

CONTRIBUTIONS TO THE MINERALOGY OF NORWAY

No. 9. On the occurrence of two rare phosphates in the Ødegården Apatite mines, Bamble, South Norway

1. A VARIETY OF WOODHOUSEITE

2. WHITLOCKITE

By

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Abstract. A description is given of varieties of woodhouseite and whitlockite found in specimens from the apatite-rich veins cutting the Precambrian rocks at Ødegårdens verk, Bamble, S. Norway. The minerals occur, together with quartz, in pockets within a matrix of chlor-hydroxy-oxypatite. Physical and optical data are given for both minerals, together with x-ray powder diffraction data. A semi-quantitative spectrographic analysis of the whitlockite is included.

The woodhouseite is a purple variety with lattice dimensions of a_h 7,001, c_h 16,265, c/a 2,325, a_r 6,76 and $\angle a$ 62° 22'; its optical constants are $N_e = 1,669 (\pm 0,003)$, $N_o = 1,662 (\pm 0,003)$, $N_e - N_o$ 0,007 ($\pm 0,003$), uniaxial positive (or occasionally biaxial with 2V of 10° to 20°). An unidentified alteration product after woodhouseite is also described.

The whitlockite is a green variety, containing approximately 0,3% V_2O_5 , with optical constants: $N_o = 1,620 (\pm 0,003)$, $N_e = 1,623 (\pm 0,003)$, $N_e - N_o$ 0,003 ($\pm 0,003$), uniaxial negative.

It is concluded that the minerals in these pockets represent either final residual products of crystallisation within the apatite vein or that they were formed during a later period of metamorphism, metasomatism and hydrothermal activity which may have affected the apatite veins.

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General Introduction

At Ødegårdens verk in Bamble, Telemark, South Norway, phosphate-bearing veins, up to 4 m thick, cut the Precambrian metamorphic rocks of the Kongsberg—Bamble formation. The metamorphic suite in the area comprises garnetiferous amphibolites, quartzites, scapolite-hornblende metagabbro (the 'Ødegårdite' of W. C. Brøgger) and scapolite-amphibolites. The most common type of phosphate-bearing vein has central lensoid bodies composed of phosphate minerals and rutile. These lenses are surrounded by a dense mass of coarse-grained phlogopite, enstatite (often pseudomorphed by talc), scapolite and phosphates. From preliminary investigations it has been concluded that a later group of granitic pegmatites cuts these phosphate-rich veins.

A list of some of the minerals found in these veins has already been published (see NEUMANN, JØSANG and MORTON 1960 p. 15). The predominant phosphates occurring within these bodies are apatites, (generally chlor-varieties). The area was extensively mined for the apatite between 1872 and 1918.

During a study of the minerals from these veins, the author had access to W. C. Brøgger's original collection from the old apatite mines. Two small specimens labelled "Apatite med grøn Varietet, Ødegården, Bamble", (i.e. Apatite with green variety) were examined in detail and found to contain as well as apatite, whitlockite and occasional tiny crystals of a variety of woodhouseite.

The samples containing these two rare phosphates were obviously collected from one of the apatite-rich veins during the mining operations. In both samples the host-matrix is a coarse grained massive chlor-hydroxy-oxyapatite (i.e. chlor-hydroxy-voelckerite). Small pockets within the apatite are filled by quartz, whitlockite and woodhouseite; see Plate I, fig. 1. The quartz generally occurs around the periphery of the pocket as colourless, transparent, euhedral prismatic crystals up to 5 mm in length and 1 mm broad. Most of the space in these pockets is occupied by whitlockite. The whitlockite occurs as coarsely crystalline masses. Always within the whitlockite, and never within the apatite, are tiny groups of woodhouseite crystals. In the specimens occasional chalcopyrite grains are seen in later veins which cut the apatite.

1. Woodhouseite from Ødegården

INTRODUCTION.

Woodhouseite, a very rare member of the Beudantite group (Alunite-Woodhouseite group of STRUNZ 1957) has only once before been found. This mineral, having the composition — $[\text{CaAl}_3(\text{PO}_4)(\text{SO}_4)(\text{OH})_6]$, was described by LEMMON (1937) from White Mountain, Mono County, California. There it is found together with masses of lazulite in vugs within quartz veins which cut andalusite deposits. Topaz, augelite, tourmaline, barite, muscovite and pyrophyllite are also found in these veins.

The type material from White Mountain is described as colourless, white, or flesh-coloured, striated rhombohedral crystals which are transparent or translucent. Their habit is predominantly pseudo-cubic. The optical character is uniaxial positive, but certain crystals were composed of six radial biaxial segments having an axial angle $2V \approx 20^\circ$ maximum. The birefringence is 0,011 and R.I. $n_\alpha = 1,636$, $n_\beta = 1,638$ and $n_\gamma = 1,647$ ($\pm 0,003$). An excellent basal cleavage parallel to (0001) was observed. The original mineral was found to be hexagonal with cell dimensions of $a_h = 6,961$; $c_h = 16,27$; $c/a = 2,338$; $a_{rh} = 6,75$; $\alpha = 62^\circ 04'$ (PABST 1947).

DESCRIPTION

a. *Physical and optical properties.*

The woodhouseite from Ødegården occurs as a few tiny clusters of euhedral crystals whose maximum dimensions are 1,5 mm. These exhibit a pseudo-cubic form ($10\bar{1}2$). The crystal faces are highly striated in all the specimens. Their colour varies from a pale lilac to a deep purple. In most crystals there is a rough zoning, with the lighter lilac-coloured woodhouseite in the central parts, grading outwards into the dark purple around the outer periphery of the crystals. All the crystals are completely transparent, possess a very poor cleavage and generally have an irregular fracture. Their lustre is vitreous and $H = \text{ca. } 4$.

Rarely the woodhouseite is altered to a cream-coloured or white, very fine-grained, powdery substance; (see below).

The optical properties, obtained from the powdered mineral, are

as follows. Very thin fragments are colourless but larger grains i.e. $> 0,25$ mm exhibit a very weak pleochroism in shades of pale lilac. It is uniaxial positive in most grains but some occasionally possess a positive biaxial character with an axial angle $2V = 10^\circ$ to 20° . The indices of refraction, measured at 20° C using monochromatic Na light are: $N_e = 1,669$ (0,003); $N_o = 1,662$ (0,003); $N_e - N_o = 0,007$ (0,003). The biaxial fragments show low-order dark interference colours between crossed nicols.

b. *Crystallographic observations from powder diffraction patterns.*

Table 1 serves as a comparison between the observed spacings and intensities (down to $d = 1,293$) for woodhouseite from Ødegården and those of woodhouseite from the White Mountains. The observed intensities of lines in the new woodhouseite pattern were obtained by comparison of peak-heights on a photometer-curve. The somewhat different observations of various authors concerning the data for material from White Mountain is also included in Table 1; (see YGBERG 1945, McCONNELL 1942 and PABST 1947).

Table 2 serves as a supplement to the preceding table and compares the lines of $d < 1,293$ observed in the pattern of the mineral from Ødegården with those previously published.

The corresponding lattice dimensions were calculated from the data given in Tables 1 and 2. The powder pattern was obtained with a 9 cm Debye-Schaeerer camera using Fe radiation with an Mn filter. Table 3 shows that the lattice dimensions of the woodhouseite from Ødegården are in relatively close agreement with the results of Lemon, Pabst and Ygberg. It is however noticeable that all these dimensions, with the exception of the hexagonal 'c' axis, differ slightly from the data obtained from the earlier studied materials.

c. *Conclusions concerning the woodhouseite.*

From the observations given above, it is concluded that the mineral found at Ødegården is definitely a member of the Beudantite group possessing properties suggest it to be a variety of woodhouseite. However, owing to the lack of material for chemical analysis, no definite conclusions can be reached concerning the causes of small, but distinct, optical and structural variations from previously recorded data on woodhouseite.

Table 1. Observed spacings and intensities in powder diffraction patterns of woodhouseite for intervals higher than d_{hkl} 1.29.

Locality: White Mtn., N. Inyo Range, Cal. USA				Ødegården				
Author: Pabst (1947)		Ygberg (1945)		McConnell (1942)		Morton		
Radiation: Cu		Cu		Fe		Fe		
hk̄l̄	h _r k _r l _r	I	d _{hkl}	I	d _{hkl}	I	d _{hkl}	hkil
10 $\bar{1}1$	100	.30	5.66	m	5.73	<0.8	5.61	0.5 6.229
0003	111							0.7 5.688
01 $\bar{1}2$	110	.40	4.84 ⁺	m	4.86	0.8	4.81	0.6 4.834
								0.2 4.139
								0.2 3.844
						<0.8	3.83	3.9 3.704
11 $\bar{2}0$	10 $\bar{1}$.90	*3.48 ⁺	s	3.51	1.7	3.46	
10 $\bar{1}4$	211							
		.20	3.27 ¹			3.3	3.21 ¹	0.8 3.241 ¹
02 $\bar{2}1$	11 $\bar{1}$					3.3	2.96	
11 $\bar{2}3$	210	2.45	*2.93	s+	2.99	10.0	2.91	10.0*2.939
01 $\bar{1}5$	221	.15	2.84					0.7 2.832
20 $\bar{2}2$	200							
0006	222	.45	2.70	w	2.72	1.7	2.68	1.7 2.721
		.15	2.56 [§]					
02 $\bar{2}4$	220	.40	*2.42	w	2.40	1.7	2.42	1.6 2.436
						3.3	2.37	
21 $\bar{3}1$	20 $\bar{1}$							
20 $\bar{2}5$	311							1.7 2.216
12 $\bar{3}2$	21 $\bar{1}$	2.10	2.19 ⁺ 2.16 ⁻	s+	2.18	5.0	2.198	3.8 2.145
10 $\bar{1}7$	32 $\bar{2}$					6.7	2.15	6.1 2.134
11 $\bar{2}6$	321							
		.20	2.09 ⁺			3.3	2.068 ¹	0.5 2.088 ¹
30 $\bar{3}0$	21 $\bar{1}$							

Table 1, continued.

Locality: White Mtn., N. Inyo Range, Cal. USA					Ødegården					
Author: Pabst (1947)					Ygberg (1943)		McConnell (1942)		Morton	
Radiation: Cu					Cu		Fe		Fe	
hkil	$h_r k_r l_r$	I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	I	d_{hkl}	hkil
022.10	442	1.55*	1.432	m	1.43	5.0	1.426	3.7	1.437	022.10
4044	400	.25*	1.416					1.0	1.418	4044
3251	302									3251
0445	331									0445
2352	312	.55B	1.366	w-	1.36			1.2	1.364	2352
1347	430									1347
000.12	444									000.12
0339	441	.40*	1.345	w-	1.34			1.2	1.349	0339
3039	522									3039
202.11	533									202.11
213.10	532	.40B	1.332	w	1.31			0.9	1.324	213.10
4150	312									4150

* Lines used in cell dimension calculations.

§ Unidentified line; contamination?

¹ β lines.

Table 2. Observed lines in woodhouseite powder diffraction patterns for the interval d_{hkl} 1.29 to d_{hkl} 0.90.

N. Inyo Range, California				Ødegården	
Pabst (1947)		Ygberg (1945)		Morton	
Cu rad.		Cu rad.		Fe rad.	
I	d_{hkl}	I	d_{hkl}	I	d_{hkl}
4	1,282	m	1,27	2,7	1,286
1	1,262				
2	1,225				
5	1,192	m	1,19	2,0	1,194
				1,2	1,171
4	1,164	w+	1,16	1,5	1,166
3-	1,138	w	1,13	0,5	1,141
2	1,124				
2	1,106			1,0	1,110
4	1,098	w-	1,10	1,0	1,103
4	1,078	w+	1,07		
2+	1,067				
2+	1,056				
2	1,036				
2		1,031			
3	1,007				0,9
3	1,003	w	1,00		
2-		0,962			
5	0,953	w+	0,95		
4	0,945	w	0,94		
5	0,935	w+	0,93		
2-	0,930				
3+	0,913	w-	0,91		
5	0,903	w	0,90		

Table 3. Lattice dimensions of woodhouseite.

Author	Hexagonal axes			Rhombohedral axes	
	a_h	c_h	c/a	a_r	$\angle a$
Lemmon (1937)	—	—	1.170 (0,5 × 2,340)	—	—
Ygberg (1946)	6,93	16,3	2,352	6,75	*61°75'
Pabst (1947)	6,961	16,27	2,338	6,75	62°04'
Morton	7,001	16,265	2,325	6,76	62°20'

* Value said to be 61°48' by Pabst (1947).

d. *The alteration product after woodhouseite.*

A feature rarely seen in these specimens is the alteration of the woodhouseite crystals to a white or cream-coloured powdery aggregate. This alteration is either confined to the periphery of the crystal or to its core. The scarcity of material made it impossible to identify this alteration product. However, certain observations were made: —

The mineral is in the form of an extremely fine-grained, powdery mass which under the microscope is seen to be composed of completely anhedral crystals. The refractive index lies in the region of 1,7 and the birefringence is moderate. An x-ray powder diffraction run gave a very weak film in which the three strongest lines lay at d_{hkl} values of 4,16 (strongest), 3,75 (2nd strongest) and 3,41 (3rd strongest).

2. Whitlockite from Ødegården

INTRODUCTION.

Whitlockite, the natural form of β — $\text{Ca}_3(\text{PO}_4)_2$ i.e. the low-temperature polymorph of tricalcium phosphate, was originally found as a hydrothermal mineral associated with siderite, quartz, apatite, ludlamite, fairfieldite, xanthoxenite and triphyllite in a pegmatite at Palermo mine near N. Groton, New Hampshire, U.S.A. (FRONDEL 1943). It has also been found in phosphate-rock deposits on the island of Sombrero near the Virgin Islands (JULIEN 1865 and FRONDEL 1943), on the Los Monges keys in the gulf of Maracaibo (FRONDEL 1943) and on Table Mountain, Curaçao in the West Indies (KLOOS 1888 and FRONDEL 1943). Whitlockite was also recorded from cave-deposits at Sebdu, Oran, in Algeria (Bannister 1947) and from certain slags (TRÖMEL 1932 [DANA]; TRÖMEL and MÖLLER 1932; BREDIG, FRANCK and FÜLDNER 1932; *ibid* 1933). As far as the author is aware, there is no previous record of whitlockite in Norway.

The whitlockites previously described were transparent to translucent, colourless, white, grey or yellowish. The lustre was said to be vitreous or subresinous. In transmitted light they were colourless with $N_o = 1,607$ to 1,629, $N_e = 1,604$ to 1,626, birefringence 0,003 and uniaxial negative; (DANA 1951).

DESCRIPTION.

a. *Physical and optical properties.*

The whitlockite from Ødegårdens verk was found as coarse- and fine-grained, crystalline massive aggregates occasionally showing fragmentary, striated crystal-faces. The mineral is highly variable in colour and ranges from colourless, in a few cases, to a fine pale emerald green in most parts. In all the specimens it is completely transparent. There is no distinct zonation of the colour and it appears to be highly irregular in its distribution. The mineral exhibits no cleavage and has a subconchoidal fracture. Its lustre is vitreous and the hardness approximately 5.

The optical properties, measured using the powdered mineral, are as follows. It is completely transparent and colourless in transmitted light, uniaxial negative with $N_o = 1,620 (\pm 0,003)$, $N_e = 1,623 (\pm 0,003)$ and birefringence 0,003.

b. *Observations from x-ray powder diffraction diagrams.*

Table 4 compares data for observed spacings and intensities in the whitlockite from Ødegården and the data for previously described whitlockites. The θ values published by BREDIG et al (1932) have been recalculated to d_{hkl} values for the purpose of direct comparison.

It will be seen from the above mentioned table that the data for the mineral from Ødegården agrees well with that from the earlier whitlockites.

c. *Spectrographic analysis.*

Owing to the scarcity of material, no detailed chemical analysis was performed. However, a semiquantitative spectrographic analysis of the bright green whitlockite was kindly done by Prof. Ivar Oftedal. The results were as follows:

Main components — P, together with Ca and less Mg.

Traces — Si, Fe, Mn, Al, Na and V. (The vanadium line was remarkably strong and appears to indicate a concentration of around 0,3% V_2O_5).

It is noteworthy that this is a vanadium-rich whitlockite and it is possible that the unusual green colour may be caused by this vanadium content.

Table 4. Observed spacings and intensities in powder diffraction patterns of natural and synthetic whitlockite.

Sebdou, Alg.		N. Groton, NH.		Palermo		Artificial prod.		Ødegården	
A.S.T.M. Ind.		Frondel (1943)		Fisher 1958		Bredig et al 1932		Morton	
Radiation:		Cu		Fe		Cu		Fe	
I	d _{hkl}	I	d _{hkl}	I	d _{hkl}	I	d _{hkl}	I	d _{hkl}
60	5.2	2.0	8.03	Only the three stron- gest lines published.	m	8.815	0.4	6.323	
		5.0	6.55		ms	6.505			
		8.0	5.24		s	5.242			
50	3.43	4.0	4.07	7.0	3.16	w	4.392	1.5	4.003
		7.0	3.45			ms	4.111		
		1.0	3.35			vw	3.831		
70	3.17	9.0	3.21	10.0	2.85	s	3.468	1.0	3.309
		1.0	3.02			vs	3.221		
100	2.85	10.0	2.88	8.0	2.58	w	3.025	6.3	3.168
		3.0	2.75			vs	2.897		
70	2.59	1.0	2.68	m	2.838	vs	2.843	10.0	2.843
		9.0	2.60			m	2.725		
20	2.39	2.0	2.52	mw	2.421	vs	2.605	8.7	2.576
		2.0	2.41			mw	2.533		
20	2.24	2.0	2.25	m	2.270	mw	2.421	1.5	2.489
		2.0	2.19			m	2.208		
20	2.15	2.0	2.16	m	2.169	m	2.270	1.0	2.379
		1.0	2.07			m	2.088		
20	2.05	2.0	2.04	m	2.043	m	2.208	0.6	2.680
20	2.01	1.0	2.00			m	2.169		
60	1.92	6.0	1.93	m	2.009	m	2.088	2.3	2.011
		5.0	1.88			m	2.043		
60	1.86	1.0	1.82	s	1.924	s	1.951	1.1	1.973
		3.0	1.77			s	1.924		
20D	1.79	7.0	1.72	m	1.850	m	1.850	5.1	1.913
		1.0	1.70			m	1.819		
100	1.71	2.0	1.67	vs	1.736	m	1.819	2.2	1.873
		1.0	1.63			m	1.789		
100	1.71	1.0	1.60	w	1.694	vs	1.736	2.9	1.857
		2.0	1.67			w	1.694		
100	1.71	1.0	1.63	mw	1.645	w	1.694	1.4	1.694
		1.0	1.60			mw	1.645		
100	1.71	1.0	1.60	m	1.612	mw	1.645	1.7	1.666
		1.0	1.63			m	1.612		
100	1.71	1.0	1.60	m	1.612	m	1.612	0.8	1.623
		1.0	1.60			m	1.612		
100	1.71	1.0	1.60	m	1.612	m	1.612	0.8	1.609
		1.0	1.60			m	1.612		
100	1.71	1.0	1.60	m	1.612	m	1.612	0.6	1.588
		1.0	1.60			m	1.612		

Table 4, continued.

Sebdou, Alg.		N. Groton, NH.		Palermo		Artificial prod.		Ødegården	
A.S.T.M. Index		Fron del (1943)		Fisher (1958)		Bredig et al (1932)		Morton	
Radiation:		Cu		Fe		Cu		Fe	
I	d _{hkl}	I	d _{hkl}	I	d _{hkl}	I	d _{hkl}	I	d _{hkl}
60	1.55	5.0	1.55			s	1.562	3.1	1.537
						vw	1.533		
						w	1.513	0.9	1.505
						mw	1.478	0.4	1.489
		1.0	1.46			mw	1.458	0.8	1.453
		1.0	1.43			mw	1.440	1.3	1.427
		1.0	1.40			m	1.418	1.8	1.398
		1.0	1.38			m	1.392	0.5	1.376
						etc.		0.9	1.292
								0.5	1.291
								0.6	1.278
20	1.26	2.0	1.25			(Data calc.		1.3	1.249
50	1.24	2.0	1.24			from published		0.5	1.241
						values of Θ .)		0.8	1.232
								0.6	1.210
50	1.18	1.0	1.18					0.7	1.178
								0.4	1.172
		1.0	1.15					0.5	1.152
								0.5	1.141
								0.4	1.121
60	1.12	3.0	1.11					1.0	1.115
20	1.10	1.0	1.09					0.7	1.087
		1.0	1.05					0.7	1.052
50	1.03	1.0	1.03					0.5	1.032
								0.5	1.029
								0.5	1.026
20	1.01							0.5	1.009
								0.4	0.991
20	0.987							0.3	0.986
								0.5	0.984
								0.5	0.981

General Conclusions

Finally it remains to consider the origin of the two phosphates just described. On the basis of the meagre evidence presented by the specimens, it is apparent that the mineral association found within these pockets could have two modes of origin. Firstly the minerals (i.e. whitlockite, woodhouseite and quartz) could be products of the last stages of crystallisation within the apatite veins. They would therefore represent the final impure residues enriched in Al, Si, Mg, Fe, Mn, Na, V, OH, SO₄ etc. after the crystallisation of the relatively pure host chlorapatite.

A second possibility is that these minerals were formed during a subsequent stage of metamorphism, metasomatism, and hydrothermal activity which might have affected the large apatite veins; (for example during the period of granitic-pegmatite introduction which obviously post-dated the apatite veins in this area).

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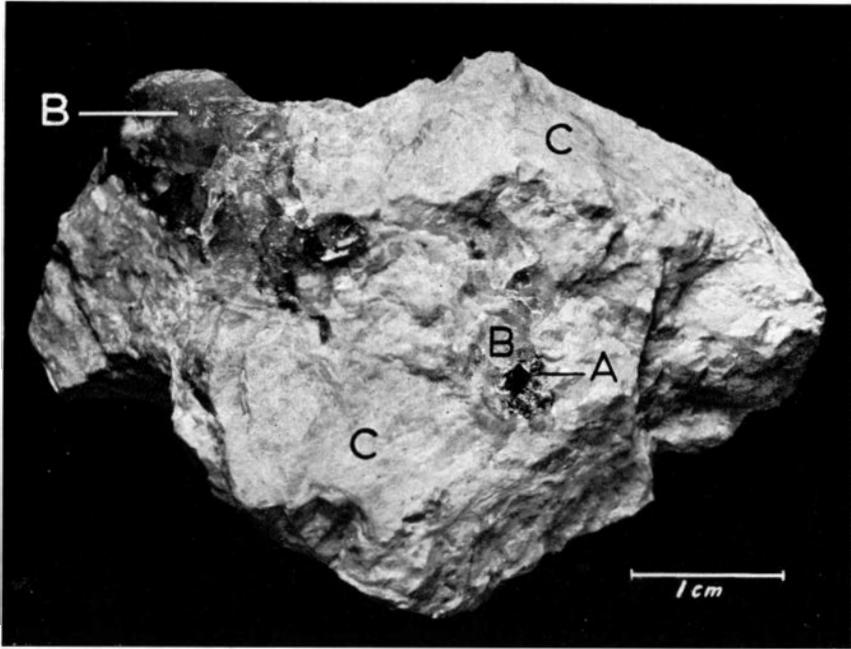


Fig. 1. Specimen from the Ødegården Apatite mines showing massive apatite enclosing pockets containing whitlockite and woodhouseite. A = woodhouseite; B = whitlockite; C = apatite.

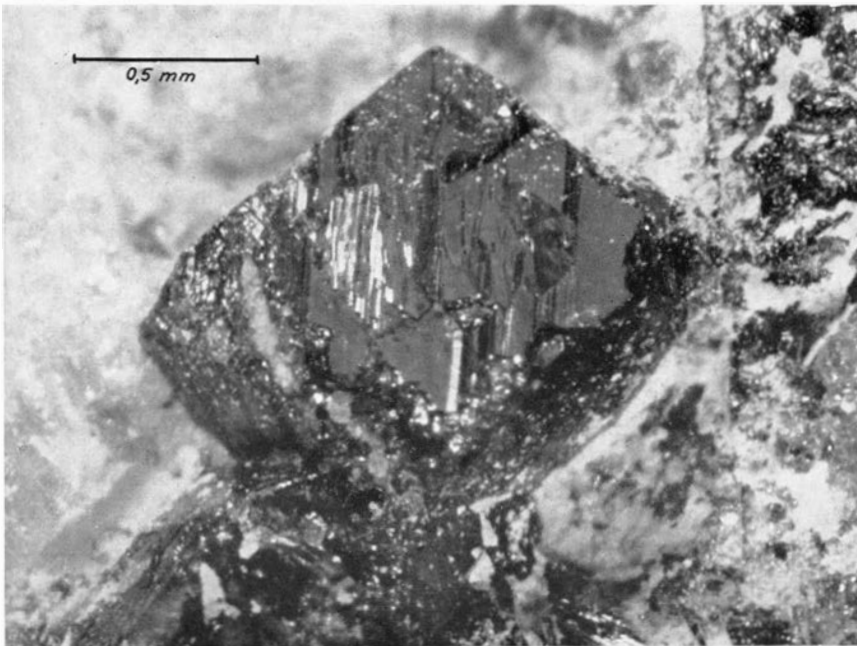


Fig. 2. A euhedral crystal of woodhouseite from the Ødegården Apatite mines illustrating the characteristic form and the nature of the striations seen on the crystal-faces.