

IDENTIFICATION OF THE COPPER ORE MINERALS
BY MEANS OF X-RAY POWDER
DIFFRACTION PATTERNS¹

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PRESENT METHODS OF MINERAL INVESTIGATION

The technique of producing good polished sections of ore minerals is now well developed, and the methods of mineral identification are highly advanced. The minerals are examined in polished section by means of the reflecting microscope. This will probably continue to be the most convenient means for the study of opaque minerals, since, in general, mineral identification is rapid and fairly accurate, and mineral textures, which are of the utmost importance, may also be observed. Micro-chemical and etch tests are used in this work, aided by the polarizing microscope and observations of color, internal reflection, hardness, magnetism, and special properties. Tables for mineral identification based on the foregoing tests have been written by Murdoch (45),² Davy and Farnham (19), Farnham (21), Schneiderhöhn and Raudoehr (60), and Short (61).

Although the majority of minerals can now be determined by the methods commonly in use, the rare minerals in particular are still difficult, and occasionally impossible, to identify. The same is often true of minerals present in minute grains. In the latter case their general appearance seems to be modified by their surroundings, and the reagents, which will be in contact with more than one mineral, may bring about electrolytic effects which will completely change the expected reactions, causing incorrect identifications. Since mineral identification is essential in economic geology, any method which promises improvement of results is well worth use and further development. Such a method of accurate determination is possible by the use of *x*-ray powder diffraction data, a fact pointed out by Kerr (41) as long ago as 1924.

POWDER DIFFRACTION METHOD

A small amount of a powdered crystalline mineral placed in a beam of *x*-rays will produce a characteristic line or ring pattern on

¹ Abstract of a dissertation submitted to the Division of Geological Sciences of Harvard University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

² In order that the footnotes may be shortened all numbers in parentheses refer to the complete bibliography at the end of this article.

a photographic film. The possible use of this method for mineral identification has long been appreciated and its greater use predicted. Physicists and mineralogists have used the method, in conjunction with other types of x -ray studies, primarily in the working out of atomic structures of minerals. The Geophysical Laboratory has employed this method effectively in the study of solid solution series in artificial melts. The gradual change in spacing of the lines on the records may often be observed as the composition of the melt is changed gradually from one end member to the other. These records can be used to determine, by comparison, the composition of unknown members of the same series. Some use has been made of the diffraction method purely for purposes of mineral identification (66); but the data for such work is available in relatively few places, and lists of diffraction data arranged in tables which would allow the general worker to make identifications of unknown minerals by this method are not yet published. The metallurgists, working also with opaque compounds, are far ahead of the economic geologist in their appreciation and use of this tool for mineral identification.

A few, however, have recognized the use of x -ray diffraction patterns as an aid to the economic geologist. In 1924 Kerr (41) published an article in which he pointed out the use of this method in mineralographic work, and explained the technique to be used. Here also he reproduced a few of his x -ray records and explained their calculation and interpretation. He did not, however, give any table of data by means of which the identification of unknown minerals can be made.

It is not necessary to know the complete theory of x -ray production or of x -ray analysis of crystal structure in order to make use of the powder method simply as a means of identification. The powder method also lends itself admirably to polished section study, since any mineral dug or drilled from such a section must of necessity be in the powdered form, and under the microscope very pure material may be secured. In addition to identification of distinct species, it is possible, by use of the accurate apparatus now available, to determine the end members of isomorphous series, and, under favorable conditions, to make some estimate of the composition of intermediate members of the series. Finally, under proper manipulation and control the method leads to results having a high degree of dependability.

SCOPE AND PURPOSE OF INVESTIGATION

Because of the advantages just enumerated, this method was adopted by the writer in the hope of advancing the general technique of ore mineral identification. It was decided to start with the investigation of the copper ore minerals, and in the time available it has not been possible to extend the study generally outside that group. It is hoped that similar tables for the remainder of the ore minerals may in time be added to the material now presented. The usefulness of this table will be greatly diminished until that is done. Most of the non-opaque copper minerals are rare in occurrence and may be identified more readily by means of the petrographic microscope than by x -ray patterns. Therefore, only the minerals in this group which are occasionally important as ores are here included.

As originally planned, this article contained a résumé of the theory of x -ray powder diffraction, and the technique necessary in order to secure good photographs, in addition to the method of indexing herein proposed and the tables here presented. It was hoped, thereby, to prepare one short article, the use of which would enable one to prepare his material, photograph it, read the record, and, finally, to identify it. Because of the lack of space and the fact that many good articles on the theory and technique are available, only the method of indexing and the tables are here presented. The articles which best cover the theory and technique of x -ray powder diffraction work include Kerr (41), Bragg and Bragg (9), Wyckoff (68), Clark (14), and Davey (18).

ACKNOWLEDGMENTS

The writer is indebted to many for suggestions and assistance in this work, especially to members of the Division of Geology and Metallurgy at Harvard. The need of further x -ray work on known ore minerals, and the organization of these and older data into a serviceable table for mineral identification was pointed out by Mr. Harry Berman of the Department of Mineralogy. He encouraged the writer to undertake the problem and gave advice and guidance during the progress of the work. Both he and Professor Charles Palache were most generous of their time in securing specimens for this study. Professor L. C. Graton helped to make the x -ray work possible, gave encouragement and advice in its progress, and placed at the writer's disposal the large collection of polished sec-

tions which permitted microscopical identification of the minerals and insured the procurance of pure material for the tests. Dr. H. H. Lester of the Department of Metallurgy gave abundantly of time and advice in the immediate technique of manipulation, and Professor Albert Sauveur of the same Department generously allowed the use of the *x*-ray equipment. Dr. L. S. Ramsdell, Dr. Wm. Foshag, Dr. Paul F. Kerr, and Mr. Samuel Gordon kindly furnished material, data, or advice. To all of these the writer is indebted and wishes to express his thanks and appreciation.

CHARACTERISTICS OF RECORDS

To be of any use in the classification here outlined a record should show at least six well distributed lines, that is, lines produced through an angle of about 30°. If the record is one composed of many closely spaced lines, then eight or ten lines produced through an angle of 15° to 20° are sufficient. Only very doubtful identifications can be made with fewer data.

There are two characteristics in each record which are noted when it is read and which are here used in its classification. The first of these is the calculation in Ångstrom units of "*d*" (the interplanar spacing) for each line on the film, the second is the estimation of the intensity of each line. The values of "*d*" are written in numerical order from the highest, the line closest to the undeviated beam (zero line), to the lowest, the line most distant from the origin (Fig. 1). The intensity of the lines is indicated on a relative scale as follows:

- s—strong
- m—medium
- w—weak
- vw—very weak
- ew—exceptionally weak

It is not now possible to use a numerical scale, each number of which represents an absolute intensity, because the same mineral will not show the same absolute intensity of lines on any two records. This is because the absolute intensity of the lines produced by a given mineral depends upon so many variables. Since some of the conditions which determine intensity of lines vary in different mountings of a mineral, the absolute intensities of the lines must also vary in different diffraction patterns of the same mineral. However, the relative intensities of the lines are fairly constant, although in a few cases lines of practically equal intensity are inter-

changeable in the relative scale. Because of these conditions the strongest line on any film is marked "s", and the rest are labeled in relation to this line. By this method, even in poor films, the few lines that do show retain their relative ratings.

METHODS OF INDEXING

Three methods of indexing the minerals are used in this work. In the first method (Index 1), the records are listed in decreasing numerical order of the reading for the first line, namely, the line with the largest interplanar spacing "*d*". In any two records in which the reading for the first line is identical, the record with the higher reading for the second line is listed ahead of the other record. The complete record for each mineral will be given in this index. Accompanying this index is a plate of drawings of the corresponding records, arranged in the same order.

In many records the first one or more lines are weak to exceptionally weak, and therefore may not appear on poorer films. On the other hand very good records might pick up exceptionally weak lines, closer to the zero line, which are not shown on the writer's records. Under such conditions indexing on the basis of the first line shown could not in all cases be depended upon. Therefore, a second method of indexing has been adopted. In this second index the three or four most intense lines are taken from each record and arranged in order of their relative intensity. These lines are the ones certain to appear on any record of value. The records are then again arranged in a numerical sequence, beginning with the record having the highest value of "*d*" for its most intense line, and progressing to the record showing the lowest "*d*" for its strongest line. Where records have identical readings for the strongest line the reading for the next most intense line is also used for determining the order. In cases where the most intense lines are so nearly equal as not to be safely distinguished in intensity, or where the relative intensity of lines for the same mineral may vary in different photographs, the record is listed in each of its possible places. This index gives the reference to the position in Index 1 which has the complete record for the mineral, as well as to the drawings of the corresponding record.

In the third index the minerals are arranged alphabetically by their mineral names, reference again being given to the complete record in Index 1.

ERROR IN READING OF RECORDS

One should keep in mind the fact that in reading and indexing these records there is a maximum error of five in the last decimal place for each line recorded. Therefore, a deviation to this extent must be permitted when comparing a given record with the index. In the case of solid solution minerals there will be a gradual spreading of the characteristic distances ("*d*") of the lines as the composition changes from one end member to the other. This is well illustrated by the work of Machatschki (42, 43) on the tetrahedrite-tennantite group. He finds that tennantite, the arsenic member of the series, has the smaller unit cell. As antimony replaces the arsenic, or as silver replaces the copper, the size of the unit cell increases. This is exactly what would be expected, since the atomic radii of silver and antimony are larger than those of copper and arsenic, respectively. As the cell size is changed by the variation in composition, the powder diffraction pattern varies accordingly in the spacing of its lines. The powder photograph is therefore characteristic not only of the mineral group, but also of a mineral in this group having a particular composition. If this variation of the record, due to chemical change, is greater than the aforementioned error in reading the record, the various members of such a series may be determined. If the variation is less than that error, such a determination is not possible.

ILLUSTRATIONS

The method of using the first two tables may be illustrated with sodium chloride, the standard used in this work for calibrating all records (Fig. 1). The complete record for sodium chloride follows:

No.	Intens.	" <i>d</i> ," Å.	No.	Intens.	" <i>d</i> ," Å.
1	vw	3.25	9	m	1.149
2	s	2.81	10	w	.995
3	s	1.990	11	w	.938
4	ew	1.696	12	w	.890
5	m	1.625	13	w	.848
6	w	1.407	14	ew	.812
7	ew	1.291	15	vw	.780
8	m	1.258	16	vw	.752

This will occur in Index 1 at the place in the sequence where 3.25 comes, which is entry No. 30.

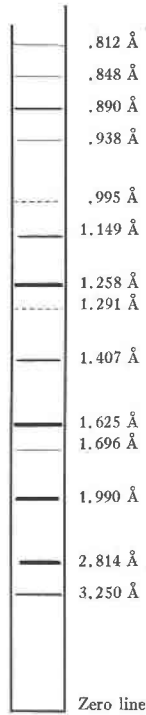


FIG. 1.

The record of the five most intense lines, in order of their intensity, is:

Intens.	"d," Å.
s.....	2.81
s.....	1.990
m.....	1.258
m.....	1.625
m.....	1.149

This will occur in Index 2 at the place in the sequence for 2.81.

This record would also be listed in Index 2 in the following order, since the first two lines are of about equal intensity (Fig. 1):

Intens.	"d," Å.
s.....	1.990
s.....	2.81
m.....	1.258
m.....	1.625
m.....	1.149

This will occur in Index 2 at the place in the sequence for 1.99.

Finally, in Index 3, reference to the complete record for sodium chloride is given at its proper alphabetical position.

INDEX 1

Records listed in decreasing numerical order of the reading for the first line, i.e. the line with the largest interplanar spacing, "*d*".

EXPLANATION OF TABLES

Small letters=Intensity symbols.

Number above columns=Number of the entry.

For *x*-ray photographs corresponding to these records see plate of line drawings.

5

4

3

2

1

Malachite (11)	Atacamite	Chalcantinite (25, 6)	Kröhnkite	Brochantite
vw 5.90	s 5.40	s 5.40	vw 5.40	m 5.35
m 5.00	s 5.00	s 4.67	vw 4.09	s 3.91
s 3.67	s 2.82	s 3.96	vw 3.67	m 3.20
s 2.84	s 2.75	s 3.69	w 3.25	w 2.93
m 2.76	ew 2.62	m 3.28	ew 3.17	ew 2.82
m 2.51	vw 2.52	w 3.02	vw 3.08	m 2.68
vw 2.46	w 2.26	w 2.82	s 2.90	vw 2.60
vw 2.41	vw 2.19	m 2.74	s 2.74	s 2.52
vw 2.32	w 2.13	m 2.65	ew 2.59	m 2.47
vw 2.29	ew 2.03	m 2.41	ew 2.64	w 2.39
ew 2.23	vw 1.945	vw 2.13	vw 2.58	vw 2.30
w 2.17	m 1.815	vw 2.07	ew 2.28	vw 2.27
vw 2.12	vw 1.780	w 2.02	ew 2.20	m 2.19
w 2.06	w 1.741	w 1.975	ew 2.12	w 2.14
	vw 1.706	ew 1.890	ew 2.06	w 2.08
	vw 1.665	ew 1.845	vw 2.00	vw 2.01
	m 1.603	vw 1.818	ew 1.960	w 1.965
	m 1.556	vw 1.770	ew 1.920	vw 1.918
		w 1.625		vw 1.885
				w 1.822
				w 1.787
				ew .819
				ew 1.740
				w 1.712
				w 1.675
				w 1.635
				w 1.595
				m 1.563
				m 1.537
				m 1.505
				w 1.463
				w 1.434
				w 1.405
				w 1.338
				w 1.312
				w 1.282
				ew 1.093
				ew 1.077
				ew 1.058
				ew 1.015
				ew 1.000
				ew .904
				ew .819

10

9

8

7

6

Azurite (10)		Boleite ³ (23, 24, 30)		Bourmonite (49)		Linarite		Domeykite ⁴ (44, 58, 40)	
s	5.20	vw	5.10	ew	4.70	vw	4.51	ew	3.90
s	3.67	ew	4.86	vw	4.32	m	3.52	ew	3.03
s	3.53	s	4.40	vw	4.09	ew	3.11	ew	2.56
vw	3.10	s	3.83	m	3.86	w	2.95	ew	2.40*
vw	2.94	m	3.50	w	3.68	w	2.80	m	2.14
vw	2.82	ew	3.34	ew	3.25	ew	2.69	s	2.04
s	2.54	s	3.13	m	2.96	w	2.57	m	1.958
w	2.35	vw	2.95	w	2.89	ew	2.39	s	1.878
m	2.28	w	2.83	m	2.81	ew	2.30	ew	1.563
m	2.24	s	2.69	s	2.73	w	2.25	vw	1.308
vw	2.18	m	2.56	m	2.67	ew	2.16	vw	1.217
vw	2.12	ew	2.47	m	2.58	ew	2.10	ew	1.186
ew	2.02	s	2.38	m	2.47	ew	2.02		
m	1.945	s	2.32	vw	2.37	ew	1.797		
ew	1.900	ew	2.15	ew	2.29	ew	1.761		
m	1.825	ew	2.12	ew	2.22	ew	1.732		
w	1.785	ew	2.07	vw	2.09	w	1.665		
ew	1.700	vw	2.02	m	1.980	m	1.571		
ew	1.645	ew	1.985	m	1.945	vw	1.405		
w	1.593	ew	.893			ew	1.278		
vw	1.560	ew	.868			ew	1.189		
w	1.513	vw	.835						
vw	1.480	vw	.818						

³ This record does not check either isometric or tetragonal structure if the size of the unit cell is that given in the references.

⁴ A good record is difficult to obtain.

* This line is not present in records obtained by the writer, but is in the record kindly sent by L. S. Ramsdell.

Antlerite	Cubanite (Chalmersite)	Ag I ^s (4, 5)	Miersite ^s (2, 4, 5)	25% CuI ^s 75% AgI (4, 5)	38% CuI ^s 62% AgI (4, 5)	Chalcostibite
s 3.85	ew 3.84	3.75	w 3.72	3.675	3.63	vw 3.63
w 3.17	w 3.48	3.24	s 3.23	3.186	3.14	s 3.10
ew 2.90	m 3.21	2.29	m 2.28	2.250	2.22	s 2.98
ew 2.80	s 3.07	1.966	m 1.948	1.920	1.893	vw 2.54
m 2.66	vw 2.78	1.873	ew 1.489	1.838	1.812	m 2.29
s 2.51	vw 2.52	1.622	ew 1.320	1.593	1.570	w 2.23
m 2.45	w 2.31	1.489	ew 1.290	1.461	1.440	m 2.11
vw 2.37	m 2.12	1.451		1.424	1.404	w 1.888
w 2.18	m 1.937	1.325		1.300	1.281	m 1.818
w 2.13	m 1.890	1.249		1.226	1.208	s 1.751
ew 2.07	m 1.858	1.147		1.126	1.110	ew 1.684
ew 2.00	w 1.803	1.086		1.077	1.061	w 1.613
ew 1.949	m 1.745	1.026		1.062	1.047	vw 1.547
w 1.810	w 1.620	.990		1.007	.993	w 1.435
	vw 1.541	.979		.971	.957	ew 1.344
				.961	.947	ew 1.309
						vw 1.286
						ew 1.258
						ew 1.226
						ew 1.198
						ew 1.159
						vw 1.139
						ew 1.068
						ew 1.006
						ew .981
						ew .870

^s Records 13, 15, 16, 18, and 23 are based on the work of Earth and Lunde (4, 5). The values of "g" listed above were calculated by the writer, and since no photographs of this series were made in this work, no intensities are listed. The approximate composition of members in the above series may be determined by comparison with these columns. The mineral miersite, number 14, was run by the writer. This mineral happens to be closer to pure AgI than to the theoretical composition listed in the texts. Mineral number 21 was supposed to be marshite. By its record it may be seen that it is not pure CuI, but contains some AgI. This whole series has patterns similar to those of sphalerite, colusite, and germanite. The variation in size of the unit cell in the CuI-AgI series is large, so that the various members may be identified; but even so the size of the unit cell in colusite, germanite, and sphalerite is different still, and so will not be confused, as the values of "g" will also differ.

18	19	20	21	22	23	24	25
50% CuI ⁵ 50% AgI (4, 5)	Umangite	Eucairite (57)	Marshite ⁵ (2, 73) (4, 5, 15)	Penroseite ⁶	Pure CuI ⁵ Marshite (4, 5)	Connellite	Chrysocolla ⁷
3.57	m 3.56	w 3.54	s 3.52	ew 3.49	3.49	ew 3.40	s 3.35
3.095	m 3.21	s 3.07	vw 3.04	m 3.05	3.02	m 3.20	vw 2.46
2.190	m 3.11	s 2.17	s 2.15	m 2.99	2.14	s 2.72	m 1.810
1.866	vw 2.88	w 1.850	ew 2.06	s 2.67	1.824	ew 2.58	w 1.536
1.787	w 2.57	m 1.768	s 1.834	s 2.44	1.746	s 2.48	m 1.373
1.548	m 2.27	w 1.530	ew 1.760	w 2.16	1.512	s 2.27	ew 1.319
1.420	m 2.14	vw 1.407	w 1.520	w 2.12	1.382	ew 2.18	ew 1.181
1.384	m 2.025	m 1.368	m 1.395	s 1.800	1.353	vw 1.950	ew 1.045
1.263	m 1.998	m 1.250	ew 1.362	m 1.660	1.234	ew 1.800	ew 1.033
1.191	vw 1.938	ew 1.181	m 1.241	m 1.599	1.164	ew 1.745	
1.094	m 1.911	vw 1.082	m 1.170	ew 1.497	1.069	s 1.607	
1.046	s 1.830	ew 1.035	w 1.077	vw 1.152	1.022	w 1.573	
1.032	s 1.775	w 1.020	w 1.028	vw 1.111	1.008	m 1.481	
.979	w 1.641	vw .967	vw .962	ew 1.057	.957	ew 1.385	
.944	ew 1.551	vw .922	ew .927	ew .972	.923	ew 1.306	
.933	ew 1.422	ew .849	ew .813		.912		
	w 1.206	ew .818	ew .792				
	w 1.186						
	w 1.166						
	ew .944						

⁵ Specimen of the type mineral, kindly sent by Mr. Samuel G. Gordon.

⁷ It is very difficult to obtain a satisfactory pattern with molybdenum radiation. This record is not very good.

26	27	28	29	30	31	32	33	34
Covellite (1, 7, 52) (57, 26, 59)	Berzelianite ⁸ (29, 16)	Rickardite	Bornite (35)	Sodium Chloride	Enargite ⁹ (22, 36)	Emplectite ¹⁰ (32)	Nantokite ¹¹ (69)	Chalcocite ¹² (3, 1, 7)
vW 3.33	3.30	m 3.30	w 3.29	vW 3.25	s 3.23	s 3.22	3.17	m 3.14
w 3.24	2.025	vW 3.10	w 3.15	s 2.814	s 3.09	m 3.11	2.74	vW 2.73
m 3.04	1.727	w 2.78	w 2.81	s 1.990	s 2.86	s 3.04	1.942	w 2.51
s 2.81	1.652	m 2.53	w 2.73	ew 1.696	m 2.23	s 2.33	1.657	m 2.38
m 2.72	1.432	s 2.06	w 2.50	m 1.625	s 1.856	vW 2.24	1.586	s 1.963
w 2.30	1.314	m 1.975	vW 2.18	w 1.407	s 1.730	s 2.16	1.373	s 1.868
ew 2.09	1.282	ew 1.913	vW 2.10	ew 1.291	m 1.592	w 1.951	1.261	w 1.690
vW 2.03	1.170	vW 1.808	s 1.925	m 1.258	w 1.557	w 1.854	1.228	m 1.643
s 1.890	1.102	w 1.703	vW 1.643	m 1.149	vW 1.423	m 1.795	1.122	ew 1.553
m 1.730	1.013	w 1.422	ew 1.575	w .995	w 1.265	s 1.651	1.057	ew 1.509
m 1.555	.954	w 1.399	ew 1.530	w .938	vW 1.218	w 1.558	.972	ew 1.273
vW 1.465		ew 1.337	ew 1.470	w .890	w 1.190	ew 1.446	.929	ew 1.070
vW 1.382		ew 1.296	vW 1.420	w .848	w 1.150	ew 1.368		
w 1.347		vW 1.220	vW 1.369	ew .812	vW 1.130	ew 1.314		
w 1.272		w 1.160	ew 1.260	vW .780	vW 1.070	ew 1.165		
w 1.210		w 1.155	w 1.118	vW .752	w 1.044	ew .996		
m 1.093		vW 1.118	ew 1.055		ew 1.028			
w 1.056		ew 1.031	ew 1.007		vW 1.010			
w 1.014		ew .893	vW .969		w .977			
vW .990			ew .925		ew .928			
w .950					vW .896			
ew .893					vW .887			
ew .847					w .865			
					ew .815			

⁸ The writer was unable to obtain specimens of this mineral satisfactory for x-ray analysis. The data listed were calculated from structural data obtained by Hartwig (29), who worked on natural, not artificial, material.

⁹ Specimens labeled famatinitite, from the type locality, gave records identical with the above. A spectroscopic analysis, made by G. A. Harcourt, indicated that this material was probably much nearer the enargite end of the series than it was the famatinitite end. Frebold (22) reports a record for famatinitite which is very different from that of enargite. If famatinitite actually exists, as is supposed, in the same crystal system as enargite, and as the opposite end member of an isomorphous series, then it should have a similar record. Apparently Frebold secured an incorrectly identified specimen. W. F. de Jong (36) states that enargite and famatinitite are isomorphous, with nearly equal lattices. His patterns of the two are so nearly alike that they are practically indistinguishable. If he also did not have material closer to the enargite end of the series than he supposed, then his results are probably closer to the truth than those of Frebold. It appears, from this work and that of the writer, that if famatinitite, with the composition assigned to it, does exist in nature, then it may not be distinguished from enargite by means of x-ray powder patterns.

¹⁰ The writer was unable to obtain any wolfsbergite. Hofman (32) has shown it to be isomorphous with emplectite but with a smaller unit cell. Wolfsbergite, therefore, should give a similar pattern to this, but the values of "g" should be slightly lower, and intermediate members of the series would show intermediate patterns.

¹¹ Data based on work by Wyckoff and Posnjak (69). Apparently the value of the first line varies down to 3.12 Å.

¹² The writer's results do not agree closely with those of Bateman and Lasky (7). They state that two types of chalcocite occur in nature; one is isometric and one orthorhombic. However, they have not proved that the isometric form is pure Cu_2S , but say that they believe it is. The writer was unable to find any size of unit cell which would satisfy more than 10 of the 15 lines they list for the isometric form. Certainly, if the isometric form does occur in nature, it does not have the same size of unit cell as the isometric form above 200°C., which was determined by Barth (3). The writer's records show lines in each complete record which have been separated by Bateman and Lasky, some being placed in their orthorhombic group, and some in their isometric. Thus, if they are right, it seems that the two forms must generally occur together, intimately intergrown. However, the writer's records also contain lines not listed in either record of Bateman and Lasky, and which do not seem to be due to impurities. The writer's record, as listed here, is in closer agreement with the work of Alsen (1).

35 36 37 38 39 40 41 42

Stannite	Nantokite ¹³ (4)	Sulvanite (22, 36, 55)	Stromeyerite	Bertholite?	Colusite ¹⁴ (71)	Germanite ¹⁴ (37)	Chalcopyrite (12, 13, 28, 54)
s 3.12	3.12	m 3.11	s 3.10	s 3.10	s 3.06	s 3.06	s 3.03
w 2.71	2.70	w 2.69	s 2.92	vw 2.73	vw 2.66	ew 2.65	w 2.61
ew 2.14	1.910	m 2.41	vw 2.79	vw 2.54	s 1.873	s 1.870	s 1.855
s 1.911	1.630	s 1.903	s 2.59	w 2.33	s 1.598	m 1.597	s 1.586
s 1.634	1.560	w 1.792	m 2.52	w 2.13	ew 1.529	vw 1.322	w 1.515
ew 1.562	1.351	m 1.624	m 2.46	m 1.950	w 1.324	w 1.213	w 1.320
vw 1.358	1.240	ew 1.558	vw 2.33	m 1.906	w 1.080	w 1.080	w 1.294
m 1.240	1.208	vw 1.495	vw 2.19	vw 1.769	m 1.218	w 1.017	w 1.205
m 1.107	1.104	w 1.347	m 2.13	vw 1.635	ew 1.185	vw 1.017	m 1.205
w 1.043	1.041	vw 1.308	ew 2.02	vw 1.551	m 1.1086	ew .937	m 1.074
vw .959	.955	w 1.235	w 1.837	ew 1.172	m 1.019	ew .895	ew 1.010
w .917	.914	ew 1.205	w 1.790	ew 1.060	vw .939	ew .837	vw .930
vw .858		ew 1.178	ew 1.635	ew 1.022	w .897	vw .892	vw .892
ew .828		m 1.098	ew 1.527		vw .838	vw .882	vw .882
		vw 1.036	ew 1.465		ew .808	w .834	w .834
		vw 1.000	ew 1.419		ew .743	ew .802	ew .802
		vw .952	ew 1.196			ew .799	ew .799
		ew .938				ew .759	ew .759
		vw .911				vw .739	vw .739
		ew .852				ew .706	ew .706
		ew .778				ew .698	ew .698
						ew .683	ew .683
						ew .647	ew .647
						ew .622	ew .622
						ew .614	ew .614
						ew .606	ew .606

¹³ Data based entirely on the work of Barth and Lunde (4, 5). Apparently the value of the first line varies up to 3.17 Å.

¹⁴ The records for colusite and germanite are indistinguishable, each having the same sized unit cell and a structure similar to that of sphalerite. These are distinguished from sphalerite with ease, since, though similar, the spacings of the lines are very different. Germanite and colusite must be distinguished by their color, the former being pink and the latter buff.

43	44	45	46	47	48	49	50	51
Cuprite (49, 50, 28) (56, 46, 67)	Tetrahedrite ¹⁵ (42, 43)	Schwartzite ¹⁵	Tennantite ¹⁵ (42, 43)	Delafoosite	Tenorite (47, 48, 63)	Algodonite ¹⁶ (58, 44, 40)	Whitneyite ¹⁷ (58, 44, 40)	Copper (see below)
vw 3.03	s 3.00	s 2.96	s 2.94	m 2.84	s 2.53	m 2.27	s 2.09	s 2.08
s 2.46	w 2.60	w 2.57	w 2.55	s 2.49	s 2.32	m 2.13	ms 1.82	m 1.810
m 2.13	vw 2.45	vw 2.42	vw 2.40	m 2.22	m 1.865	s 2.00	m 1.29	m 1.273
ew 1.740	vw 2.04	vw 2.02	vw 2.00	m 1.650	w 1.710	w 1.56	m 1.095	m 1.087
m 1.506	vw 1.900	vw 1.872	vw 1.862	m 1.507	vw 1.578	w 1.31		w 1.040
m 1.282	s 1.839	s 1.813	s 1.803	m 1.428	m 1.501	w 1.20		vw .901
w 1.230	ew 1.784	ew 1.763	ew 1.749	m 1.332	m 1.410	w 1.12		w .828
vw 1.065	ew 1.734	ew 1.712	ew 1.700	w 1.289	m 1.370			w .807
w .978	ew 1.687	ew 1.664	ew 1.654	w 1.247	ew 1.302			vw .735
w .952	m 1.568	m 1.547	m 1.537	vw 1.113	w 1.260			(8, 51, 52, 70,
w .870	ew 1.502	ew 1.480	ew 1.472	w 1.036	w 1.155			34, 53, 17, 65,
w .822	ew 1.471	ew 1.452	ew 1.443	vw .988				31, 39, 62, 58,
	ew 1.301	ew 1.282	ew 1.274	ew .962				64, 20, 33)
	ew 1.243	ew 1.228	ew 1.219	ew .949				
	ew 1.209	ew 1.195	ew 1.185	vw .898				
	vw 1.193	vw 1.176	vw 1.170	vw .853				
	ew 1.122	ew 1.110	ew 1.100	ew .813				
	ew 1.096	ew 1.083	ew 1.075	vw .804				
	vw 1.061	vw 1.048	vw 1.041					
		ew .987						
		ew .944						
		ew .913						
		ew .812						

¹⁵ Machatschki (42, 43) finds that tennantite, the arsenic member of the series, has the smaller unit cell. As antimony replaces the arsenic, or as silver replaces the copper, the size of the unit cell increases. As the cell size is changed by the variation in composition, the powder diffraction pattern varies accordingly in the spacing of its lines. This variation is large enough so that the end members of the series may be identified by their patterns, as may the intermediate members. Schwatzite, the mercurial member of the series, has a record identical to that of the intermediate members, and thus can not be distinguished from them by *x*-ray pattern alone. This last named mineral seems to give much better pictures, however, than the other members of the group. The record above for tetrahedrite is from a silver rich specimen, and thus is at one extreme of the series. The record for tennantite is from a specimen tested microchemically by Mr. M. Lewis, who reports it to be truly representative of the other end of the series.

¹⁶ This is considered by Ramsdell (58) to be a definite mineral, generally mixed with Cu-As solid solution, but easily distinguishable and identifiable when a good record is obtained. If too much of the Cu-As solid solution (whitneyite) is present, both the algodomite and whitneyite records will be recorded. Record and information kindly furnished by L. S. Ramsdell. Machatschki (44) considers this to be a mixture and not a true mineral.

¹⁷ The whitneyite pattern is almost indistinguishable from that of copper. The spacings run about one per cent larger. The lines are rather diffuse because of the distortion of the Cu lattice by the As atoms. Most specimens of either "algodomite" or "whitneyite" are mixtures of algodomite and the Cu-As solid solution, and may show lines of both. Information and record kindly sent by L. S. Ramsdell.

INDEX 2

Numbers after mineral names refer to the entry number in Index 1, where the complete record may be found.

EXPLANATION

Lines arranged in order of their relative intensity. Records lacking intensity symbols will not be listed here.

. . . . indicates intensity of line is equal or interchangeable.

Increase ←	Intensity				→ Decrease	Mineral	Entry No.
5.40	5.00	2.82	2.75	2.26		Atacamite	2
5.40	4.67	3.69	3.96			Chalcanthite	3
5.20	3.53	3.67	2.52			Azurite	6
5.00	5.40	2.82	2.75	2.26		Atacamite	2
4.67	5.40	3.69	3.96			Chalcanthite	3
4.40	3.83	2.69	2.38			Boleite	7
3.82	4.40	2.69	2.38			Boleite	7
3.69	5.40	4.67	3.96			Chalcanthite	3
3.67	5.20	3.53	2.52			Azurite	6
3.53	5.20	3.67	2.52			Azurite	6
3.52	2.15	1.831				Marshite	21
3.35	1.810	1.373	1.536			Chrysocolla	25
3.23	1.948	2.28	3.72			Miersite	14
3.23	1.730	1.856	2.86	3.09		Enargite	31
3.22	3.11	3.04	2.33			Emplectite	32
3.22	3.04	2.33	2.16			Emplectite	32
3.12	1.911	1.634				Stannite	35
3.11	3.52	1.797				Linarite	9
3.11	3.22	3.04	2.33			Emplectite	32
3.10	2.98	1.751	2.29			Chalcostibite	17
3.10	2.92	2.59				Stromeyerite	38
3.10	1.950	1.906				Berthomite	39
3.09	1.730	1.856	2.86	3.23		Enargite	31
3.07	3.21	1.937	1.858			Cubanite	12
3.07	2.17	1.368	1.768			Eucairite	20
3.07	1.937	1.858	3.21			Cubanite	12
3.06	1.870	1.596				Colusite	40
3.06	1.870	1.592				Germanite	41
3.04	3.22	3.11	2.16			Emplectite	31
3.03	1.855	1.586				Chalcopyrite	42
3.00*	1.837	1.565	1.259			Tetrahedrite	44
2.98	3.10	1.751	2.29			Chalcostibite	17
2.96*	1.831	1.547	2.57			Schwartzite ^a	45
2.94*	1.803	1.537	2.55			Tennantite	46

* Members of a continuous series from 3.00Å to 2.93Å.

^a Intermediate tetrahedrite-tennantite series.

Increase ← ————— Intensity ————— → Decrease				Mineral	Entry No.
2.93	1.803	1.540	2.54	Tennantite	46
2.92	3.10	2.59		Stromeyerite	38
2.90	2.74			Kröhnkite	4
2.86	1.730	1.856	3.09	Enargite	31
2.83	3.65	4.98	2.48	Malachite	1
2.82	5.40	5.00	2.75	Atacamite	2
2.81	1.990	1.258	1.625	NaCl (salt)	30
2.81	1.890	3.04	2.72	Covellite	26
2.75	5.40	5.00	2.82	Atacamite	2
2.74	2.90			Kröhnkite	4
2.73	1.763	2.96	2.58	Bournonite	8
2.72	2.48	2.27	1.697	Connellite	24
2.67	2.44	1.800	1.599	Penroseite	22
2.59	3.10	2.92		Stromeyerite	38
2.53	2.23	1.865	1.501	Tenorite	48
2.52 ^b	5.35	3.91	2.68	Brochantite	5
2.51 ^b	3.85	2.66	2.45	Antlerite	11
2.49	2.84	2.22	1.650	Delafosite	47
2.48	2.72	2.27	1.607	Connellite	24
2.47	2.14	1.510	1.287	Cuprite	43
2.44	2.67	1.800	1.599	Penroseite	22
2.33	3.22	3.11	3.04	Emplectite	31
2.32	2.53	1.865	1.501	Tenorite	48
2.29	3.10	2.98	1.751	Chalcostibite	17
2.27	2.72	2.48	1.607	Connellite	24
2.26	5.40	5.00	2.82	Atacamite	2
2.17	3.07	1.768	1.368	Eucairite	20
2.15	3.52	1.831		Marshite	21
2.09	1.820	1.29	1.095	Whitneyite	50
2.08	1.810	1.273	1.087	Copper	51
2.06	3.30	2.53	1.975	Rickardite	28
2.04	1.878	2.14	1.958	Domeykite	10
2.00	2.13	2.27		Algodonite	49
1.990	2.814	1.259	1.625	NaCl (salt)	30
1.963	1.868	2.38	3.14	Chalcocite	34
1.925	3.29	3.15	2.81	Bornite	29
1.911	3.12	1.634		Stannite	35
1.903	3.11	1.624	2.41	Sulvanite	37
1.890	2.81	3.04	2.72	Covellite	26
1.878	2.04	1.958	2.14	Domeykite	10
1.870	3.06	1.596		Colusite	40
1.870	3.06	1.592		Germanite	41
1.856	1.730	2.86	3.23	Enargite	31
1.831	3.52	2.15		Marshite	21

^b These two have nearly identical records.

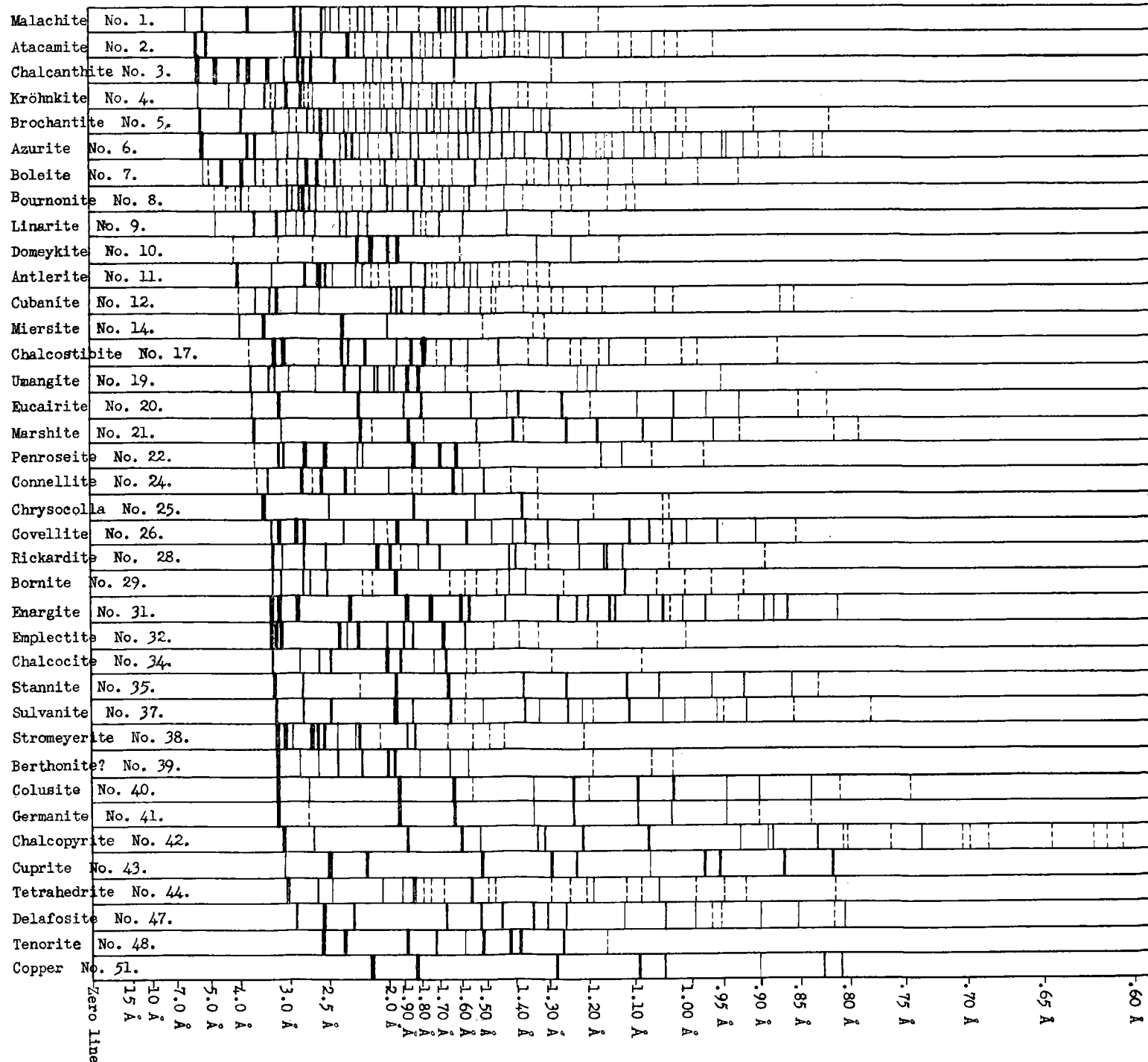
Increase ← Intensity → Decrease			Mineral	Entry No.		
1.830	1.775	2.27	Umangite	19		
1.800	2.67	2.44	1.599	Penroseite	22	
1.775	1.830	2.27	Umangite	19		
1.751	3.10	2.98	2.29	Chalcostibite	17	
1.730	1.856	2.86	3.23	3.09	Enargite	31
1.607	2.72	2.48	2.27	Connellite	24	

INDEX 3

Minerals arranged alphabetically. Reference to Index 1.

Mineral	Entry No.	Mineral	Entry No.
Algodonite	49	Enargite	31
Antlerite	11	Eucairite	20
Atacamite	2	Famatinite	31
Azurite	6	Germanite	41
Berthonite	39	Kröhnkite	4
Berzelianite	27	Linarite	9
Boleite	7	Malachite	1
Bornite	29	Marshite	21, 23
Bournonite	8	Melaconite	48
Brochantite	5	Miersite	14
Chalcanthite	3	Nantokite	33, 36
Chalcocite	34	Penroseite	22
Chalcopyrite	42	Rickardite	28
Chalcostibite	17	Sodium Chloride	30
Chrysocolla	25	Schwartzite	45
Colusite	40	Stannite	35
Connellite	24	Stromeyerite	38
Copper	51	Sulvanite	37
Covellite	26	Tennantite	46
Cubanite	12	Tenorite	48
Cuprite	43	Tetrahedrite	44
Delafosite	47	Umangite	19
Domeykite	10	Whitneyite	50
Emplectite	32	Wolfsbergite	32

(see Emplectite)



Powder photographs arranged in order of Index 1.

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