COMPOSITION AND OPTICS OF COPIAPITE

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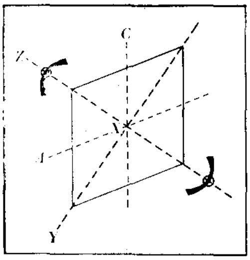

FIG. 1.—Copiapite: optical orientation.

COPIAPITE, the commonest of the many ferric sulphates known in nature, was first described and analysed by Rose (1833) and later named by Haidinger (1845). Rose proposed the formula $2Fe_2O_3.5SO_3.18H_2O$ in which ferric iron and sulphur are in the ratio of 4 to 5. This formula has been widely accepted by later authors, although some authors have preferred 16, 17, or 19 H_2O (Table 1). Copiapite analyses commonly show small amounts of a variety of bases other than ferric oxide, but most authors have rejected these bases as extraneous and have retained the original type of formula proposed by Rose. Studies of artificial hydrous ferric sulphates by Posnjak & Merwin (1922) revealed a compound agreeing with the commonly accepted type of formula, but this work did not indicate the rôle played by bases other than ferric oxide.

Melville & Lindgren (1890) were the first to propose a formula (Table 1), for copiapite from Knoxville, California, in which ferric iron and sulphur are in the ratio of 4 to 6 and divalent metals are included. This formula was not accepted by later authors as applying to copiapite in general. Scharizer (1913) proposed a complex formula containing divalent metals for some copiapites. Walker (1922), after careful optical examination of copiapite from Liard Post, British Columbia, concluded that there was no reason for rejecting the MgO and Al_2O_3 found in the analysis, as had been done by Rose (1833) and other early authors, and he proposed a formula which differs from that of Melville & Lindgren only in the number of H_2O. Finally, Bandy (1938) gives a list of 16 analyses and suggests several formulae containing a divalent metal and a hydroxyl group.

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[1] Part II of a Thesis accepted for the degree of M.A., University of Toronto, 1938. The principal results were given in abstract (Berry, 1939) and the present account has been prepared in collaboration with Professor M. A. Peacock.

The principal refractive indices of copiapite vary in different sets of measurements more widely than is commonly the case in different specimens of one species. This variation strongly suggests that some variation in chemical composition is truly a property of the mineral.

This paper presents some chemical and optical observations on copiapite with a review and interpretation of the numerous existing analyses and optical measurements. The work thus constitutes a sequel to the recent paper on the crystallography of this interesting mineral by Palache, Peacock & Berry (1946).

TABLE 1

COPIAPITE: CHEMICAL FORMULAE

Formula	Author
$2Fe_2O_3.5SO_3.18H_2O$	Rose (1833) Scharizer (1913) McCaughey (1918) Schairer & Lawson (1924)
$2Fe_2O_3.5SO_3.16H_2O$	Darapsky (1890)
$2Fe_2O_3.5SO_3.17H_2O$	Posnjak & Merwin (1922)
$2Fe_2O_3.5SO_3.19H_2O$	Linck (1889)
$RO.2R_2O_3.6SO_3.20H_2O$	Melville & Lindgren (1890)
$n(RO.2Fe_2O_3.6SO_3.20\text{-}23H_2O)$ $m(2RO.2Fe_2O_3.7SO_3.26\text{-}27H_2O)$	Scharizer (1913)
$RO.2R_2O_3.6SO_3.22H_2O$	Walker (1922)
$MgFe_4(SO_4)_6(OH)_2.19$ or $21H_2O$ $CuFe_4(SO_4)_6(OH)_2.14H_2O$ $CuFe_4(SO_4)_5(OH)_4.17H_2O$	Bandy (1938)

EMPIRICAL CELL CONTENT OF COPIAPITE

As shown in Palache, Peacock & Berry (1946) the cell dimensions, specific gravity and analysis (Table 2, No. 12) of well developed crystals of copiapite from Chuquicamata, Chile, give the following numbers of atoms in the unit cell: Fe'' 0.08, Al 0.41, Fe''' 4.18, S 6.09, O (exclusive of H_2O) 25.24, H_2O 20.34. The number of sulphur atoms in the cell is very nearly 6. If the amount of ferric iron in excess of that required to make normal ferric sulphate be added to the ferrous iron and aluminium, the combined oxygen equivalent is nearly 1. The total oxygen exclusive of water is close to 25: 18 for sulphur, 6 for ferric iron, and 1 for the extra constituents. The cell content is therefore : $X(OH)_2Fe'''_4(SO_4)_6 \cdot nH_2O$, where X represents ferrous iron, aluminium, and ferric iron amounting to one oxygen equivalent, oxygen exclusive of water amounts to 25, and *n* appears to be 19.

Similarly, it was shown that the geometrical and *x*-ray measurements, specific gravity, and analysis (Table 2, No. 6) on crystals from Sierra Gorda, Chile, give the cell contents: Fe''' 4.85, S 5.89, O (exclusive of H_2O) 24.94, H_2O 19.66. Again we have definitely 6 sulphur atoms and 25 oxygen atoms exclusive of water. The oxygen equivalent of ferric iron in excess of that required for normal ferric sulphate is approximately 1. Thus the cell content of this material can also be expressed by the formula $X(OH)_2Fe'''_4(SO_4)_6 \cdot nH_2O$, in which X is now entirely ferric iron, and *n* is again apparently 19.

DISCUSSION OF AVAILABLE ANALYSES OF COPIAPITE

Co-ordinated cell dimensions and specific gravities combined with analyses of two copiapites, differing in composition and from different localities, indicate a general structural formula:

$$X(OH)_2Fe'''_4(SO_4)_6 \cdot nH_2O$$

which represents the unit cell content in each case. In the above examples, X, the variable constituent, is one oxygen equivalent of ferrous iron, aluminium, and ferric iron, or entirely ferric iron. It is indicated beyond doubt that the correct number of sulphur atoms in the formula is 6, not 5, as first suggested by Melville & Lindgren (1890) and definitely proposed by Walker (1922), and the total number of oxygen atoms, exclusive of water, is found to be 25.

Since the number of oxygen atoms, 25, may be expected to be less reliable and is approached a little less closely than the number of sulphur atoms, 6, it was decided that an unprejudiced picture of the composition of copiapite would best be obtained by reducing the 42 available analyses to atomic proportions to the basis of 6 atoms of sulphur. The analyses include two artificial copiapites and several natural copiapites consisting wholly of Fe_2O_3, SO_3, and H_2O; all the rest have small amounts of one or more of the elements Na, K, Cu, Fe'', Mn, Mg, Zn, Ca, Al.

In Table 2 the 42 available analyses are arranged in vertical columns with the analyses in the upper part of the table and the corresponding numbers of atoms in the unit cell, on the basis of 6 atoms of sulphur, below. The atoms contributing to the X component of the structural formula, including ferric iron in

TABLE 2

COPIAPITE: ANALYSES AND CELL CONTENTS ON BASIS OF 6 SULPHUR ATOMS

	1	2	3	4	5	6	7	8	9
Na_2O	....	....	....	....	....	....	....	0.31	....
FeO	....	....	....	....	....	....	0.33	1.56	0.52
CaO	....	....	....	tr.	....	....	....	....	....
Al_2O_3	....	....	....	tr.	....	....	tr.	....	1.31
Fe_2O_3	30.75	30.68	29.98	30.10	30.24	31.92	29.66	29.16	28.95
SO_3	39.28	38.72	39.68	38.91	38.62	38.89	39.81	39.03	39.56
H_2O	29.97	30.60	30.45	30.74	30.75	[29.19]	29.95	[29.94]	28.60
Insol.	....	....	0.31	....	0.90	....	0.30	....	1.06
Total	100.00	100.00	100.42	99.75	100.51	100.00	100.05	100.00	100.00
X Na	....	....	....	....	....	....	....	0.12	....
Fe''	....	....	....	....	....	....	0.06	0.27	0.08
Al	....	....	....	....	....	....	....	....	0.32
Fe'''	0.72	0.77	0.55	0.65	0.71	0.90	0.48	0.50	0.40
O for X	1.08	1.15	0.81	0.98	1.07	1.35	0.78	1.08	1.16
$R'''=Fe'''$	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
O for R'''	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
S	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
O for S	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Total O	25.08	25.15	24.81	24.98	25.07	25.35	24.78	25.08	25.16
H_2O	20.3	21.1	20.5	21.6	21.3	20.0	20.1	20.2	19.3

1—10, *Ferricopiapite*: 1. Artificial; anal. Posnjak & Merwin (1922). 2. Artificial; anal. Scharizer (1913). 3. Formed in museum on melanterite from Congo coalmine, Ohio; anal. McCaughey (1918). 4. Tierra Amarilla, Chile; anal. Linck (1889). 5. Sierra de l'Alcaparossa, Chile; anal. Scharizer (1913). 6. Sierra Gorda, Chile; anal. Ungemach (1935). 7. Copiapò, Chile; anal. Manasse (1911), average of two analyses. 8. Tierra Amarilla, Chile; anal. Mackintosh (1889). 9. Atacama, Chile; anal. Foshag in Bandy (1938). 10. Tierra Amarilla, Chile; anal. Manasse (1911).

excess of 4 atoms, are given first, followed by the sum of the oxygen equivalents of these atoms. In some analyses, where ferric iron amounts to less than 4 atoms, aluminium is added to ferric iron to

TABLE 2 (*Continued*)

		10	11	12	13	14	15	16	17
Na_2O K_2O		....	....	....	0.30	0.40	0.16	....	....
CuO		....	....	....	....	....	1.00	....	....
FeO		0.48	0.94	0.44	0.90	0.78	4.01	....	0.64
MgO		....	tr.	....	0.44	....	....	0.15	2.21
CaO		....	....	....	....	....	....	tr.	0.28
Al_2O_3		tr.	4.15	1.72	4.04	3.49	3.62	2.95	2.22
Fe_2O_3		30.51	21.91	27.28	24.00	24.93	23.21	28.18	26.02
SO_3		38.87	38.87	39.83	40.03	39.10	38.44	38.47	38.46
H_2O		28.54	33.33	29.92	30.52	29.92	27.76	29.50	30.28
Insol.		2.55	0.61	0.55	....	1.24	0.52	0.78	0.27
Total		100.95	99.81	99.74	100.23	99.86	98.72	100.03	100.38
X	Na K	....	....	....	0.08	0.12	0.05	....	....
	Cu	....	....	....	....	....	0.16	....	....
	Fe″	0.09	0.17	0.07	0.15	0.13	0.70	....	0.11
	Mg	....	....	....	0.13	....	....	0.05	0.69
	Ca	....	....	....	....	....	....	....	0.09
	Al	....	0.40	0.41	0.58	0.68	0.52	0.73	0.54
	Fe‴	0.72	....	0.12	....	....	....	0.41	0.08
O for X		1.17	0.77	0.86	1.19	1.21	1.67	1.75	1.79
R‴	Fe‴	4.00	3.40	4.00	3.62	3.84	3.64	4.00	4.00
	Al	....	0.60	....	0.38	0.16	0.36	....	....
O for R‴		6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
S		6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
O for S		18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Total O		25.17	24.77	24.86	25.19	25.21	25.67	25.75	25.79
H_2O		19.6	22.9	20.1	20.4	20.4	19.3	20.5	21.0

11—17, *Aluminocopiapite*: 11. Vigneria, Elba; anal. Manasse (1911), average of two analyses. 12. Chuquicamata, Chile; anal. Gonyer in Palache, Peacock & Berry (1946). 13. Tmavýdul coalmine, Bohemia; anal. Rost (1940). 14. Temple Rock, Utah; anal. Foshag in Bandy (1938). 15. Island Mountain, California; anal. Foshag in Bandy (1938). 16. Tierra Amarilla, Chile; anal. Darapsky (1890). 17. Giglio, Italy; anal. Rossoni (1936).

TABLE 2 (*Continued*)

		18	19	20	21	22	23	24	25	26
Na_2O		....	....	....	....	0.53	....	....	....	....
K_2O		....	....	....	....	0.27	....	0.32	....	....
FeO		....	0.46	0.33	....	0.54	1.04	....	0.27	0.52
MnO		....	0.21	....	....	0.10	....	....	0.16	....
MgO		3.19	3.06	1.73	3.10	3.04	3.47	2.81	3.75	3.26
ZnO		....	....	1.45	....	....	....	2.49	0.58	....
CaO		0.27	....	....	....	0.67	....	....	....	....
Al_2O_3		....	....	....	0.52	2.94	0.08	....	....	....
Fe_2O_3		26.39	26.54	26.39	24.96	18.88	26.25	30.06	24.46	27.44
SO_3		39.79	39.97	38.27	37.92	40.09	39.24	42.92	38.48	39.47
H_2O		29.92	30.43	30.60	31.51	33.42	28.32	[21.39]	32.39	27.84
Insol.		0.30	....	0.79	1.96	....	0.48	....	0.09	1.16
Total		99.86	100.67	99.56	99.97	100.48	98.88	99.99	100.18	99.69
X	Na	....	....	....	....	0.20	....	....	....	....
	K	....	....	....	....	0.06	....	0.08	....	....
	Fe''	....	0.08	0.06	....	0.09	0.18	....	0.05	0.09
	Mn	....	0.04	....	....	0.02	....	....	0.03	....
	Mg	0.95	0.91	0.54	0.97	0.90	1.05	0.78	1.16	0.98
	Zn	....	....	0.22	....	....	....	0.15	0.09	....
	Ca	0.06	....	....	....	0.14	....	....	....	....
	Al	....	....	....	0.09	....	0.02	....	....	....
	Fe'''	....	....	0.15	....	....	0.02	0.22	....	0.19
O for X		1.01	1.03	1.04	1.11	1.28	1.29	1.31	1.33	1.35
R'''	Fe'''	3.99	4.00	4.00	3.96	(2.84)	4.00	4.00	3.83	4.00
	Al	....	....	....	0.04	(0.68)	....	....	....	....
O for R'''		5.98	6.00	6.00	6.00	(5.28)	6.00	6.00	5.74	6.00
S		6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
O for S		18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Total O		24.99	25.03	25.04	25.11	24.56	25.29	25.31	25.07	25.35
H_2O		20.1	20.3	21.3	22.1	22.2	19.2	(13.3)	22.5	18.8

18—27, *Magnesiocopiapite*: 18. Santa Maria Mountains, California; anal. Schairer & Lawson (1924). 19. Redington mine, Knoxville, California; anal. Melville & Lindgren (1890). 20. Rammelsberg; anal. Scharizer (1913). 21. Liard Post, British Columbia; anal. Todd in Walker (1922). 22. Kladno, Czechoslovakia; anal. Rost (1937). 23. Las Vegas, New Mexico; anal. Foshag in Bandy (1938). 24. Goslar, Rammelsberg; anal. Kerl (1854). 25. Fahlun, Sweden; anal. Mauzelius in Sjögren (1895). 26. Blythe, California; anal. Foshag in Bandy (1938). 27. Copiapo, Chile; anal. Rose (1833).

TABLE 2 (*Continued*)

		27	28	29	30	31	32	33	34	35
CuO		....	....	....	5.72	....	....	....	....	....
FeO		....	4.06	3.28	....	0.44	....	0.72	....	....
MnO		....	....	tr.	....	....	....	....	....	1.26
MgO		2.64	....	0.16	....	0.29	....	0.50	....	....
ZnO		....	....	....	....	....	....	....	2.00	2.30
CaO		....	....	0.26	....	....	....	0.50	....	....
Al_2O_3		1.95	tr.	0.37	1.47	0.31	tr.	....	....	....
Fe_2O_3		26.11	26.10	26.79	27.66	25.04	29.50	30.65	28.00	26.03
SO_3		39.60	38.37	38.82	41.62	38.36	42.27	47.97	39.44	38.07
H_2O		29.67	30.68	[29.57]	23.51	29.71	28.50	18.72	30.64	30.50
Insol.		1.37	0.71	0.75	0.21	5.43	....	0.10	....	....
Total		101.34	99.92	100.00	100.19	99.58	100.27	99.16	100.08	98.22
X	Cu	....	....	....	0.83	....	....	....	....	....
	Fe''	....	0.71	0.56	....	0.07	....	0.10	....	....
	Mn	....	....	....	....	....	....	....	....	0.22
	Mg	0.79	....	0.05	....	0.09	....	0.12	....	....
	Zn	....	....	....	....	....	....	....	0.30	0.36
	Ca	....	....	0.06	....	....	....	0.09	....	....
	Al	0.44	....	0.09	0.33	....	....	....	....	....
	Fe'''	....	0.09	0.16	....	....	0.20	....	0.27	0.11
O for X		1.45	0.84	1.04	1.33	0.16	0.30	0.31	0.73	0.75
R'''	Fe'''	3.97	4.00	4.00	4.00	3.92	4.00	3.84	4.00	4.00
	Al	0.03	....	....	....	0.08	....	....	....	....
O for R'''		6.00	6.00	6.00	6.00	6.00	6.00	5.76	6.00	6.00
S		6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
O for S		18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Total O		25.45	24.84	25.04	25.33	24.16	24.30	24.07	24.73	24.75
H_2O		20.0	21.3	20.3	(15.1)	20.7	(18.0)	(10.4)	20.7	21.4

28—29, *Ferrocopiapite*: 28. Capo d'Arco, Elba; anal. Manasse (1911), average of two analyses. 29. Sulphur Bank, California; anal. Melville & Lindgren (1890).

30—*Cuprocopiapite*: Chuquicamata, Chile; anal. Gonyer in Bandy (1938).

31—42, Ill-defined and mixed types: 31. Leona Heights, Alameda Co., California; anal. Schaller (1903). 32. Vashegy; anal. Emszt in Toborffy (1907). 33. Huelva, Spain; anal. Collins (1923); material kept over strong sulphuric acid for 48 hours before analysis. 34, 35. Rammelsberg; anal. Ahrend & Ulrich

TABLE 2 (*Concluded*)

		36	37	38	39	40	41	42	A	B
Na_2O		....	....	....	....	....	1.74	....		
K_2O		....	....	....	....	....	0.24	....		
CuO		....	....	....	....	....	2.26	....		
FeO		....	....	0.45	1.51	1.53	0.38	3.81		
NiO		....	....	....	....	....	....	0.84		
MgO		0.84	....	0.85	0.66	0.98	....	3.22		
ZnO		....	5.80	2.47	1.67	2.11	....	....		
CaO		1.39	....	....	....	....	....	....		
Cr_2O_3		....	....	....	....	....	....	7.41		
Al_2O_3		1.16	....	....	....	....	....	4.83		
Fe_2O_3		24.66	24.24	26.19	26.78	26.36	27.12	15.36		
SO_3		38.00	38.00	38.22	38.47	38.44	38.45	35.91		
H_2O		28.74	30.06	31.33	30.07	30.09	31.03	26.89		
Insol.		5.20	....	0.40	0.27	0.15	....	1.73		
Total		99.99	98.10	99.91	99.43	99.66	101.22	100.00		
X	Na	....	....	....	....	....	0.70	....		
	K	....	....	....	....	....	0.06	....		
	Cu	....	....	....	....	....	0.35	....		
	Fe''	....	....	0.08	0.26	0.27	0.07	0.69		
	Ni	....	....	....	....	....	....	0.15		
	Mg	0.25	....	0.27	0.21	0.30	....	1.04		
	Zn	....	0.90	0.38	0.26	0.32	....	....		
	Ca	0.31	....	....	....	....	....	....		
	Cr	....	....	....	....	....	....	1.28		
	Al	0.21	....	....	....	....	....	....		
	Fe'''	....	....	0.12	0.19	0.13	0.25	....		
O for X		0.88	0.90	0.91	1.01	1.07	1.20	(3.80)	1.06	1.00
R'''	Fe'''	3.91	3.84	4.00	4.00	4.00	4.00	2.52	3.98	4.00
	Al	0.09	....	....	....	....	....	1.24		
O for R'''		6.00	5.76	6.00	6.00	6.00	6.00	5.64	5.97	6.00
S		6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
O for S		18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
Total O		24.88	24.66	24.91	25.01	25.07	25.20	(27.45)	25.03	25.00
H_2O		20.2	21.1	21.9	20.9	20.9	21.5	19.5	20.7	21.0

(1854). 36. Chile; anal. Domeyko (1846). 37. Rammelsberg; anal. Kerl (1854). 38. Rammelsberg; anal. Scharizer (1913). 39. 40. South America; anal. Scharizer (1913). 41. United Verde mine, Arizona; anal. Buehrer in Lausen (1928). 42. "Knoxvillite," Knoxville, California; anal. Melville & Lindgren (1890).

A. Average cell content.

B. Ideal cell content for $X(OH)_2R'''_4(SO_4)_6.20H_2O$.

bring the total of the R‴ component to 4 atoms with an oxygen equivalent of 6 atoms. The number of sulphur atoms, the basis of the calculation, is 6 with an oxygen equivalent of 18 atoms. The second line from the bottom gives the total of the oxygen equivalents of X, R‴, and S. The last line gives the number of H_2O.

The average cell content is given in column A. With 6 atoms of sulphur the arithmetic mean of the total oxygen atoms, apart from water, is 25.03, and therefore it is established beyond question that copiapites have 6 atoms of sulphur and 25 atoms of oxygen of which 18 satisfy the sulphur and 7 balance the ferric iron and other cations. Furthermore the compilation shows that the oxygen equivalent of X, which includes some ferric iron in a number of analyses, averages 1.06 and R‴ averages 3.98 with an oxygen equivalent of 5.97. The arithmetic mean of H_2O is 20.7 from 38 analyses, omitting numbers 25, 31, 33, and 34 in which the water content quoted is obviously low. This points to 21 rather than 20 for the H_2O content of the fully hydrated compound. The general structural formula of copiapite, as inferred from special cases, is therefore:

$$X(OH)_2R'''_4(SO_4)_6.nH_2O$$

where X is one oxygen equivalent of one or more of the following elements: Na, K, Cu, Fe″, Mn, Mg, Zn, Ca, Al, Fe‴ and n equals 20. This we consider to be the composition of the species copiapite, within which it seems proper to recognize certain important varieties according to the nature of the main component of X. This variation in the nature of X appears to be the cause of the sensible variations in the crystal form noted by Palache, Peacock & Berry (1946) and in optical properties listed below.

The copiapite analyses (Table 2) are arranged in groups on the basis of the principal constituent of the X component. An analysis is placed in one of the first five groups if the oxygen equivalent of the principal constituent of X exceeds 0.5; the sixth group includes a variety of analyses which cannot be included in any of the five well-defined groups. The following names[2] are appropriate for

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[2] The names ferricopiapite, ferrocopiapite and magnesiocopiapite have already appeared in Berry (1938*b*, 1939) and in Spencer (1940). The name *aluminocopiapite* is here proposed for the first time.

the varieties of copiapite represented by the first four groups of analyses in the table:

Ferricopiapite, in which X is mainly ferric iron, includes the artificial compounds and some natural copiapites represented by analyses 1 to 10. All the natural materials in this group are from localities in Chile.

Aluminocopiapite, in which X is mainly aluminium, is represented by analyses 11 to 17. In analyses 11, 13, 14, and 15 part of the aluminium is included in the R‴ component and in analyses 12, 16, and 17 it is wholly included in the X component.

Magnesiocopiapite, in which X is principally magnesium, is represented by analyses 18 to 27. This group includes material from several different localities including only one occurrence in Chile. Magnesiocopiapite is apparently the most common variety found in nature. Magnesium also appears in important amounts in analyses 17, 36, 38, 39, 40 and 42.

Ferrocopiapite, in which X is chiefly ferrous iron, is represented by analyses 28 and 29. Ferrous iron also appears in minor amounts in many other analyses.

Cuprocopiapite, in which X is mainly copper, is represented by analysis 30. This variety name has already been proposed by Bandy (1938) for this material from Chuquicamata, Chile.

The remainder of the analyses, 31 to 42, are chiefly those in which the X component consists of a variety of bases. Ferrous iron, magnesium, zinc, and ferric iron are the principal constituent of X in this group. In analysis 37 the X component amounts to 0.9 zinc, however this one old analysis unsupported by optical data is not sufficient to establish a zinc-bearing variety of copiapite. Analysis 42 represents "knoxvillite" of Melville & Lindgren (1890), which was considered to be a copiapite by Larsen (1921). The physical and optical properties of the material leave little doubt that the mineral is copiapite, although the analysis fits the general copiapite formula rather poorly. The chromium content shown in the analysis may well be due to admixed redingtonite, a hydrous chromium sulphate, with which it is closely associated at the locality described by Melville & Lindgren.

Optical Properties

The numerous published optical observations on copiapite indicate that the optic sign, orientation, and absorption scheme are practically constant while the indices of refraction vary noticeably with variation of chemical composition. Copiapite is optically

TABLE 3

Copiapite: Optics of Analysed Materials

Variety	nX	nY	nZ	$2V$	Author
Ferricopiapite	1.531	1.546	1.597	52°	Artificial, Merwin in Posnjak & Merwin (1922), anal. 1.
	1.525	1.545	1.592	....	McCaughey (1918), anal. 3.
	1.53	1.548	1.599	61°	Measured on crystals desc. by Ungemach (1935), anal. 6.
	1.506	1.529	1.573	....	Manasse (1911), anal. 7.
	1.530	1.550	1.592	69°	Larsen (1921), anal. 10.
Aluminocopiapite	1.507	1.531	1.575	74° 43′	Manasse (1911), anal. 11.
	1.527	1.53-1.54	1.58	....	Rost (1940), anal. 13.
	....	1.540	....	....	Bandy (1938), anal. 14.
	1.525	1.540	1.590	moderate	Larsen (1921), anal. 15.
Magnesiocopiapite	....	1.53	1.57	....	Ford in Schairer & Lawson (1924), anal. 18.
	....	1.538	1.578	....	Walker (1922), anal. 21.
	1.511	1.543	1.583	....	Rost (1937), anal. 22.
	....	1.530	....	....	Bandy (1938), anal. 23.
	1.510	1.535	1.575	moderate	Larsen (1921), anal. 26.
Ferrocopiapite	1.509	1.532	1.577	72° 55′	Manasse (1911), anal. 28.
Cuprocopiapite	1.558	1.575	1.620	63°	Peacock (unpublished data), anal. 30.
"Pseudocopiapite"	1.510	1.531	1.578	56°	Measured on crystals desc. by Ungemach (1935).
"Knoxvillite"	1.507	1.529	1.576	67°	Larsen (1921), anal. 42.

positive. *X* (obtuse bisectrix) is apparently normal to (010), the plane of perfect cleavage and platy development, while *Y* and *Z* appear to coincide with the nearly rectangular diagonals, [$\bar{1}$01] and [101] respectively, of the pseudo-orthorhombic plates (Fig. 1). The absorption scheme is $X \div Z > Y$, with *X* commonly greenish yellow to yellow, *Y* yellow to colourless, *Z* sulphur-yellow to yellow-green. In cuprocopiapite *X* and *Z* are distinctly green. These markedly pseudo-orthorhombic optics led several authors (Bertrand, 1881; Des Cloizeaux, 1881; Posnjak & Merwin, 1922) to refer copiapite to the orthorhombic system; the true triclinic symmetry of the mineral could not have been established without the detailed crystallographic work of Ungemach (1935) and Palache, Peacock & Berry (1946).

The observed refractive indices for a number of the analysed copiapites are given in Table 3; the considerable variation is probably due to both variation in the nature of the X component and in the water content. Ferricopiapite and aluminocopiapite are optically indistinguishable from each other but they have noticeably higher indices than ferrocopiapite, magnesiocopiapite, and "pseudocopiapite," which are optically similar. Cuprocopiapite shows the highest indices, and this may be partly due to the conspicuously low water content shown by the analysis. The indices of "pseudocopiapite" suggest that it is in reality a ferrocopiapite or a magnesiocopiapite rather than ferricopiapite as Ungemach assumed. The optical data given by Manasse (1911) for ferricopiapite (anal. 7) and aluminocopiapite (anal. 11) are inconsistent with other values given for these varieties.

SUMMARY

X-ray and density measurements on analysed copiapite from Chuquicamata, Chile, and on analysed material described by Ungemach (1935) from Sierra Gorda, Chile, yield triclinic structural elements and the structural formula (Palache, Peacock & Berry, 1946):

$$\mathrm{X(OH)_2R'''_4(SO_4)_6.}n\mathrm{H_2O}$$

in which X represents several bases amounting to one oxygen equivalent and R''' is ferric iron.

Recalculation of all the available analyses of copiapite to atomic proportions on the basis of 6 atoms of sulphur confirms this formula and shows that the component of X may be $\frac{2}{3}R'''$ (Fe''', Al), $1R''$ (Fe'', Mn, Cu, Mg, Zn, Ca) or $2R'$ (Na, K). R''' is essentially Fe''' but at times includes a small amount of Al, and the probable value of n is 20. For the varieties in which X is mainly Fe''', Al, Mg, or Fe'' the names *ferricopiapite, aluminocopiapite, magnesiocopiapite,* and *ferrocopiapite,* respectively, are proposed. Each variety is represented by several good analyses and ferricopiapite includes both natural and artificial compounds. For the variety in which X is mainly copper the name *cuprocopiapite* was proposed by Bandy (1938).

Optically, the varieties of copiapite fall into three distinct groups which differ from one another in the values of the principal indices of refraction: cuprocopiapite with the highest indices; ferricopiapite and aluminocopiapite, which are similar with intermediate indices; magnesiocopiapite and ferrocopiapite, which are indistinguishable with the lowest indices.

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