

A GIESSENITE-COSALITE-GALENA-BEARING MINERAL SUITE FROM THE BJØRKÅSEN SULPHIDE DEPOSIT AT OFOTEN IN NORTHERN NORWAY

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Giessenite $\text{Pb}_9\text{Cu}_{0.5}\text{Bi}_6\text{Sb}_1\text{S}_{20}$ known only from its type locality at Binnatal in Switzerland has been found in a mineral suite from the Bjørkåsen sulphide deposit at Ofoten in northern Norway. It occurs as fine needles in quartz and as elongated grains in contact with galena and pyrrhotite. Mineral 'B' ($\text{Bi}_2\text{Cu}_4\text{Fe}_5\text{Pb}_6\text{S}_{16}$) present as lamellae in galena in insufficient amounts to permit a complete mineralogical investigation is a new mineral (Karup-Møller 1971). Additional minerals are chalcopyrite, pyrite, sphalerite, cosalite, joseite, breithauptite, ullmannite, stannite, machiwanite, bismuth, two secondary bismuth minerals and secondary calcium-bearing gangue minerals. Galena contains a great variety of minerals shaped as lamellae. The textural relationships of these suggest that they formed directly from the mineralizing fluids and not during exsolution from their galena host. The relationships between the other sulphides are described. The temperature of formation is concluded to lie somewhere between 200 and 269 °C.

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Galena from Bjørkåsen containing a lamellar exsolution mineral and associated with an unknown lead-bismuth sulphide was described by Oftedal (1941, 1942). A few years ago the present author borrowed a specimen of the Bjørkåsen material from Mineralogisk-Geologisk Museum in Oslo in order to examine the lamellar mineral (Karup-Møller 1971). Later Prof. I. Oftedal, Institutt for geologi, Universitetet i Oslo provided the author with further material.

Geology of the Bjørkåsen deposit

The Bjørkåsen sulphide deposit is located in Ofoten in northern Norway. The only information published on its geology is that listed by Foslie (1926). It occurs as two massive sulphide lenses which have developed along a conformable sulphide impregnated horizon in garnet-mica schist of Cambro-Silurian age intruded by granite and gabbro. The horizon can be traced for a distance of more than 25 kilometres. Each sulphide lens has a maximum thickness of 6 metres and they are separated by some 30 metres of schist. The ore is composed of pyrite crystals in a quartz matrix. Other sulphides are present in insignificant amounts, and amongst these are the galena and

associated minerals described below. A total of 523,000 tons averaging 30.5 % sulphur and 0.4 % copper was mined during the period 1915 to 1924. Reserves in 1923 were some 2.5 million tons of ore.

Mineral descriptions

The material studied is characterized by a structureless, transparent, medium- to coarse-grained and very brittle quartz aggregate disseminated with 10–20 % sulphides. The major sulphides are pyrite, pyrrhotite, sphalerite and galena, some chalcopyrite, cosalite and giessenite and minor bismuth, stannite, joseite, machiwanite, breithauptite, ullmannite, mineral 'B' and a few secondary bismuth minerals. Pyrrhotite, pyrite, chalcopyrite and sphalerite have conspicuous properties, which may be regarded as generally known. A description of these minerals has therefore been omitted below.

According to Oftedal (1941) this material was collected from a quartz-rich body enclosed in the major sulphide deposit along its contact zone. Similar material was found in areas where sulphides pinch out against gangue and disappear.

GALENA

Microprobe analyses on galena gave a bismuth content of 0.5 to 1.8 % but copper and silver values of less than 0.3 %. The bismuth content has caused a weak anisotropism of the mineral by crossed nicols.

GIESENITE

Giessenite is only known from its type locality at Binnatal in Switzerland, where it occurs as fine needles in gangue rarely associated with galena (Graeser 1963). Giessenite at the Björkåsen deposit in Norway also occur as needles. They are very regularly shaped and less than 3 millimetres in length. The host mineral is quartz. The mineral is also intergrown with

Table 1. Reflectance measurements on one giessenite needle showing maximum anisotropism. Each value is the average of 8 to 10 individual determinations. Standard used was WC (from Zeiss) and the instrument was a Carl Zeiss photometer, type 2.

λ (nm)	440	460	480	500	520	540	560	580	600	620	640	660
In air:												
R_p	44.4	44.0	43.0	43.3	42.5	42.0	41.4	40.0	39.6	39.4	40.1	40.0
R_g	49.0	48.7	48.5	47.7	47.2	46.6	46.3	45.9	45.0	45.2	45.3	44.9
In oil:												
R_p	28.7	28.2	27.1	26.5	26.0	25.8	25.2	24.9	24.8	23.9	23.8	23.7
R_g	33.2	32.7	31.6	31.0	30.2	29.9	29.7	29.1	29.2	28.7	28.2	27.8

galena and pyrrhotite and is then present as elongated and irregularly shaped grains up to a few millimetres in size.

Giessenite is weakly pleochroic in air, distinctly so in oil. The reflectance colours range from slight creamish-grey in its brightest position to more dullish grey in the darkest position, but still containing a faint cream tint. Reflectance measurements on one giessenite needle showing maximum anisotropism are listed in Table 1. The anisotropism of the mineral is distinct in air, strong in oil. The anisotropic colours range from black to reddish brown. Deep violet colours are sometimes seen very close to the extinguished positions. These optical data are very similar to those of cosalite and the two minerals cannot be distinguished from each other in polished sections by means of these properties.

The polishing hardness is higher than that of galena. Microindentation hardness on a giessenite needle mounted parallel to the polished surface gave the value of 188 ± 13 (VHN_{50g}).

The polished surface of giessenite turns completely black due to dissolution after less than ten seconds treatment with HNO₃ (1:1). Negative results were recorded using the following reagents for one minute: HCl (1:1), KOH (40 %) KCN (20 %), HgCl₂ (5 %) and FeCl₃ (20 %).

X-ray powder data on giessenite using the guinier method are listed in Table 3. The powder data using the Debye Scherre method on the mineral from Binnatal and published by Graser (1963, 1965) are listed in Table 3 for comparison. Serious discrepancies in the intensity of apparently identical lines occur. However, the chemical composition and Weissenberg data on the mineral have clearly established its identity as giessenite. Satisfactory indexing of the lines naturally is uncertain due to the long *a* and *b* axes. The indexing was carried out so that the powder lines with strong intensity correspond to reflections on the Weissenberg diagrams with similar strong intensities. Refined cell dimensions using a programme (REFBASE 2) described by E. S. Leonardsen are listed in Table 2 and compared with those on giessenite from Binnatal (Graeser 1963) and those on cosalite from Nordmarken (Weitz & Hellner 1960). A simple approximate relationship between the cell dimensions of giessenite and cosalite exists:

$$a_{\text{cosalite}} = \frac{2}{3} \times b_{\text{giessenite}}$$

$$b_{\text{cosalite}} = \frac{2}{3} \times a_{\text{giessenite}}$$

$$c_{\text{cosalite}} = c_{\text{giessenite}}$$

Table 2. Cell dimensions of giessenite and cosalite.

Giessenite from Björkåsen, Norway	Giessenite from Binnatal, Switzerland (Graeser 1963)	Cosalite from Nordmarken, Sweden (Weitz & Helner 1960)
$a = 34.326 \text{ \AA} \pm 0.039 \text{ \AA}$	34.5 \text{ \AA}	19.101 \text{ \AA}
$b = 37.369 \text{ \AA} \pm 0.070 \text{ \AA}$	38.3 \text{ \AA}	23.913 \text{ \AA}
$c = 4.067 \text{ \AA} \pm 0.04 \text{ \AA}$	4.08 \text{ \AA}	4.061 \text{ \AA}

The following extinguish rules were determined:

$$h00, h = 2n$$

$$0k0, k = 2n$$

$$00l, l = 2n$$

which gives D_2^4 ($P2_12_12_1$) as the most likely space group.

Microprobe analyses on three giessenite grains gave the results listed in Table 4. Those on giessenite from Binnatal are listed in the Table for comparison. The standard material used was galena for lead and native bismuth, antimony and copper for the remaining metals. The sulphur content was not determined experimentally but assumed to be 16 %. An ARL model EMX microprobe was used. Analyses on Pb and Bi were also carried out using natural cosalite ($Pb_2Bi_2S_8$) from Nordmarken in Sweden as the standard material to check the results listed in Table 4. Very similar values were obtained for Bi but those for Pb were 1.5–2.0 % higher.

The best possible formula for giessenite appears to be



which compares well with that suggested by Graeser



except that his sulphur value appears much too high. The latter formula is based on X-ray fluorescence and electron microprobe analyses.

Sb-free giessenite has not been found among the relative numerous known occurrences of Pb-Bi sulphosalt minerals. (Its Pb:Bi ratio is identical to that of lillianite ($Pb_3Bi_2S_6$)). This suggests that Sb is necessary for the formation of giessenite. The element may therefore not be statistically distributed on bismuth positions in the crystal lattice but occupy certain fixed positions in this.

Cosalite from many localities contains small amounts of Cu (up to 5 %). Weitz & Hellner (1960) have suggested that the element has substituted for Pb in the crystal lattice. It is, therefore, by analogy, possible that Cu has substituted for Pb in giessenite.

Sufficient material for density measurements could not be isolated. A density of 7.47 would allow for the presence of 6 formula units in the unit cell. This density appears too high when compared with that of most sulphosalt minerals which have densities around 7.0.

COSALITE

Cosalite generally occurs as elongated, slightly irregularly shaped grains which range in size up to half a centimetre (Fig. 5). Rare equidimensional and very irregularly shaped cosalite grains have a size of less than one millimetre.

Table 3. X-ray powder data on giessenite.

Giessenite from Björkåsen, Norway (Guinier method)				Giessenite from Binnatal, Switzerland (data from Graesser 1963 Debye Scherre method)			
I	d _{hkl} (meas.)	d _{hkl} (calc.)	Indices	I	d _{hkl} (meas.)	d _{hkl} (calc.)	Indices
3	4.295	4.291	800	2	4.53	4.53	370
3	3.940	3.934	211	3	4.28	4.23	800
4	3.908	3.903	390	2	3.92	3.94	121
3	3.831	3.831	301	3	3.82	3.83	480
5	3.792	3.794	910			3.82	131
4	3.654	3.657	411				
4	3.610	3.618	680	10	3.62	3.61	390
5	3.564	3.552	151				
4	3.476	3.483	511				
9	3.436	3.433	10.0.0	3	3.45	3.45	10.00
4	3.420	3.419	441			3.44	864
9	3.404	3.409	351				
	—			5	3.32	3.32	061
1	3.279						
1	3.206						
5	3.169						
	—			5	3.15	3.16	790
1	3.139					3.14	101
2	3.116						
5	3.047			10	3.05	3.06	5.10.0
4	3.033					3.03	880
5	3.006						
1	2.9484						
2	2.9337						
3	2.9205						
7	2.9061						
7	2.8867						
2	2.8651						
7	2.8413						
4	2.8143						
4	2.7986						
7	2.7432				2.75	2.75	761
1	2.6946						
2	2.6455						
1	2.6222			3	2.63	2.63	681
1	2.6097						
1	2.4722			4	2.49		
5	2.4566						
1	2.3294						
2	2.3196						
3	2.2552						
2	2.1730						
2	2.1653						
9	2.1514						
3	2.1322						
2	2.1141						
3	2.0996						
2	2.0623						
3	2.0492			2	2.04		

Table 3 (cont.)

Giessenite from Björkåsen, Norway (Guinier method)				Giessenite from Binnatal, Switzerland (data from Graeser 1963 Debye Scherre method)			
I	d _{hkl} (meas.)	d _{hkl} (calc.)	Indices	I	d _{hkl} (meas.)	d _{hkl} (calc.)	Indices
10	2.0271						
1	2.0204						
2	1.9994			1	1.99		
1	1.9914			2	1.95		
1	1.9536						
2	1.9126						
2	1.8775						
2	1.8502			2	1.86		
2	1.7875						
2	1.7711						
5	1.7546			4	1.75		
4	1.7432						
3	1.7188						
1	1.7096						
1	1.6984						
1	1.6866						
1	1.6694			2	1.63		
5	1.5413						

Table 4. Microprobe analyses on three giessenite grains. The first analysis is on a grain associated with galena and pyrrhotite. The last two analyses are on laths isolated in quartz. The sulphur content was not determined but assumed to be 16 %.

	Wt. %	Mol. %	Wt. %	Mol. %	Wt. %	Mol. %	Ideal metal ratios
Pb	49.4	25.8	48.2	25.1	47.4	24.8	9
Cu	0.6	1.1	0.8	1.3	0.8	1.3	0.5
Bi	31.1	16.1	31.9	16.5	32.0	16.6	6
Sb	3.3	3.0	3.6	3.2	3.5	3.2	1
S	16.0	54.0	16.0	53.9	16.0	54.1	20
Total	100.4	100.0	100.5	100.0	99.7	100.0	

The optical properties of the mineral cannot be distinguished from those of giessenite. They compare well with those of cosalite from Nordmarken in Sweden; McElroy, Ontario in Canada and Ivigtut in Greenland.

X-ray powder data of the mineral were identical with those of cosalite from Nordmarken.

Microprobe analyses on two grains gave rather equal amounts of lead and bismuth and an additional 0.25 % copper and 0.75 % antimony. These values thus compare very well with the ideal composition of the mineral ($\text{Pb}_2\text{Bi}_2\text{S}_5$) assuming that copper and antimony have substituted for either bismuth or lead or both.

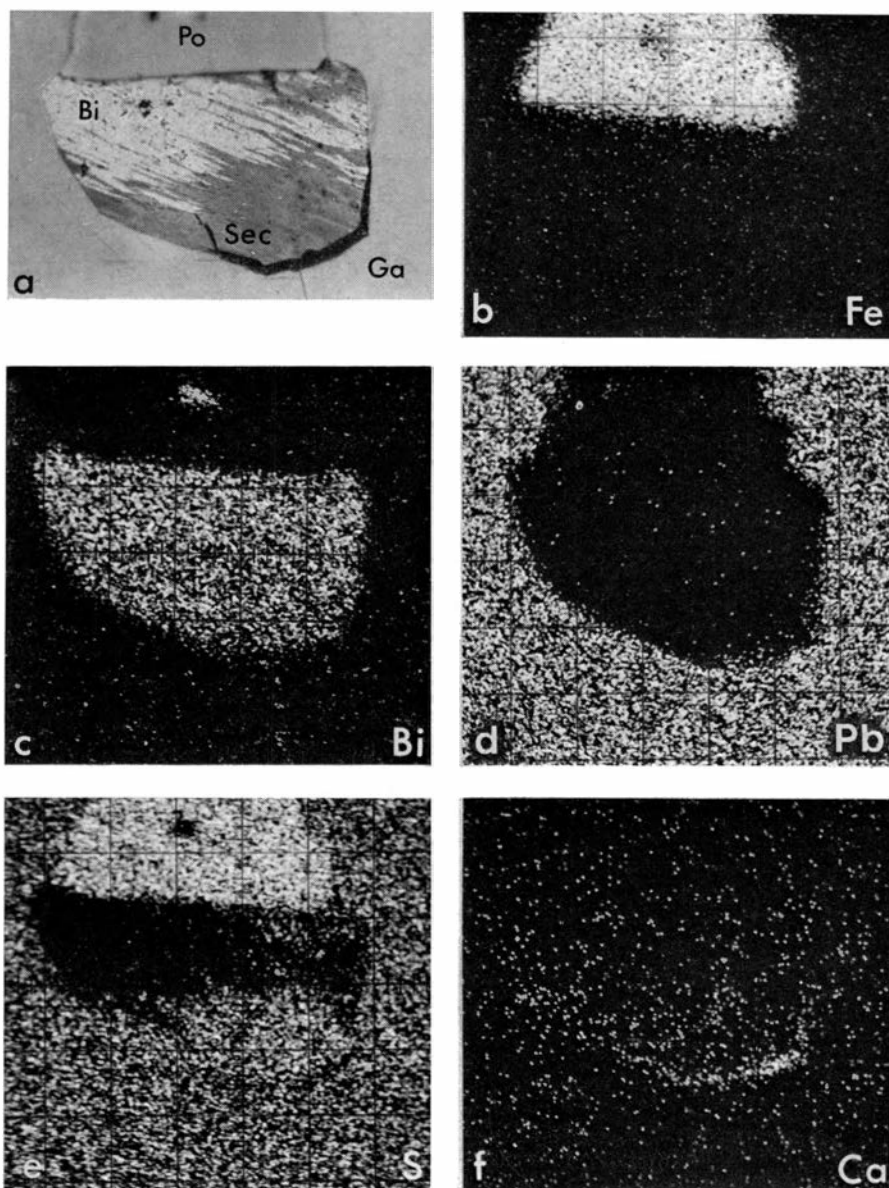


Fig. 1. A bismuth grain in galena has crystallized at the end of a pyrrhotite projection into the galena from a large pyrrhotite grain located outside the figure. The bismuth grain has been partially altered to a secondary bismuth sulphide possibly mixed with very minor amounts of a submicroscopic Ca-bearing mineral as indicated by the scanning photograph Fig. 1 f. A Ca-bearing mineral has crystallized as a rim along a portion of the contact between the secondary bismuth sulphide and galena before projecting into the former as a fracture filling. The electron scanning photographs Figs. 1 b-f show the distribution of Fe, Bi, Pb, S and Ca. Fig. 1 a: Oil immer. 1 nicol. $\times 900$.

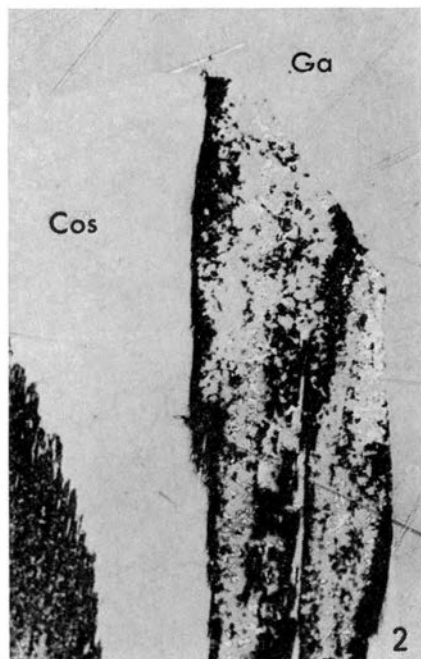


Fig. 2. A cosalite grain in galena has been altered along its margin to secondary galena, bismuth and a bismuth-bearing gangue mineral (black). Oil immer. 1 nicol. $\times 310$.



Fig. 3. Lamellar intergrowth along the margin of a large galena and pyrrhotite grain. Oil immer. 1 nicol. $\times 180$.

MINERAL 'B'

This mineral, present as lamellae in galena (Figs. 12 and 13) was described by Karup-Møller (1971). Microprobe analyses gave the following ideal formula: $\text{Bi}_2\text{Cu}_4\text{Fe}_5\text{Pb}_6\text{S}_{16}$. As insufficient material was present to permit a complete mineralogical examination, no new mineral name has been proposed.

BISMUTH

Bismuth occurs both as equidimensional grains (Figs. 1, 5, 7 and 8) and as fine laths (Figs. 11 g-i). Its identity is easily established due to its high reflectivity, yellow colour and strong anisotropism. In general the mineral is not twinned. The habit of the mineral distinctly shows that it has not been present as a liquid. Its temperature of formation therefore must have been below 269°C , the temperature at which bismuth melts at a pressure of one atmosphere.

Secondary bismuth mineral derived from alteration of bismuth

Many bismuth grains have been partially to completely altered to secondary minerals. This alteration has progressively developed from the margin of a bismuth grain towards its central areas (Figs. 1 and 11 h). It has also de-

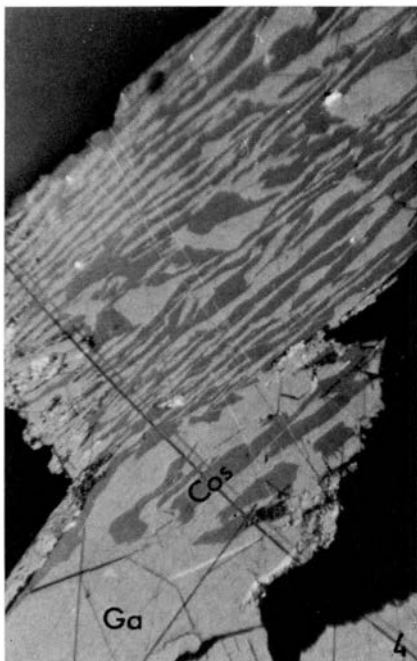


Fig. 4. Myrmekitic intergrowth between galena and cosalite. Some cosalite grains have partially decomposed to secondary galena, bismuth and gangue as in Fig. 2. Oil immer. 1 nicol. $\times 160$.

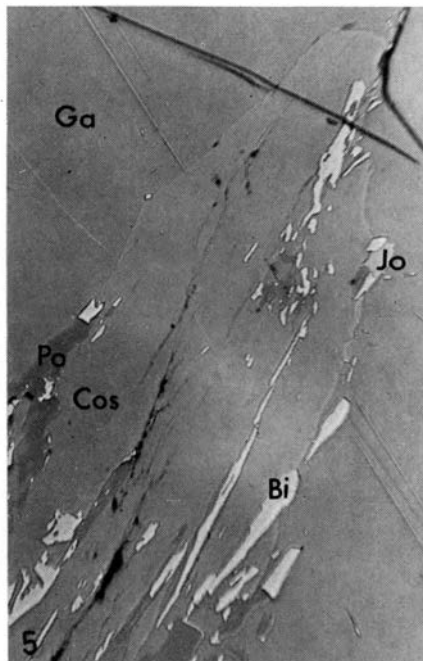


Fig. 5. Elongated cosalite grain in galena containing elongated and irregularly shaped aggregates of bismuth, pyrrhotite and galena. The latter occurs as a narrow layer or sometimes as films around the bismuth grains and is difficult to recognize on the photograph. A grain of joseite along the cosalite-galena contact on the upper right in the figure has a slightly lower reflectance than adjacent bismuth. Oil immer. 1 nicol. $\times 160$.

veloped around cross-cutting fractures which are often filled with similar material. The scanning photos (Fig. 1 b-f) distinctly show that the alteration product is composed of almost as much bismuth as the original bismuth grains and contains more sulphur than the adjacent galena. Small amounts of calcium are also present but oxygen and carbon could not be detected although this does not exclude their presence in small amounts. The material is therefore termed 'secondary bismuth sulphide' and cannot be classified as 'bismuth ochre' known to develop from the oxidation of bismuth. It is possibly a very fine-grained mixture of bismuthinite and a calcium-bearing gangue mineral.

Optically the altered areas appear as if composed of only one well-defined mineral grain. Some grains show a lamellar intergrowth of a lighter and slightly darker grey phase (Fig. 1 a) resembling a twin structure.

The colour of the mineral is very similar to that of sphalerite, and the reflectance is slightly higher. No internal reflections have been observed. The material is isotropic in air and lacks reflection pleochroism. In oil it

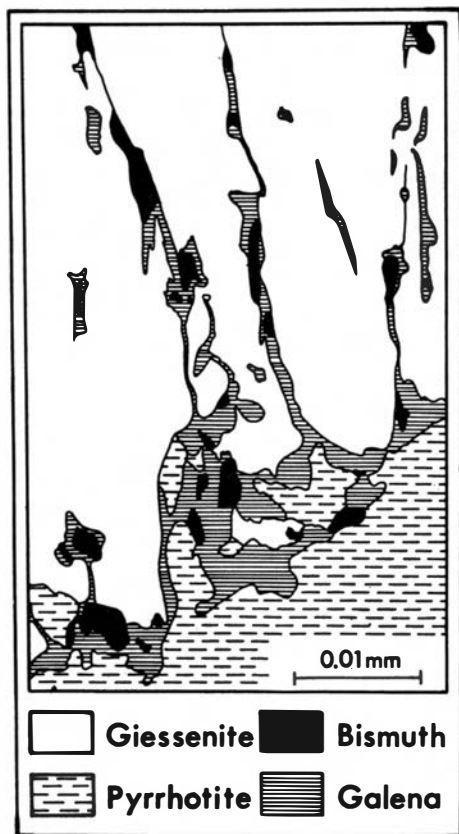


Fig. 6. Galena and bismuth form irregular bands which extend deep into the giessenite from the contact zone between this mineral and pyrrhotite. (Traced from a photograph.)

may sometimes be weakly pleochroic and weakly anisotropic, properties best developed in grains showing lamellar textures.

Secondary bismuth mineral derived from alteration of cosalite and giessenite

The marginal areas of most cosalite and rare giessenite grains have decomposed to a fine-grained mixture of galena, bismuth and an unidentified gangue mineral (Fig. 2). Scanning profiles across such areas show that the gangue mineral is composed of bismuth and sulphur only. No calcium, as contained in the decomposition product of bismuth, could be detected. Under the microscope the gangue mineral occurs as very small grains. Consequently the mineral is not considered to be a sulphide but may possibly be a sulphate, although oxygen could not be detected by the microprobe.

BREITHAUPTITE

Breithauptite occurs as 0.05 millimetres large, rounded to slightly elongated grains present mainly along the giessenite-pyrrhotite contact zone as described on p. 55. It is distinctly to strongly pleochroic in both air and oil and has pink to yellow-pink reflection colours. Reflectance is distinctly

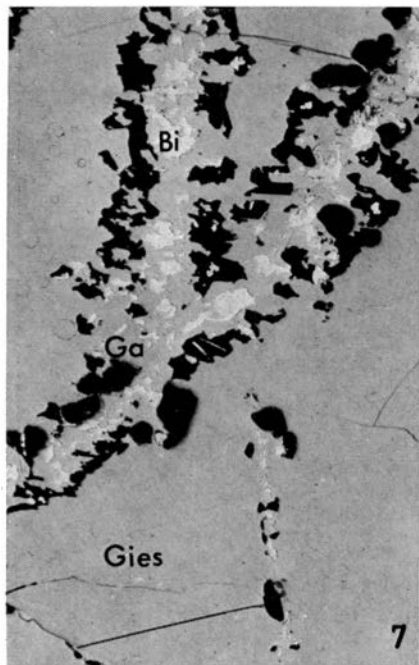


Fig. 7. Alteration veins of galena, bismuth and a Ca-bearing gangue mineral cutting giessenite. Oil immer. 1 nicol. $\times 210$.

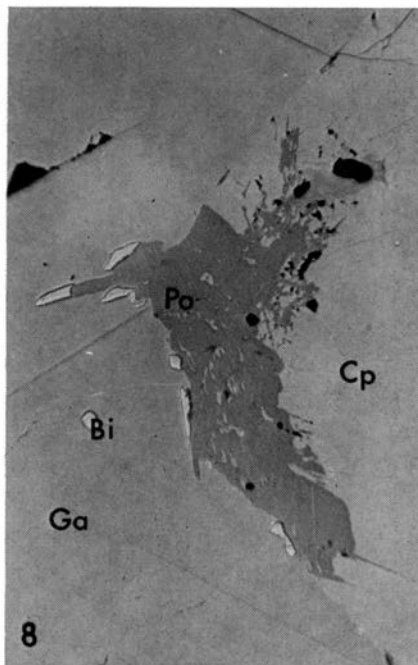


Fig. 8. Pyrrhotite present along the margin of chalcopyrite form a very irregular contact with this mineral, but occurs like chalcopyrite with a smooth boundary against galena except when bismuth grains are present here. Then pyrrhotite may sometimes form projections into the galena at the end of which the bismuth grain has crystallized. Oil immer. 1 nicol. $\times 130$.

higher than that of galena, but only slightly higher than that of ullmannite. Anisotropism is strong in both air and oil and the anisotropy colours are light yellow to deep purple. The polishing hardness is higher than that of pyrrhotite. All these properties compare well with those on the mineral listed by Ramdohr (1960).

Qualitative microprobe tests showed the presence of only nickel and antimony agreeing with the composition (NiSb) of the mineral.

ULLMANNITE

Ullmannite occurs like breithauptite as 0.03 millimetres large, rounded grains along the giessenite-pyrrhotite contact zone. The mineral is isotropic. Reflectance is higher than that of galena. The colour is bright greyish-white against the more dullish and slightly darker grey galena. The polishing hardness is higher than that of pyrrhotite. Microprobe analyses confirmed the formula NiSbS for this mineral.

JOSEITE

Joseite occurs as short lamellae up to 0.1 millimetre in length (Fig. 11) but also in irregularly shaped grains with a maximum grain size of 0.05 millimetres (Figs. 5 and 13 d).

Reflection pleochroism is absent in air, and absent to weak in oil. The colour is bright yellow, sometimes with a weak greenish tint against galena, but pale white-yellow against the much deeper yellow bismuth. Reflectance is higher than that of galena but lower than that of bismuth. Anisotropism is weak in air, distinct to strong in oil and the anisotropy colours are yellow to black, closely resembling those of bismuth. Polishing hardness is less than that of galena, cosalite and giessenite, but higher than that of bismuth.

Microprobe analyses on three joseite lamellae gave the results listed in Table 5. These agree best with the formula: $(\text{Bi}, \text{Pb})_4(\text{Te}, \text{S})_8$, which compare closely with that of joseite $(\text{Bi}_4\text{Te}_2\text{S})$. Standards used were galena for Pb and S and pure metals for Te and Bi.

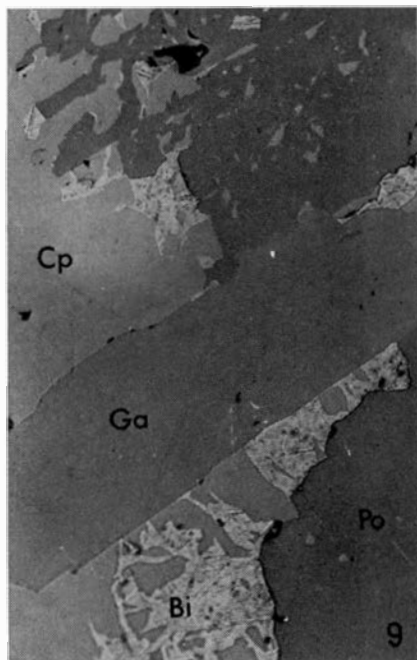


Fig. 9. Direct replacement of chalcopyrite by pyrrhotite in the upper part and indirect replacement via a layer of bismuth in the lower part of the photograph. The centrally located galena grain was present in chalcopyrite before its replacement and has not been affected by this process. Oil immer. 1 nicol. $\times 480$.

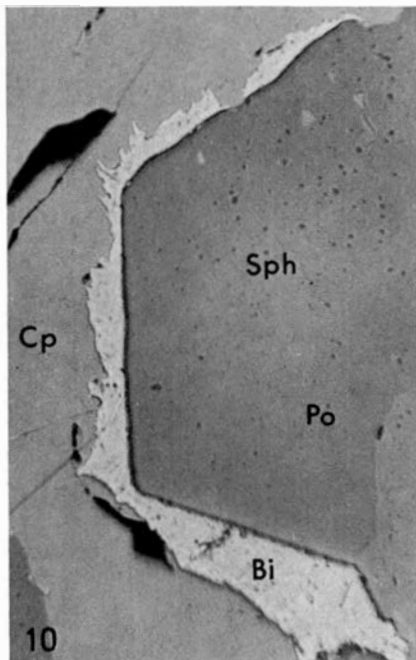


Fig. 10. Idiomorphic pyrrhotite crystal has grown during replacement of chalcopyrite via a narrow layer of bismuth. A few unreplaced chalcopyrite remnants occur enclosed in the pyrrhotite. The idiomorphic shape of the mineral is due to the presence of the bismuth. Mutual pyrrhotite-chalcopyrite boundary is irregular as in the very upper portion of the photograph. Very fine sphalerite blebs have exsolved from the pyrrhotite. Oil immer. 1 nicol. $\times 260$.

Table 5. Microprobe analyses on three joseite lamellae.

	Wt. %	Mol. %	Wt. %	Mol. %	Wt. %	Mol. %
Pb	10.2	7.2	6.1	4.2	9.3	6.1
Bi	75.3	52.4	74.3	51.2	76.8	50.0
Te	6.4	7.3	10.1	11.4	6.1	6.5
S	7.3	33.1	7.4	33.2	8.8	37.3
Total	99.2	100.0	97.9	100.0	101.0	99.9

STANNITE

Stannite is a relatively common mineral present as irregularly shaped grains with an average size of 0.1 millimetres. The mineral also occurs as extremely small exsolution blebs in sphalerite.

Pleochroism is absent in both air and oil. Reflection colours are olive to greenish-grey. Anisotropism is weak to distinct in air but strong in oil. The anisotropy colours are dark olive-grey to violet. The polishing hardness is slightly lower than that of sphalerite.

A microprobe spectrograph showed the presence of Fe, Cu, Sn, Zn and S.

Mineral relationships

Contact relationships of galena

The galena-pyrrhotite boundary is generally smooth. Numerous very small grains of chalcopyrite and stannite lie in contact with pyrrhotite and project into galena. Grains of bismuth along the same contact have crystallized at the end of small pyrrhotite projections into the galena (Figs. 8 and 11 h-i). Local concentrations of bismuth have resulted in the sudden irregular trend of the pyrrhotite boundary. The bismuth here is always intergrown with galena and pyrrhotite and sometimes joseite and chalcopyrite are also present. Generally the dominating mineral is galena which then appears as the host mineral (Fig. 12 upper left). All pyrrhotite grains within such aggregates extinguish at the same position as the adjacent large pyrrhotite grain.

Myrmecitic intergrowth, sometimes developed between galena and pyrrhotite, is characterized by long regular pyrrhotite lamellae alternating with thinner lamellae of galena (Fig. 3). Such intergrowths have in general only developed as a contact zone between large and homogeneous pyrrhotite and galena grains.

Small grains of chalcopyrite and stannite and lamellae of bismuth and joseite occur in galena against sphalerite. Stannite is present in galena against chalcopyrite. No irregularity of the sphalerite and chalcopyrite boundaries has developed due to the presence of these mineral grains. No minerals have crystallized along the galena-pyrite contact. Pyrite occurs as sub-euhedral crystals up to half a centimetre in size.

Galena-cosalite relationships

Cosalite occurs in galena as isolated, elongated and irregularly shaped grains. The mineral has very rarely been replaced by galena. Myrmekitic intergrowth between the two minerals has been observed in one polished section only. This intergrowth has gradually developed across a large galena grain as can be seen by the rapidly increasing number of parallel oriented cosalite laths (Fig. 4), suggesting that the two minerals formed simultaneously. Similar myrmekitic intergrowths between galena and cosalite are described by Ramdohr (1960, Fig. 89), who suggests that they may have developed from the decomposition of an unknown mineral. Recently Klomínský et al. (1971) have described such an intergrowth as a decomposition product of keyrovskýite. However, the mineral relationships of cosalite and galena from Björkåsen suggest that both are primary in origin and of the same age.

Galena-pyrrhotite-bismuth rich aggregates isolated in galena

Aggregates of galena, pyrrhotite, bismuth, cosalite and rare grains of breithauptite and joseite are enclosed in galena. The minerals occur in an irregular intergrowth and myrmekitic textures have sometimes developed between galena and bismuth and between galena and pyrrhotite.

Relatively large and regularly shaped cosalite grains occur in contact with these aggregates and are partially or completely enclosed by them. Such grains may either be completely homogeneous or they may contain irregularly shaped galena-bismuth-pyrrhotite areas (Fig. 5).

Cosalite and associated mineral aggregates are considered to have crystallized from fluids trapped in already solid galena. The presence of the galena-bismuth-pyrrhotite areas in the large cosalite grains suggest that these minerals developed shortly after the crystallization of the host mineral possibly when rest fluids penetrated and partially replaced it.

Contact relationships of giessenite

The only sulphides found in contact with giessenite are galena and pyrrhotite. The boundary of giessenite against the former is very smooth but it is always extremely irregular against the latter. Galena associated with abundant bismuth and pyrrhotite and rare grains of breithauptite, ullmannite and chalcopyrite have crystallized as an irregular contact zone between giessenite and pyrrhotite. Direct giessenite-pyrrhotite contacts have rarely developed and then only over a very short distance. The irregular trend of the pyrrhotite boundary is due to numerous projections of this mineral into the contact zone (Fig. 6). The galena-bismuth-pyrrhotite contact zone itself forms numerous projections which extend as narrow irregular bands relatively deep into giessenite (Fig. 6). The bands vary in width 0.01 millimetres down to nothing but a galena film. Bismuth grains embedded in galena or surrounded by a thin galena layer occur isolated in the giessenite grain. The large adjacent pyrrhotite grains and all the small pyrrhotite grains along the contact zone extinguish in the same position. Breithauptite and ullmannite occur as

minute grains along the contact zone generally in direct contact with pyrrhotite.

Giessenite is cut by alteration veins (Fig. 7). The minerals along these are galena, bismuth and a calcium-bearing gangue mineral, possibly a sulphate. Galena appears as the host for bismuth which is concentrated in the central areas of the veins and also as the host for the calcium-bearing mineral, present along the margins. The veins may narrow down to a very fine galena stringer before pinching out and disappearing or they may join up with and form a natural extension of the contact zone minerals into the giessenite grains. However, different minerals occur along the contact zone and along the veins.

The minerals along the contact zone may have crystallized from rest fluids which were concentrated here as the crystallization of giessenite and pyrrhotite progressed. The presence of sparse chalcopyrite, breithauptite and ullmannite suggests that these fluids were enriched in the elements Cu, Ni and Sb. The galena-bismuth-pyrrhotite bands projecting from the contact zone into the giessenite grain suggest that the fluids penetrated and replaced giessenite, possibly along fine fractures. The numerous projections from the large pyrrhotite grain into the contact zone suggest that the large pyrrhotite grain continued to develop at the same time as the rest fluids penetrated and replaced already solid giessenite. The smaller areas of bismuth and galena completely isolated in the giessenite may also have crystallized from entrapped rest fluids or from fluids emplaced along submicroscopic (or recrystallized?) fractures. They resemble the galena-bismuth-pyrrhotite areas in cosalite described above (Fig. 5).

The natural extension of the contact zone into the alteration veins suggests that both zone and veins crystallized from the same fluids. However, due to the different minerals along the vein and the contact zone these may not have crystallized simultaneously. It is possible that the rest fluids after the formation of the contact zone were depleted in the elements Cu, Ni and Sb but enriched in Ca. These final fluids may have penetrated giessenite, partially dissolved it and then crystallized as the 'alteration veins', and thus represent the final phase in the crystallization of galena, giessenite and pyrrhotite.

The chalcopyrite-pyrrhotite-bismuth contact relationships

The chalcopyrite-pyrrhotite boundary is generally smooth but has an irregular trend due to the anhedral shape of the two minerals. A few exceptions to this general rule have been observed.

Minor pyrrhotite has developed locally along the margin of chalcopyrite grains in contact with galena. The pyrrhotite-galena contact resembles that between chalcopyrite and galena but the pyrrhotite-chalcopyrite boundary in contrast is extremely irregular which suggests intense replacement of chalcopyrite by pyrrhotite (Fig. 8).

Two large and intergrown pyrrhotite grains shaped as a 'cauliflower head'

have developed during replacement of chalcopyrite. A narrow band of bismuth separates most of the pyrrhotite from the chalcopyrite. A portion of the contact zone is shown in Fig. 9. A steady growth of the pyrrhotite has forced the bismuth to penetrate chalcopyrite, break it up and partially replace it. Numerous unreplaced remnants are enclosed in the bismuth. The major portion of these remnants are replaced by pyrrhotite as they come in contact with this mineral (Fig. 9, bottom). When bismuth is absent and pyrrhotite occurs in direct contact with chalcopyrite then this mineral is intensively broken up and penetrated by the replacing pyrrhotite. Here numerous unreplaced chalcopyrite fragments occur enclosed in the pyrrhotite (Fig. 9, top). This contact relationship resembles that between the same two minerals described above and shown in Fig. 8. A galena grain present in the chalcopyrite before its replacement was not affected by the advancing bismuth-pyrrhotite mineral association (Fig. 9, centre).

In Fig. 10 an idiomorphic pyrrhotite crystal is separated from chalcopyrite by a thin layer of bismuth. No inclusions of chalcopyrite occur in the bismuth and only a few in the pyrrhotite. However, the shape of the bismuth-chalcopyrite boundary resembles that between the same two minerals in Fig. 9. This suggests a pattern of growth of all three minerals similar to that of the same minerals in Fig. 9. Very fine sphalerite has exsolved from the pyrrhotite grain.

Machiwanite and sphalerite (?) exsolved from chalcopyrite

Machiwanite occurs in chalcopyrite as irregular lamellae oriented after different crystallographic directions of this mineral. Some lamellae follow chalcopyrite grain boundaries while others appear as fracture fillings around enclosed stannite. Machiwanite undoubtedly formed during exsolution from the chalcopyrite host which indicates that the chalcopyrite crystallized at a minimum temperature of around 200 °C.

Chalcopyrite also contains very short and extremely thin lamellae or rather wisps of an unidentified mineral which could possibly be sphalerite. These lamellae are oriented parallel to only one direction in the chalcopyrite. Machiwanite lamellae also occur parallel to this direction.

Mode of occurrence of stannite

Stannite occurs as rounded to elongated grains along the contact between galena, sphalerite, pyrrhotite and chalcopyrite. The grains are most abundant along the chalcopyrite-sphalerite boundary. They may straddle it or lie on either side of it. Stannite has rarely penetrated sphalerite along its grain boundaries. It occurs rarely as inclusions in this mineral and then only along its very marginal areas.

Stannite is enclosed as extremely irregularly shaped grains in chalcopyrite or along chalcopyrite grain boundaries. Pyrrhotite in contact with chalcopyrite may also contain similarly shaped stannite grains, but pyrrhotite elsewhere does not contain this mineral.

Stannite frequently contains very fine, exsolved sphalerite grains. These occur randomly mainly in the central areas of the stannite grains and they closely resemble the small sphalerite grains exsolved from pyrrhotite (Fig. 10).

Lamellar minerals enclosed in galena

Mode of occurrence of the lamellar minerals

Galena contains a great variety of minerals present as lamellae oriented parallel to its (111) crystallographic direction. These minerals are mineral 'B', joseite, bismuth, chalcopyrite, pyrrhotite and stannite. The first three mentioned have been observed in small amounts in most of the polished sections and occur generally as monomineralic lamellae. Chalcopyrite and pyrrhotite, both of which are associated with bismuth and sometimes also stannite and mineral 'B', form composite lamellae. These are very rare except in one polished section where they are present in abundance.

Mineral 'B' lamellae are regularly shaped and have a constant thickness which varies from one lamellae to another. The maximum thickness is 0.01 millimetre. The lamellae generally terminate abruptly in the galena host. When several lamellae are present in a galena grain they always lie parallel and close to each other (Karup-Møller 1971, Fig. 2).

Joseite lamellae are shorter than mineral 'B' lamellae but have a similar thickness. They are generally orientated parallel to the (111) crystallographic direction of the galena host and are then more regularly shaped than when present with random orientation. Sometimes a lamella is distinctly cut and apparently replaced by galena (Figs. 11 e and 13 h).

Joseite lamellae may project from the boundary against cosalite into the galena and pinch out over a short distance (Figs. 11 a and d). The lamellae in Fig. 11 b distinctly lie on the cosalite side of the contact. In Figs. 11 c and d the lamellae vaguely disturb the trend of the cosalite-galena boundary, while this has been distinctly modified by the composite joseite-bismuth lamellae in Fig. 11 g. Joseite lamellae may very rarely straddle the boundary between galena and the minerals chalcopyrite, pyrrhotite and sphalerite (Figs. 11 e, f and h).

Bismuth, when shaped as lamellae, resembles the regularly shaped joseite lamellae although it may be considerably larger. The lamellae occur like joseite, isolated in galena or along its contact with adjacent minerals. Bismuth lamellae often contain very fine inclusions of galena (Fig. 11 g). Sometimes the lamellae are cut across by galena as if replaced by this mineral. Lamellae have been found to straddle the galena-sphalerite boundary thus resembling joseite lamellae straddling the boundary between the same two sulphides. Bismuth lamellae may reach the pyrrhotite contact and here the pyrrhotite has developed its characteristic projections into the galena (Figs. 11 h and i).

Chalcopyrite- and pyrrhotite-rich lamellae always contain bismuth, often stannite and galena but only very rarely mineral 'B' and joseite. Such

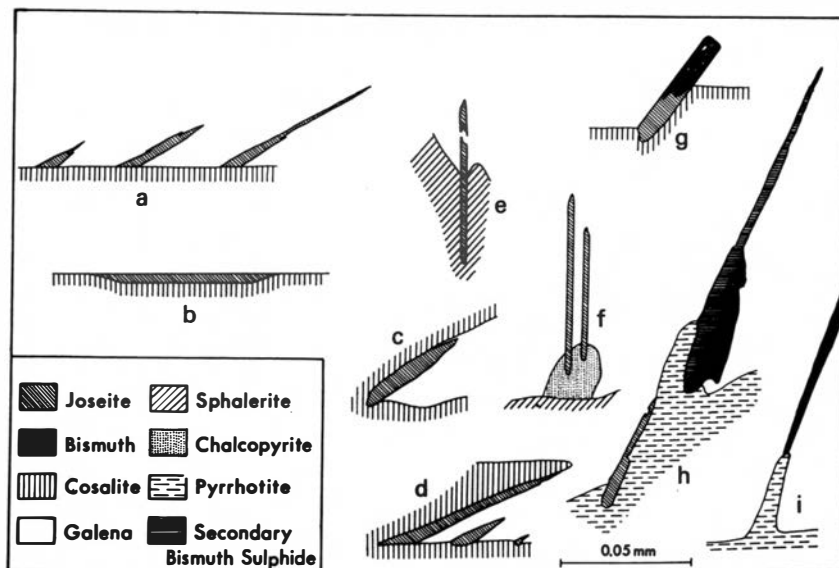


Fig. 11. Contact relationships between various sulphides and lamellar joseite and bismuth. (Traced from photographs.)

lamellae as well as monomineralic lamellae of mineral 'B', joseite and bismuth occur in abundance in one galena grain (Fig. 12). Their delicate textures traced from photographs are shown in Fig. 13.

The chalcopyrite lamella in Fig. 13 a has a relatively smooth outside boundary but enclose equidimensional grains of bismuth and irregularly shaped areas of galena. The lamella in Fig. 13 b is more massive containing a few inclusions of bismuth and galena but it has a very irregular outside boundary. It is surrounded by numerous bismuth grains, some of which are slightly elongated and are then oriented parallel to the (111) crystallographic directions of the galena host. The lamella in Fig. 13 c is actually an aggregate of isolated chalcopyrite and bismuth grains. This aggregate is elongated parallel to a single (111) crystallographic direction of the galena host while most of the individual grains are elongated parallel to another of the (111) directions. The left portion of the lamella in Fig. 13 d is representative of a relatively thick but short lamella. Other lamellae may have a similar thickness but may obtain much greater length as shown in Fig. 12. Thinner chalcopyrite-rich lamellae generally show less spectacular textures than the thicker lamellae (Fig. 13 d at right). Most lamellae terminate abruptly in the galena host and only a few by gradually thinning out.

Certain portions of chalcopyrite-rich lamellae may consist of pyrrhotite and very rarely of mineral 'B' (Fig. 13 e) but only one lamella containing joseite has been observed (Fig. 13 d). Stannite is present as very small grains along many chalcopyrite-rich lamellae (Figs. 13 b and d). No lamellae are dominated by this mineral.

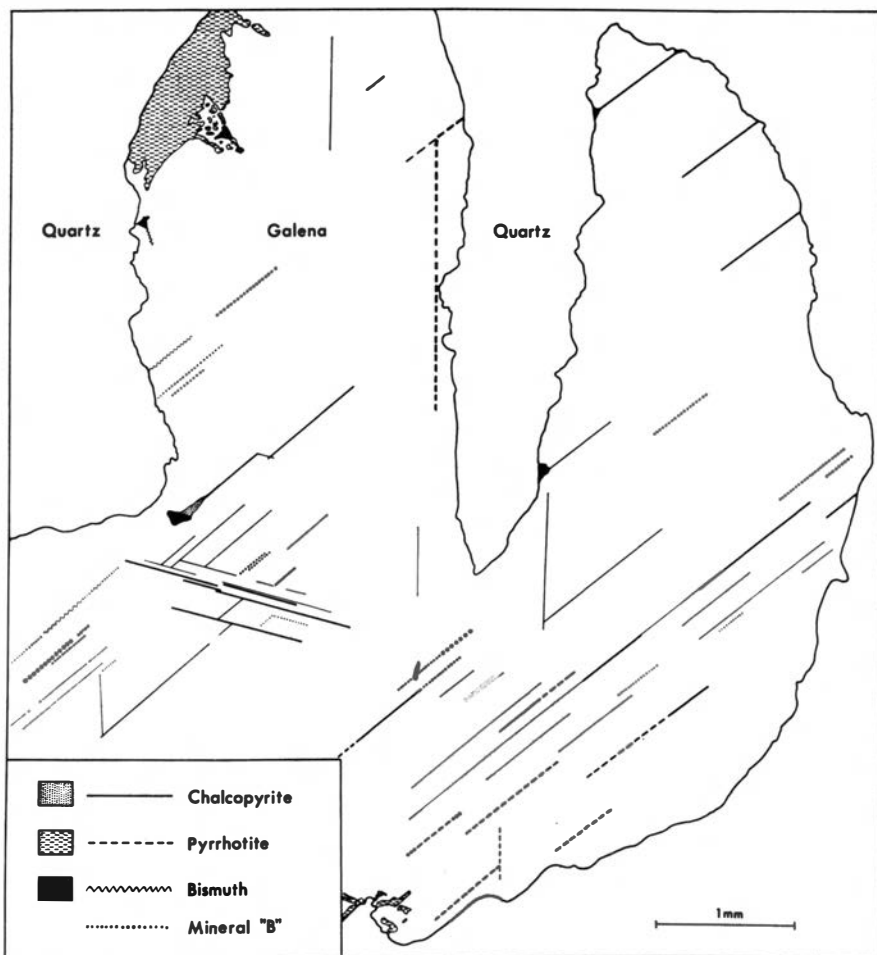


Fig. 12. Relatively large galena grain containing an unusual large number of lamellae of various minerals oriented parallel to its (111) crystallographic directions. Thick and thin lines, large and small dots, etc. indicate thick and thin lamellae. An irregular aggregate of pyrrhotite, bismuth and galena has developed along the galena-pyrrhotite boundary on the upper left in the Figure. (Traced from photographs.)

Pyrrhotite-rich lamellae occur less frequently than the chalcopyrite-rich lamellae. Texturally some lamellae resemble chalcopyrite-rich lamellae and always contain bismuth and sometimes also galena and mineral 'B' (Fig. 13 f). Other lamellae have very regular and straight boundaries against galena. They contain no galena and only minor bismuth (Fig. 14 b, left).

A portion of a rare lamella composed of alternating sections of bismuth and mineral 'B' is shown in Fig. 13 g and a very bismuth-rich lamella with minor chalcopyrite and stannite in Fig. 13 h.

Slightly elongated pyrrhotite, chalcopyrite and bismuth grains concentrated along the margin of the galena host are distinctly controlled by the (111) crystallographic direction of this mineral (Fig. 14). The elongated

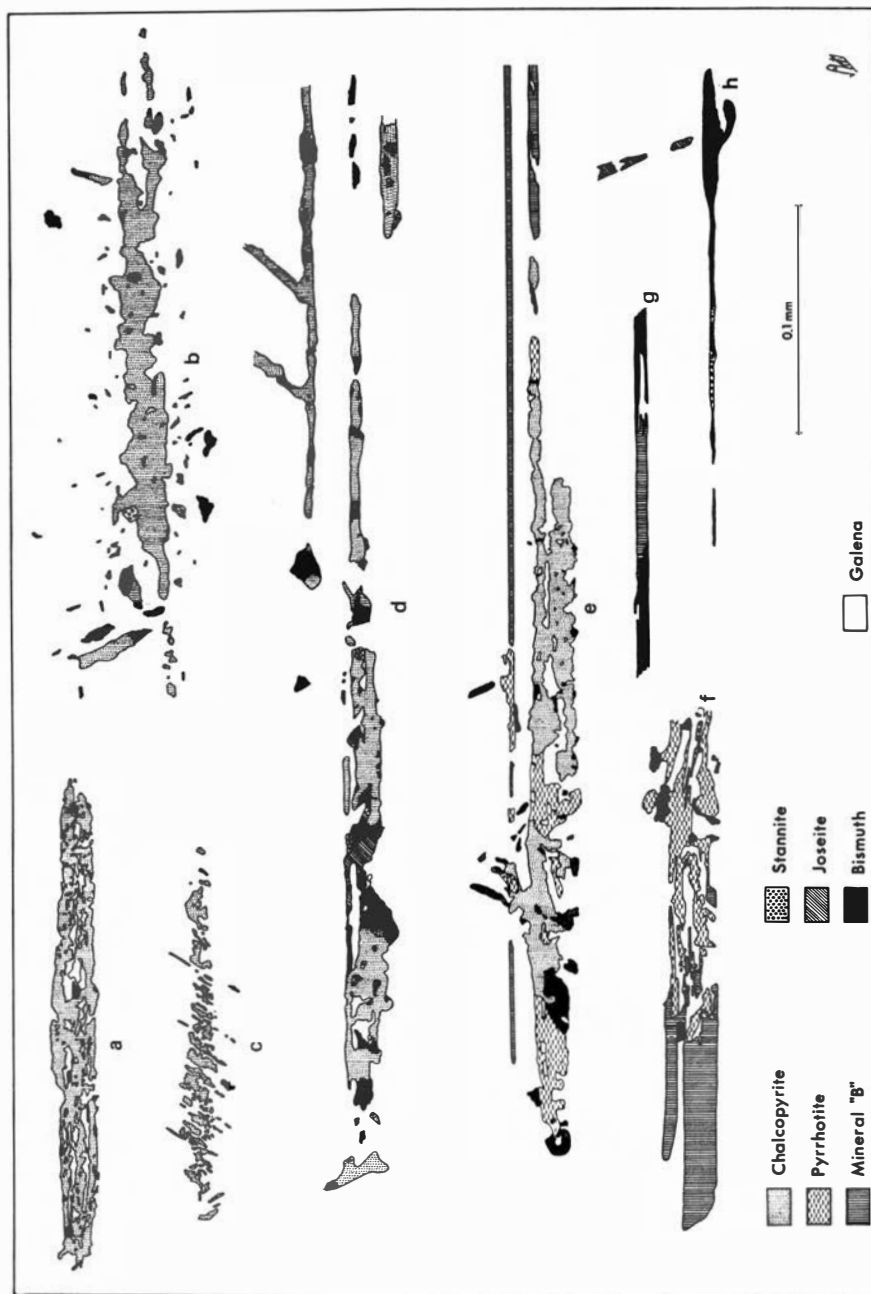


Fig. 13. Textures of various lamellar minerals all of which are present in the galena grain shown in Fig. 12, except the lamellae Fig. 1 c. (Traced from photographs.)

pyrrhotite grains along the galena boundary in Fig. 14 b are orientated parallel to an isolated pyrrhotite lamella in the galena. Chalcopyrite lamellae sometimes extend into an area of granular chalcopyrite, bismuth and stannite which is also located along the margin of the galena host.

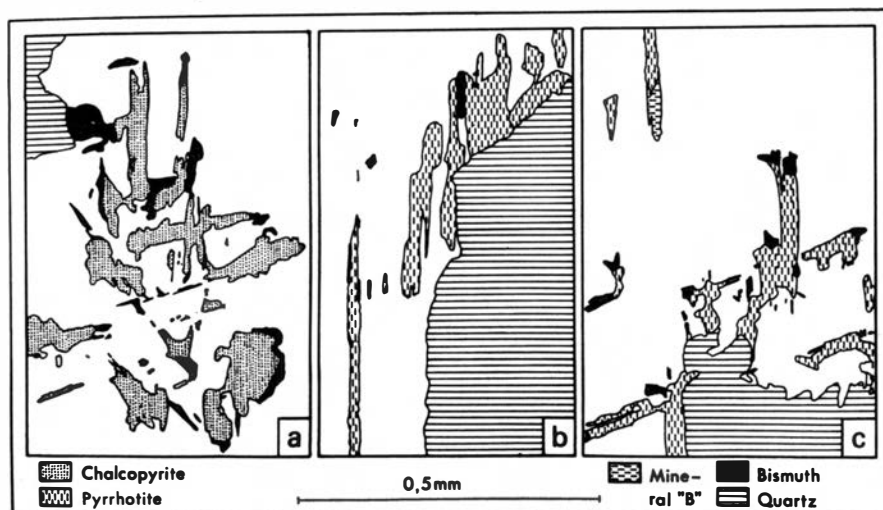


Fig. 14. Aggregate of elongated chalcopyrite and pyrrhotite grains present along the margin of the galena grain shown in Fig. 12. The individual grains are oriented parallel to the (111) crystallographic directions of the galena host. (Traced from photographs.)

Origin of the lamellar minerals in galena

Initially mineral 'B' was found as rare monomineralic lamellae in galena and was considered to have exsolved from this mineral (Karup-Møller 1971). Since then more material has been studied and for the reasons listed below it is concluded that the lamellar minerals including mineral 'B' could not have formed by simple exsolution from the galena host due to decreasing T-P conditions.

Joseite lamellae straddle the boundary between galena and adjacent minerals and are located along the boundary between them distinctly modifying its trend (Fig. 11). Bismuth grains and bismuth lamellae in contact with pyrrhotite have caused a very irregular trend in the boundary of this mineral (Figs. 8 and 11 h - i). All these textural relationships strongly exclude the possibility that joseite and bismuth exsolved from galena.

Some chalcopyrite lamellae extend into aggregates of granular chalcopyrite, bismuth and sometimes also stannite. Chalcopyrite and bismuth grains have crystallized as slightly elongated grains in galena being distinctly controlled by the (111) crystallographic direction of this mineral, a direction along which chalcopyrite-rich lamellae are arranged elsewhere in the same galena grain (Fig. 14 a). Elongated pyrrhotite grains along the galena boundary are oriented parallel to isolated pyrrhotite lamellae in galena (Fig. 14 b and c). These textural relationships strongly suggest a common mode of formation of mineral lamellae and mineral aggregates. Since the latter are considered to have formed pene-

contemporaneously with the galena host, this excludes the possibility that the lamellae could have exsolved from it.

All the lamellar minerals are considered to have formed penecontemporaneously. If they had developed as a result of exsolution, then the elements Cu, Fe, Sn and Bi dissolved in the galena lattice would have become unstable in the same T-P interval – a very unlikely possibility.

The irregular distribution of the lamellae in Fig. 12, their considerable thickness compared to their relatively great and variable inter-lamellar distance also does not favour an origin through exsolution.

The textural relationships summarized above thus exclude the possibility that the lamellar minerals exsolved from their galena host due to decreasing T-P conditions. However, the often delicate textures of the lamellae certainly do not support a simple penecontemporaneous crystallization of these and their galena host. The following mode of formation is suggested:

The large galena grain shown in Fig. 12 crystallized from fluids entrapped in already solid quartz. Gradual crystallization of the galena grain caused the elements Fe, Cu, Sn and Bi to be enriched in the rest fluids. When the saturation point was reached for these elements, they were precipitated together with lead as a meta-stable phase in contact with already solid galena. The removal of the surplus elements from the fluids was followed by renewed crystallization of galena until the saturation point for some or all of the elements was reached again, etc. The metastable phase may, immediately after its formation and possibly before the crystallization of galena recommenced, have recrystallized and produced galena as a host for the various minerals present, shaped either as lamellae or elongated grains.

The delicate textures of the lamellae and the arrangement of isolated bismuth grains around many of these is best explained this way rather than by direct crystallization of the minerals from the fluids, although this is a possibility which naturally cannot be disregarded. Epitaxial growth of the lamellar minerals with galena appears very unlikely due to the different structures of these minerals and the galena.

The proposed mode of formation also explains the distribution of the lamellae in the galena grain. The greater portion of this grain contains most lamellae arranged parallel to only one of its (111) crystallographic directions. Within some smaller areas the lamellae are contained parallel to another of the (111) directions. This arrangement suggests that the growth of the galena grain took place along the direction perpendicular to that of its (111) crystallographic directions parallel to which the lamellae are arranged.

The same mode of formation may also explain the origin of the joseite lamellae which straddle the boundary between galena and either of the minerals pyrrhotite, sphalerite and chalcopyrite. The simultaneous crystalli-

zation of one of these minerals and galena may temporarily have been interrupted and a layer of joseite precipitated which now appears as joseite lamellae. Joseite, mineral 'B' and bismuth lamellae isolated in galena throughout the mineral suite are therefore considered to have formed in a similar way.

Conclusion

The investigated mineral suite from the Björkåsen sulphide deposit has attracted attention because of the presence of giessenite known only from its type locality at Binnatal in Switzerland and the presence of the new mineral, mineral 'B'. Another feature of interest is the mode of occurrence of different minerals contained in galena as lamellae.

Both giessenite and cosalite have crystallized in galena. No features have been found to suggest anything but penecontemporaneous crystallization of these. Sb-free giessenite has not been produced experimentally, although the system $\text{Bi}_2\text{S}_3\text{-PbS}$ has been thoroughly investigated (Salanci & Moh 1969, and others). Cosalite has not been synthesized either, and is therefore assumed to crystallize at low temperatures only. The occurrence of both minerals in galena is no doubt due to the presence of a little antimony. Had this element not been present then all the bismuth tied up in the giessenite lattice would undoubtedly have crystallized as cosalite. Antimony therefore, as previously concluded, is considered to be a necessary element for the formation of giessenite.

The presence of the new mineral, mineral 'B', is another interesting feature of the Björkåsen sulphide deposit. Unfortunately it was not possible to carry out a complete mineralogical investigation due to insufficient amounts of material available. No mineral name has therefore been proposed.

The abundance and textural varieties of the different minerals contained as lamellae in galena are unusual. In general, fine mineral lamellae in galena are considered to have formed during exsolution from this mineral. The textural relationships between the lamellar minerals and their galena host of the Björkåsen sulphide deposit has shown that the lamellae could not have formed as a result of exsolution. On the contrary, they are considered to have crystallized penecontemporaneously with the galena host from the same fluids as this mineral. Thus the presence of lamellar minerals in galena is no proof in itself that they formed during exsolution from their host.

It is concluded that the temperature of formation of the sulphides lies somewhere between 200 °C (the temperature around which valeriite exsolves from chalcopyrite) and 269 °C (the temperature at which bismuth melts at one atmosphere pressure).

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