of bastnäsite (Oftedahl, 1931 [1035]; Donnay and Donnay, 1953 [1038]). The latter has only CeF sublayers along the c axis (c' = 4.89), whereas these minerals have layers of CeF and Ca, with c' decreasing regularly in the sequence parisite to synchysite (Semenov, 1959 [345]). Cordylite and huanghoite have bastnäsite cells alternating with cells of smaller size (3.27) along the c axis, the CO_3 radicals in the latter being horizontal (Fig. 61e), which produces different c parameters (and the negative optical sign).

Chem. All have Ce replaced by La and other large TR (Pr, Nd, Sm), often up to 1:1 or more. The Ce in parisite is also replaced by Y (≤7.86%), while in synchysite (to judge from the parameters of 'doverite') this appears to extend even further.

Var. Y-parisite, Y-synchysite.

Phys. Mainly columnar, moderate cleavage or parting on (0001).

2. AURICHALCITE GROUP. Orth.→mon., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Aurichalcite	$Zn_3Cu_2[CO_3]_2(OH)_6$	$D_2^5 - B22_12$	27.2	6.41	5.29	—	3.9	(4)
Rosasite	$ZnCu[CO_3](OH)_2$	Not det.	9.42	12.33	3.44	?	4.2	4.5
Loseyite	$Mn_4Zn_3[CO_3]_2(OH)_{10}$	$C_{2h}^6 - C2/c$	14.95	5.56	16.25	95°24′	3.3	3.5—4

Str. Not generally known. Rosasite has the malachite structure, with half of the Cu replaced by Zn, which applies to Cu_{II} only, as this is surrounded by O and OH in a less distorted octahedron, which corresponds more closely in size to the Zn octahedron. Aurichalcite is of the hydrozincite type, as is clear from the maximum possible Zn:Cu ratio of 3:2, which is possible if the Cu replaces only Zn in fourfold coordination (see hydrozincite). Loseyite also has different coordination for Mn and Zn.

Chem. Zn content of rosasite often less than 1:1 (Palache et al., 1951 [154]). The Zn:Cu ratio of aurichalcite varies from 3:2 to 3:1. Mn in loseyite is replaced by Mg (≤3.4%).

Phys. Columnar to laths. Perfect cleavage in two directions in rosasite; perfect on (100) in aurichalcite.

3. NORTHUPITE GROUP. Cubic. $O_h^7 - Fd3m$

		a	Z	ρ	H
Northupite	$Na_3Mg[CO_3]_2Cl$	14.08	16	2.36	3.75—4
Tychite	$Na_6Mg_2[CO_3]_4[SO_4]$	13.90	8	2.59	3.75—4

Str. Known for both (Shiba and Watanabe, 1931 [1040]). Mg has an octahedron of O atoms in CO_3 groups; Na in northupite has six O + two Cl, and in tychite has eight O. The CO_3 groups are oriented along the planes of a tetrahedron and thus produce no nett anisotropy. Mean interatomic distances in northupite $Mg-O_6 = 2.11$; $Na-(O, Cl)_8 = 2.67$; $C-O_3 = 1.15$; in tychite $Mg-O_6 = 1.90$ (?); $Na-O_8 = 2.56$; $C-O_3 = 1.10$ (?) (pp. 80; 98 [176]).

Chem. Mg in northupite replaced by Fe ($\leq 9\%$).

Phys. Isometric, no cleavage.

DIVISION C. HYDRATED WITHOUT ADDITIONAL ANIONS

Subdivision I. Simple

1. TENGERITE GROUP. Orth.

		S.g.	a	b	c	ρ	H
Tengerite	$Y_2(H_2O)_3[CO_3]_3$	Not det	9.18	11.34	7.60	(3.2)	(3.5)

Str. Not known. The lattice parameters have been obtained for the artificial compound (Nagashima and Wakita, 1970 [1283]).

Chem. In natural minerals much Ca and Be are present, the first being an isomorphic constituent of Y (Dana [154]).

2. LANSFORDITE GROUP. Tricl. → mon.→trig. (?)

		S.g.	a	b	c	β	Z	ρ	H
Borringtonite	$Mg(H_2O)_2[CO_3]$	$C_1^1 - P1$	9.16	6.20	6.09	95°32′	4	2.83	3.5
			$\alpha = 94°00'$			$\gamma = 108°12'$			
Nesquehonite	$Mg(H_2O)_3[CO_3]$	$C_{2h}^5 - P2_1/n$	7.68	5.39	12.00	90°45′	4	1.85	3
Lonsfordite	$Mg(H_2O)_5[CO_3]$	$C_{2h}^2 - P2_1/m$	12.50	7.57	7.35	101°49′	4	1.69	3
Hellyerite	$Ni(H_2O)_6[CO_3]$	Trig. (?)	—	—	—	—	—	1.97	3

Str. Not known.

Phys. Short columns, perfect cleavage on (001) and (110) (nesquehonite), (100) (lansfordite), three directions (hellyerite); barringtonite has moderate cleavage in three pinakoids, as seen under the microscope.

3. MONOHYDROCALCITE GROUP. Hex.→mon.

		a	*b*	*c*	β	*Z*	ρ	H
Monohydrocalcite	$Ca(H_2O)[CO_3]$	10.62	—	7.54	—	9	2.38	—
Ikaite (hexahydrocalcite)	$Ca(H_2O)_6[CO_3]$	—	—	—	—	—	1.77	2.5

Str. Not known; cell parameters of monohydrocalcite for the artificial compound, whose space group (D_3^3 or D_3^6) is not exactly known (Lippmann, 1959 [1041]).

Phys. Habit not known; synthetic $Ca(H_2O)_6[CO_3]$ has short columns to tablets (Krauss and Schriever, 1930).

4. THERMONATRITE GROUP. Orth.→mon., $Z = 4$

		S.g.	*a*	*b*	*c*	β	ρ	H
Thermonatrite	$Na_2(H_2O)[CO_3]$	$D_{2h}^1 - Pmmm$	10.74	6.45	5.25	—	2.55	1.5—2
Natronite	$Na_2(H_2O)_{10}[CO_3]$	$C_{2h}^6 - C2/c$	12.76	9.01	13.47	122°48′	1.46	1.5

Str. Known for thermonatrite (Harper, 1936 [1042]), with two types of Na: Na_I with five O + one H_2O, Na_{II} with four O + two H_2O. CO_3 groups parallel to (010), H_2O linked to two Na and two O ($d_m \approx 2.7$). Interatomic distances: $C-O_3$ = 1.22, 1.22, and 1.25; $Na_I-O_5H_2O$ = 2.46, 2.58, 2.54, 2.48, 2.32, and 2.38; $Na_{II}-O_4(H_2O)_2$ = 2.30, 2.40, 2.35, 2.74, 2.56, and 2.70.

Phys. Tabular, imperfect cleavage on (010) (thermonatrite) or (001) natronite.

Subdivision II. Complex

1. LANTHANITE GROUP. Orth.→trig.→hex.

		S.g.	*a*	*b*	*c*	*Z*	ρ	H
Calcinsite	$LaCe(H_2O)_4[CO_3]_3$	$D_2^3 - P2_122_1$	9.57	12.65	8.94	4	3.3	(3,5)
Lanthanite	$LaCe(H_2O)_8[CO_3]_3$	Not det.	9.52	17.1	9.02	4	2.72	3—3.5
Mackelveyite	$Na_2Ba_4CaY_2(H_2O)_5[CO_3]_9$	$C_{3i}^1 - P\bar{3}$	9.17	—	19.15	2	3.6	(3)
Welaganite	$Sr_5Zr_2(H_2O)_4[CO_3]_9$	$C_3^2 - P3_1$ (?)	8.96	—	18.06	2	3.2	3.5—4
Thorbastnäsite	$CaTh(H_2O)_3[CO_3]_2F_2$	$D_{3h}^4 - P\bar{6}2c$	6.99	—	9.74	3	4.7	(4.5—5)

Str. Not known. Thorbastnäsite seems to be isostructural with stnäsite (Pavlenko et al., 1965 [1039]).

Chem. La:Ce close to 1:1. The stoichiometric relationships in mackelveyite are appreciably disturbed by Na−Ca−Y−TR isomorphism.

Phys. Platy on b axis (calcinsite) and c axis (lanthanite). No cleavage in mackelveyite; perfect on (100) and (010) in calcinsite, on (010) in lanthanite. Weloganite columnar with perfect (0001) cleavage [1280].

2. ANDERSONITE GROUP. Trig., $C_{3i}^2 - R\bar{3}(?)$, $Z = 18$

		a_h	c_h	a_{rh}	α	ρ	H
Andersonite	$Na_2Ca(UO_2)(H_2O)_6[CO_3]_3$	18.04	23.90	13.11	86°56′	2.8	—

Str. Not known.

Phys. Isometric, no cleavage observed.

3. PIRSSONITE GROUP. Orth.→mon., $Z = 8;4$

		S.g.	a	b	c	β	ρ	H
Pirssonite	$Na_2Ca(H_2O)_2[CO_3]_2$	$C_{2v}^{19} - Fdd2$	11.32	20.06	6.00	—	2.35	3.5—3.75
Gaylussite	$Na_2Ca(H_2O)_5[CO_3]_2$	$C_{2h}^6 - C2c$	14.35	7.78	11.21	127°51′	1.99	3—3.5
Chalcanatranite	$Na_2Cu(H_2O)_3[CO_3]_2$	—	—	—	—	—	2.27	—

Str. In pirssonite the Ca atoms have eightfold coordination, while the Na atoms have sixfold coordination (distorted octahedra); the latter form crossed chains which are joined by Ca polyhedra and CO_3 triangles. The interatomic distances are: Na−(O, H_2O)$_6$ = 2.28-2.76 (d_m = 2.46); Ca−$O_6(H_2O)_2$ = 2.47; C−O_3 = 1.28 (2) and 1.30 (Corazza and Sabelli, 1967 [1144]). The lattice parameters of gaylussite are based on data by Menchetti [1116]; closely agreeing data are presented by McKie (1284).

Phys. Thick tablets or short columns, nearly isometric. Chalconatrite occurs as thin plates. Only gaylussite has a cleavage: perfect on (110).

DIVISION D. HYDRATED WITH ADDITIONAL ANIONS OR RADICALS

Subdivision I. Simple

1. ZARATITE GROUP. Cubic (?), s.g. not det., $Z = 1$

		a	ρ	H
Zaratite	$Ni_3(H_2O)_4[CO_3](OH)_4$	6.16	2.65	3.5—4

Str. Not studied (not indexed on basis of simple cubic cell).

Chem. Composition needs to be checked.

Phys. Cleavage not observed.

2. ARTINITE GROUP. Mon.→mon. (pseudoorth.)

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Artinite	$Mg_2(H_2O)_3[CO_3](OH)_2$	C_2^3-C2	16.69	3.15	6.21	99°45′	2	2.02	3
Hydromagnesite	$Mg_5(H_2O)_4[CO_3]_4(OH)_2$	$D_2^5-C222_1$	18.58	9.06	8.42	90°	4	2.24	3.75
Dypingite	$Mg_5(H_2O)_5[CO_3]_4(OH)_2$	Not det.	—	—	—	—		2.15	(3.5)

Str. Known approximately for artinite (Wolf, 1952 [1043]); brucite blocks are considered to be present. Mg surrounded by two OH and four H_2O. CO_3 groups lie in $(10\bar{1})$, plane of the b axis. The hydroxyl-hydrogen bonds from O (in CO_3) to H_2O vary in strength (O–H–O = 2.65-2.88).

Phys. Needles to laths, perfect cleavage on (100) and (001) (artinite), or (010) (hydromagnesite).

Subdivision II. Complex

1. ANCYLITE GROUP. Orth., s.g. not det., $Z = 1$

		a	*b*	*c*	ρ	H
Ancylite	$(Sr, Ca)_2LaCe(H_2O)_2[CO_3]_4(OH)_2$	5.00	8.48	7.01	4.3—3.8	4—4.5

Str. Not known. Cell parameters from Motychko (1959) [1044]; formula simplified by Semenov and Kazakova (1961) [1045].

Chem. Perfect Sr–Ca isomorphism (Palache et al., 1951 [154]), subspecies strontioancylite and calcioancylite. La:Ce close to 1:1, but some specimens are low in La. Ca in calcioancylite replaced by Mn (≤5.6%) and Y (≤1%); Sr in strontioancylite replaced by Ba (≤1.6%). Th (≤0.2%) replaces La and Ce.

Var. Mn-calcioancylite, Ba-strontioancylite.

Phys. Isometric, no cleavage.

2. CALLAGHANITE GROUP. Mon., C_{2h}^6-C2/c, $Z = 4$

		a	*b*	*c*	β	ρ	H
Callaghanite	$Mg_2Cu_2(H_2O)_2[CO_3](OH)_6$	10.06	11.80	8.24	107° 18′	2.71	3.5—4

Str. CO_3 radicals linked to Cu and Mg polyhedra (Brunton et al., 1957 [1046]) and lying parallel to (001); two O atoms linked to Mg, while one forms a hydroxyl-hydrogen bond to H_2O. Mg surrounded by one O,

four OH, and one H_2O. Cu has fivefold (pyramidal) coordination, four OH and one H_2O. Interatomic distances: $C-O_3$ = 1.41, 1.41, and 1.29; $Mg-(O, OH, H_2O)_6$ = 2.03; $Cu-(OH, H_2O)_5$ = 2.01 (4) and 2.23.

Phys. Isometric, perfect (111) and ($\bar{1}11$) cleavages.

Subclass 2. Chain

1. ALUMOHYDROCALCITE GROUP. Mon. →orth.

		a	*b*	*c*	*Z*	ρ	H
Alumohydrocolcite	$CaAl_2(H_2O)_3[CO_3]_2(OH)_4\,{}^{1}_{\infty}$	—	—	—	—	2.23	3
Dundosite	$Pb_2Al_4(H_2O)_3[CO_3]_4(OH)_8\,{}^{1}_{\infty}$	9.05	16.35	5.61	2	3.6	2.5–3
Schuilingite	$Ca_6Pb_3Cu_2(H_2O)_6[CO_3]_6(OH)_6\,{}^{1}_{\infty}$	—	—	—	—	5.2	3.5—4
Dresserite	$Ba_2Al_4(H_2O)_3[CO_3]_4(OH)_8\,{}^{1}_{\infty}$	9.27	16.8	5.63	2	3.1	3—3.5

Str. Not known. Assigned from morphology.

Chem. Al partly replaced by Fe^{3+} (up to 5.5% in dundasite).

Phys. Acicular to fibrous, perfect cleavage in one direction [(110) in schuilingite].

2. DAWSONITE GROUP. Orth. →tetr.

		S.g.	*a*	*b*	*c*	*Z*	ρ	H
Dowsonite	$NaAl[CO_3](OH)_2\,{}^{1}_{\infty}$	C_{2v}^{22}—*Ima*2	6.73	10.36	5.58	4	2.44	3.5
Tunisite	$NaHCa_2Al_4[CO_3]_4(OH)_{10}\,{}^{1}_{\infty}$	D_{4h}^{7}—*P*4/*nmm*	11.22	—	6.58	2	2.51	4.5

Str. Na and Al have distorted octahedral coordination; the first is surrounded by four O and two OH, while the second has two O and four

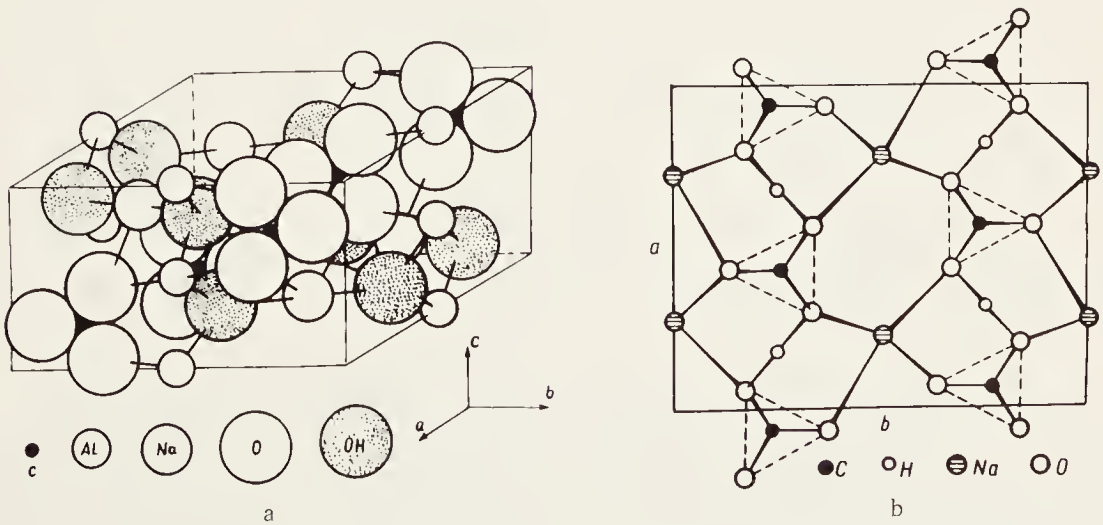


Fig. 268. Structure of: a) dawsonite, b) nahcolite, with $[HCO_3]^{1}_{\infty}$ chains along *a* axis.

OH. The Al octahedra are linked by common OH edges into columns of rutile type parallel to the c axis, while the Na octahedra alternate with CO_3 groups in heterogeneous chains in the same direction, sharing vertices with the columns of Al octahedra (Fig. 268a). Interatomic distances: $Na-O_4(OH)_2$ = 2.47 (4); 2.39 (2); $Al-O_2(OH)_4$ = 1.95 (2); 1.86 (4); $C-O_3$ = 1.27. (Frueh and Golightly, 1967 [1047]). The structure of tunisite is not known; it may be layer [1282].

Phys. Laths to needles (on c axis), (110) cleavage perfect. Tunisite is tabular; perfect (001) and (110) cleavage.

3. NAHCOLITE GROUP. Mon.→orth.→tricl.

		S.g.	a	b	c	β	Z	ρ	H
Nahcolite	$Na[HCO_3]\frac{1}{\infty}$	$C_{2h}^5-P2_1/n$	7.53	9.72	3.54	93° 19′	4	2.21	3
Teschemacherite	$NH_4[HCO_3]\frac{1}{\infty}$	$D_{2h}^{10}-Pccn$	7.30	10.81	8.78	—	8	1.57	1.5
Wegscheiderite	$Na_5\{H_3(CO_3)_4\}\frac{1}{\infty}$	C_1^1-P1	10.04	15.56	3.47	—	2	2.34	3—3.5
			α = 91° 55′	β = 95° 40′	γ = 108° 40′				

Str. Planar chains of CO_3 groups linked via hydrogen bonds (Fig. 268b), the position of H half-way along the O—O line being chosen arbitrarily (O—H—O = 2.55). These chains run along the a axis, and their planes are parallel to (101); they are linked via Na (CN = 6), $Na-O_6$ = 2.47 (Zachariasen, 1933 [350]). Teschemacherite has analogous chains, but with a somewhat different orientation (Brooks and Alcock, 1950 [351]). Wegscheiderite has not been studied.

Phys. Short columns to plates. Nahcolite has perfect (101) cleavage, moderate (100); teschemacherite has perfect (110). Wegscheiderite has moderate prismatic cleavage.

Subclass 3. Layer

DIVISION A. ANHYDROUS

1. RUTHERFORDITE GROUP. Orth., $D_{2h}^{13}-Pmmn$ or $C_{2v}^7-Pmn2_1$, $Z = 2$

		a	b	c	ρ	H
Rutherfordite (urocite)	$UO_2[CO_3]\frac{2}{\infty}$	4.84	4.29	9.20	5.7	(3—3.5)

Str. Layers of CO_3 groups parallel to (001), with linking uranyl groups normal to these, U^{6+} lying in the plane of the layer and linking to its own two O as well as to six O derived from four CO_3 groups (Fig. 269). The setting has been altered (b and c interchanged). Interatomic distances: $U-O_8$ = 1.67 (2), 2.43 (2), 2.52 (4) (Christ et al., 1955 [353]).

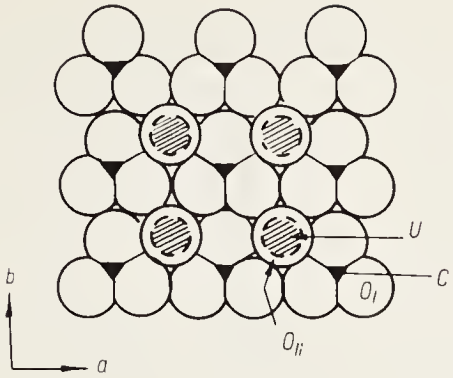


Fig. 269. Structure of rutherfordite, projection of a UO_2CO_3 layer on (001).

Phys. Morphology not studied; perfect (001) cleavage.

2. BISMUTITE GROUP. Tetr., $Z = 2$

		S.g.	a	c	ρ	H
Bismutite	$Bi_2[CO_3]O_2$	$D_{4h}^{17} - I4/mmm$	3.87	13.69	8.3	3—3.75
Beyerite	$CaBi_2[CO_3]_2O_2$	$D_{4h}^{17} - I4/mmm$	3.79	21.81	6.6	2.5—3.5
Kettnerite	$CaBi[CO_3]OF$	$D_{4h}^{7} - P4/nmm$	3.79	13.59	(5.8)	(3—3.5)

Str. Alternating $(BiO)_{2n}$ and $(CO_3)_n$ layers. Bi has fourfold pyramidal coordination (as for Pb in PbO), with O atoms projecting to both sides of the central layer (Fig. 270a). At larger distances it is linked to O atoms in CO_3 groups (Lagercrantz and Sillén, 1948 [355]). Beyerite has Ca (CN = 8) between these layers (Fig. 270b). The order in bismutite

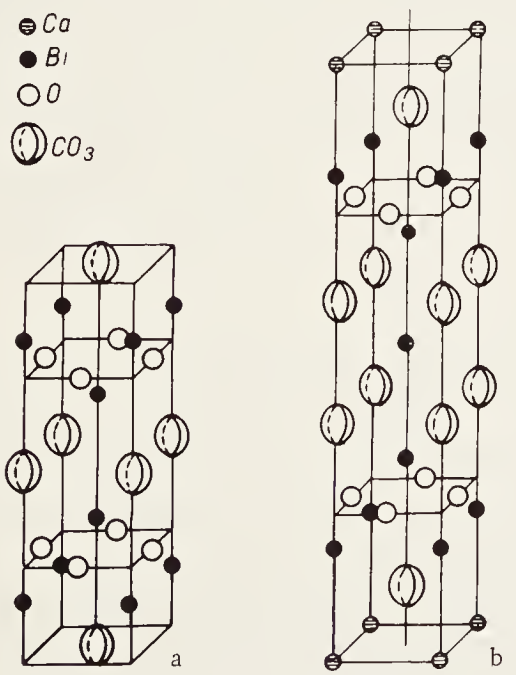


Fig. 270. Structure of: a) bismutite, b) beyerite.

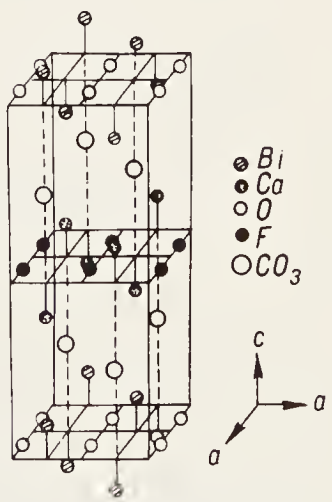


Fig. 271. Structure of kettnerite.

is $(BiO)_2-CO_3-(BiO)_2-CO_3-(BiO)_2$, while in beyerite it is $(BiO)_2-CO_3-Ca-CO_3-(BiO)_2$. Kettnerite (Fig. 271) has the same sequence as bismutite, but with regular alternation of BiO and CaF. Mean interatomic distances: in bismutite $Bi-O_4 = 2.29$ and $Bi-O_4 = 2.74$ (O from CO_3); in beyerite $Ca-O_8 \approx 2.80$; $Bi_1-O_4 = 2.29$, and $Bi-O_4 = 2.66$; $C-O_3 = 1.31$ (p. 319); in kettnerite $Bi-O_4 = 2.29$; $Ca-F_4 = 2.33$; distances between layers 2.68 (Synečck and Žak, 1960 [1048]). It is considered that the CO_3 groups rotate in two planes parallel to the c axis (Lagercrantz and Sillén, 1948 [355]). The layered pattern parallel to (001) arises solely from the difference in the Bi–O and Ca–O distances (in beyerite), which produces the difference [by a factor of 2-3] in bond strengths within layers and between them.

Phys. Platy on basal plane, moderate (001) cleavage.

3. HYDROCERUSSITE GROUP. Trig.→mon. (pseudohex.)

		S.g.	a	b	c	β	Z	ρ	H
Hydrocerussite	$Pb_3[CO_3]_2(OH)_2$	Not det.	5.24	—	23.65	—	3	6.8	3.5—4
Leadhillite	$Pb_4[SO_4][CO_3]_2(OH)_2$	$C_{2h}^5 - P2_1/a$	9.09	11.57	20.74	90° 29′	8	6.6	3—3.5
Susannite	$Pb_4[SO_4][CO_3]_2(OH)_2$	$C_{3i}^2 - R\bar{3}$	9.05	—	11.54	—	4	(6.6)	(3—3.5)

Str. Hydrocerussite has heterogeneous layers of Pb polyhedra and CO_3 groups oriented parallel to (0001) (Cowley, 1956 [1049]). The Pb atoms lie in three types of position; two have CN = 10 and are surrounded by six O on one side and four OH on the other (one of these has distorted coordination). The third has CN = 8 (four O + four OH). The layer pattern arises from alternation of stronger Pb–O bonds and weaker Pb–OH ones and is very pronounced parallel to the plane of orientation of the CO_3 groups. Interatomic distances: $C-O_3 = 1.45$; $Pb_I-(O, OH)_{10} = 2.86$; $Pb_{II}-(O, OH)_{10} = 2.86$; $Pb_{III}-(O, OH)_8 = 3.0$ (very distorted polyhedron). Leadhillite has not been studied; assigned here on the basis of properties.

Phys. Tabular and platy, perfect cleavage on (0001) (hydrocerussite) or (001) (leadhillite).

4. PHOSGENITE GROUP. Tetr., $D_{4h}^5 - P4/mbm$, $Z = 4$

		a	c	ρ	H
Phosgenite	$Pb_2[CO_3]Cl_2$	8.15	8.87	6.1	2.5—3.5

Str. Heterogeneous layers of Pb atoms and CO_3 groups, nearly parallel to c axis. These layers have square holes, which take paired Cl_I atoms. The layers are connected via layers of Cl_{II} atoms, which produce the weakest bonds in the structure (Fig. 272). Pb has CN = 6 (four O and two Cl). Interatomic distances: $C-O_3 = 1.25$; $Pb-(O, Cl)_6 = 2.74$. The $Pb-Cl_{II} = 3.44$ bonds are the weakest (Sillén and Pettersson, 1945 [1050]).

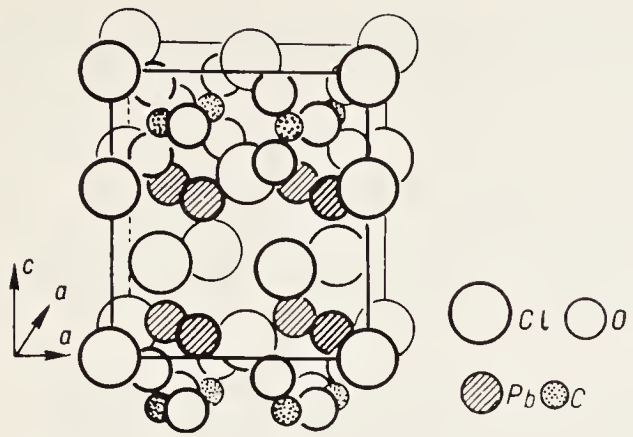


Fig. 272. Structure of phosgenite.

Phys. Short columns to tabular, moderate (001) and (110) cleavages, (100) imperfect.

DIVISION B. HYDRATED

1. LIEBIGITE GROUP. Mon.→orth.→tricl.

	S.g.	a	b	c	Z	ρ	H
Bayleyite	$C_{2h}^5 - P2_1/a$	26.65	15.31	6.53	4	2.05	—
$Mg_2\{UO_2[CO_3]_3\}\cdot 18H_2O$		$\beta = 93°04'$					
Swartzite	$C_{2h}^2 - P2_1/m$	11.12	14.72	6.74	2	2.30	—
$CaMg\{UO_2[CO_3]_3\}\cdot 12H_2O$		$\beta = 99°26'$					
Rabbittite	Nat det.	32.6	23.8	9.45	8	2.57	3—3.5
$Ca_3Mg_3\{(UO_2)_2[CO_3]_6(OH)_4\}\cdot 18H_2O$		$\beta = 90°$					
Liebigite	$C_{2v}^{17} - Bba2$	16.71	17.55	13.79	8	2.41	3—3.5
$Ca\{UO_2[CO_3]_2\}\cdot 10H_2O$							
Zellerite	$D_{2h}^{13} - Pmnm$ (?)	11.22	19.25	4.93	4	3.2	2–2.5
$Ca\{UO_2[CO_3]_2\}\cdot 5H_2O$							
Metazellerite	$D_{2h}^{16} - Pbnm$ (?)	9.72	18.23	4.97	4	3.4	(2.5)
$Ca_2\{UO_2[CO_3]_3\}\cdot 3H_2O$							
Voglite	Nat det.	—	—	—	—	—	—
$Ca_2Cu\{UO_2[CO_3]_4\}\cdot 6H_2O$							

Str. Known for liebigite (Appleman, 1956 [354]). The layer pattern is due to $UO_2[CO_3]_3$ groups with the three CO_3 groups lying in a plane perpendicular to the linear UO_2 group and parallel to (100). The Ca atoms link these groups into double layers, between which lie the H_2O molecules. Bayleyite and swartzite are evidently also of this type; rabbittite and voglite have been studied only chemically.

Chem. Compositions constant, except that Mg in bayleyite is replaced by Ca ($\leq$3.4%).

Phys. Generally short columns; rabbittite, zellerite, and metazellerite are acicular, voglite occurs as foliated aggregates. Rabbittite

has moderate cleavage on (001), as does liebigite on (100); voglite has perfect (010) cleavage, while zellerite and metazellerite show no cleavage (Coleman et al., 1966 [1051]).

2. SCHRÖCKINGERITE GROUP. Tricl., C_i^1—$P\bar{1}$ (?) (pseudohex), $Z = 2$

		a	b	c	ρ	H
Schröckingerite	$NaCa_3\{UO_2[SO_4][CO_3]_3F\} \cdot 10H_2O$ ∞	9.60	9.62	14.46	2.55	3
	$\alpha = 91°42'$ $\beta = 91°48'$ $\gamma = 120°05'$					

Str. Not known; assigned from properties and crystallochemical arguments. The lattice parameters according to data of Smith [1285].

Phys. Platy on (001), highly perfect (mica-type) cleavage on (001).

3. TRONA GROUP. Mon., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Trona (hydronatrite)	$Na_3(H_2O)_2\{H[CO_3]_2\}$ ∞	$C_{2h}^6 - C2/c$	20.41	3.49	10.31	106° 20′	2.14	3—3.5
Kalicinite	$K[HCO_3]$ ∞	$C_{2h}^5 - P2_1/a$	15.13	5.63	3.71	103° 49′	2.17	(2.5—3)

Str. Trona consists (Brown et al., 1949 [1052]) of layers parallel to (100) consisting of CO_3 groups and Na atoms in octahedral and prismatic coordination (Fig. 273). Within a layer there are hydrogen bonds (O—H—O = 2.53) between the O of two adjacent CO_3 groups; between layers there are hydroxyl-hydrogen bonds (O—H_2O = 2.76). Interatomic distances: C—O_3 = 1.23, 1.23, and 1.26; Na_1—O_6 = 2.41; Na_2—$O_4(H_2O)_2$ = 2.47 (4) and 2.38 (2) (Candlin, 1956 [1053]).

Kalicinite consists of paired CO_3 groups linked by a double hydrogen bond (O—H—O = 2.61) to give planar $H_2C_2O_6$ radicals parallel to (100), which are linked together by weak bonds to K atoms between them in

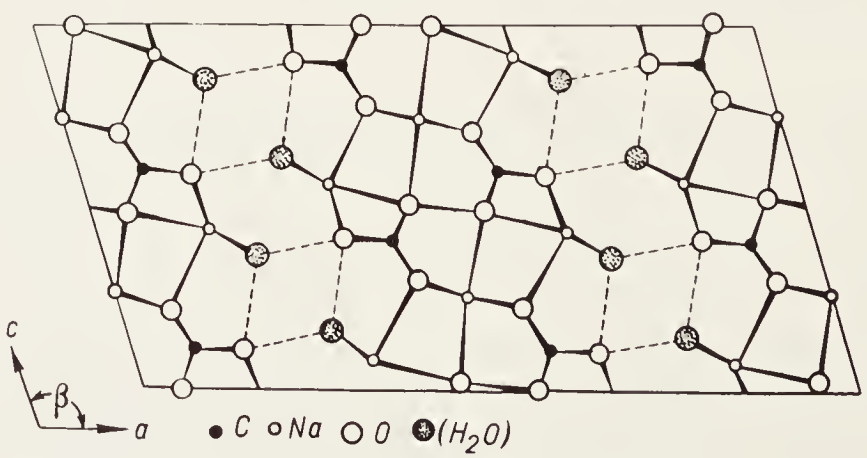


Fig. 273. Structure of trona, layer pattern due to weak H_2O—O bonds (broken lines) parallel to the a axis.

distorted eightfold coordination (Koo, 1952 [352]). Interatomic distances: $C-O_3$ = 1.28, 1.32, and 1.32; $K-O_8$ = 2.68, 2.69, 2.74, 2.82, 2.88, 2.92, 2.92, and 3.13 (d_m = 285) (Nitta et al., 1954 [1054]). Strictly speaking, the structure is sublayered.

Phys. Trona tabular to platy, perfect (100) cleavage. Artificial kalicinite forms short prisms, with cleavage on (100), (001), and (101).

Inadequately Characterized and Doubtful

Ambatoarinite $Sr(La, Ce)_2[CO_3]_3O$ (?)
Beryllium tengerite $Be(Ce, Y)[CO_3](OH)_3 \cdot H_2O$ (?)
Nasledovite $Pb_2Mg_2Mn_3Al_6[SO_4][CO_3]_7(OH)_{16} \cdot 2H_2O$ (?)
Pentahydrocalcite $Ca(H_2O)_5[CO_3]$ (?)
Plumbomalachite $PbCu_3[CO_3]_3(OH)_2$ (?)
Sharpite $UO_2[CO_3] \cdot H_2O$ (?)
Studtite (hydrated U^{6+} carbonate?)
Trihydrocalcite $Ca(H_2O)_3[CO_3]$
Waltherite (hydrated Bi carbonate?)
Widenmannite (Pb and U^{6+} carbonate?)

CLASS 13. IODATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1																	H 2	
2																O 5		
3																	Cl 1	
4		Ca 2				Cr 1					Cu 2							
5																	I 5	
6														Pb 1				
7																		

Type III. Oxygen compounds
Class 13. Iodates

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						4				1	

Subclass 1. Insular

Division A. Without Water and Additional Anions

1. Lautarite $Ca[IO_3]_2$ group

Division B. With Additional Anions or Radicals

1. Salesite $Cu[IO_3]OH$ group
2. Dietzeite $Ca_2[CrO_4][IO_3]_2$ group

Division C. Hydrated

1. Bellingerite $Cu_3(H_2O)_2[IO_3]_6$ group

Subclass 2. Layer

1. Schwarzembergite $Pb_3[IO_3]O(OH)Cl_2$ $2\frac{2}{\infty}$ group

Subclass 1. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. LAUTARITE $Ca[IO_3]_2$ GROUP $C_{2h}^5 - P2_1/n$, Z = 4

		a	b	c	β	ρ	H
Lautarite (calciodite)	$Ca[IO_3]_2$	7.19	11.40	7.33	106° 22′	4.6	3.75—4(?)

Str. Not known.

Chem. Composition constant.

Phys. Short columns on c axis, perfect (011) cleavage, imperfect (100) and (110).

DIVISION B. WITH ADDITIONAL ANIONS OR RADICALS

1. SALESITE GROUP. Orth., $D_{2h}^{16} - Pbmn$, Z = 4

		a	b	c	ρ	H
Salesite (cupriohiodite)	$Cu[IO_3]OH$	4.79	10.79	6.71	4.8	3.5

Str. Cu has very distorted octahedral coordination (Ghose, 1962 [356]); two O and two OH lie in a plane with it (Cu–O = 2.01, Cu–OH = 1.95), while two O lie at a much greater distance (Cu–O = 2.59). These Cu octahedra form zigzag chains (Fig. 274) parallel to the c axis, which are connected via pyramidal IO_3 groups (I–O = 1.78 and 1.82); this is comparable with the olivine structure (the analogous Pbmn setting is used).

Chem. Composition constant, apart from isomorphous (?) Na (≤0.6%).

Phys. Short columns, perfect (110) cleavage.

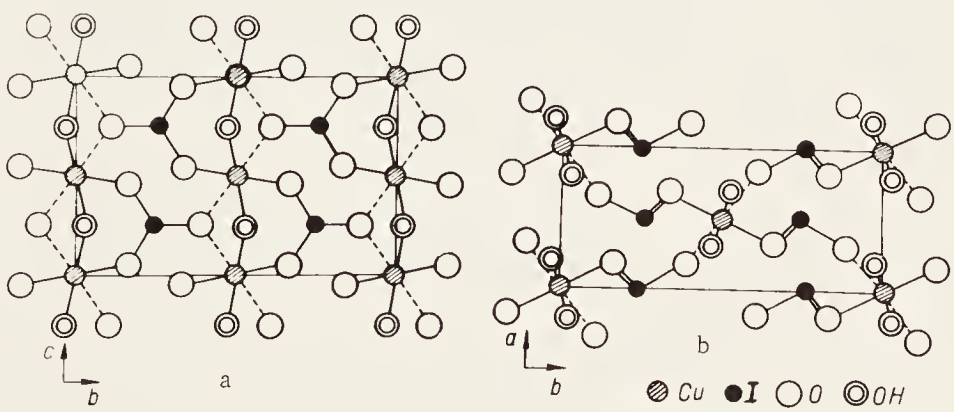


Fig. 274. Structure of salesite in projection on: a) (100), b) (001).

2. DIETZEITE GROUP. Mon., $C_{2h}^5 - P2_1/c$ (?), Z = 4

		a	b	c	β	ρ	H
Dietzeite (calcchromatiadite)	$Ca_2[CrO_4][IO_3]_2$	10.18	7.31	14.06	106° 32′	3.6	3.75

Str. Not known.

Chem. Composition constant.

Phys. Platy, usually fibrous aggregates; (100) cleavage imperfect.

DIVISION C. HYDRATED

1. BELLINGERITE GROUP. Tricl., $C_i^1 - P\bar{1}$, Z = 1

		a	b	c	ρ	H
Bellingerite (cuprihydraiodite)	$Cu_3(H_2O)_2[IO_3]_6$	7.23	7.84	7.94	4.9	4 (?)
		α = 105° 06′	β = 96° 57.5′	γ = 92° 55		

Str. Not known.

Chem. Composition constant.

Phys. Short columns or tabular, no cleavage observed.

Subclass 2. Layer

1. SCHWARZEMBERGITE GROUP. Tetr., Z = 1

		a	c	ρ	H
Schwarzembergite (plumachlariodite)	$Pb_3[IO_3]O(OH)Cl_2$?	3.97	12.54	7.4	2.5—3

Str. Not known; assigned from morphology, properties, crystallotallochemical considerations, and on the pyramidal conformation of the PbO_4 and IO_3 polyhedra. The powder pattern of schwarzembergite is very similar to that of perite and nadorite (Davis et al., 1970 [1248]).

Chem. Pb replaced by Ca (≤0.7%), and Cl by SO_4 (≤0.5%).

Phys. Tabular, perfect (001) cleavage.

CLASS 14. NITRATES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1																	H 5	
2															N 9	O 9		
3	Na 2	Mg 1													P 1	S 1		
4	K 1	Ca 1									Cu 2							
5																		
6		Ba 1																
7																		

Type III. Oxygen compounds
Class 14. Nitrates

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
						9					

Subclass 1. Insular

Division A. Without Water and Additional Anions

1. Nitrobarite $Ba[NO_3]_2$ group
2. Nitronatrite $Na[NO_3]$ group
3. Nitrokalite $K[NO_3]$ group
4. Nitrammite $NH_4[NO_3]$ group

Division B. With Additional Anions or Radicals

1. Gerhardite $Cu_2[NO_3](OH)_3$ group

Division C. Hydrated

1. Nitromagnesite $Mg(H_2O)_6[NO_3]_2$ group
2. Darapskite $Na_3(H_2O)[SO_4][NO_3]$ group

Subclass 1. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. NITROBARITE GROUP. Cubic. $T^4 - P2_13$, $Z = 4$

		a	ρ	H
Nitrobarite (barynitrite)	$Ba[NO_3]_2$	8.13	3.2	3

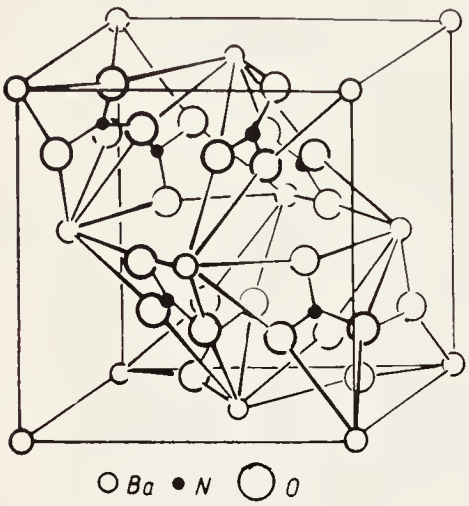


Fig. 275. Structure of nitrobarite.

Str. $Pb[NO_3]_2$ type (p. 73 [176]). Ba surrounded by twelve O atoms from six different NO_3 radicals, whose planes of pyramidal bases are parallel to four faces of an octahedron (Fig. 275). The NO_3 radicals are pyramids with height h = 0.1 Å and with angle O–N–O = 119°. Interatomic distances are: $Ba-O_{12}$ = 2.86 (3), 2.94 (3), 2.90 (3), 2.97 (3) (Birnstock, 1967 [1249]); $N-O_3$ = 1.22 (Vegard and Bilberg, 1931 [1055]).

Chem. No complete analyses.

Phys. Isometric, no cleavage.

2. NITRONATRITE GROUP. Trig., $D_{3d}^6 - R\bar{3}c$, $Z = 4; 2$

		a_{rh}	α	a_{rh}	α'	ρ	H
Nitronatrite (natranitrite)	$Na[NO_3]$	6.49	102° 49′	6.33	47° 15′	2.27	2

Str. Isostructural with calcite; Na has CN = 6 (Fig. 58). Interatomic distances $Na-O_6$ = 2.40; $N-O_3$ = 1.12, 1.22 (2) (p. 360 [553]). It is considered that the $[NO_3]$ radicals rotate around threefold axes.

Phys. Rhombohedral crystals, perfect $(10\bar{1}1)$ cleavage.

3. NITROKALITE GROUP. Orth., $D_{2h}^{16} - Pcmn$, $Z = 4$

		a	b	c	ρ	H
Nitrokalite (kalinitrite)	$K[NO_3]$	5.43	9.19	6.46	2.11	2

Str. Isostructural with aragonite; K has CN = 9 (Figs. 60 and 264). Interatomic distances: $K-O_9 \approx 2.90$; $N-O_3$ = 1.25 (p. 339 [175]).

Chem. Data inadequate; no modern analyses, but isomorphous components are restricted.

Phys. Short columns; perfect (011) and (010) cleavages, (110) imperfect.

4. NITRAMMITE GROUP. Orth., $D_{2h}^{13} - Pmmn$, $Z = 2$

		a	b	c	ρ	H
Nitrammite (amnitrite)	$NH_4[NO_3]$	5.76	5.46	4.97	1.72	(1.5)

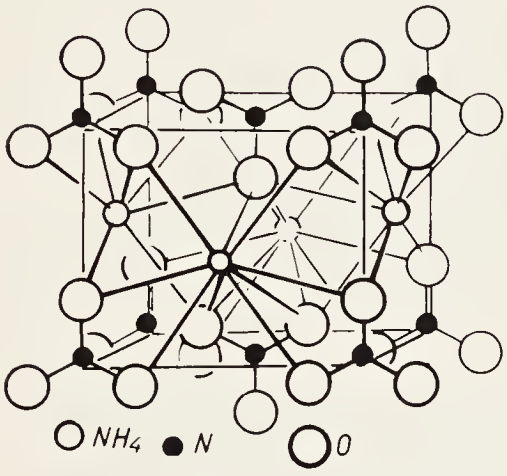


Fig. 276. Structure of nitrammite.

Str. NH_4 (Fig. 276) surrounded by twelve O atoms, with eight nearer than the other four. Mean interatomic distances: $NH_4-O_{12} = 3.14$; $N-O_3 = 1.24$ and 1.26 (2) (Hendricks et al., 1932 [1057]).

Chem. Data inadequate. Very rare, because hygroscopic and very soluble in water.

Phys. Not studied.

DIVISION B. WITH ADDITIONAL ANIONS OR RADICALS

1. GERHARDITE GROUP. Orth.

		S.g.	a	b	c	Z	ρ	H
Gerhardite (cupriohnitrite)	$Cu_2[NO_3](OH)_3$	$D_2^4 - P2_12_12_1$	5.56	6.07	13.71	4	3.4	2
Likasite (cuphosohnitrite)	$Cu_6[PO_4[[NO_3]_2(OH)_7$	$D_{2h}^9 - Pcma$	5.79	6.72	21 65	2	3.0	(3)

Str. Not known. A synthetic crystal of $Cu_2[NO_3](OH)_3$ revealed distorted sixfold coordination of Cu as $CuO_2(OH)_4$ and $CuO(OH)_5$ (Nowacki and Scheidegger, 1951 [1058]). Interatomic distances: $Cu-O_2(OH)_4 = 2.35$ (2), 2.08 (2), and 2.00 (2); $Cu-O(OH)_5 = 2.18$, 2.27, and 2.05 (4); $N-O_3 = 1.21$ (p. 322 [1059]).

Chem. Only minor isomorphous components.

Phys. Thick tablets, highly perfect (001) cleavage.

DIVISION C. HYDRATED

1. NITROMAGNESITE GROUP. Mon., $C_{2h}^5 - P2_1/c$, $Z = 2$

		a	b	c	β	ρ	H
Nitramagnesite (maghexahynitrite)	$Mg(H_2O)_6[NO_3]_2$	6.19	12.71	6.60	92° 59′	1.64	(1.5 — 2)
Nitracalcite (calctetrahynitrite)	$Ca(H_2O)_4[NO_3]_2$	—	—	—	—	1.82	(1.5 — 2)

Str. The structure of nitromagnesite consists of $Mg(OH)_6$ octahedra and NO_3 triangles which are bound together by hydroxyl−hydrogen bonds (O−OH = 2.75-2.90). Interatomic distances are: $Mg-(OH)_6 = 2.06$; $N-O_3 = 1.20$, 1.25, and 1.26 (Braibanti et al., 1967 [1060]).

Chem. No modern analyses.

Phys. Solid masses and incrustations; artificial crystals columnar on (001), perfect (110) cleavage.

2. DARAPSKITE GROUP. Mon., C_{2h}^2—$P2_1/m$, $Z = 2$

		a	b	c	β	ρ	H
Darapskite (nahysulnitrite)	$Na_3(H_2O)[SO_4][NO_3]$	10.56	6.91	5.19	102°47′	2.20	3

Str. In the darapskite structure there are two types of atom: six- and sevenfold coordinated. The mean interatomic distances: $Na-O_6 = 2.43$; $Na-O_7 = 2.47$. The SO_4 and NO_3 polyhedra are regular in form and have the normal distances (Sabelli, 1967 [1150]).

Chem. Isomorphous components almost absent.

Phys. Tabular on (100), pseudotetragonal, perfect (100) and (010) cleavages.

Type IV. HALIDES

CLASS 1. CHLORIDES, BROMIDES, AND IODIDES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type IV. Halides																H 12	
2	Class 1. Chlorides, bromides and iodides														N 1	O 11	F 1	
3	Na 3	Mg 4											Al 1				Cl 28	
4	K 9	Ca 4					Mn 2	Fe 6			Cu 4						Br 1	
5											Ag 3						I 3	
6												Hg 1		Pb 3				
7																		

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
15	3					5	1	2		4	1

Subclass 1. Coordination

Division A. Without Water and Additional Anions

1. Cotunnite $PbCl_2$ group
2. Nantokite CuCl group
3. Cerargyrite Ag(Br, Cl) group
4. Iodargyrite AgI group
5. Halite NaCl group
6. Sal-ammoniac NH_4Cl group

Division B. Hydrated

Subdivision I. Simple

1. Chloraluminite $Al(H_2O)_6Cl_3$ group
2. Eriochalcite $Cu(H_2O)_2Cl_2$ group
3. Bischofite $Mg(H_2O)_6Cl_2$ group
4. Hydrohalite $Na(H_2O)_2Cl$ group

Subdivision II. Complex

1. Tachyhydrite $CaMg_2(H_2O)_{12}Cl_6$ group
2. Carnallite $KMg(H_2O)_6Cl_3$ group

Subclass 2. Insular

Division A. Without Water and Additional Anions

1. Rinncite $K_3Na[FeCl_6]$ group
2. Pseudocotunnite $K_2[PbCl_4]$ group

Division B. Hydrated

1. Erythrosiderite $K_2[Fe(H_2O)Cl_5]$ group
2. Mitscherlichite $K_2[Cu(H_2O)_2Cl_4]$ group

Subclass 3. Chain

1. Calomel $(Hg_2^+)Cl^1_{2\infty}$ group
2. Hydrophilite $CaCl^1_{2\infty}$ group

Subclass 4. Layer

1. Molysite $FeCl^2_{3\infty}$ group
2. Lawrencite $FeCl^2_{\infty}$ group
3. Matlockite $PbClF^2_{\infty}$ group

Inadequately Characterized and Doubtful

Subclass 1. Coordination

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. COTUNNITE GROUP. Orth. D^{16}_{2h} — $Pcmn$, $Z = 4$

		a	b	c	d	ρ	H
Cotunnite (plumchlite)	$PbCl_2$	9.05	4.53	7.63	2.99	5.8	3

Str. Each Pb is surrounded by seven Cl at distances from 2.86 to 3.08, the next two Cl being at 3.64 (Sahl and Zemann, 1961 [1061]). The two types of Cl atom have environments of four Pb and five Pb. There is some sign of layering parallel to (001) and (100). The Cl_I may be replaced by OH, which gives the hydroxychlorides of the laurionite group.

Chem. Composition constant. Traces of F and Sb.

Phys. Varied habit, perfect cleavage on (100).

2. NANTOKITE GROUP. Cubic, $T_d^2 - F\bar{4}3m$, $Z = 4$

		a	d	ρ	H	Cl.
Nontokite (cuchlite)	CuCl	5.42	2.34	4.2	2—2.5	(110)
Morshite (cuite)	CuI	6.06	2.62	5.6	2—2.5	(110)
Miersite (orgiite)	AgI	6.50	2.80	5.8	2	(110)

Str. Isostructural with sphalerite, CN = 4/4 (Fig. 11).

Chem. Composition of nantokite constant. The Cu in marshite is replaced isomorphously by Ag (up to 1.2% and probably more), while the Ag in miersite is replaced by Cu (≤5.6%); in both a little I is replaced by Cl.

Var. Ag-marshite, Cu-miersite.

3. CERARGYRITE GROUP. Cubic, $O_h^5 - Fm3m$, $Z = 4$

		a	d	ρ	H
Cerorgyrite	Ag(Br, Cl)	5.79—5.55	2.88—2.77	6.4—5.5	2.5

Str. Halite type, CN = 6/6 (Fig. 8).

Chem. Composition varies widely, perfect Cl—Br isomorphism, so we have the subspecies bromcerargyrite and chlorcerargyrite. There are also isomorphous I (≤10.4%) and Hg (≤1.8%).

Var. I-cerargyrite, Hg-cerargyrite.

4. IODARGYRITE GROUP. Hex., $C_{6v}^4 - P6_3mc$, $Z = 2$

		a	c	d	ρ	H	Cl.
Iodorgyrite (hexoorgiite)	AgI	4.59	7.50	2.78	5.5	1.5	(0001) perf.

Str. Wurtzite type, CN = 4/4 (Fig. 12).

Chem. Composition varies to a restricted extent; isomorphous Br (≤0.8%) and Cl (≤0.5%).

Var. Br-iodargyrite, Cl-iodargyrite.

5. HALITE GROUP. Cubic, $O_h^5 - Fm3m$, $Z = 4$

		a	d	ρ	H	Cl.
Holite	NaCl	5.64	2.82	2.17	2	(100) perf
Sylvine	KCl	6.29	3.14	1.99	1.75	(100) perf
Chlorocolcite (kocolcochlite)	$KCaCl_3$	Orth. (?)	—	—	3	perf. (3 dir.)

Str. NaCl type, CN = 6/6 (Fig. 8). Structure of chlorocalcite not known.

Chem. Halite is of constant composition; up to 0.01% isomorphous Br, and very rarely Ag (≤11%). Sylvine contains isomorphous Na (≤5.3%) and NH_4 (≤3%).

Var. Ag-halite, Na-sylvine, NH_4-sylvine.

6. SAL-AMMONIAC GROUP. Cubic, $O_h^1 - Pm3m$, $Z = 1$

		a	d	ρ	H	Cl.
Sal-ammoniac (amchlite)	NH_4Cl	3.87	3.35	1.53	1.5	(111) imperf.

Str. CsCl type, CN = 8/8 (Fig. 7).

Chem. Slight variations due to Br (0.12%) and I.

DIVISION B. HYDRATED

Subdivision I. Simple

1. CHLORALUMINITE GROUP. Trig., $D_{3d}^6 - R\bar{3}c$, $Z = 2; 6$

		a_{rh}	α	a_h	c_h	ρ	H
Chloraluminite (alhexahychlite)	$Al(H_2O)_6Cl_3$	7.87	97°	11.82	11.82	1.68	(1.5–2)
Hydramalysite (ferrihexahychlite)	$Fe(H_2O)_6Cl_3$	—	—	—	—	(1.98)	(4.5)

Str. $Al(H_2O)_6$ octahedra and triangular groups of Cl atoms alternate along the c axis, the Cl_3 groups being turned through 180° one relative to the next, so the surroundings of an Al octahedron above and below form a trigonal antiprism of Cl atoms (total surroundings of Al octahedron 12 Cl). The mean Al–H_2O distance is 1.87 (Andress and Carpenter, 1934 [1062]). Hydromolysite is probably isostructural with chloraluminite.

Chem. Data inadequate.

2. ERIOCHALCITE GROUP. Orth., $D_{2h}^7 - Pbmn$, $Z = 2$

		a	b	c	ρ	H
Eriochalcite (cuhychlite)	$Cu(H_2O)_2Cl_2$	7.39	8.06	3.73	2.55	3

Str. Molecular, may be assigned to insular type. The molecule consists of Cu surrounded by a square of two Cl and two H_2O (Fig. 277). The molecules are held together by weak hydroxyl bonds. Interatomic distances Cu–Cl_2 = 2.31; Cu–$(H_2O)_2$ = 2.01; H_2O–H_2O = 3.72 (Harker, 1936 [1063]).

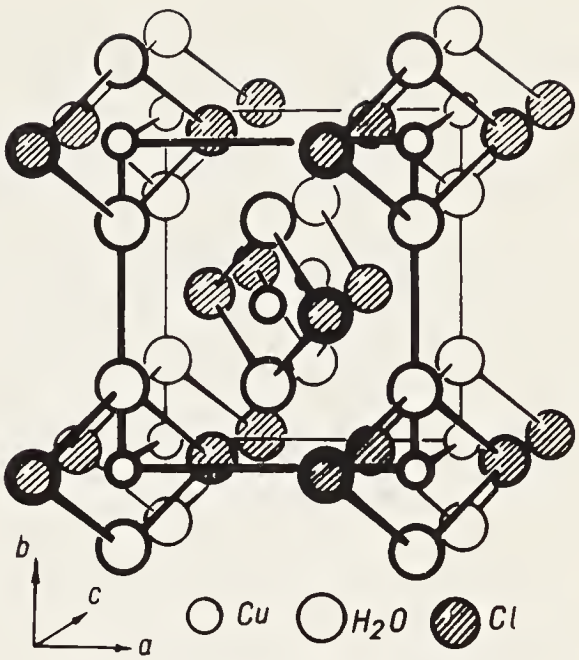


Fig. 277. Structure of eriochalcite.

Chem. Composition constant.

Phys. Short columns, cleavage on (110) perfect, on (001) moderate.

3. BISCHOFITE GROUP. Mon→hex.

		S.g.	a	b	c	β	Z	ρ	H
Bischofite (mahexahychlite)	$Mg(H_2O)_6Cl_2$	$C_{2h}^3 - C2/m$	9.92	7.17	6.11	93° 42′	2	1.59	1.5—2
Antarcticite (calchexahychlite)	$Ca(H_2O)_6Cl_2$	$D_3^2 - P321$	7.88	—	3.88	—	1	1.75	1.5

Str. Submolecular, with distinct $Mg(H_2O)_6Cl_2$ groups (Fig. 278). The H_2O molecules form a regular octahedron around the Mg, while the Cl adjoin faces of the octahedron above and below. Six Cl atoms not in this group form a ring in a plane perpendicular to the axis of the mole-

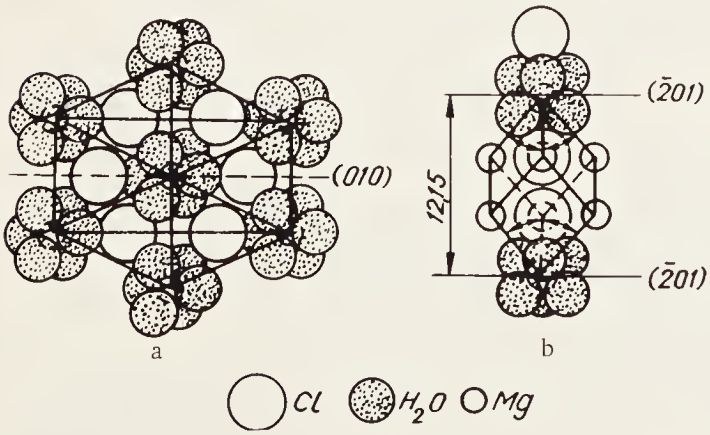


Fig. 278. Structure of bischofite in projection on: a) (201), b) a plane perpendicular to the previous.

cule. Interatomic distances: $Mg-(H_2O)_6 = 2.01$ (4) and 2.07 (2); $Mg-Cl_8 = 3.99$ (2), 4.61 (4), and 4.81 (2); $Cl-(H_2O)_8 = 3.22$ (2), 3.28 (2), 3.53 (2), 3.25, and 3.27 (Andress and Gundermann, 1934 [1064]). Antarcticite is sublayered on (0001); perpendicular to the c axis lie alternate layers of $Ca(H_2O)_6$ octahedra and Cl atoms [543].

Chem. Composition largely constant. Bischofite sometimes contains up to 1% isomorphous bromine, while antarcticite contains Mg, Na, and K (Torii and Ossaka, 1965 [1065]).

Phys. Habit of bischofite very variable, no cleavage. Antarcticite has not been studied; it has been observed at low temperatures in the Antarctic.

4. HYDROHALITE GROUP. Mon. (?)

		a	*b*	*c*	β	ρ	H
Hydrohalite	$Na(H_2O)_2Cl$	—	—	—	—	1.6	1.5—2

Str. Not known. Formed and stable in brine between +0.15 and −21.9°C.

Subdivision II. Complex

1. TACHYHYDRITE GROUP. Trig.

		c/a	α	ρ	H	Cl.
Tachyhydrite (calcmahychlite)	$CaMg_2(H_2O)_{12}Cl_6$	1.76	~78°	1.66	2—2.5	$(10\bar{1}1)$ perf.

Str. Not known.

Chem. Slight variations due to Cl−Br replacement (≤0.2%) and to replacement of Mg by Fe^{2+} (≤ 0.1%) and Sr (≤0.2%).

2. CARNALLITE GROUP. Orth., $D^6_{2h} - Pbnn$, $Z = 12$

		a	*b*	*c*	ρ	H	Cl.
Carnallite (kamahexahychlite)	$KMg(H_2O)_6Cl_3$	9.60	16.14	22.52	1.60	2.5—3	None

Str. Sublayered perpendicular to c axis. Mg surrounded by six H_2O, and K by six Cl. Interatomic distances: $Mg-(H_2O)_6 = 2.14$ (2), 2.16 (2), and 2.25 (2); $K-Cl_6 = 3.39$. Space group and cell parameters refined from data of Fischer (1965) [1066].

Chem. Slight variations, traces of isomorphous Br (≤0.6%), Rb (≤0.01%), NH_4, Cs, and Tl.

Subclass 2. Insular

1. RINNEITE GROUP. Trig., $D_{3d}^6 - R\bar{3}c$, $Z = 2; 6$

		a_{rh}	α	a_h	c_h	ρ	H
Rinneite (kanafechlite)	$K_3Na[FeCl_6]$	8.42	92° 25′	11.89	13.84	2.35	3.5
Chlarmanganakalite (kamanchlite)	$K_4[MnCl_6]$	8.48	89° 32′	11.98	14.84	2.31	3

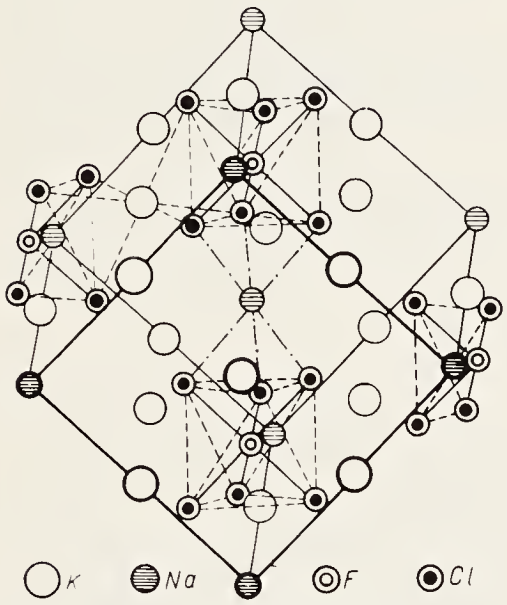


Fig. 279. Structure of rinneite; the Na is replaced by K in chlormanganokalite.

Str. The minerals are analogous in structure (the Na of rinneite is replaced by K in chlormanganokalite). The Na in rinneite is placed between the faces of two adjacent Fe octahedra, while the K atoms lie along the sides, also in sixfold coordination (Fig. 279). The bonds in the Fe(Mn) octahedra are 3.5-4 times stronger than those in the K(Na) octahedra. Interatomic distances in rinneite: $Fe-Cl_6 = 2.30$; $Na-Cl_6 = 3.00$; $K-Cl_6 = 3.00$; in chlormanganokalite $Mn-Cl_6 = 2.51$; $K-Cl_6 = 3.14$ (Bellanca, 1948 [1067]).

Chem. Up to 0.38% isomorphous Na in chlormanganokalite; rinneite contains Mn (0.18%) and Br (0.04%).

Phys. Isometric crystals (rhombohedra). Moderate cleavage on $(11\bar{2}0)$ in rinneite only.

2. PSEUDOCOTUNNITE GROUP. Orth., D_{2h}^{16} (?)

		a	b	c	ρ	H
Pseudocotunnite (kaplumchlite)	$K_2[PbCl_4]$	11.80	5.77	9.82	(4.0)	(3–3.5)

Str. Not known; parameters given for the artificial compound (Bellanca and Sgarlata, 1952 [1068]).

Phys. Columnar to tabular (on c axis). Properties not studied.

DIVISION B. HYDRATED

1. ERYTHROSIDERITE GROUP. Orth., $D_{2h}^{16} - Pnma$, $Z = 4$

		a	b	c	ρ	H
Erythrosiderite (kaferrihychlite)	$K_2[Fe^{3+}(H_2O)Cl_5]$	13.78	9.94	6.94	2.32	(3—3.5)
Douglasite (kafehychlite)	$K_2[Fe^{2+}(H_2O)_2Cl_4]$	—	—	—	2.16	(3)

Str. Fe^{3+} in erythrosiderite surrounded by an octahedron consisting of five Cl and one H_2O; these octahedra form a somewhat distorted CaF_2 structure with the K atoms. Interatomic distances in octahedron: $Fe-Cl_5(H_2O)$ = 2.40 (3), 2.45 (2), and 2.04 (p. 419 [553]). Douglasite (monoclinic) has not been studied.

Chem. K in erythrosiderite replaced by NH_4 ($\leq$6.17%). The formula of douglasite is doubtful.

Var. NH_4-erythrosiderite.

Phys. Erythrosiderite isometric to tabular, perfect cleavage on (210) and (011).

2. MITSCHERLICHITE GROUP. Tetr., $D_{4h}^{14} - P4_2/mnm$, $Z = 2$

		a	c	ρ	H
Mitscherlichite (kacuhychlite)	$K_2[Cu(H_2O)_2Cl_4]$	7.46	7.90	2.42	3

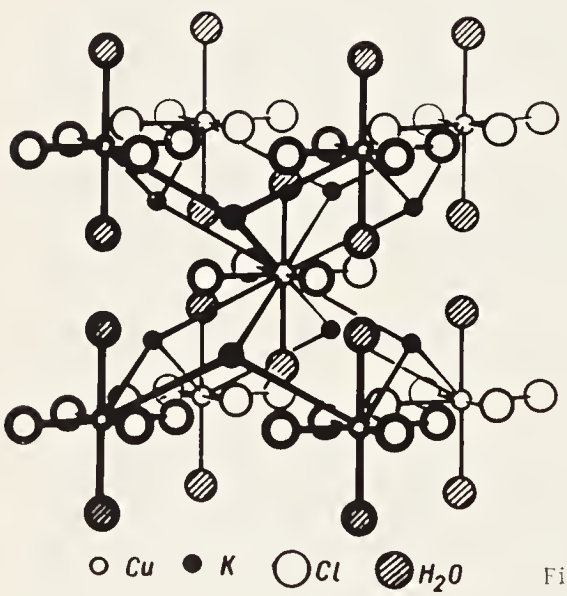


Fig. 280. Structure of mitscherlichite.

Str. Octahedron of Cu atom consists of four Cl atoms (forming a distorted square) and two H_2O placed perpendicular to the square (Fig. 280). The K atoms link these octahedra together and have cubic coordination. Interatomic distances in the octahedron: $Cu-(H_2O)_2$ = 1.97; $Cu-Cl_4$ = 2.32 (2), and 2.95 (2) ([175]).

Chem. Composition constant.

Subclass 3. Chain

1. CALOMEL GROUP. Tetr., $D_{4h}^{17} - I4/mmm$, $Z = 4$

		a	c	ρ	H
Calomel (merchlite)	$(Hg_2^+)Cl_{2\infty}^{1}$	4.46	10.91	7.2	2—2.5

Str. Consists of double uneven layers (Fig. 281) parallel to (001), but

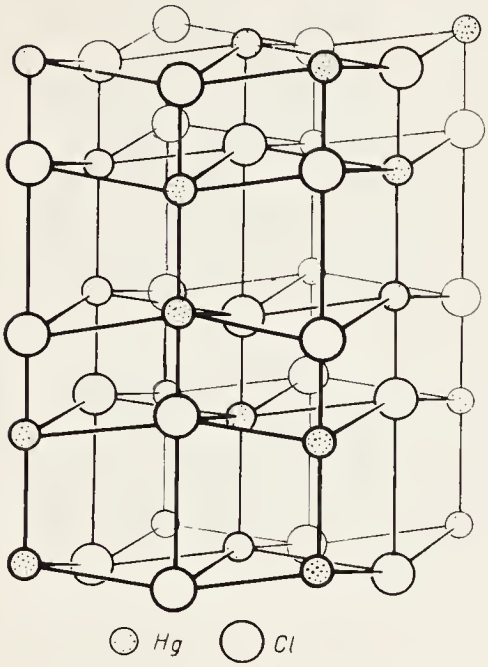


Fig. 281. Structure of calomel.

the strength of the Hg–Hg bonds between these is almost equal to the strength of the bonds in the perpendicular (100) direction. There are distinct chains along the c axis composed of Cl–Hg–Hg–Cl links coupled by their Hg–Cl ends to form a zigzag avoiding the Cl–Cl sections. Hg^{+} is surrounded by five Cl + one Hg. Distances: Hg–Hg = 2.55; Hg–Cl = 2.57; Cl–Cl = 3.30 (p. 237 [175]).

Chem. Composition variations not known.

Phys. Columnar to tabular, moderate cleavage on (100).

2. HYDROPHILITE GROUP. Orth., $D_{2h}^{12} - Pnnm$ (?), $Z = 2$.

		a	b	c	ρ	H
Hydrophilite (colechlite)	$CaCl_2 {}^{1}_{\infty}$	6.25	6.44	4.21	2.22	(1—2)

Str. Rutile type, slightly deformed. Interatomic distances: $Ca–Cl_6$ = 2.67 (2) and 2.76 (4) (p. 146 [525]). All data are for the artificial compound.

Phys. Perfect cleavage on (110).

Subclass 4. Layer

1. MOLYSITE GROUP. Trig., $C_{3i}^{2} - R\bar{3}$, $Z = 2; 6$

		a_{rh}	α	a_h	c_h	ρ	H
Molysite (ferrichlite)	$FeCl_3 {}^{2}_{\infty}$	6.70	52°30′	5.93	17.29	3.1	~1

Str. Fe^{3+} surrounded by Cl octahedron (Fig. 282); octahedra linked by their edges into layers parallel to (0001), the structure of a layer following the corundum law (with empty octahedra in a hexagonal pattern). Mean $Fe–Cl_6$ = 2.17 (Wooster, 1932 [1069]).

Chem. Not analyzed.

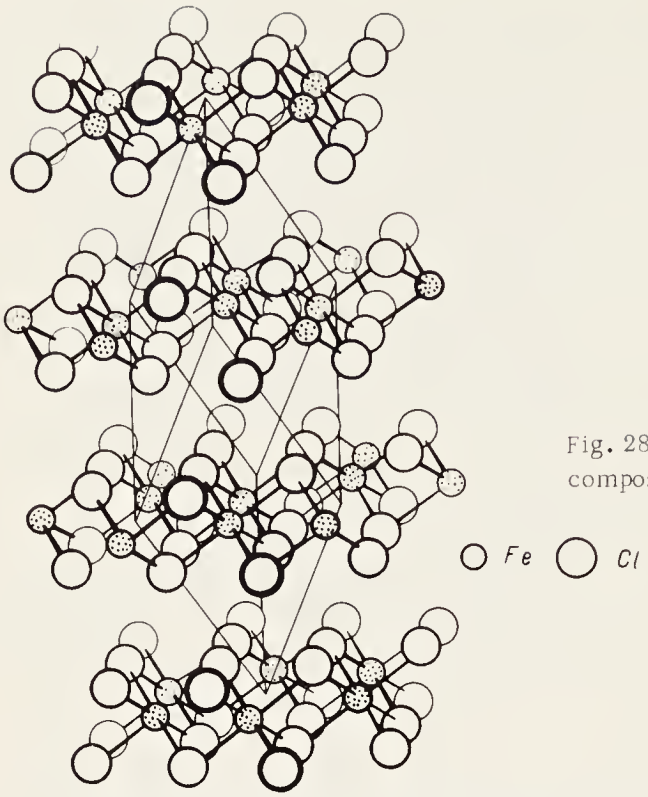


Fig. 282. Structure of molysite; layers of $FeCl_3$ composition held together by residual bonds.

Phys. Tabular, perfect cleavage on (0001).

2. LAWRENCITE GROUP. Trig., $D_{3d}^5 - R\bar{3}m$, $Z = 1;\ 3$

		a_{rh}	α	a_h	c_h	ρ	H
Chloromagnesite (machlite)	$MgCl_2$	6.23	33°30′	3.59	17.56	2.33	(1–1.5)
Scacchite (manchlite)	$MnCl_2$	6.21	34°32′	3.68	17.49	3.1	(1–1.5)
Lawrencite (ferrochlite)	$FeCl_2$	6.20	33°33.5′	3.60	17.64	3.2	(1–1.5)

Str. $CdCl_2$ type, CN = 6/3; may be interpreted as cubic close packing of Cl, with Fe(Mn, Mg) filling half of the octahedral holes, layers of populated octahedra alternating with layers of empty ones (Fig. 18). This sequence of firmly bound triple layers (2Cl + 1Fe) has a repeat distance of four layers.

Chem. Data inadequate; analyses of lawrencite indicate a little Ni.

Phys. Compact, earthy; artificial compounds are in hexagonal plates with perfect cleavage on (0001).

3. MATLOCKITE GROUP. Tetr., $D_{4h}^7 - P4/nmm$, $Z = 2$

		a	c	ρ	H
Matlockite (plumchlorflite)	PbClF	4.10	7.22	7.1	3–3.5

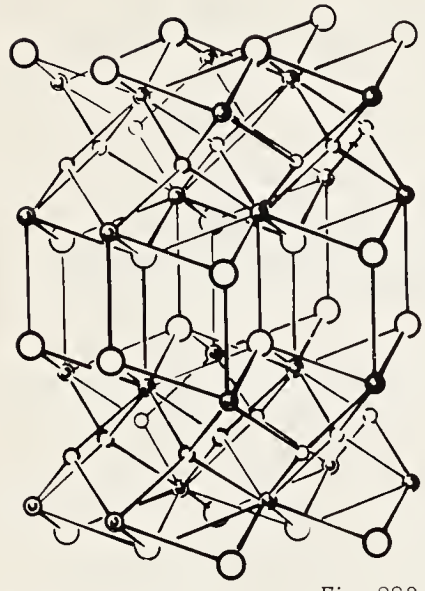


Fig. 283. Structure of matlockite; layers of five-atom composition linked together by weak Pb–Cl bonds.

Str. Layered structure of complex layers, in which homoatomic Cl–Pb–F–Pb–Cl layers alternate along the c axis (Fig. 283); Pb has CN = 9, with four F on one side and five Cl on the other, the fifth Cl atom being further away (along the c axis) than the other four and being responsible for the weakest bonds between layers. Interatomic distances: $Pb-F_4 = 2.52$; $Pb-Cl_5 = 3.07$ (4) and 3.21 (1) (Nieuwenkamp and Bijvoet, 1931 [1070]).

Chem. Composition constant.

Phys. Tabular, perfect (001) cleavage.

Inadequately Characterized and Doubtful

Almeraite $KNaMgCl_4 \cdot H_2O$
Coccinite HgI (?)
Nickhydrochlite $Ni(H_2O)_6Cl_2$ (?)
Tocornalite (Ag, Hg)I (?)

CLASS 2. OXYHALIDES AND HYDROXYHALIDES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1																	H 28	
2															N 1	O 43	F 10	
3	Na 2	Mg 1											Al 9			S 4	Cl 34	
4		Ca 5					Mn 1	Fe 2			Cu 12				As 2			
5		Sr 2									Ag 3				Sb 3			
6												Hg 3		Pb 22	Bi 3			
7																		

Type IV. Halides
Class 2. Oxyhalides and hydroxyhalides

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	complex	simple	complex	simple	complex	simple	complex	simple	complex	simple	complex
5	11	1						2	2	10	12

Subclass 1. Coordination

Division A. Without Water and Additional Anions

Subdivision I. Simple

1. Atacamite $Cu_2(OH)_3Cl$ group
2. Eglestonite $(Hg_2^+)_3OCl_4$ group

Subdivision II. Complex

1. Zirklerite $Fe_2AlO(OH)Cl_4$ group
2. Jahrlite $NaSr_2Al_2(OH)F_{10}$ group
3. Boleite $AgPb_3Cu_3(OH)_6Cl_7$ group

Division B. With Water and Additional Radicals

1. Trudellite $Al_{10}[SO_4]_3(OH)_{12}Cl_{12} \cdot 30H_2O$ group
2. Connelite $Cu_{19}[SO_4](OH)_{32}Cl_4 \cdot 4H_2O$ group

Subclass 2. Framework

1. Ralstonite $Al_2(OH)_2F_4 \cdot H_2O^3_\infty$ group

Subclass 3. Chain

Division A. Without Water and Additional Anions

Subdivision I. Simple

1. Mendipite $Pb_3O_2Cl_{2\infty}^{1}$ group
2. Terlinguaite $Hg^{+}Hg^{2+}OCl_{\infty}^{1}$ group

Subdivision II. Complex

1. Prosopite $CaAl_2(OH)_4F_4{}_{\infty}^{1}$ group

Division B. Hydrated

1. Gearksutite $CaAl(H_2O)(OH)F_4{}_{\infty}^{1}$ group

Subclass 4. Layer

Division A. Simple

1. Bismoclite $BiOCl_{\infty}^{2}$ group
2. Blixite $Pb_4O_3Cl_{2\infty}^{2}$ group
3. Penfieldite $Pb_2OHCl_{3\infty}^{2}$ group
4. Laurionite $Pb(OH)Cl_{\infty}^{2}$ group

Division B. Complex

1. Hematophanite $Pb_5Fe_4O_{10}(OH)Cl_{\infty}^{2}$ group
2. Nadorite $PbSbO_2Cl_{\infty}^{2}$ group
3. Ekdemite $Pb_6As_2O_7Cl_4{}_{\infty}^{2}$ group
4. Diaboleite $Pb_2Cu(OH)_4Cl_{2\infty}^{2}$ group
5. Koenenite $Na_4Ca_2Mg_7Al_4(OH)_{22}Cl_{12\infty}^{2}$ group

Division C. With Water and Additional Radicals

1. Creedite $Ca_3Al_2(H_2O)_2[SO_4](OH)_2F_{8\infty}^{2}$ group
2. Tikhonenkovite $SrAl(H_2O)(OH)F_{4\infty}^{2}$ group

Inadequately Characterized and Doubtful

Subclass 1. Coordination

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

Subdivision I. Simple

1. ATACAMITE GROUP. Orth.→trig.→mon.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Atacamite	$Cu_2(OH)_3Cl$	D_{2h}^{16} — *Pnam*	6.02	9.15	6.85	—	4	3.8	3.5—3.75
Paratacamite (trigoatacamite)	$Cu_2(OH)_3Cl$	D_{3d}^{5} — $R\bar{3}m$	13.68	—	13.98	—	24	3.7	3.5
Botallackite (clinoatacamite)	$Cu_2(OH)_3Cl$	C_{2h}^{2} — $P2_1/m$	5.63	6.12	5.71	92°45′	2	3.6	(3.25)
Kempite	$Mn_2(OH)_3Cl$	D_{2h}^{1}—*Pmmm* (?)	—	—	—	—	—	2.94	~3.5

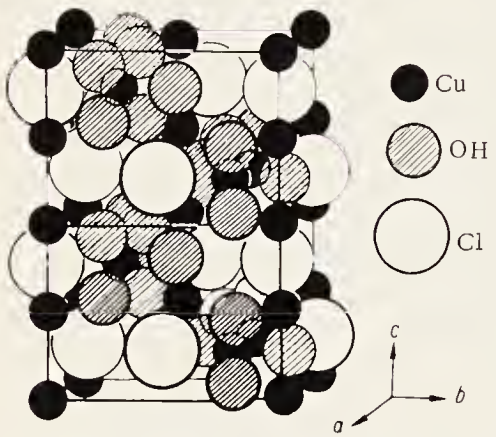


Fig. 284. Structure of atacamite (general view).

Str. Atacamite has been studied in detail. The centers of the OH and of the Cl lie in cubic close packing. The sixfold coordination is of two types: four OH + two Cl and five OH + one Cl (Fig. 284). Interatomic distances: Cu− $(OH)_4Cl_2$ = 2.00 (2), 2.04 (2), and 2.76 (2); Cu− $(OH)_5Cl$ = 1.94 (2), 207 (2), 2.36, and 2.75 (Wells, 1949 [1071]). Paratacamite and botallackite have structures similar to that of atacamite but less stable (Embrey, 1957 [1072]).

Chem. Composition constant.

2. EGLESTONITE GROUP. Cubic., O_h^9 — *Im3m*, $Z = 2$

		a	ρ	H	Cl.
Eglestonite (mercurochlite)	$(Hg_2^+)_3OCl_4$	8.04	8.3	3—3.5	None

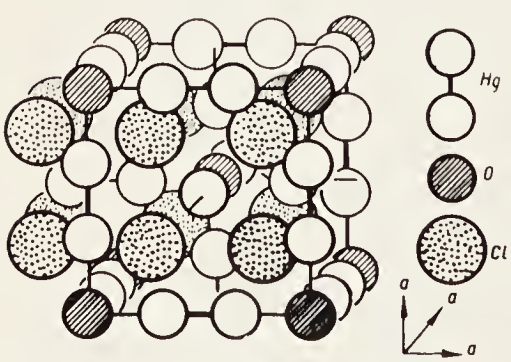


Fig. 285. Structure of eglestonite (general view).

Str. Hg_2 pairs and Cl atoms lie as in Pt_3O_4, while the O atoms lie on two sides of each Hg_2 at sites that are vacant in Pt_3O_4 (Fig. 285). Part (up to 0.5) of the Cl is replaced by O, leaving vacant positions (Hedlik, 1950 [1073]).

Subdivision II. Complex

1. ZIRKLERITE GROUP. Trig. (?)

		a_h	c_h	ρ	H	Cl.
Zirklerite	$Fe_2AlO(OH)Cl_4$ (?)	—	—	~2.6	~3.5—4	$(10\bar{1}1)$

Str. Not known, assigned to isodesmic from properties.

Chem. Composition needs verification; Fe^{2+} replaced by Mg and Ca.

2. JAHRLITE GROUP. Mon.

		S.g.	a	b	c	β	Z	ρ	H
Johrlite (nostrolohflite)	$NaSr_2Al_2(OH)F_{10}$	$C_{2h}^3 - C2/m$ (?)	16.02	10.84	7.25	101°49′	6	3.6	4—5

Str. Not known, but judged isodesmic from the high hardness.

Chem. The Na and Sr are replaced by Ca (3.2%) and Ba (2.25%), and Al is replaced by Mg (1.38%).

Phys. Tabular; cleavage, none observed.

3. BOLEITE GROUP. Cubic→tetr., s.g. not det.

		S.g.	a	c	Z	ρ	H
Percylite	$AgPb_3Cu_3(OH)_6Cl_7$ (?)	$O_h^1 - Pm3m$	15.4	—	9	5.3	3.5—3.75
Boleite	$AgPb_3Cu_3(OH)_6Cl_7$ (?)	$D_{4h}^{17} - I4/mmm$	15.27	60.94	36	5.1	3.5
Pseudoboleite	$Pb_5Cu_4(OH)_8Cl_{10} \cdot 2H_2O$	Not det.	15.4	31.2	12	4.9	3
Cumengéite	$PbCu(OH)_2Cl_2$ (?)	$D_{4h}^{17} - I4/mmm$	15.20	24.76	40	4.7	3
Bideouxite	$AgPb_2(OH)Cl_3F$	$O_h^7 - Fd3m$	14.13	—	16	6.3	3.5

Str. Known only for boleite (Fig. 286), where Pb has CN = 9 (three types of environment), Ag has CN = 8 (distorted), and Cu has CN = 6. The stronger dsp^2 bond of the Cu in a square with two Cl and two OH allows us to distinguish $[Cu(OH)Cl]_{24}$ pseudomolecules and $[Cu(OH)Cl]_\infty$ pseudochains (Ito, 1950 [748]). Interatomic distances: $Pb_I - OHCl_8$ = 3.52 (1), 3.02 (4), 3.20 (4); $Pb_{II} - (OH)_3Cl_6$ = 3.65 (2), 3.14 (1), 3.19 (2), 3.36 (4); $Pb_{III} - (OH)_3Cl_6$ = 3.52 (2), 2.97 (1), 3.02 (2), 3.29 (4); $Ag - (OH)_4Cl_4$ = 1.95 (3), 3.71 (1), 2.94 (3), 3.71 (1); $Cu - (OH)_2Cl_4$ = 1.95 (2), 2.40 (2), 2.61, and 2.64.

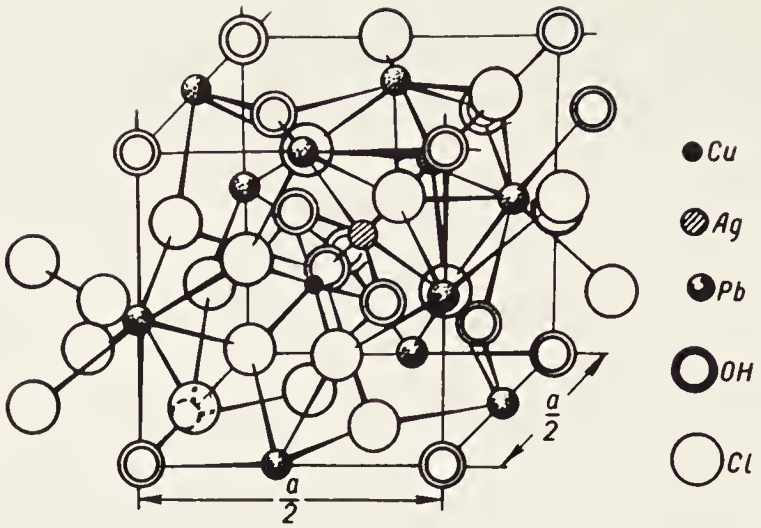


Fig. 286. Structure of boleite showing coordination of Ag, Cu, and Pb.

The similarity of the *a* parameters and the multiplicity of the c parameters show that the other minerals have structures close to that of boleite.

Chem. Compositions need fresh careful study. Replacement of Cu and Pb (?) by Ag has been reported, and of Cl by OH. In bideauxite the ratio F : OH = 1 : 1 (Williams, 1970 [1251]).

Phys. Isometric or short columns (cumengéite), cleavage in two or three directions.

DIVISION B. WITH WATER AND ADDITIONAL RADICALS

1. TRUDELLITE GROUP. Trig. (?)

		a_h	c_h	ρ	H
Trudellite	$Al_{10}[SO_4]_3(OH)_{12}Cl_{12} \cdot 30H_2O$ (?)	—	—	1.93	3

Str. Not known. Symmetry deduced from rhombohedral cleavage.

2. CONNELITE GROUP. Hex., $D^4_{6h} - P6_3/mmc$ (?), $Z = 2$

		a	c	ρ	H
Connelite	$Cu_{19}[SO_4](OH)_{32}Cl_4 \cdot 4H_2O$	15.85	9.16	3.4	2.5—3.5
Buttgenbachite	$Cu_{19}[NO_3]_2(OH)_{32}Cl_4 \cdot 2H_2O$	15.85	9.16	3.4	3.5
Arzrunite	$Pb_2Cu_4[SO_4](OH)_4Cl_6 \cdot 2H_2O$	—	—	—	—

Str. Not known; but it is clear that connelite and buttgenbachite are isostructural. Arzrunite (orth., pseudohex.) has not been examined. The habit indicates that the first two minerals may be of chain type.

Chem. Connelite and buttgenbachite are of constant composition. Arzrunite has Cu replaced by Zn and Pb by Ca.

Phys. Needles to prisms of connelite and buttgenbachite, no cleavage.

Subclass 2. Framework

1. RALSTONITE GROUP. Cubic., $O_h^7 - Fd3m$, $Z = 8$

			a	ρ	H	Cl.
Ralstonite (alohflite)	$Al_2(OH)_2F_4 \cdot H_2O$	$^3_\infty$	9.91	2.52	4–4.5	(111) imperf.

Str. Similar to that of pyrochlore (Pabst, 1939 [1074]), but not identical, as is implied by the chemical composition. The framework consists of Al(OH, F) octahedra. The H_2O lies in large holes and is of zeolite type; Na (CN = 12) also lies in these holes and serves to balance the negative charge when Al is partly replaced by Mg; $Al-(OH, F)_6 \approx 1.85$ (Cowley and Scott, 1948 [1075]).

Chem. Requires further study; varies as a result of replacement of Al by Mg + Na, the Al:Mg ratio varying from 6:1 (Stepanov and Moleva, 1962 [1076]) to 3:2 (Pauly, 1965 [1077]). The full (dynamic) formula is $Na_XMg_XAl_{2-X}(OH, F)_6 \cdot H_2O^3_\infty$.

Subclass 3. Chain

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

Subdivision I. Simple

1. MENDIPITE GROUP. Orth., $D_2^4 - P2_12_12_1$, $Z = 4$

			a	b	c	ρ	H
Mendipite (triplumochlite)	$Pb_3O_2Cl_2$	$^1_\infty$	9.52	11.95	5.87	7.2	3

Str. Pb has three types of coordination: Pb_I, distorted trigonal prism consisting of two O and four Cl; Pb_{II}, four O and three Cl; and Pb_{III}, two O and five Cl. The chain pattern arises from the strong Pb–O bond, the paired OPb_4 tetrahedra being linked by their edges into chains along the c axis (Fig. 287). Interatomic distances: $Pb_I-O_2Cl_4 = 2.33$ (2), 3.12, 3.25 (2), 3.44; $Pb_{II}-O_4Cl_3 = 2.33$ (4), 2.95, 3.44 (2); $Pb_{III}-O_2Cl_5 = 2.33$, 2.93 (2), 3.02, 3.21 (2) (Gabrielson, 1958 [1078]).

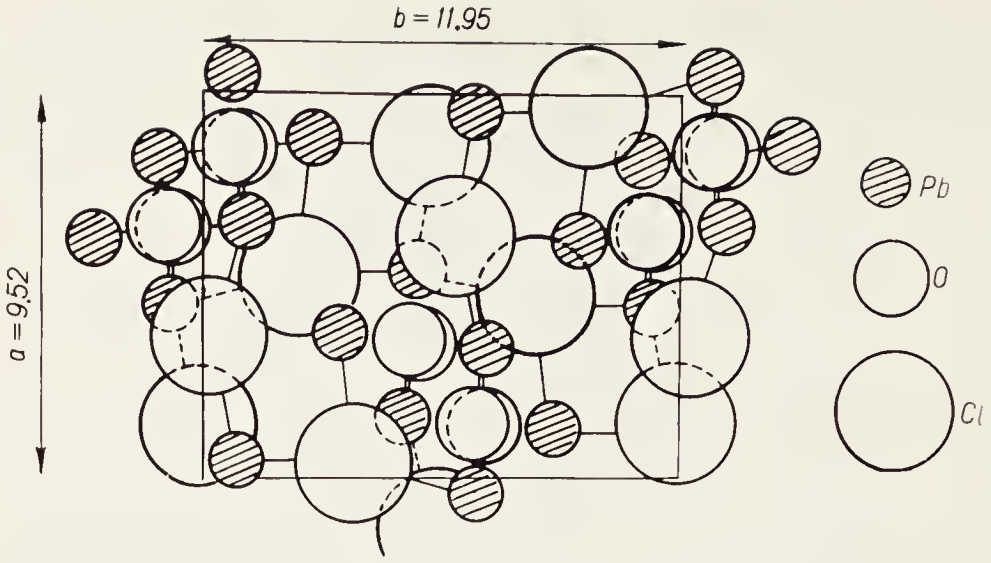


Fig. 287. Structure of mendipite in projection on (001).

Chem. Composition constant.

Phys. Habit not examined; perfect cleavage on (110), moderate on (100) and (010).

2. TERLINGUAITE GROUP. Mon., C_{2h}^6-C2/c, $Z = 8$

		a	b	c	β	ρ	H
Terlinguaite (mermeriochlite)	$Hg+Hg^{2+}OCl\frac{1}{\infty}$	19.53	5.92	9.48	144°	8.7	2.5—3.5

Str. Zigzag ...Hg−O−Hg−O−Hg... chains run along the c axis (Fig. 288). The plane of the chain is $(\bar{1}01)$, parallel to which lies the cleavage, so we may say that we have a sublayered chain structure, as in HgO. Parallel to the ...Hg−O−Hg... chains lie Hg_2Cl_2 chains. Interatomic distances: $Hg-O_2 = 2.03$; $Hg-Cl_2 = 2.57$ (Ščavnicar, 1956 [1079]).

Chem. Composition constant.

Phys. Columnar, elongated on b axis, isometric, perfect cleavage on $(\bar{1}01)$.

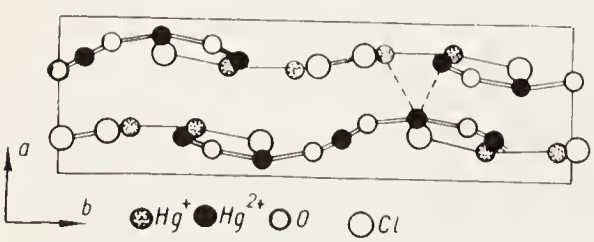


Fig. 288. Structure of terlinguaite in projection on (001) showing $Hg-O-Hg^{2+}-Cl$ chains.

Subdivision II. Complex

1. PROSOPITE GROUP. Mon.

		S.g.	a	b	c	β	Z	ρ	H
Prasapite (calcalahflite)	$CaAl_2(OH)_4F_4\frac{1}{\infty}$	C^6_{2h}—$C2/c$	6.76	11.12	7.32	95°00	4	2.89	5

Str. The $AlF_2(OH)_4$ octahedra are bound to each other by OH-edges and form the chains along [$\bar{1}$01]. The chains are connected by Ca ions in eightfold coordination. The F and OH are distributed in the structure in strict, regular order. The interatomic distances are: $Al_1-F_2(OH)_4$= 1.82(2), 1.89(2), 1.93(2); $Al_2-F_2(OH)_4$=1.83(2), 1.87(2), 1.91(2); $Ca-F_6(OH)_2$= 2.29(2), 2.36(2), 2.39(2), 2.58(2)(Pudovkina and Pyatenko, 1970 [1249] (Giacovazzo and Menchetti, 1969 [1250]).

Chem. The Ca are replaced by Na (0.5%) and Mg (0.2%).

Phys. Tabular; cleavage on (111) perfect.

DIVISION B. HYDRATED

1. GEARKSUTITE GROUP. Mon., s.g. not det.

		a	b	c	β	Z	ρ	H
Gearksutite (calcalhyohflite)	$CaAl(H_2O)(OH)F_4\frac{1}{\infty}$	—	—	—	—	—	2.78	(4)

Str. Not known; assigned only on basis of needle habit, which is inadequate.

Chem. Composition fairly constant.

Phys. Cryptocrystalline aggregates revealed by electron microscopy to consist of laths.

Subclass 4. Layer

DIVISION A. SIMPLE

1. BISMOCHLITE GROUP. Tetr., D^7_{4h} — $P4/nmm$ $Z = 2$

		a	c	ρ	H	Cl.
Bismoclite	$BiOCl\frac{2}{\infty}$	3.90	7.38	7.4	2,5—3	(001) perf.
Zavaritskite (bismaflite)	$BiOF\frac{2}{\infty}$	3.75	6.23	7.9	(3—3.5)	(001) perf.

Str. Isostructural with matlockite (Fig. 283), with the Pb positions taken by Bi and the F or Cl positions by O. Interatomic distances: $Bi-O_4$= 2.31; $Bi-Cl_5$ = 3.49 (Sillen, 1941 [1080]).

Chem. The Cl in bismoclite is replaced by OH up to 1:1.

Var. OH-bismoclite.

Phys. Artificial crystals tabular, perfect cleavage on (001).

2. BLIXITE GROUP. Orth.→tetr.

		S.g.	*a*	*b*	*c*	*Z*	ρ	H
Blixite	$Pb_4O_3Cl_2{}^2_\infty$	Not det.	5.83	5.69	25.47	4	7.4	3,5 (?)
Lorettoite	$Pb_7O_6Cl_2{}^2_\infty$	Tetr.	—	—	—	—	7,7	3
Lead oxyfluoride (plumoflite)	$Pb_2OF_2{}^2_\infty$	$D^5_{2d}-P\bar{4}m2$	8.16	—	5.72	4	8.2	(4)

Str. Known for synthetic Pb_2OF_2, which is close to that of matlockite; the rest assigned from morphology, cleavage, and close crystallochemical resemblance to nadorite and ekdemite. Interatomic distances in lead oxyfluoride: $Pb-F_4$ = 2.33 (2) and 2.68 (2); $Pb-O_4$ = 2.30 (2) and 2.52 (2) (Byström, 1947 [1081]).

Chem. Requires further study.

Phys. Platy habit in lorettoite and lead oxyfluoride; perfect cleavage in one direction.

3. PENFIELDITE GROUP. Hex., C^1_{6h}—$P6/m$ (?)

		a	*c*	*Z*	ρ	H
Penfieldite (diplumohchlite)	$Pb_2OHCl_3{}^2_\infty$	11.28	48.65	40	6.8	(3.5)

Str. Not known; assigned from crystallochemical arguments. New cell parameters (Cesbron and Schubnel, 1968 [1165]).

Chem. Composition variously treated in accordance with differing analyses; further study needed.

Phys. Columnar to tabular, moderate cleavage on (0001).

4. LAURIONITE GROUP. Orth.→mon.→tricl.

		S.g.	*a*	*b*	*c*	β	*Z*	ρ	H
Laurionite (plumohchlite)	$Pb(OH)Cl{}^2_\infty$	$D^{16}_{2h}-Pcmn$	9.62	4.03	7.12	—	4	6.3	3.5—3.75
Porolaurionite (clinoplumohchlite)	$Pb(OH)Cl{}^2_\infty$	$C^3_{2h}-C2/m$	10.79	3.98	7.19	117°13′	4	6.3	~2
Fiedlerite (triplumohchlite)	$Pb_3(OH)_2Cl_4{}^2_\infty$	$C^5_{2h}-P2_1/a$	16.62	8.02	7.20	102°12′	4	5.6	~3.5
Onorotoite (stibochlite)	$Sb_8O_{11}Cl_2{}^2_\infty$	$C^1_i-P\bar{1}$	18.92	4.03	10.31	110°	4	5.5	—
		α = ~90°		γ = ~90°					

Str. The minerals are similar in structure, as is clear from the relationship between the cell parameters; laurionite is similar to matlockite (Fig. 283) and to cotunnite, being derived from the latter by replacing all Cl_1 by OH, which increases the bond anisotropy, especially along the c axis, though the effect is clear only in paralaurionite. The interatomic distances in laurionite are $Pb-(OH)_4 = 2.85$; $Pb-Cl_5 = 3.23$ (Brasseur, 1940 [1082]).

Chem. Composition constant.

Phys. Tabular (on *a* axis) or flat (elongated on b axis); moderate cleavage on (101) in laurionite and on (100) in fiedlerite; perfect cleavage on (001) in paralaurionite. Onoratoite is needlelike; cleavage is not observed [1252].

DIVISION B. COMPLEX

1. HEMATOPHANITE GROUP. Tetr., $D_{4h}^{17} - I4/mmm$, $Z = 3$

			a	*c*	ρ	H
Hematophanite		$Pb_5Fe_4O_{10}(OH)Cl\,{}^{2}_{\infty}$	7.82	15.26	7.7	2—3

Str. Not known; assigned from morphology and properties.

Chem. Traces of Ca, Mn, Fe^{2+}, and Mg. See also [1410].

Phys. Tabular, perfect cleavage on (001).

2. NADORITE GROUP. Orth., $D_{2h}^{17} - Bmmb$, $Z = 4$

			a	*b*	*c*	ρ	H
Nadorite	(plumstibochlite)	$PbSbO_2Cl\,{}^{2}_{\infty}$	5.60	5.44	12.22	7.0	3.5—4
Perite	(plumbisochlite)	$PbBiO_2Cl\,{}^{2}_{\infty}$	5.62	5.57	12.43	8.2	3.5

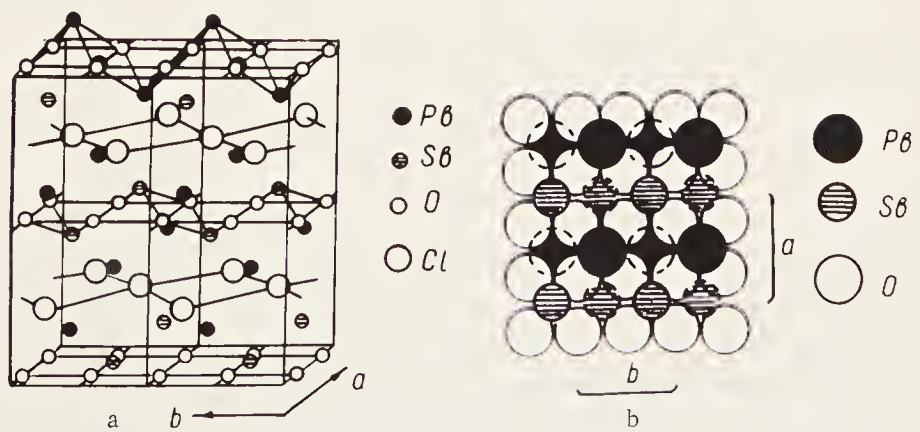


Fig. 289. Structure of nadorite: a) general view, b) $PbSbO_2$ layer with fourfold pyramidal coordination of Pb and Sb.

Str. Isostructural; nadorite has a layered structure as in litharge, Pb and Sb having fourfold pyramidal coordination, with layers of Cl atoms parallel to (001) (Fig. 289); CN = 8 for Pb and Sb (four O + four Cl). Interatomic distances: $Pb-O_4Cl_4$ = 2.44 (4) and 3.18 (4); $Sb-O_4Cl_4$ = 2.17 (4), 3.39 (2), and 3.54 (2) (Sillén and Melander, 1941 [1083]); in perite $Pb-O_4Cl_4$ = 2.45 (4), 3.30 (2), and 3.25 (2); $Bi-O_4Cl_4$ = 2.27 (4), 3.45 (2), and 3.42 (2) (Gillberg, 1961 [1084]).

Chem. No substantial isomorphous components.

Phys. Tabular, (001) cleavage perfect.

3. EKDEMITE GROUP. Tetr.→orth.

		S.g.	*a*	*b*	*c*	*Z*	*ρ*	H
Ekdemite	$Pb_6As_2O_7Cl_4\,{}^{2}_{\infty}$	Not det.	10.8	—	25.6	8	7.1	2.5—3.5
Heliophyllite (orthockdemite)	$Pb_6As_2O_7Cl_4\,{}^{2}_{\infty}$	Not det.	10.8	10.8	25.6	8	6.9	2.5—3.5
Ochrolite	$Pb_6Sb_2O_7Cl_4\,{}^{2}_{\infty}$	Orth.	—	—	—	—	—	3.5

Str. The first two minerals are very similar (Sillén and Melander, 1941 [1083]); their structure, like that of nadorite, is layered, and is probably defective (Strunz, 1942 [1085]); some of the As positions should be taken by Pb, with reduction in the number of O atoms. In the ideal case, the transition from the nadorite structure to the ekdemite one is represented by $Pb_4As_4O_8Cl_4 \rightarrow Pb_6As_2O_7Cl_4$. Any further increase in the number of Pb atoms in the structure can occur only by reduction in the number of As, which ultimately gives us the structure of blixite: $Pb_6As_2O_7Cl_4 \rightarrow Pb_8O_6Cl_4$.

Chem. Pb:As ratio varies; also, As is replaced by Sb (≤1.15%) and Pb by Ca and Mn (≤0.5%). Ochrolite is probably identical with nadorite [154].

Phys. Tabular and platy, perfect cleavage on (001).

4. DIABOLEITE GROUP. Tetr.→mon.

		S.g.	*a*	*b*	*c*	β	*Z*	*ρ*	H
Dioboleite	$Pb_2Cu(OH)_4Cl_2\,{}^{2}_{\infty}$	C^{1}_{4v} — $P4mm$	5.87	—	5.49	—	1	5.4	3
Chloroxiphite	$Pb_3CuO_2(OH)_2Cl_2\,{}^{2}_{\infty}$	C^{2}_{2h} — $P2_1/m$	10.36	5.74	6.53	97° 11′	2	6.9	3

Str. Known only for diaboleite (Fig. 290). Layers produced by stronger Pb—OH and Cu—OH bonds in layers, as compared with weaker Cl—OH ones between layers. Pb is surrounded by four OH and four Cl in the form of a twisted cube (OH square at 45° to Cl square), while Cu has an octahedron of four OH and two Cl (OH square placed equatorially). Interatomic distances: $Pb-(OH)_4Cl_4$ = 2.57 (4), 3.01 (2), and 3.18 (2);

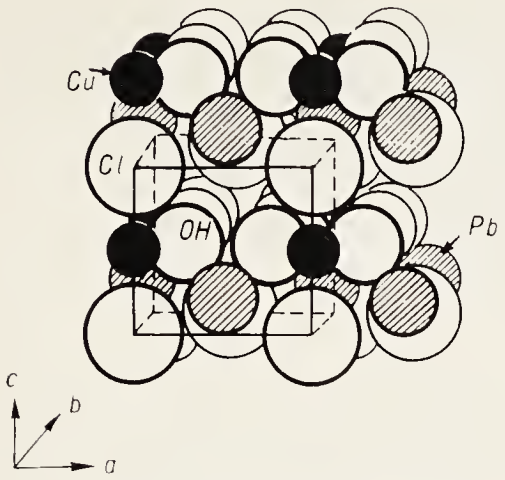


Fig. 290. Structure of diaboleite showing layers parallel to (001).

$Cu-(OH)_4Cl_2$ = 2.07 (4) and 2.75 (2) (Byström and Wilheimi, 1950 [1086]). Chloroxiphite has *a* and b similar to diaboleite, but the c of the two differ. Direct evidence for the structural similarity is required.

Chem. Compositions constant.

Phys. Diaboleite is platy, while chloroxiphite is tabular; cleavage perfect on (001) for the first, on $(\bar{1}01)$ for the second.

5. KOENENITE GROUP. Trig.

		S.g.	a_h	c_h	Z	ρ	H
Koenenite	$Na_4Ca_2Mg_7Al_4(OH)_{22}Cl_{12}$	D^3_{3d}—$P\bar{3}ml$	—	32,64	—	2,15	1—2

Str. Consists of alternating double layers of composition $[Mg_7Al_4(OH)_{22}]^{4+}$ and $[Na_4Ca_2Cl_{12}]^{4-}$, which differ in cell parameters; the first has a_n = 3.05, c_h = 10.88, while the second has a_h = 4.07, c_h = 32.64 (Lohse et al., 1963 [1087]). The mean distances of Me—Cl and Me—OH are correspondingly 2.79 and 2.02; distances between layers: Cl—Cl = 3.02, OH—OH = 1.99 and Cl—OH = 2.94 (Allmann et al., 1968 [1253]).

Chem. Isomorphism between Na, Ca, Mg, and Sr; Cl replaced by Br (≤0.05%).

Phys. Varied habit, columnar to acicular (acute scalenohedra) and tabular, (0001) cleavage perfect.

DIVISION C. WITH WATER AND ADDITIONAL RADICALS

1. CREEDITE GROUP. Mon., C^6_{2h}—$C2/c$, Z = 4

		a	*b*	*c*	β	ρ	H
Creedite (calcalhysulohflite)	$Ca_3Al_2(H_2O)_2[SO_4](OH)_2F_8$	14.03	8.51	9.93	94°30′	2.74	3.75—4

Str. Al octahedra combined with SO_4 tetrahedra and Ca polyhedra (CN = 8), the last being twisted cubes in two types of position. Ca_1 is linked via edges to paired Al octahedra giving compact heterogeneous layers parallel to (100), which are linked by fairly widely spaced bonds to SO_4

tetrahedra (at vertices) and Ca_2 polyhedra. Interatomic distances: $Ca_1-OF_5(OH)H_2O$ = 2.46; 2.35 (5); 2.53 (2); $Ca_2-O_2F_4(H_2O)_2$ = 2.59 (2); 2.30 (4); 2.60 (2); $Al-F_4(OH)_2$ = 1.79 (4); 1.88 (2); $S-O_4$ = 1.46 (2); 1.47 (2) (Borisov and Brusentsov, 1964 [1088]).

Phys. Columnar, perfect (100) cleavage, (110) moderate.

2. TIKHONENKOVITE GROUP. Orth.→mon.

		S.g.	a	b	c	β	Z	ρ	H
Joroslovite (tricolcolhyohflite)	$Ca_3Al_2(H_2O)(OH)_2F_{10}$ [2]	Not det.	8.76	5.54	4.52	—	1	3.2	4-4.5
Tikhonenkovite (stralhyohflite)	$SrAl(H_2O)(OH)F_4$ [2]	$C_{2h}^5-P2_1/c$	5.02	10.62	8.73	102°43′	4	3.3	3.75

Str. Tikhonenkovite has heterogeneous layers of $AlF_4(OH)_2$ octahedra (OH groups on a common edge) and Sr polyhedra (CN = 9, trigonal prism with pyramids on each four-cornered face), which are linked via edges and vertices (Fig. 291a). These layers are parallel to (100) and are linked via rather widely spaced and weak Sr–F and $Sr-H_2O$ bonds (Fig. 291b). Mean interatomic distances: $Al-F_4(OH)_2$ = 1.82 (4); 1.87 (2); $Sr-F_6(OH)(H_2O)_2$ = 2.52 (6); 3.03; 2.70 (2) (Pudovkina and Pyatenko, 1967 [1089]). Jaroslavite may not belong to this group (Novikova et al., 1966 [1090]).

Chem. Ca in jaroslavite is replaced by Na and Mg; Sr in tikhonenkovite is replaced by Ca (≤1%).

Phys. Perfect (001) cleavage for jaroslavite, (100) for tikhonenkovite.

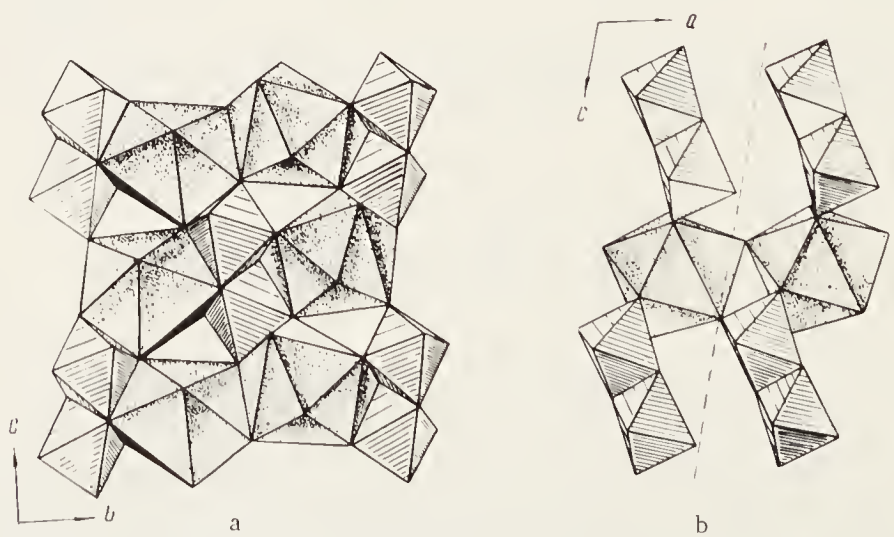


Fig. 291. Structure of tikhonenkovite: a) Al–Ca layer in projection on (100), b) mode of linking of two adjacent layers.

Inadequately Characterized and Doubtful

Cadwaladerite $Al(OH)_2Cl \cdot 4H_2O$
Hemimorphite (Pb oxychloride)
Hydromelanothallite $Cu_2(OH)_2Cl_2 \cdot H_2O$ (?)
Melanothallite Cu(OH)Cl (?)

CLASS 3. FLUORIDES

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa		VIIIa		Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb
1	Type IV. Halides Class 3. Fluorides																H 5	
2	Li 1												B 2	C 1	N 2	O 5	F 24	
3	Na 13	Mg 4											Al 11	Si 4	P 1	S 1		
4	K 4	Ca 5																
5		Sr 2	Y 2															
6		Ba 1																
7						Ce 1												

Coordination		Framework		Ring		Insular		Chain		Layer	
simple	com-plex	simple	com-plex	simple	com-plex	simple	com-plex	simple	com-plex	simple	com-plex
3	1	3	3			4	2	1	1	3	3

Subclass 1. Coordination

Division A. Simple

1. Fluorite CaF_2 group
2. Villiaumite NaF group

Division B. Complex

1. Gagarinite $NaCaYF_6$ group

Subclass 2. Framework

Division A. Without Water and Additional Anions

1. Neighborite $Na[MgF_3]^3_\infty$ group
2. Elpasolite $K_2[NaAlF_6]^3_\infty$ group
3. Cryolithionite $Na_3[Li_3Al_2F_{12}]^3_\infty$ group

Division B. With Water and Additional Anions

1. Chukhrovite $Ca_3YAl_2(H_2O)_{10}[SO_4]F_{13}{}^3_\infty$ group
2. Thomsenolite $Na[Ca(H_2O)AlF_6]^3_\infty$ group

Subclass 3. Insular

Division A. Without Water and Additional Anions

1. Hieratite $K_2[SiF_6]$ group
2. Avogadrite $K[BF_4]$ group

Division B. With Additional Radicals

1. Stenonite $Sr_2Al(CO_3)F_5$ group

Subclass 4. Chain

1. Sellaite $MgF_{2\infty}^{1}$ group
2. Cryolite $Na_2[NaAlF_6]_{\infty}^{1}$ group

Subclass 5. Layer

1. Tysonite $CeF_{3\infty}^{2}$ group
2. Weberite $Na_2[MgAlF_7]_{\infty}^{2}$ group
3. Chiolite $Na_4[NaAl_3F_{14}]_{\infty}^{2}$ group
4. Malladrite $Na_2[SiF_6]_{\infty}^{2}$ group

Inadequately Characterized and Doubtful

Subclass 1. Coordination

DIVISION A. SIMPLE

1. FLUORITE GROUP. Cubic, $O_h^5 - Fm3m$, $Z = 4$

			a	d	ρ	H	Cl.
Fluorite	(calcflite)	CaF_2	5.46	2.36	3.18	4	(111) perf.

Str. Fluorite type, CN = 8/4 (Fig. 15).

Chem. Composition usually constant, the main changes being due to isomorphous Y and Ce, which range up to (Y, Ce):Ca = 1:6. This gives rise to a defect structure represented by $Ca_{1-x}Y_{2/3x}F_2$, with slight alteration in the lattice parameters.

Var. Y-fluorite, Ce-fluorite.

2. VILLIAUMITE GROUP. Cubic, $O_h^5 - Fm3m$, $Z = 4$

			a	d	ρ	H	Cl.
Villiaumite	(naflite)	NaF	4.63	2.31	2.79	2.5	(100) perf.
Carobbiite	(kaflite)	KF	5.40	2.66	2.51	(1.75)	(100)

Str. Halite type, CN = 6/6 (Fig. 8).

Chem. No substantial variations, only traces of K (≤0.32%), Ca (≤1.2%), and Mg. The K in carobbite is partly replaced by Na, and F by Cl.

DIVISION B. COMPLEX

1. GAGARINITE GROUP. Trig., $C_{3i}^1 - P\bar{3}$, $Z = 1$

		a_h	c_h	ρ	H
Gagarinite (nacalcyflite)	$NaCaYF_6$	5.99	3.5?	4.5	4—4.5

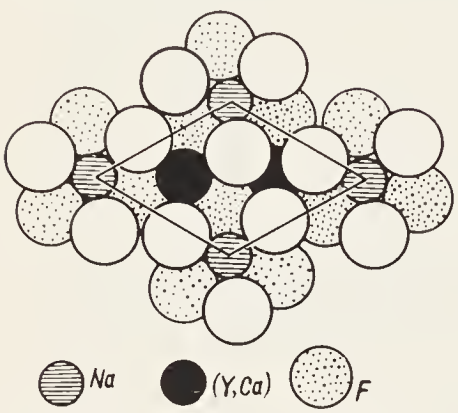


Fig. 292. Structure of gagarinite in projection on (0001).

Str. The NaF_6 octahedra (Fig. 292) are linked to CaF_9 and YF_9 polyhedra (trigonal prisms with pyramidal faces), the latter being linked via their triangular bases and forming columns along the c axis. The NaF_6 octahedra lie along this direction but alternate with empty octahedra. The different octahedra are linked by edges. Interatomic distances: Na—Fe_6 = 2.33; (Ca, Y)—F_9 = 2.30 (3) and 2.39 (6) (Voronkov et al., 1962 [1091]).

Chem. Ca:Y ratio varies with Y—Ca replacement as in 2Ca → Y + Na. The F is replaced by Cl (≤3.79%) and OH (≤2%). The TR (replacing Y) have the composition Dy, Er, Gd, Nd, Ce, Yb, Sm, Ho, Pr, Tb, La, Tu, Lu, Eu.

Phys. Short columns, perfect cleavage on $(10\bar{1}0)$.

Subclass 2. Framework

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. NEIGHBORITE GROUP. Orth., $D_{2h}^{16} - Pcmn$, $Z = 4$

		a	b	c	ρ	H	Cl.
Neighborite (namaflite)	$Na[MgF_3]_\infty^3$	5.36	7.68	5.50	3.0	3	None

Str. Perovskite type. MgF_6 octahedra linked by vertices into a framework (Fig. 293), with Na in holes, CN = 12 (Chao et al., 1961 [1092]).

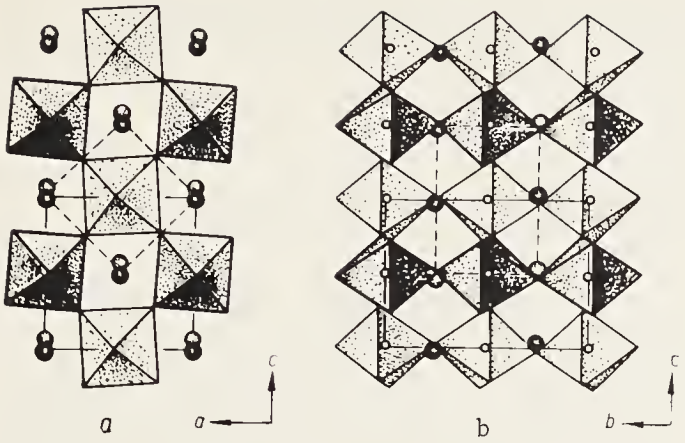
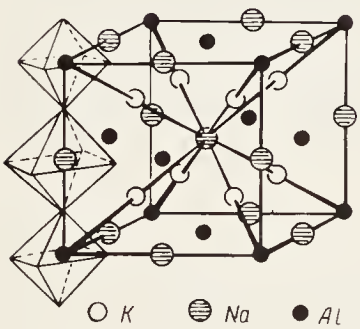


Fig. 293. Structure of neighborite; framework of MgF_6 octahedra, the Na (large circles) lying in holes.

Chem. Data inadequate.

2. ELPASOLITE GROUP. Cubic, $T_h^6 - Pa3$, $Z = 4$

		a	ρ	H	Cl.
Elpasolite (kanalflite)	$K_2[NaAlF_6]^3_\infty$	8,11	3,0	3	None



Str. Framework of AlF_6 octahedra (at vertices and face centers of cubic cell) alternating with NaF_6 ones (at center and at middle of edges). The K(CN = 12) atoms lie at the centers of eight small cubes (Fig. 294).

Fig. 294. Structure of elpasolite, with AlF_6 and NaF_6 octahedra linked into a single framework.

3. CRYOLITHIONITE GROUP. Cubic, $O_h^{10} - Ia3d$, $Z = 8$

		a	ρ	H	Cl.
Cryolithionite (nalialflite)	$Na_3[Li_3Al_2F_{12}]^3_\infty$	12,16	2.77	3—3.5	(110) perf.

Str. Garnet type. AlF_6 octahedra linked via common vertices to LiF_4 tetrahedra to form a framework whose holes contain Na (CN = 8). Bonds in framework polyhedra appreciably stronger than those in NaF_8 polyhedra. Interatomic distances: Na–F_8 = 2.35 (4) and 2.54 (4); Li–F_4 = 1.85; Al–F_6 = 1.81 (Menzer, 1930 [1093]; Geller, 1971 [1408]).

DIVISION B. WITH WATER AND ADDITIONAL ANIONS

1. CHUKHROVITE GROUP. Cubic, $T_h^4 - Fd3$, $Z = 8$

		a	ρ	H
Chukhravite (calcytalhyflite)	$Ca_3YAl_2(H_2O)_{10}[SO_4]F_{13}$ ∞	16.80	2.34	3.5

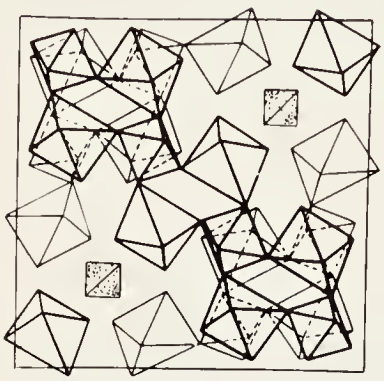


Fig. 295. Structure of chukhrovite represented in polyhedra.

Str. The framework consists of Al and (Ca, Y) octahedra linked via vertices (Fig. 295). The large holes contain the SO_4 radicals, which are linked to the H_2O vertices of adjacent polyhedra by hydrogen bonds. The Ca and Y should be randomly distributed over the octahedral positions. Interatomic distances: (Ca, Y) $-(H_2O)_3F_3$ = 2.48 (3) and 2.29 (3); Al $-F_6$ = 1.85; S $-O_4$ = 1.48 (Bokii and Gorogotskaya, 1965 [1094]).

Chem. Ca and Y have an isomorphous relation; Y also is replaced by Ce, Nd, Sn, Gd, and other TR.

Phys. Isometric, (111) cleavage imperfect.

2. THOMSENOLITE GROUP. Mon.

	S.g.	a	b	c	β	Z	ρ	H
Thamsenolite (nacalchyalflite) $Na[Ca(H_2O)AlF_6]$ ∞	$C_{2h}^5 - P2_1/c$	5.58	5.51	16.13	96°26′	4	2.98	2.5-3
Pachnolite (paranocolchyalflite) $Na[Ca(H_2O)AlF_6]$ ∞	$C_{2h}^6 - A2/a$	9.92	10.43	15.72	142°16′	8	2.97	3.5

Str. Known fully for thomsenolite, which has a framework of Al octahedra and Ca polyhedra (CN = 8) linked via common F vertices. Four Ca $-$ F bonds (to four adjacent Al octahedra) lie in a plane parallel to (001), while two others and two Ca $-H_2O$ bonds are nearly perpendicular to this, so there are clear sublayers, which correspond to the perfect cleavage. Na has CN = 8 (trigonal prism with two pyramids on the side faces) and lies between the sublayers, sharing edges with Al and Ca polyhedra, the latter being linked together via H_2O molecules into chains. Pachnolite has not been studied in detail; there are AlF_6 octahedra, Ca $-F_6(H_2O)_2$ polyhedra, and Na with CN = 12 (Gerhard, 1966). Interatomic distances in thomsenolite: Na $-F_8$ = 2.32-2.65 (mean = 2.46); Ca $-F_6(H_2O)$ = 2.29-2.46 (mean = 2.36); 2.50 (2); Al $-F_6$ = 1.77-1.82 (mean = 1.80) (Cocco et al., 1967 [1095]).

Phys. Columnar to tabular; cleavage of thomsenolite on (001) perfect, on (110) moderate. No cleavage reported for pachnolite.

Subclass 3. Insular

DIVISION A. WITHOUT WATER AND ADDITIONAL ANIONS

1. HIERATITE GROUP. Cubic, $O_h^5 - Fm3m$, $Z = 4$

			a	ρ	H	Cl.
Hieratite	(kasiflite)	$K_2[SiF_6]$	8.19	2.66	3	(111) perf.
Cryptohalite	(amsiflite)	$(NH_4)_2[SiF_6]$	8.35	2.02	3	(111) perf.

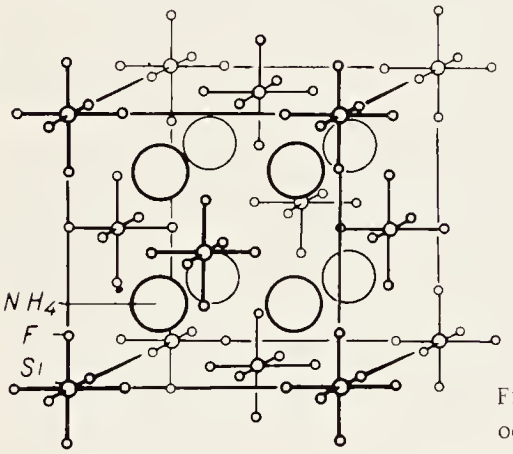


Fig. 296. Structure of cryptohalite, with insular SiF_6 octahedra, between which lie the ammonium ions.

Str. K_2PtCl_6 or antifluorite type, with K or NH_4 taking the F positions and SiF_6 the Ca positions (Fig. 296); CN for K (NH_4) or 12 F. Interatomic distances: $K-F_{12} = 2.90$; $Si-F_6 = 1.75$; $NH_4-F_{12} = 2.97$; $Si-F_6 = 1.71$ (p. 121 [177]).

2. AVOGADRITE GROUP. Orth., $Z = 4$

		S.g.	a	b	c	ρ	H
Ferruccite (nabaflite)	$Na[BF_4]$	$D_{2h}^{17} - Ccmm$	6.26	6.83	6.78	2.50	~3.5
Avogadrite (kaboflite)	$K[BF_4]$	$D_{2h}^{16} - Pnma$	8.10	5.18	6.64	2.51	(3)

Str. Ferruccite is isostructural with anhydrite (Fig. 254); each Na is surrounded by eight F. Avogadrite is isostructural with baryte (Fig. 255); each K is surrounded by twelve F. Interatomic distances in ferruccite: $B-F_4 = 1.41$; $Na-F_8 = 2.18$-2.20 (Bellanca, 1948 [1067]); in avogadrite $B-F_4 = 1.29$, 1.39 (2), and 1.53; $K-F_{12} \approx 2.8$ (Bellanca and Sgarlata, 1950 [1096]).

Chem. Ferruccite contains K ($\leq 3\%$); avogadrite has K replaced by Cs ($\leq 18\%$).

Var. Cs-avogadrite.

DIVISION B. WITH ADDITIONAL RADICALS

1. STENONITE GROUP. Mon., $Z = 4$

		S.g.	a	b	c	β	ρ	H
Stenonite (strolcitoflite)	$Sr_2Al[CO_3]F_5$	$C_{2h}^2 - P2_1/m$	5.45	8.69	13.14	98° 20′	3.9	3.5
Boggildite (nostrolphitoflite)	$Na_2Sr_2Al_2[PO_4]F_6$	$C_{2h}^5 - P2_1/c$	5.24	10.48	18.52	107° 21′	3.7	4.5—5.5

Str. Not known.

Chem. Fairly constant composition; both minerals contain a little Ba.

Phys. Stenonite has moderate cleavage on (001) and (120), while böggildite has imperfect cleavage in two directions.

Subclass 4. Chain

1. SELLAITE GROUP. Tetr., $D_{4h}^{14} - P4_2/mnm$, $Z = 2$

		a	c	ρ	H	Cl.
Selloite (moflite)	$MgF_2{}^1_\infty$	4.65	3.07	3.15	4.25—4.75	(100) and (110) perf.

Str. Rutile type, CN = 6/3 (Fig. 16); $Mg-F_6 = 1.99$ (Baur, 1956 [1097]).

Chem. Composition constant.

2. CRYOLITE GROUP. Mon., $C_{2h}^5 - P2_1/n$, $Z = 2$

		a	b	c	β	ρ	H
Cryolite (nonolflite)	$Na_2[NaAlF_6]{}^1_\infty$	5.47	5.62	7.82	90° 11′	2.96	3—3.5

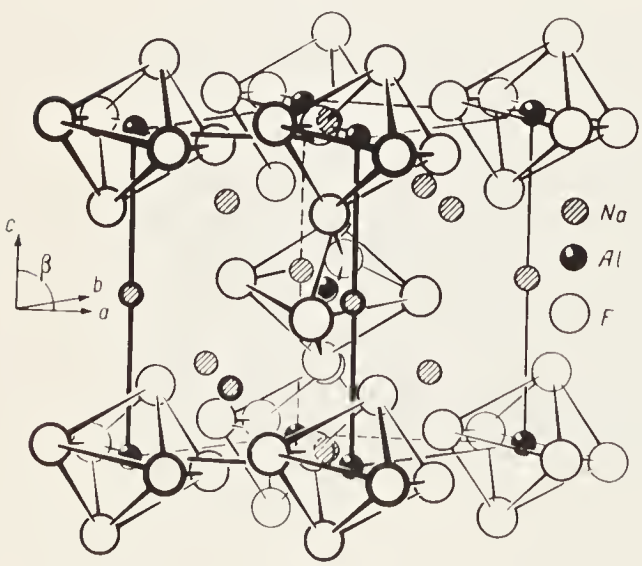


Fig. 297. Structure of cryolite; only the AlF_6 octahedra are shown in the heterogeneous chains parallel to the c axis.

Str. Heteroatomic chains of composition $NaAlF_6$ run parallel to the c axis (Fig. 297); in large holes between the chains lie the other 2/3 of the Na (CN = 12). Interatomic distances: $Al-F_6$ = 1.79-1.83; $Na-F_6$ = 2.32-2.42; $Na-F_{12}$ = 2.21-2.68 (Náray-Szabo and Sasvari, 1938 [1098]).

Chem. Composition constant.

Phys. Columnar to isometric; no cleavage (?).

Subclass 5. Layer

1. TYSONITE GROUP. Hex., $D_{6h}^4 - P6_3/mmc$, $Z = 6$

		a	c	ρ	H	Cl.	
Tysanite (ceflite)	CeF_3 $^2_\infty$	7.12	7.29	6.1	5—5.5	(0001)	imperf.

Str. Corrugated layers of F atoms enclose planar hexagonal layers of Ce and F atoms (Fig. 298). Ce has complicated coordination: three F atoms lie in a triangle at 2.37, while two F lie at 2.36 along the c axis, and six F form a prism at 2.70 (Öftedahl, 1929 [1099]; Mansmann, 1965 [1100]). The space group is given by the latter as $D_{3d}^4 - P\bar{3}c1$.

Chem. Ce replaced by La up to Ce:La = 1:1; there are also smaller amounts of isomorphous Nd, Pr, Y, Sm, and Gd.

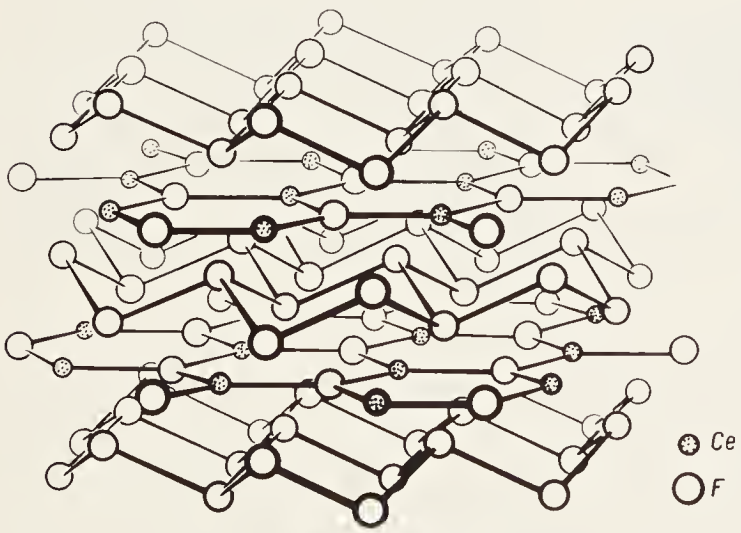


Fig. 298. Structure of tysonite.

2. WEBERITE GROUP. Orth., $D_{2h}^{28} - Ibmm$, $Z = 4$

		a	b	c	ρ	H	Cl.	
Weberite (namagalflite)	$Na_2[MgAlF_7]$ $^2_\infty$	7.31	7.06	9.99	2.97	3.75	(101)	m
Usavite (bamagalflite)	$Ba_2[MgAl_2F_{12}]$ $^2_\infty$	—	—	—	4.2	3.5-4.5	Dir?,	perf.

Str. Not adequately studied. Layers of $(Mg, Al)F_6$ octahedra are linked by vertices, but in such a way that all the vertices of MgF_6 are shared, whereas only four of the six are shared for AlF_6. Each Na is surrounded by eight F; the Na atoms lie between the layers in two positions. Interatomic distances: $Al-F_6$ = 1.83 (4) and 1.85 (2); $Mg-F_6$ = 1.94; Na_I-F_8 = 2.40 (4) and 2.70 (4); $Na_{II}-F_8$ = 2.21 (2), 2.56 (4), and 2.69 (2) (Byström, 1945 [1101]). Usovite assigned here on basis of perfect cleavage and platy habit (Nozhkin et al., 1967 [1102]).

3. CHIOLITE GROUP. Tetr., D_{4h}^6 — $P4/mnc$, $Z = 2$

		a	c	ρ	H	Cl.
Chialite (tetrananalflite)	$Na_4[NaAl_3F_{14}]_\infty^2$	7.01	10.41	2.99	2.5–3	(001) perf.

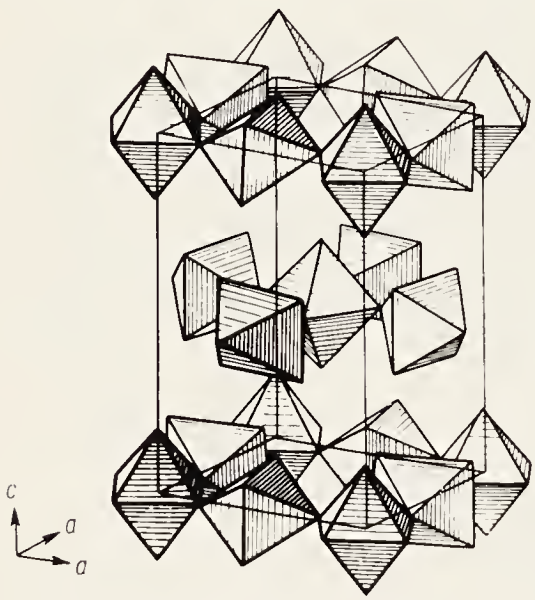


Fig. 299. Structure of chiolite; only the AlF_6 octahedra connected in layers are shown.

Str. Layer pattern produced by AlF_6 octahedra, with one-third linked by four vertices and the rest by only two (Fig. 299). The layers are parallel to the basal plane and are displaced one relative to another by half a diagonal. The large holes in the planes of the layers contain NaF_6 octahedra, which form a single structure with the AlF_6 octahedra. The other 4/5 of the Na atoms have CN = 8 and lie between the layers. Interatomic distances: Al_I-F_6 = 1.82 (4) and 1.92 (2); $Al_{II}-F_6$ = 1.82 (2) and 1.94 (4); Na_I-F_6 = 2.23 (4) and 2.56 (2); $Na-F_8$ = 2.40. Distance between layers 5.2 (Brosset, 1938 [1103]).

4. MALLADRITE GROUP. Trig., $D_3^2 - P\bar{3}ml$

		a_h	c_h	Z	ρ	H
Malladrite (nasiflite)	$Na_2[SiF_6]_\infty^2$	8.87	5.07	3	2.74	(3.0)
Bararite (trigaamsiflite)	$(NH_4)_2[SiF_6]_\infty^2$	5.77	4.78	1	2.15	~3

Str. Layers of SiF_6 and NaF_6 octahedra parallel to (0001); distances $Na-F_6$ = 2.32; $Si-F_6$ = 1.69 (Zalkin et al., 1964 [1104]), with CN = 9 for NH_4 in bararite. Interatomic distances NH_4-F_9 = 2.91; $Si-F_6$ = 1.66 (Gossner and Kraus, 1934 [1105]).

Chem. No complete analyses available.

Phys. Tabular, perfect cleavage on (0001), not observed (?) for malladrite.

Inadequately Characterized and Doubtful

Kamagflite $K[MgF_3]$ (?)
Yttrocalciofluorite $Ca(Y, Er)F_5$ (?)

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FORMULA INDEX

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Au

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Ce

Co

Cr

Cs

Cu

La

Li

Mg

Mn

Mo

Na

NH_4

Pd

Pt

Rh

Zr

Index of Mineral Names*

* Mineral names followed by page numbers are the principal names used throughout this book. The index contains many other names (obsolete or less-commonly-used names, variant spellings, etc.) which direct one to either a principal name or a location where pertinent information may be found.

Calcium hilgardite-2M (Cc) = hilgardite
Calcium hilgardite-3Tc = parahilgardite
Calcium jarosite = Ca-jarosite
Calcium larsenite = esperite
Calcium pyromorphite = Ca-phosphoro-mimetite
Calcium seidozerite = Ca-seidozerite
Calciumsiderit = Ca-ferromagfercite
Calcium smithsonite = Ca-smithsonite
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Ferribraunite = Fe^{3+}-braunite
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Ferrichromite = Fe^{3+}-chromite
Ferricopiapite = Fe^{3+}-copiapite
Ferrierite 355
Ferrifayalite = Fe^{3+}-ferroolivine
Ferrigehlenite = Fe^{3+}-alumomelilite
Ferrihalloysite = Fe^{3+}-halloysite
Ferrihastingsite = ferroferribarkevikite
Ferriilmenite = Fe^{3+}-ilmenite
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Ferrimuscovite = Fe^{3+}-muscovite
Ferrinatrite 594
Ferripalygorskite = Fe^{3+}-palygorskite
Ferriphlogopite = Fe^{3+}-phlogopite
Ferrisaponite = Fe^{3+}-saponite
Ferrisepiolite = Fe^{3+}-sepiolite
Ferrisicklerite = subspecies of sicklerite
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Ferrobrucite = Fe-brucite
Ferrocalcite = Fe-calcite
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Ferrochrysotile = Fe-chrysotile
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Hydrobiotite 445
Hydroboracite 481
Hydrobritholite = partially decomposed hydrated britholite
Hydrocalcite = monohydrocalcite
Hydrocalumite 330
Hydrocassiterite = mixture of cassiterite with FeOOH
Hydrocatapleiite = altered catapleiite
Hydrocerite = mixture of oxides of TR, Th, Fe, Si, P, etc
Hydrocerussite 624
Hydrochloroborite 491
Hydrocyanite = chalcocyanite
Hydrofranklinite = Fe-chalcophanite
Hydrogen autunite 556
Hydrogen-uranospinite = trögerite
Hydroglauberite 606
Hydrogrossular = plazolite
Hydrohalite 640
Hydrohausmannite = mixture of hausmannite with MnO(OH)
Hydrohauyne = hauyne
Hydrohematite = colloidal hematite with adsorption H_2O
Hydrohetaerolite = mixture of hetaerolite with MnO(OH)
Hydromagnesite 620

Hydrometanothallite 659
Hydromolysite 638
Hydromuscovite 445
Hydroniccite 324
Hydronium jarosite = carphosiderite
Hydrophilite 643
Hydroromeite = Ca-stibiconite
Hydroscarbroite 333
Hydrosodalite (of Vlasov, Kuzmenko, and Eskova) 350
Hydrotalcite = magalumohydrite-3R
Hydrothorite = mixture of Fe_2O_3, TiO_2, MnO_2, ThO_2, SiO_2, etc
Hydrotungstite 320
Hydrougrandite 382
Hydroxonotlite 419
Hydroxylascharite 491
Hydrozincite 615
Hydrozircon = mixture of ZrO_2, SiO_2, UO_2, Fe_2O_3, etc
Hypersthene 408
Hypersthene (old) = Mg-ferrohypersthene

Ianthinite 320
Ice-I 294
Ice-Ic 294
Idaite 265
Idocrase = vesuvianite
Igalikite = mixture of analcime with muskovite
Igdloite 295
Iimorite 397
Ikaite 618
Ikunolite 261
Ilesite 602
Ilimaussite 368
Illite = colloidally dispersed hydromuscovite
Ilmenite 279
Ilmenite (old) = ferroilmenite
Ilmenorutile = Fe, Nb-rutile
Ilsemannite = $Mo^{4+}[MoO_4]_2 \cdot nH_2O$ (may belong to sedovite group)
Ilvaite 400
Imgreite 210
Imhofite 236
Inderborite 476
Inderite 476
Indialite 376
Indigirite = $Mg_2Al_2[Co_3]_4(OH)_2 \cdot 15H_2O$ (hydrocalumite group)
Indite 223
Indium 194
Inesite 419
Innelite 453
Inyoite 476
Iodargyrite 637
Iodembolite = I-cerargyrite
Iodobromite = I-cerargyrite
Iolite = cordierite
Iowaite 324
Iozite = wüstite
Iranite 577
Irarsite 244
Iridic gold = Ir-auroargaurite
Iridium 192
Iridosmine 192
Iridosmine = osmiosmirite
Iriginite 572
Irinite = Th-loparite
Iron 193
Iron-boracite = Fe-boracite
Iron-cordierite = Fe-cordierite
Iron diaspore = Fe-diaspore
Iron-dolomite = Fe-magnesiodolomite
Iron gahnite = Fe^{2+}-gahnite
Iron hercynite = Fe^{3+}-hercynite
Iron-knebelite = Mn-ferroknebelite
Iron kutnahorite = Fe-kutnahorite
Iron magnesiochromite = Fe-magnesiochromite
Iron-magnesium retgersite = Fe, Mg-retgersite
Iron spherocobaltite = Fe-cobaltocalcite
Irontephroite = Fe-tephroite
Ishiganeite = mixture of cryptomelane and birnessite
Ishikawaite = U-niobiosamarskite
Isoclasite 549
Isokite 546
Istisuite 458

Itoite 589
Ittnerite = altered nosean
Ivaarite = Ti-ferrigrossular
Ivanovite 491
Ixiolite 302
Ixionit = ixiolite
Ixionolite = ixiolite

Jacobsite 285
Jadeite 410
Jadeite-acmite = Fe^{3+}-jadeite
Jagoite 401
Jahrlite 649
Jaipurite 220
Jalpaite 241
Jamesonite 251
Japanite = kämmererite
Jargon = zircon
Jarosite 588
Jarošite = Mg-melanterite
Jaroslavite 658
Jefferisite = Ni-vermiculite
Jeffersonite = Zn-diopside
Jennite 419
Jeremejevite 466
Jeromite = Se-orpiment (?)
Ježekite = morinite
Jimboite 466
Jiningite = metamict Fe-thorite
Joaquinite 366
Joesmithite 426
Johachidolite 468
Johannite 604
Johannsenite 409
Johnstrupite = rinkolite
Jonstonotite = mixture of garnets with other minerals
Jordanite 237
Jordanite (old) = arsenojordanite
Joseite 214
Josephinite = Fe-nickelite
Jouravskite 600
Julgoldite 404
Jurupaite = xonotlite
Justite = koenenite (?)

Kaersutite 425
Kahlerite 522
Kainite 600
Kainosite 372
Kaliborite 485
Kalicinite 626
Kalinite 597
Kaliophyllite 345
Kalistrontite 583
Kalkmagnesit = Ca-magnesiomagfercite
Kalkowskyn = altered davidite (?)
Kalkrhodochrosit = Ca-manganomanfercite
Kallilite = Bi-ullmannite
Kalsilite 345
Kamacite = Ni-iron
Kamagflite 669
Kamarezite = brochantite
Kamiokalite = Zn-veszelyite
Kämmererite 444
Kampylite = PO_4-arseniomimetesite
Kanaekanite 374
Kanasite 421
Kanbarite = montmorillonite with silica gel
Kaneite 203
Kaolinite 431
Karachaite 458
Karamsinite = tremolite
Karelianite 270
Karinthine = Al-barkevikite (?)
Karnasurtite = mixture of Al_2O_3, TR_2O_3, TiO_2, SiO_2, P_2O_5, etc
Karpinskite 350
Kasoite = var. of celsian
Kasolite 456
Kašparite 600
Kassite 319
Katoptrite 390
Kawazulite 214
Kehoeite 532
Keilhauite = Y-titanite
Keldyshite 364
Kemmlitzite 513
Kempite 648
Kennedyite 304
Kentrolite 400

Kenyaite 458
Kerchenite = ferrivivianite (colloidally dispersed)
α-Kerchenite = Fe^{2+}-ferrivivianite (colloidally dispersed)
β-Kerchenite = Fe^{3+}-ferrovivianite (colloidally dispersed)
γ-Kerchenite = Fe^{3+}-ferrovivianite (colloidally dispersed)
Kermesite 247
Kernite 482
Kerolite = mixture of serpentine with stevensite
Kerrite = parsettensite
Kerstenine 525
Kerstenite 575
Kettnerite 623
Khinganite = Zn-stannite (altered kësterite)
Khlopinite = Ti-niobiosamarskite
Khunite 577
Kieserite 590
Kilchoanite 396
Kimzeyite 382
Kingite 562
Kinoite 407
Kirovite = Mg-melanterite
Kirschtenite 385
Kischtimite = La, OH-bastnäsite
Kitkaite 259
Kivuite 559
Kleinite 201
Klementite = Mg, Al-alumochamosite
Klockmannite 265
Knebelite 384
Knebelite (old) = Fe-manganoknebelite
Knipovichite = hydrous carbonate of Ca, Al, and Cr
Knopite = Ce-perovskite
Knorringite = hanleite
Kobaltadamin = Co-adamite
Kobaltcalcit = Co-calcite
Kobeite = Y, U-zirconolite (?)
Kobellite 252
Kobokobite 562
Kochite = mixture of zunyite, diaspore, and sericite
Kochubeite = Cr-clinochlore
Koechlinite 312
Koenenite 657
Kogarkoite = $Na_3[SO_4]F$ (belongs to sulfohalite group)
Kokkolite = Fe-diopside
Koksharovite = Al-magnesiocarinthite
Koktaite 594
Kolbeckite = sterrettite
Kolbekin = herzenbergite
Kollophane finegrained CO_3-fluorapatite
Kolovratite 504
Kolskite 458
Komarovite = $(Ca, Mn)\{Nb_2[Si_2O_7]O_3\} \cdot 3.5H_2O$ (belongs to nacalniotitasilite group)
Kongsbergite 195
Koninckite 531
Koppite = pyrochlore
Kornelite 593
Kornerupine = prismatine
Korynite = Sb-gersdorfite
Korzhinskite 491
Kosterite 228
Kostovite 213
Kotoite 466
Köttigite 523
Kotulskite 210
Koutekite 204
Kõzulite 416
Krausite 603
Krauskopfite 422
Kreittonite = Fe^{2+}, Fe^{3+}-gahnite
Kremersite = NH_4-erythrosiderite
Krennerite 212
Kribergite = $Al_5[PO_4]_3[SO_4](OH)_4 \cdot 2H_2O$ (?) (belongs to wavellite group)
Kröhnkite 603
Kryzhanovskite 562
Ktenasite 598
Kulerudite 243
Kunzite = Mn^{3+}-spodumene
Kupfferite = magnesiocummingtonite
Kupletskite = manganoastrophyllite
Kurchatovite 472
Kurgantaite = strontiohilgardite (?)

Kurnakite = bixbyite
Kurnakovite 477
Kurskite = carbonate-apatite
Kurumsakite 458
Küstelite = argentoargaurite
Kutinaite 205
Kutnahorite 612
Kuttenbergite = kutnahorite
Kyanite 386
Kyanophylite = diorthosilicate of Ca, Na, and Al (?)
Kylindrite = cylindrite
Kyrosite = As-marcasite

Labite 458
Labuntsovite = titanonakalniotisilite
Lacroixite 545
Laitakarite 261
Lamprophyllite 451
Lanarkite 586
Landauite 278
Landesite = Fe^{3+}-phosphoferrite
Långbanite 287
Långbanite = hexabraunite
Langbeinite 583
Langisite 203
Langite 598
Lansfordite 617
Lanthanite 618
Lapparentite = $Al_2(H_2O)_9[SO_4]_2(OH)_2$(?) (felsöbanyite group)
Larderellite 479
Larnite 386
Larsenite 385
Latiumite 394
Latrappite 295
Laubmannite = dufrenite (?)
Laueite 560
Laumontite 357
Launayite 253
Laurionite 654
Laurite 243
Lausenite 593
Lautarite 629
Lautite 256
Lavendulan 518
Låvenite 399
Lavrovite = V-magnesiodiopside
Lawrencite 644
Lawsonite 403
Laxmannite = vauquelinite
Lazarevićite = arsenosulvanite
Lazulite 544
Lazulite (old) = magnesiolazulite
Lazurite 350
Lead 193
Lead aragonite = Pb-aragonite
Lead calcite = Pb-calcite
Lead dolomite = Pb-magnesiodolomite
Leadhillite 624
Lead hydroxyapatite 541
Lead oxyfluoride 654
Lead smithsonite = Pb-smithsonite
Lecontite 595
Ledouxite = mixture of Cu_6As and NiAs
Legrandite 516
Lehiite 550
Leifite 350
Leightonite 594
Lembergite (of Sudo) = Fe^{3+}-saponite (of Svanderg)
Lemoynite 369
Lengenbachite 263
Lenoblite 333
Leonhardite = partly dehydrated laumontite
Leonhardtite 602
Leonite 595
Lepidocrocite 322
Lepidolite 443
Lepidomelane = Mg-ferrobiotite
Lermontovite = ningyoite (?)
Lesserite = inderite
Lessingite = britholite
Letovicite 604
Leuchtenbergite = var. of chlorite
Leucite 346
β-Leucite 346
Leucophanite 447
Leucophoenicite 391

Leucophosphite 551
Leucosphenite 363
Leucoxene = alteration product of ilmenite
Levyne 351
Lewisite = Ti-roméite
Lewistonite = K, Al-hydroxylapatite
Liberite 358
Libethenite 540
Liebigite 625
Likasite 633
Lillianite 252
Lillite = cronstedtite (?)
Limaite = Sn-gahnite
Limassolite = $4FeS \cdot 3(Mg, Fe)(OH)_2$ (belongs to valleriite group)
Lime 271
Limonite = mixture of hydrous iron oxides (mainly goethite)
Linarite 587
Lindackerite 516
Lindgrenite 571
Lindströmite 254
Linnaeite = cobaltpolydymite
Lipscombite = $(Fe,Mn)Fe_2[PO_4]_2(OH)_2$, tetragonal (lazulite group)
Liroconite 517
Liskeardite 517
Litharge 310
Lithidionite 458
Lithiophilite = manganotriphylite
Lithiophorite 328
Lithiophosphate 537
Lithium hureaulite = Li-hureaulite
Liveingite 235
Livingstonite 263
Lizardite 431
Lodochnikite = Th-brannerite
Loeweite = löweite
Lohey North tobermorite = hydroxonotlite
Lokkaite = $(Y, Ca)_2[CO_3]_3 \cdot 2H_2O$ (tengerite group)
Löllingite 206
Lombaardite = cerioepidote
Lomonosovite = phosphate-murmanite
β-Lomonosovite = H_2O-phosphate-murmanite
Lonchidite = As-marcasite
Lonsdaleite 192
Loparite 295
Lopezite 575
Lorandite 257
Loranskite = euxenite (?)
Lorenzenite = Zr-ramsayite
Lorettoite 654
Loseyite 616
Lotrite = pumpellyite
Louderbackite = Al-römerite
Loughlinite 420
Lovozerite 367
Löweite 594
Luckyite = Mn-melanterite
Ludlamite 553
Ludlockite 289
Ludwigite 467
Ludwigite (old) = magnesioludwigite
Lueshite 295
Lüneburgite 475
Lusakite = Co-staurolite
Lusungite 543
Luzonite 229
Luzonite (old) = arsenoluzonite
Lyndochite = Ca, Th-euxenite

Macallisterite 487
Macconnelite 313
Macedonite = makedonite
Macdonaldite 434
Macgovernite 394
Mackayite 565
Mackelveyite 618
Mackinawite 220
Mackinstryite 241
Mackintoshite = metamict U-thorite
Madocite 253
Magadiite 458
Magbasite 414
Magcerepidote 405
Magchlorophoenicite 514
Magferalsilite 382

Nuissierite = Ca-phosphoromimetite
Nyerereite 613

Obruchevite = Y, U-pyrochlore
Ochrolite 656
Octahedrite = anatase
Oellacherite = Ba-muscovite
Offretite 358
Okenite 434
Oktibbehite = Fe-nickel
Oldhamite 220
Oligonite = ferromanfercite
Oliveiraite 333
Olivenite 510
Olivine 384
Olivine (old) = Fe-magnesioolivine
Olsacherite 575
Olshanskyite 491
Omphacite 409
Ondřejite = mixture of huntite and magnesite
Onofrite (of Haidinger) = sulfometacinnabarite
Onoratoite 654
Oosterkoschite 221
Orange-bornite = renierite (may in part be idaite)
Orangite = var. of thorite
Orcelite 204
Ordinary hornblende 425
Ordoñezite 301
Oregonite 203
Orientite 407
Orlite 458
Orpheite 562
Orpiment 259
Orthochevkinite = orthorhombic chevkinite (?)
Orthoclase 346
Orthocobaltite 243
Orthoericssonite 398
Ortholåvenite 399
Ortholomonosovite = phosphate-murmanite
Orthopinakiolite 467
Orthose = orthoclase
Orthotorbernite = torbernite
Oruetite = sulfojoseite
Osannite = Al-arfvedsonite
Osarizawaite 588
Osbornite 200
Osmiridium = iridiosmirite
Osmite = osmiosmirite
Osumilite 379
Otavite 609
Ottemannite 248
Ottrelite = Mn-chloritoid (?)
Overite 550
Owyheeite 253
Oxychildrenite = Fe^{3+}- or Mn^{3+}-eosphorite
Oxykaersutite = ferrikaersutite (?)
Oxykerchenite = Fe^{2+}-ferrivivianite
Oyamalite = TR, PO_4-zircon

Pabstite 362
Pachnolite 664
Paigeite = ferroludwigite
Painite 280
Palermoite 544
Palladinite 313
Palladium 192
Pallite 551
Palmierite 583
Palstibite 203
Palygorskite 420
Pandaite 276
Pandermite 483
Papagoite 373
Parabutlerite 599
Paracelsian 344
Paracoquimbite 593
Paracostibite 245
Paradamite 510
Paradocrasite = Sb_3As (belongs to special group in class of simple substances)
Paragearksutite = gearksutite
Paragonite 442
Paraguanajuatite 261
Parahilgardite 488
Parahopeite 532

Picromerite 595
Picroorthite = Mg-cerioepidote
Picropharmacolite 515
Picrosmine = chrysotil
Picrotephroite = Mg-manganoknebelite
Piedmontite = piemontite
Piemontite 405
Pierrotite 236
Pigeonite = Ca, Al-clinohypersthene
Pilinite = bavenite
Pilolite = Al-palygorskite
Pimelite = Ni-talc (?)
Pinakiolite 467
Pinnoite 473
Pintadoite 504
Pirssonite 619
Pisanite = Cu-melanterite
Pisekite = Th, Ti-samarskite
Pistomesite = Mg-ferromagfercite
Pitticite 525
Plagioclase 344
Plagionite 234
Plancheite 413
Planerite = evansite (?)
Planoferrite 606
Platarsulite 244
Platinum 192
Platinum gold = Pt-electrom
Platstibite 203
Plattnerite 297
Platynite 261
Playfairite 253
Plazolite 382
Pleonaste = Fe^{3+}-magnesiospinel
Plinthite = mixture of kaolinite, montmorillonite, and hematite
Plumangite 313
Plombierite 435
Plumbocalcite = Pb-calcite (partly)
Plumbocolumbit = Pb-niobiosamarskite
Plumbodolomite = Pb-magnesiodolomite
Plumboferrite 280
Plumbogummite 543
Plumbojarosite 588
Plumbomalachite 627
Plumbomicrolite 276
Plumbonacrite = impure hydrocerussite
Plumbopalladinite = Pb_2Pd_3 (moschellandsbergite group)
Plumbosvanbergite = Pb-svanbergite
Plumbosynadelphite = Pb-synadelphite
Plumcusulasite 513
Poitevinite 590
Polarite 194
Polianite = pyrolusite
Pollucite 346
Polybasite 240
Polybasite (old) = stibiopolybasite
Polycrase = Ti-euxenite
Polydymite 223
Polydymite (old) = nickel-polydymite
Polyhalite 594
Polylithionite = group name of Li-mica
Polymignite = Fe, Nb-zirconolite (?)
Polysphaerite = Ca-phosphoromimetite
Polyxen = Fe-platinum
Porpezite = Pb-electrum
Portlandite 324
Posnjakite = poznyakite
Potarite 194
Potash alum = alum
Poughite 565
Powellite 569
Poznyakite 598
Pravdite = altered britholite
Prehnite 439
Prelaumontite = var. of laumontite
Preobrazhenskite 484
Priazovite = metamict Ta-betafite
Pribramite (of Huot) = Cd-sphalerite
Priceite 491
Priderite 306
Priorite 296
Priorite (old) = Nb-priorite
Prismatine 392
Proarizonite = mixture of rutile, ilmenite, and hematite
Probertite 484
Prochlorite = ripidolite
Prosopite 653
Protodoloresite 328
Protovermiculite 446
Proustite 239
Przhevalskite 556

Sommairite = Zn-melanterite
Sonolite 391
Sonomaite 606
Sonoraite 565
Sorbyite 253
Sorensenite 362
Souesite = Fe-nickelite
Souxite = colloidal cassiterite + FeOOH
Souzalite 551
Spadaite = stevensite (?)
Spangolite 332
Specularite = hematite
Spencerite 549
Spencite = Al-yttromelanocerite
Sperrylite 206
Spessartine = manganoferalsilite and manganocalcmanalsilite
Sphaerobertrandite 401
Sphalerite 222
Sphene = titanite
Spherocobaltine = cobaltocalcite
Spinel 284
Spinel (old) = magnesiospinel
Spiroffite 564
Spodiosite 562
Spodumene 410
Spurrite 394
Staffelite = carbonate-apatite
Stainierite = heterogenite
Stannite 228
Stannoenargite = Sn-enargite
Stannoidite 228
Stannoluzonite = Sn-stibioluzonite
Stannopalladinite 198
Stannoplatinite 198
Stannotantalite = wodginite
Stannotetrahedrite = Sn-stibiotetrahedrite
Staringite 301
Starkeyite = leonhardtite
Stasite = dewindtite
Stassfurtite = boracite (fibrous aggregates)
Stassfurtite I = Fe-boracite
Stassfurtite II = Fe-boracite
Staszicite = Zn-conychalcite
Staurolite 388
Steenstrupine 370
Steigerite 496
Stellerite = stilbite
Stenhuggarite 289
Stenonite 666
Stephanite 240
Stercorite 548
Sternbergite 265
Sterrettite 531
Sterryite 253
Stetefeldtite 277
Stevensite 446
Stewartite 560
Stibianite = stibiconite
Stibiconite 277
Stiblite = stibiconite
Stibiobismuthine = Sb-bismuthinite
Stibiocolumbite 274
Stibiodomeykite = Sb-domeykite
Stibioenargite = Sb-enargite
Stibiomicrolite = Sb-microlite
Stibioniobite = niobostibiocolumbite
Stibiopalladinite 205
Stibiotantalite = tantalostibiocolumbite
Stibiotellurobismutite = Sb-tellurobismutite
Stibnite 246
Stichtite = magchromohydrite-3R
Stiepelmannite = La-florencite
Stilbite 354
Stilleite 222
Stillwellite 423
Stilpnochlorane 436
Stilpnomelane 436
Stishovite 297
Stistaite = SnSb (belongs to special group of arsenides etc. class with sphalerite structure)
Stokesite 419
Stolzite 569
Stottite 316
Stranskiite 509
Strashimirite 516
Strengite = ferrivariscite
Stromeyerite 241
Strontianite 610

Wiserite 473
Wismuthantimon = Bi-antimony
Witherite 610
Wittichenite 254
Wittite = Se-hammarite
Wodanite = Ti-biotite
Wodginite 302
Wöhlerite 399
Wolchonskoite = volkonskoite
Wolfachite = Sb-gersdorffite
Wolframite 302
Wolframoixiolite = W-ixiolite
Wolfeite = ferrotriploidite
Wolfram-Powellite = WO_4-powellite
Wollastonite 410
Wölsendorfite 327
Woodfordite = ettringite (?)
Woodhouseite 543
Woodruffite 319
Wulfenite 569
Wurtzite 223
Wüstite 271
Wyartite 327
Wyarite I = wyartite
Wyarite II = parawyartite

Xanthiosite 509
Xanthochroite = var. of greenockite
Xanthoconite 239
Xanthophyllite 441
Xanthoxenite 550
Xenotime 536
Xonotlite 417
Xylotilite = $Fe^{2+}Fe^{3+}$-chrysotile

Yagiite 379
Yamaguchilite = metamict PO_4-zircon
Yamatoite = Mn^{2+}-goldmanite
Yavapaiite 583
Yberisilite 446
Yeatmanite 390
Yellow yttrotantalite = Ta-yttrofergusonite
Yoderite 388
Yokosukaite = nsutite
Yoshimuraite 453
Yttergarnet = Y-grossular
Yttrialite-I 396
Yttrialite-II 396
Yttrium aeschynite = Y-aeschynite
Yttrium spessartine = Y-manganomanferalsilite
Yttrobastnäsite 613
Yttrocalciofluorite 669
Yttrocalcite = Y-calcite
Yttrocerite = Ce-fluorite
Yttrocrasite = Th, Ti-euxenite
Yttrofluorite = Y-fluorite
Yttromanganoilmenite = Mn, Y-ferroilmenite
Yttro-orthite = muromontite
Yttrosynchysite = Y-synchysite
Yttrotantalite (black) = Nb-formanite (part), tantalosamarskite (part)
Yttrotitanite = Y-titanite
Yttrotungstite 573
Yugawaralite 357
Yukonite 525
Yuksporite = rosenbuschite

Zaratite 619
Zavaritskite 653
Zellerite 625
Zemannite 565
Zeophyllite 430
Zeunerite 521
Zeyringite = mixture of aragonite with aurichalcite
Zinalsite = var. of sauconite (?)
Zinc 194
Zincaluminite 332
Zinc-aragonite = Zn-aragonite (?)
Zinc blende = sphalerite
Zincboothit = Zn-boothite
Zinc cerussite = Zn-cerussite (?)
Zinc chromite = Zn-ferrochromite
Zinc dannemorite = Mn, Zn-cummingtonite
Zinc-fauserite = Zn-fauserite
Zinc hexahydrite 591
Zincite 272
Zinc jacobsite = Zn-jacobsite