Nukundamite, a new mineral, and idaite

C. M. RICE

Department of Geology and Mineralogy, The University, Aberdeen AB9 1AS

D. ATKIN, J. F. W. BOWLES

Geochemical Division, Institute of Geological Sciences, 64/78 Gray's Inn Road, London WC1X 8NG

AND

A. J. CRIDDLE

Department of Mineralogy, British Museum (Natural History), Cromwell Road, London SW7 5BD

SUMMARY. A new mineral, nukundamite, from a Fijian kuroko deposit is described. It has been referred to as idaite, Cu_5FeS_6, or $Cu_{5.5x}Fe_xS_{6.5x}$. Electron-probe analyses gave Cu 56.51, Fe 9.64, and S 33.51, total with traces of Ag and As is 99.79 %. Hexagonal with a 3.782, c 11.187 Å, $Z = 1$. Empirical formula $Cu_{3.37}$, $Fe_{0.66}$, $S_{3.97}$ on the basis of eight atoms. Copper-coloured, metallic lustre, cleavage {0001} perfect. Density (g cm^{-3}) 4.53 (calc), 4.30 (meas). Strongly pleochroic from reddish orange (R_o) to pale grey (R_e). Parallel extinction. Very strong anisotropy with pale green-grey rotation colours. Reflectance values and quantitative colour values in air and oil are given. Similarities with the covelline structure are indicated.

An attempt to fully describe idaite from the Ida mine was unsuccessful. The description of the type material therefore remains inadequate.

THE aim of this paper is to continue the work begun by Frenzel (1959), and others mentioned below, in describing the naturally occurring Cu–Fe sulphides idaite and 'Cu$_{5.5x}$Fe$_x$S$_{6.5x}$'. Clark (1970) and Constantinou (1975) summarize much of the literature on this subject.

Frenzel (1959) described a mineral occurring as a very fine-grained lamellar weathering product of bornite from the Ida Mine, Khan, South West Africa and called it idaite. He was unable to obtain pure material for chemical or X-ray analysis but suggested the formula was Cu_5FeS_6 on the basis of similarities in the optical properties with synthetic

Cu_5FeS_6 produced by himself and by Merwin and Lombard (1937).[1] In addition he noted similarities between the X-ray powder patterns of the synthetic material and 'idaite' from Tarvis Township, Ontario, and proposed that the 'idaite' from the Ida mine, was also hexagonal. Yund (1963) and Wang (1976) have provided good evidence that Frenzel's powder pattern of synthetic Cu_5FeS_6 was indexed incorrectly and that the material was probably contaminated by pyrite (Yund, 1963) or pyrite and covelline (Wang, 1976). It is clear, therefore, that idaite must be regarded as an inadequately defined mineral since the published optical data refers to the type material from the Ida mine but the X-ray data refers to material from Tarvis Township, Ontario, with no proof that the two minerals are identical. This situation will persist as long as the incompletely described Ida mine material is to be taken as the type idaite.

Frenzel and Ottemann (1967) described a mineral indexed on a hexagonal unit cell with a composition close to Cu_5FeS_6 from the Undu mine, Nukundamu, Fiji, and also called this idaite. However, the Fijian mineral has significantly different cell dimensions to those given for non-topotype

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[1] Some later workers (e.g. Yund, 1963) have used the formula $Cu_{5.5x}Fe_xS_{6.5x}$ instead of Cu_5FeS_6 and this will be continued in the present paper.

'idaite' by Frenzel (1959) and Frenzel and Otte-mann suggested that it represented a new polytype of idaite. Sillitoe and Clark (1969) and Cabri (1973) have suggested instead that the Fijian mineral is a new mineral and according to the former authors is perhaps the true natural analogue of the synthetic compound '$Cu_{5.5x}Fe_xS_{6.5x}$'. Clark (1970) described a mineral from Chile and noted that its composi-tion, optical properties, and X-ray powder pattern matched the Fijian mineral.

Ottemann and Frenzel (1971) report that super-gene idaites from various localities, including the Ida mine, show a range of compositions from Cu_5FeS_6 to Cu_3FeS_4 and maintain that Cu_5FeS_6 and Cu_3FeS_4 are the end-members of a solid-solution series rather than two distinct minerals. Intermediate compositions between Cu_5FeS_6 and Cu_3FeS_4 have also been reported by Briggs *et al.* (1977). Constantinou (1975) and Sillitoe and Clark (1969) have found that 'idaite' from the Skourio-tissa ore body, Cyprus, and 'idaite' from Copiapó, Chile, respectively are close to stoichiometric Cu_3FeS_4. It should be emphasized at this point that Ottemann and Frenzel, Briggs *et al.*, Sillitoe and Clark, and Constantinou do not give X-ray data for their 'idaites'.

The only X-ray data for 'idaite' is from the Tarvis Township material (Frenzel, 1959) and the agree-ment between the *d*-spacings of the Tarvis Town-ship 'idaite' and '$Cu_{5.5x}Fe_xS_{6.5x}$' is poor. Lévy (1967) has suggested that the former is a mixture of mawsonite and covelline and Wang (1976) reports that a tetragonal unit cell with $a = 10.50$ Å and $c = 10.72$ Å (mawsonite) gives 'excellent agreement between the observed and the calculated *d*-values'. Lévy (1967) on the basis of a careful study of the optical properties and compositions of 'idaites' from a number of localities (*excluding* the Ida mine) has suggested that these 'idaites' belong to the $Cu_{2+x}Sn_{1-x}FeS_4$ solid-solution series, which in-cludes mawsonite.

In conclusion there is good evidence that at least two distinct phases exist currently referred to as 'idaite'. Phase 1 is the Lévy-phase, which is prob-ably tetragonal with a composition Cu_3FeS_4 and is not yet fully described. Phase 2, the Fijian (and Chilean) mineral, which is hexagonal with a composition close to Cu_5FeS_6, is the natural analogue of synthetic Cu_5FeS_6 and '$Cu_{5.5x}Fe_xS_{6.5x}$', and is distinct from the Tarvis Township mineral. Since the description of the idaite holotype is inadequate it is impossible to say whether Phase 1 or 2 is idaite.

During recent field-work by C. M. R. and H. Colley (Instituut voor Aardwetenschappen, Vrije Universiteit, Amsterdam) good specimens of '$Cu_{5.5x}Fe_xS_{6.5x}$' were obtained from the Undu

mine and it was decided to complete the description of this mineral. We were also kindly lent a polished section of idaite (Durham catalogue number 9420) from the Ida mine by Mr R. Phillips of Durham University for comparison with the Undu material and the results of this study are given.

The present authors propose in this paper that since the Fijian 'idaite' is fully described it becomes the type material for a new mineral, for which the name *nukundamite* has been suggested by H. Colley, from the locality, Nukundamu, where the Undu mine is. The species and name have been approved by the Commission on New Minerals and Mineral Names of the IMA. Type specimens are lodged in the Department of Geology and Mineralogy, Aber-deen, and in the British Museum (Natural History).

Nukundamite from Undu mine, Nukundamu, Fiji

The mineral occurs as copper-coloured, hexa-gonal, tabular crystals with a metallic lustre in a kuroko-type deposit (Colley and Rice, 1975). It is found in four locations within the deposit: co-existing with sphalerite in brecciated black ore, as fine lamellae in sphalerite, as cavity infillings in brecciated pyrite ore, and as an alteration product of primary chalcopyrite. Although the ore zones are not as well defined as in the Japanese kuroko deposits, the first three locations are assigned to the black-ore zone and the fourth to the underlying yellow-ore zone. The textural relationships in the first location suggest that nukundamite is, like sphalerite, a primary mineral of hypogene origin. A similar interpretation may be applied to the third location, and the fourth could represent partial re-equilibration of chalcopyrite to a lower tempera-ture phase in the Cu–Fe–S system. Nukundamite is usually partially altered to covelline and pyrite and sometimes to chalcopyrite only.

The largest crystals occur in the brecciated pyrite ore as fan-shaped groups, which are typically 1–2 mm across. Single crystals may reach 2 mm in length but are typically between 0.5 and 1 mm. Larger irregular masses of nukundamite up to 4 cm along the maximum dimension often show a palm-like branching texture as noted by Frenzel and Ottemann (1967). The following detailed descrip-tion is based on this material catalogued as speci-men no. 12113 in the Mineral Collection of the Department of Geology and Mineralogy, Univer-sity of Aberdeen.

Composition. Five crystals were analysed on a Cambridge Microscan 5 electron microprobe using the quantitative methods described by Bowles (1975) and the results are in good agreement with those of Frenzel and Ottemann (1967) (Table I). In addition to the major elements small amounts of

TABLE I. *Composition of nukundamite and synthetic 'Cu$_{5.5x}$Fe$_x$S$_{6.5x}$'*

	Nukundamite			Synthetic	
	Present study (analyst J. F. W. B.)†	Frenzel and Ottemann (1967)	Clark (1970)	Merwin and Lombard (1937, p. 242)	Sugaki et al. (1975)‡
S	33.51 ± 0.16	33.7	33.9 ± 0.5	33.98	33.8 ± 0.2
Fe	9.64 ± 0.13	9.8	9.5 ± 0.6	9.87	9.0 ± 0.3
Cu	56.51 ± 0.14	56.3	56.7 ± 0.4	56.15	56.9 ± 0.4
Ag	0.09 ± * ⎫	n.r.	n.r.		
As	0.04 ± 0.02 ⎭				
Total	99.79	99.8	100.1	100.00 (normalized)	99.7

* Range = 0.00–0.34, n.r. = not reported, † mean + 1σ of five analyses, ‡ mean + 1σ of seventeen analyses.

Ag and As were found. The composition is close to that of natural material from Chile described by Clark (1970) and also of synthetic material, thus supporting Clark's suggestion that only a limited degree of solid solution can occur. Experimental work by Sugaki et al. (1975) found no solid solution for nukundamite under hydrothermal conditions at 300 °C and 350 °C.

X-ray data. The d-spacings data (Table II) were determined from powder photographs taken in a 114.6 mm diameter Debye-Scherrer camera using Cu-Kα radiation. Values of the measured d-spacings compare closely with those of synthetic Cu$_{5.5x}$Fe$_x$S$_{6.5x}$ (Yund, 1963; Sugaki et al., 1975). Intensities were visually estimated in conjunction with a calibrated intensity scale, the sample mount being prepared in the form of a sphere to avoid preferred orientation effects. Only limited single-crystal work was undertaken because of the bent nature of the crystals isolated for examination. Laue photographs revealed the presence of a sixfold rotation axis showing nukundamite to belong to the hexagonal system. Cell dimensions were determined by the method of least squares, utilizing ThO$_2$ as an internal standard: $a = 3.782 \pm 0.004$ Å, $c = 11.187 \pm 0.008$ Å; $a:c = 1:2.958$; $V = 138.6 \pm 0.4$ Å^3. These values compare well with those of other workers.

The present authors have re-examined the X-ray powder data of Frenzel (1959) for synthetic Cu$_5$FeS$_6$ and agree in part with Yund (1963) and Wang (1976). It cannot be indexed satisfactorily on a hexagonal cell size of $a = 3.90$ Å and $c = 16.95$ Å, the error between calculated and observed lines being unacceptably large (mean error 0.71%). However, it can be interpreted as a mixture of nukundamite (with cell size $a = 3.78$ and $c = 11.18$, mean error 0.15%) and other phases. The presence of pyrite is indeed likely, but we agree with Frenzel

(1963) that Yund's (1963) interpretation of some lines as Kβ reflections is suspect. In our view some or all of these lines relate to an unidentified phase

TABLE II. *X-ray powder data and unit cell dimensions for nukundamite (analyst D. A.)*

(Unit cell dimensions for natural and synthetic material derived by other workers are also given)

hkil	d_{calc}	d_{obs}	I	hkil	d_{calc}	d_{obs}	I
0001	11.19 Å	11.21 Å	10	1126	1.328 Å	—	
0002	5.59	5.59	6	2025	1.321	1.322 Å	6
0003	3.729	3.732	13	1018	1.286	—	
1010	3.275	3.273	30	0009	1.243	—	
1011	3.143	3.143	100	2130	1.238	—	
1012	2.826	2.826	70	2131	1.230 ⎫	1.231	3
0004	2.797	2.796	45	2026	1.230 ⎭		
1013	2.461	2.460	5	1127	1.221	—	
0005	2.237	2.235	1	2132	1.209	1.209	2
1014	2.127	2.127	6	2133	1.175	—	
1120	1.891	1.891	60	1019	1.162	1.162	4
0006	1.865	—		2027	1.144	1.145	1
1121	1.864	—		2134	1.132	—	
1015	1.847	1.847	55	1128	1.124	—	
1122	1.791	—		00010	1.119	—	
1123	1.686	1.686	3	3030	1.092	1.092	3
2020	1.638	1.635	1	3031	1.087	—	
2021	1.620 ⎫	1.619	10	2135	1.083	1.083	4
1016	1.620 ⎭			3032	1.071	—	
0007	1.598	1.599	1	2028	1.063	—	
2022	1.572	—		10110	1.059	1.058	2
1124	1.566	1.568	25	3033	1.048	—	
2023	1.499	—		1129	1.039	—	
1125	1.444	—		2136	1.031	—	
1017	1.436	1.436	4	3034	1.017 ⎫	1.018	2
2024	1.413	—		00011	1.017 ⎭		
0008	1.398	—					

Unit cell dimensions (Å):

	Present study	Frenzel and Ottemann (1967)	Clark (1970)	Yund (1963)	Sugaki et al. (1975)
a	3.782 ± 0.004	3.78$_0$ ± 0.001	3.77$_8$ ± 0.002	3.77$_7$	3.78
c	11.187 ± 0.008	11.18$_7$ ± 0.003	11.18$_3$ ± 0.003	11.18	11.19
	Undu mine		Chile	Synthetic	

(or phases) and they cannot be satisfactorily accounted for by CuS as suggested by Wang (1976).

Optical properties. The specimen preparation techniques used by C. M. R. and A. J. C. were as follows. C. M. R.: Hand grinding on glass plates with 500 and 800 grade carborundum followed by 14 μm, 6 μm, 3 μm, and 1 μm diamond pastes on Hyprocel laps. A. J. C.: Hand grinding on glass plates with 600 and 800 grade carborundum and 1200 grade alumina followed by 14 μm, 6 μm, and 3 μm diamond pastes on water-lubricated Hyprocel laps and a final polishing with MgO in distilled-water paste, by hand, on a stationary cloth lap. Nukundamite is very susceptible to fine scratching, which can only be observed under crossed polars. The scratching is most easily removed by the final polish with MgO mentioned above. Extreme care

TABLE III. *Reflectance (R %) values for nukundamite*

λ nm	Air				Oil	
	R_o		$R_{e'}$		R_o	$R_{e'}$
	A.J.C.	C.M.R.	A.J.C.	C.M.R.	A.J.C.	A.J.C.
400	15.14	—	23.64	—	5.41	10.83
10	14.83	—	23.65	—	5.09	10.63
20	14.58	13.7	23.73	23.3	5.01	10.70
30	14.36	—	23.81	—	5.13	10.89
40	14.14	13.0	23.74	23.6	5.07	10.99
450	13.94	—	23.60	—	5.11	11.10
60	13.88	12.9	23.52	24.1	5.17	11.16
70	13.81	12.9	23.49	24.0	5.29	11.20
80	13.80	13.0	23.47	23.8	5.46	11.19
90	13.89	—	23.51	—	5.71	11.26
500	14.08	13.3	23.55	23.6	6.02	11.28
10	14.35	—	23.57	—	6.41	11.32
20	14.73	14.0	23.59	23.6	6.86	11.32
30	15.20	—	23.60	—	7.37	11.33
40	15.74	15.1	23.58	23.5	7.93	11.33
46	—	15.4	—	23.4	—	—
550	16.40	—	23.61	—	8.52	11.33
60	17.11	16.4	23.64	23.3	9.14	11.32
70	17.89	—	23.66	—	9.86	11.42
80	18.71	18.0	23.70	23.3	10.59	11.53
89	—	18.8	—	23.2	—	—
90	19.62	—	23.84	—	11.36	11.69
600	20.38	19.8	23.90	23.2	11.91	11.75
10	21.26	—	24.15	—	12.68	12.08
20	22.19	21.7	24.54	23.5	13.46	12.54
30	23.15	—	25.18	—	14.09	13.02
40	24.00	23.4	25.86	24.7	14.80	13.73
650	24.84	24.3	26.74	25.5	15.51	14.55
60	25.68	25.3	27.77	26.4	16.22	15.48
70	26.46	—	28.72	—	16.75	16.20
80	27.20	27.0	29.57	28.9	17.24	16.81
90	27.89	—	30.26	—	17.85	17.40
700	28.47	28.6	30.88	30.1	18.39	17.87

had to be taken when cleaning the specimen to avoid scratching with cleaning tissues and it is worth noting that these fine scratches were not observed in plane polarized light even when using Normarski interference-contrast equipment. Nukundamite is strongly pleochroic from reddish orange (R_o) to pale grey (R_e) at a colour temperature of about 3300 °K and has marked bireflectance (fig. 1A). It shows straight extinction and is strongly anisotropic under crossed polars with pale green-grey rotation colours in the 45° position (fig. 1B). Oil immersion slightly enhances these properties.

Reflectance values by C. M. R. and A. J. C. are given in Table III and are in reasonable agreement with those obtained by Lévy (1967) on synthetic material referred to as Cu_5FeS_6. A brief account of the salient features of the measurement procedures follows. C. M. R.: R_o is the average of measurements on five crystals, which were chosen for their extreme bireflectance and anisotropy. $R_{e'}$ values were somewhat variable and the value given is the most extreme obtained. The coefficient of variation for R_o varied from 3–4 %. The apparatus used was a Vickers-EEL spectral microphotometer equipped with a continuous line-interference filter, a × 10 air objective and a Zeiss SiC standard no. 212. Some difficulty was found in obtaining suitable areas for measurement due to the presence of minute, but common, covelline inclusions. A. J. C.: R_o air and $R_{e'}$ air are mean values taken from five areas; the extreme reflectances were so consistent that averaging them was justified. The coefficient of variation for R_o air and $R_{e'}$ air is reasonably constant between about 480–700 nm but deteriorates rapidly towards 400 nm as shown below:

λ nm	400	410	420	430	440
Coeff. of var. $\{$ R_o	10.58	10.34	9.83	8.88	6.99
$R_{e'}$	6.90	7.14	7.00	6.26	4.84

λ nm	450	460	470	480–700	
Coeff. of var. $\{$ R_o	5.21	3.58	2.82	(0.42–2.10)	
$R_{e'}$	3.52	2.42	(1.12 – 1.69)		

The values given in brackets refer to the minimum and maximum coefficients of variation obtained within that spectral range.

Several sets of immersion measurements were rejected as their reflectances had been affected by the presence of air bubbles in, or near, the measuring field. Thus, the oil values in Table III are the arithmetic mean values for four spectral runs for R_o and three runs for $R_{e'}$.

The apparatus used was a Zeiss microscope equipped with a line-interference filter controlled by a Hewlett Packard computer with 'on line' facilities for the computation of the measured

DVM values, × 16 air and oil objectives and a Zeiss SiC standard no. 055.

The spectral reflectance values for R_o measured at the two laboratories, while differing in magnitude (mean of the difference 0.7%) are approximately sympathetic, hence the differences are systematic (see Embrey and Criddle (1978) for a general discussion of such differences). The $R_{e'}$ values tend, but less definitely, towards sympathy, as is to be expected from the measurement of a variable extreme value: the mean of the difference, 0.6%, is, however, of the same order as that for R_o.

The two laboratories did not attempt to measure the same areas, or grains—the specimen was completely repolished between the two series of measurements. It is encouraging therefore that the combination of random and systematic differences resulting from the use of two sets of apparatus by C. M. R. and A. J. C. are so small. Nevertheless, owing to this disparity, the optical constants, n and k, derived from A. J. C.'s data are not included.

Quantitative colour values were computed using the weighted ordinate method. The CIE spectral tristimulus values (Publication CIE No. 15 (E-1.3.1) 1971) were used but weighted for the shorter spectral range, 400-700 nm (Criddle et al., in preparation). Colour values were obtained relative to the CIE recommended illuminants A, D_{65}, and C with colour temperatures of 2855.6 °K, 6504 °K, and 6774 °K respectively. Those for the A illuminant are nearest the colour temperatures of the tungsten halogen sources used in this study and so they are included along with those for the C illuminant (Table IV).

With respect to the A illuminant the deeply saturated reddish orange of the ordinary reflectance and the brighter, but indeterminate, grey of the extraordinary reflectance are readily explicable in quantitative terms: the excitation purity differences between the two vibration directions are large, c. 25% R_o, c. 2% $R_{e'}$, the 'luminance' is 5% higher for $R_{e'}$ than for R_o and both have dominant wavelengths in the orange to red part of the spectrum. In immersion oil the perceived colours are enhanced at the same time as their reflectances are diminished: the reddish orange of the R_o is more deeply saturated, but the saturation of the $R_{e'}$ is also increased so that the grey that was observed in air takes on a slight, but perceptible pinkish tint. The reflectance dispersion curves (fig. 3) show very clearly why there is such disparity between the
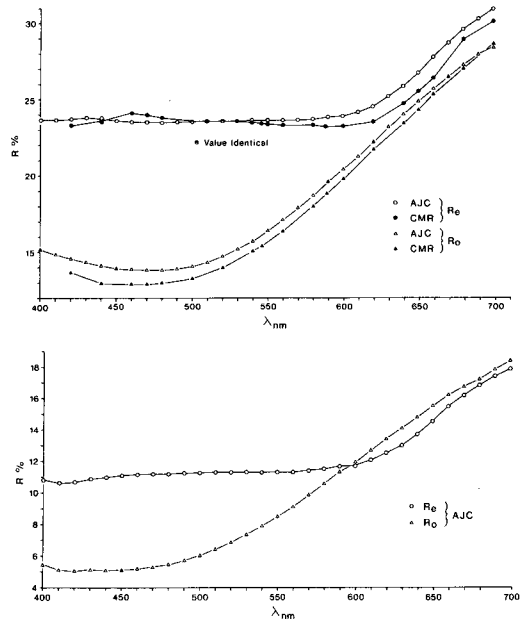

FIG. 3A and B. Reflectance curves in air (A, top) and oil (B, bottom) for nukundamite.

TABLE IV. Quantitative colour values for nukundamite

Air						Oil				
	x	y	λ_D	Pe%	Y	x	y	λ_D	Pe%	Y
Illuminant C										
A. J. C. $\{R_o$	0.3517	0.3319	591	15.3	17.4	0.3950	0.3626	586	35.2	9.3
$\quad\quad\ \ R_{e'}$	0.3141	0.3162	621	1.1	23.8	0.3212	0.3194	595	3.8	11.6
C. M. R. $\{R_o$	0.3558	0.3349	590	17.3	16.8					
$\quad\quad\ \ R_{e'}$	0.3103	0.3147	−545	0.7	23.5					
Illuminant A										
A. J. C. $\{R_o$	0.4885	0.4022	597	24.6	18.4	0.5178	0.4060	593	47.8	10.2
$\quad\quad\ \ R_{e'}$	0.4531	0.4053	618	2.3	24.0	0.4614	0.4036	605	6.9	11.8
C. M. R. $\{R_o$	0.4917	0.4025	597	27.0	17.8					
$\quad\quad\ \ R_{e'}$	0.4490	0.4056	−531	0.9	23.6					

excitation purity levels for the two vibration directions and, similarly, why the 'luminance' levels differ. The R values for the R_o, in air and in oil, climb steeply from the blue to the red end of the spectrum whereas the R_e curve is fairly flat (at a higher level) until 600 nm when it also climbs steeply into the red. The reason for the discrepancies between the dominant wavelengths of R_e in air as determined by C. M. R. and A. J. C. is that the chromaticity coordinates are very close to A and C and hence small variations in these parameters are reflected in large variations in the dominant wavelengths.

Physical properties. Microhardness values were impossible to obtain at 100 newtons due to excessive fracturing but consistent results were obtained with 20 newtons, which gave a slightly fractured concave indentation with $VHN_{20} = 103$-110 (mean of ten indentations). The hardness is comparable to that of covelline, with which nukundamite is often intimately associated.

The streak is dark grey to black. The measured density is 4.30 ± 0.07 g cm^{-3}, which is the mean of four determinations on a coarse powder (containing 1.5 % covelline impurity) by pyknometry using toluene as a displacement liquid. Frenzel (1959) and Yund (1963) report values of 3.80 g cm^{-3} and 4.2 g cm^{-3} respectively on artificial material but the former author suggests his value may be a little low.

The measured density and unit cell volume give a total of 7.6 atoms in the unit cell, of which 3.8 are sulphur. Assuming a volume of 35 Å^3 for the sulphur atom (Appleman, pers. comm., in Yund, 1963) the calculated number of sulphur atoms in the unit cell is 3.96 atoms. It would appear, therefore, that the unit cell contents are close to 8 atoms and on this basis are $(Cu_{3.37}Fe_{0.66}S_{3.97})_{\Sigma 8}$ and the corresponding density is 4.53 g cm^{-3}. There is a significant discrepancy between the observed and calculated densities, which could be due either to the unit cell contents being significantly under 8 atoms (nearer 7.5 atoms) or the measured density being too low.

Comparison with covelline. Nukundamite and covelline have a number of features in common, which suggest that the atomic structures of these minerals may be closely similar. These are hexagonal symmetry, length of a, excellent basal cleavage, hardness, density, and strong pleochroism, bireflectance, and anisotropy. In both minerals R_o is the most saturated vibration and $R_e > R_o$ over most of the spectral range. The metal/sulphur ratios are both essentially unity and it is worth noting that the ratio of the unit cell volumes (0.66) and the ratio of the number of sulphur atoms in the unit cells (0.63) are similar in these minerals.

Although a similarity in structure is thus indicated it is not clear why substitution of Fe and Cu in a covelline-type structure should be limited to one atom in six when the two Cu sites are in the ratio 1:2.

Conditions of formation. Recent experimental work by Sugaki *et al.* (1975) on the Cu–Fe–S system under hydrothermal conditions at 300 °C and 350 °C shows that '$Cu_{5.5x}Fe_xS_{6.5x}$' is stable up to at least 350 °C. At 300 °C and 350 °C it coexists with pyrite, covelline, bornite, and chalcopyrite. Under dry conditions Roseboom and Kullerud (1958) found '$Cu_{5.5x}Fe_xS_{6.5x}$' to be stable below 501 °C and based on this work Clark (1970) suggested that his volcanic assemblage native sulphur, covelline, and $Cu_{5.5x}Fe_xS_{6.5x}$ formed between 434 °C and 482 °C. Since this assemblage is of hydrothermal origin these temperatures may be rather high.

At Undu mine primary nukundamite is restricted to the black-ore horizon, which by analogy with Japanese kuroko deposits may have formed between 80 °C and 200 °C (Tokunaga *et al.*, 1970). The absence of nukundamite from the yellow ore (except as a secondary phase) suggests that the nukundamite–chalcopyrite tie line disappears slightly below 300 °C; assuming an upper limit of formation for yellow ore of 290 °C (Tokunaga *et al.*, 1970). Sillitoe and Clark (1969) suggested that '$Cu_{5.5x}Fe_xS_{6.5x}$' is unstable at 25 °C, which is consistent with the common alteration of this phase to covelline and pyrite at Undu mine. In view of the wide temperature range over which nukundamite is apparently stable the rarity of this phase is surprising and remains to be explained.

'Idaite' from the Ida mine, Khan, South West Africa

Optical properties. The specimen consists of an extremely fine-grained oriented intergrowth, probably composed of two minerals occurring in roughly equal proportions. In general appearance it is similar to the idaite described by Frenzel (1959) from the Ida mine. It has proved difficult to determine the optical properties of the two minerals because of their very small size but one phase occurring as spindles has properties consistent with chalcopyrite or pyrite. The other phase occurring as lamellae has proved even more difficult to describe to the extent that one of us (A. J. C.) considers it is beyond the resolution of his microscope to do so. C. M. R. considers that with difficulty he can distinguish a pale-blue to reddish-brown pleochroism (fig. 2A) somewhat similar to the pale-grey to reddish-brown colours described by Frenzel (1959). Other lamellae are present that are reddish brown and show no detectable pleochroism and these have been interpreted as basal sections, although they may represent a third phase

in the intergrowth. The rotation colours are as described by Frenzel (1959) (fig. 2B).

This assemblage appears to form from the breakdown of bornite and is itself undergoing further alteration to covelline and blaubleibender covelline along grain boundaries and fractures.

TABLE V. *Reflectance data for 'idaite(?)' from the Ida mine, Khan, South West Africa*

λ	$R_{\text{min (air)}}$	$R_{\text{max (air)}}$
470 (nm)	16.0 ± 1.2	23.6 ± 2.3
546	22.7 ± 2.5	28.1 ± 3.9
589	26.9 ± 2.9	28.6 ± 3.4
650	31.1 ± 1.9	32.1 ± 2.4

Results are the mean + 1σ of measurements on four areas using a × 40 objective; in each area the crystals are in optical continuity.

Reflectance values were determined on four areas as free as possible from chalcopyrite (Table V). These areas are very small (about 7 μm in diameter) and are composed of crystal aggregates in optical continuity. A poor precision is to be expected but these were the best areas that could be found. The curves, particularly R_{min}, bear some resemblance to those reported by Lévy (1967) and Sillitoe and Clark (1969) for 'idaites' with a composition close to Cu_3FeS_4 and are different to those for nukundamite. R_{max} clearly shows the effect of chalcopyrite contamination (visually estimated at 10%) because the observed pale-blue colour is not predicted by the reflectance profile.

Composition. The fine-grained nature of the intergrowth made it impossible to resolve the individual minerals with the electron probe. The four areas used for reflectance measurements or similar ones could not be located. Using the smallest spot size (about 1 μm) and the slowest scanning speed (3 μm/minute) only minor variations in Fe and Cu were detected, i.e. 14–19% and 43–53% respectively. Four spot analyses along a traverse yielded very similar values (Table VI) demonstrating the fineness and homogeneity of the intergrowth. The mean composition of $Cu_{3.1}FeS_{4.1}$ is very close to that obtained for some idaites from the Ida mine by Ottemann and Frenzel (1971) (Table VI).

X-ray data. Three small samples of the intergrowth were taken for examination and each sample showed poorly crystallized chalcopyrite and blaubleibender covelline along with two faint unidentifiable lines at 3.14 Å and 3.28 Å. The latter is a covelline line but appeared to be too strong,

TABLE VI. *Electron-microprobe analysis of chalcopyrite-'idaite(?)' intergrowth from the Ida mine, Khan, South West Africa, together with analyses of 'idaite' from the same locality by Ottemann and Frenzel (1971)*

	Present study (mean + 1σ of four analyses)	Ottemann and Frenzel (1971)		
		anal. 10	anal. 11	anal. 12
S	34.13 ± 0.06	33.5	34.9	33.9
Fe	14.78 ± 0.24	15.0	15.4	15.8
Cu	51.69 ± 0.45	50.7	49.6	52.1
Total	100.60	99.2	99.9	101.8

Analyst G. D. Taylor, Department of Geology and Mineralogy, University of Aberdeen.
Instrument—Cambridge Microscan 5.

indicating that another phase may be present. This line is also the sixth strongest line of nukundamite and the presence of this phase is supported to some extent by the line at 3.14 Å, which is the strongest line (Table II). However, in view of the absence of all lines stronger than 3.28 Å, with the exception of the line at 3.14 Å, the authors consider that the presence of nukundamite has not been established.

The X-ray data indicate that the mineral occurring as spindles is chalcopyrite rather than pyrite. This would mean that the lamellar phase is either responsible for the β-covelline pattern, or responsible for the two faint lines at 3.14 Å and 3.28 Å (in part), or too poorly crystallized to produce a pattern. The last possibility is unlikely since the well-defined anisotropy suggests an adequate degree of crystallinity to produce an X-ray pattern. The second possibility is also thought unlikely but cannot be ruled out; the lamellar phase forms at least 50% of the intergrowth and might be expected to give a pattern of at least comparable strength to the chalcopyrite. If this possibility is correct then the identity of the lamellar phase is unknown. It does not appear to be related to the Tarvis Township material. It is thought that the most likely possibility is the first and it is worth noting that if one subtracts the chalcopyrite contribution (assuming 50% chalcopyrite) from the aggregate composition of the intergrowth then one is left with a covelline composition. The implication of this is that the lamellar phase may have a similar X-ray pattern and possibly composition to β-covelline but with quite different optics. Clearly further work is required to characterize this phase.

In conclusion the above study of idaite from the type locality has not succeeded in producing an adequate description; the nature of idaite from the

Ida mine therefore remains unknown. If this speci-
men is representative of the type material then the
type material is clearly unsatisfactory.

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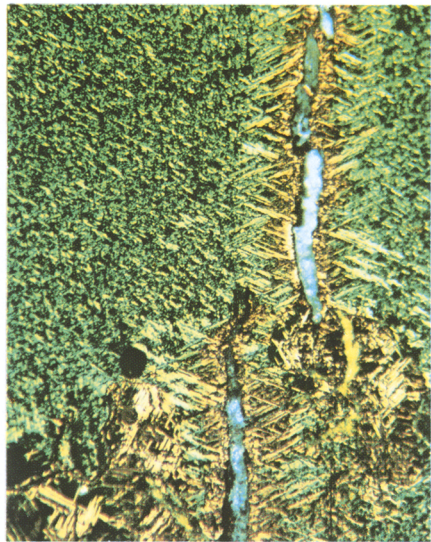
Figs. 1 and 2: Fig. 1A (*top left*), (plane-polarized light) and 1B (*top right*), (crossed polars. Reflected-light pictures (air) of nukundamite showing the distinctive pleochroism and rotation colours. Also present are covelline (blue) and pyrite (pale yellow). Fig. 2A (*bottom left*), (plane-polarized light) and 2B (*bottom right*), (crossed polars). Reflected-light pictures (air) of 'idaite(?)'–chalcopyrite intergrowth from the Ida mine, Khan, South West Africa showing the unusual pale-blue–reddish-brown pleochroism and distinctive yellowish-green rotation colours of the phase accompanying chalcopyrite. Magnification: Figs. 1A and 1B ×80; Figs. 2A and 2B ×160.