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A GUSTAVITE-COSALITE-GALENA-BEARING  
MINERAL SUITE FROM  
THE CRYOLITE DEPOSIT AT IVIGTUT,  
SOUTH GREENLAND

BY

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WITH 4 FIGURES AND 1 TABLE IN THE TEXT,  
AND 10 PLATES

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### Abstract

A suite of rare bismuth-lead-silver-copper sulphides associated with various gangue minerals was found in the cryolite deposit. The mineral suite occurred close to the contact between the siderite- and fluorspar-zones. It was exposed over an area about half a meter in diameter and is characterized by sulphide-disseminated topaz-fluorspar material contained in a mixture of fluorspar, weberite, fine grained muscovite and very minor amounts of quartz, referred to as "the matrix gangue minerals".

The sulphides present are gustavite (with an exsolved mineral referred to as phase X), cosalite and galena associated with some aikinite, berryite and pyrite. Matildite, argentite(?), gold, bismuth, chalcopyrite, sphalerite, pyrrhotite, marcasite and a new mineral earlier described as "Mineral A" are present in very minor amounts. Rare grains of coffinite sometimes with a core of a sulphide-uraninite intergrowth are also present. Data on gustavite, phase X, berryite and mineral A have already been published; the properties of the other minerals present and their relationships are described.

Investigations of fluids entrapped in fluorspar indicates a maximum temperature of formations of the sulphides around 300° C. The minimum temperature of formation may lie around 200° C.

The mineral suite is concluded to have crystallized from fluids without introduction of additional material as the crystallization took place. The fluids may possibly have been present as a low temperature sulphide melt. The crystallization sequence of the mineral suite and the possible changes in the composition of the fluids as the crystallization progressed are discussed.

The mineralizing fluids may have developed from mobilization of silver-bismuth-bearing galena which constitutes slightly less than half a percent of the cryolite-siderite ore zone of the cryolite deposit. This mobilization took place when late fluorspar-zone material reacted with galena-disseminated siderite-rich material.

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## I. INTRODUCTION

Sulphides, mainly sphalerite, galena, chalcopyrite and pyrite constitute an average two percent of the cryolite deposit at Ivigtut. A large number of other sulphides are present in insignificant amounts. Some of these are listed by PAULY (1960), while others have been found since then. The most interesting sulphide is galena, which contains about  $\frac{3}{4}$  percent silver and  $1\frac{1}{2}$  percent bismuth dissolved in its lattice. The galena contains very small amounts of different sulphides, some of which have not previously been described. A study of these is currently in progress.

During the summer of 1961 HANS PAULY (at that time chief geologist of the Cryolite Company) found a pocket of minerals characterized by a number of bismuth-lead-silver-copper bearing sulphides. Four of these, namely gustavite, berryite, phase X and mineral A were new and have already been described (KARUP-MØLLER, 1966, 1970 and 1971). A general description of the discovered material, its location, its mode of formation and its possible relationships to the common Ivigtut galena is the subject of the present paper. The material is referred to as "the gustavite bearing-mineral suite", or in many places simply as "the mineral suite".

## II. LOCATION OF THE DISCOVERED MINERAL SUITE

A comprehensive geological description of the cryolite deposits has not yet been published although several papers dealing with individual minerals and mineral parageneses have been produced. The major economic rock type of the deposit, the siderite-cryolite ore, was described by PAULY (1960).

The following information about the cryolite deposit and the location of the gustavite-bearing mineral suite has been taken from PAULY (1960) and provided by Professor H. Pauly in personal communication:

“The siderite-cryolite ore is characterized by an average 70 percent cryolite and 30 percent siderite. Sulphides constitute about two percent and the minerals quartz, thomsenolite, fluorspar and others another two percent. This peculiar rock forms a lensoid-shaped body within the granite stock which is host to the deposit.

The proportion between cryolite and siderite varied throughout the deposit. In places cryolite was the only mineral present, whereas in other places siderite dominated.

Underlying the siderite-cryolite body in the eastern part of the deposit occurred a shell-like mass with up to 90 percent siderite containing only minor amounts of cryolite. Sulphides were present in amounts usually corresponding to a few percent. This material, known as the siderite-zone, occurred in sharp contact with the overlying siderite-cryolite material. In spite of this sharp contact the two rock types are considered closely related in respect of formation.

Underlying the siderite-cryolite body in the western half of the deposit occurred a shell characterized by the presence of abundant fluorspar associated with various silicates, mainly fine grained muscovite (described from the deposit under the name “ivigtite”) and topaz. This shell is known as the fluorspar-zone.

The contact between the fluorspar-zone and the siderite-zone is invariably brecciated and the cementing material belongs to the fluorspar zone. The later consolidation of the fluorspar zone as



Fig. 1. Aerial photograph of the cryolite deposit open pit. The location at which the gustavite-bearing mineral suite was discovered is marked by the arrow. (G.G.U. Photo).



Fig. 2. Oblique photograph of the cryolite deposit open pit taken from west towards east the same summer as the gustavite-bearing mineral suite was discovered. Exact location of the sulphide suite was on the wall slope shown by the arrow. The aerial photograph Fig. 1 was taken several years earlier. This is the reason for the bottom surface of the open pit being different on the two photographs. (H. PAULY Photo).

compared to the siderite-zone has been established in all places where these two zones were observed in contact with each other.

The gustavite-bearing mineral suite was found in the eastern part of the mine in the siderite-zone a few meters east of exposed fluorspar-zone materials (figs 1 and 2 at arrows). Diamond drilling in the vicinity has confirmed that the mineral suite material is located in the partly brecciated border zone between the siderite-zone and the fluorspar-zone. The gangue minerals, fluorspar, topaz, muscovite and weberite, associated with the sulphides suggest a close genetic relationship of the mineral suite to the fluorspar-zone. Consequently, the gangue of the discovered gustavite-bearing mineral suite is considered as belonging to material of the fluorspar-zone which extends from this into the siderite-zone. The disseminated sulphides in contrast are considered to have been derived from mobilized sulphides mainly galena, which were originally present within the siderite zone replaced by fluorspar zone material.



### III. MODE OF OCCURRENCE AND MINERALOGICAL COMPOSITION OF THE DISCOVERED MINERAL SUITE

The mineral suite was separated from the siderite-rich material by a rim of white fluorspar some 5 to 15 centimetres in thickness. The contact between the fluorspar and the siderite is sharp, whereas that between the fluorspar and the mineral suite is either sharp or gradual over a very short distance, a few centimeters or less. Unfortunately, none of the mineral specimens collected contains the contact zone to allow a more detailed study of this.

The specimens with the white fluorspar are massive to slightly coarse grained, grey to white and associated with very small amounts of topaz, weberite, muscovite and siderite. Very fine pyrite disseminations are also present. Apart from siderite the specimens are composed of the same minerals as those forming the gangue minerals of the mineral suite; however, these are in strikingly different proportions.

The mineral suite, surrounded by the white fluorspar rim, consists of two rock varieties, one richly disseminated with sulphides, the other without substantial amount of these. The latter variety is in the following referred to as "the matrix gangue minerals". It occurs as host or matrix material for the other variety, which is developed in irregularly shaped areas. About 50 kilograms of material was collected. One of the specimens 10×10×25 centimeter in size represents a fine cross section of the exposed mineral suite when discovered in the open pit. It is shown on plate I and the two mentioned rock varieties can easily be distinguished from each other. (The specimen is described in more detail on page 18 to 20).

The matrix gangue minerals comprise fluorspar (two generations), muscovite, weberite, topaz and quartz. Fluorspar and muscovite are by far the most dominant minerals. Weberite and topaz are fairly well represented. Quartz is rare. The gangue minerals are disseminated with less than 3 percent pyrite, aikinite, berryite, galena and rare chalcopyrite.

The sulphide-rich variety is composed of topaz and fluorspar disseminated with about 25 percent sulphides and sulphosalt minerals.

(To simplify the description below only the term "sulphides" has been used). The dominant sulphides are gustavite, phase X (which has exsolved from gustavite), cosalite and galena associated with some aikinite, berrylite and pyrite. Matildite, argentite (?), mineral A, gold, bismuth, chalcopyrite, sphalerite, pyrrhotite and marcasite are present in very minor amounts. Estimated relationship by volume of gustavite (before exsolution of phase X), cosalite and galena is 6:2:1. Aikinite constitutes less than 3 percent of the sulphides, berrylite and pyrite less than 2 percent each, and the total of the remainder less than one percent. Extremely small amounts of coffinite and uraninite are also present.

A bulk chemical analysis on a gustavite-cosalite-galena-rich specimen containing relatively small amounts of the other sulphides listed above gave the following metal values:

Pb = 16.5 percent  
 Bi = 15.3 -  
 Ag = 2.8 -

(Wet chemical analysis by H. BUCHWALD,  
 A/S Kryolitselskabet Øresund.

X-ray fluorescens analyses on the same material gave the following results:

Cu = 0.2 percent  
 Zn = 0.02 -  
 Fe = 0.6 -  
 Sb = 0.004 -  
 Te = nil -

The mineral suite has contributed four new minerals. These are gustavite, phase X, berrylite and mineral A (KARUP-MØLLER, 1966, 1970 and 1971). Mineral A and phase X are present in amounts insufficient to permit a complete mineralogical examination. No new mineral names for these have therefore been proposed. Three minerals gold, coffinite and uraninite have not previously been found in the cryolite deposit.

## IV. MINERAL DESCRIPTION

### **Topaz**

Topaz occurs as extremely small needles, the majority of which are arranged in rosettes (Pl. II, 1 and 2). Sometimes the rosettes are red-brown coloured, due possibly to very fine iron oxide impregnations. The mineral also occurs as isolated needles in sulphides (Pl. VII, 4).

### **Fluorspar**

An early and a late fluorspar generation have been recognized. The former is coarse grained, dark purple and colloform. It is often fractured and always intensively corroded by the other minerals present (Pl. II, 3 and Pl. III, 2). The late fluorspar is fine grained and colourless to pale purple.

### **Weberite**

Weberite is granular, fine to medium grained and white (Pl. II, 3 and Pl. III, 2).

### **Quartz**

Quartz is granular, fine to medium grained and unstrained. It contains abundant very fine muscovite flakes.

### **Muscovite**

Muscovite is extremely fine grained (Pl. II, 3) and green coloured. The mineral is a common mineral of the cryolite deposit and has unfortunately been given the name "ivigtite", a name which should be discarded.

### **Coffinite-uraninite**

Coffinite, identified by its x-ray powder pattern and by microprobe analyses, occurs as submicroscopic grains forming pseudomorphs after an unknown mineral. These pseudomorphs are very sparsely represented as no more than around fifty of them have been observed in the polished sections studied. They contain fine sulphide disseminations in amounts estimated by the naked eye in the ore microscope to range from 2 to 20 percent. The original mineral generally crystallized idiomorphically

Table 1. *X-ray powder data on coffinite.*

Coffibite from Ivigtut (Debye Scherrer method)				Coffinite (a = 6.94 Å, c = 6.31 Å. Data from ASTM card 8-304	
I	d <sub>hkl</sub> (meas.)	d <sub>hkl</sub> (calc.)	Indices	I	d <sub>hkl</sub> (calc.)
9...	4.66	4.67	101	10	4.66
2...	4.16	(not identified)			—
6...	3.44	3.47	200	10	3.47
10...	3.15	3.16	002		—
8...	2.98	3.04	201		—
4...	2.80	2.79	211	4	2.78
8...	2.65	2.65	112	7	2.64
2...	2.467	2.454	220	1	2.46
4...	2.182	2.172	301	4	2.18
5...	2.097	2.103	003		—
2...	1.999	2.013	103	1	2.01
1...	1.929	1.925	320		—
1...	1.846	1.841	321	4	1.841
8...	1.801	1.802	312	7	1.801
3...	1.740	1.741	213	4	1.737
2...	1.712	1.735	400		—
2...	1.652	1.643	322		—
2...	1.643	1.636	330	1	1.629
3...	1.558	1.556	303	1	1.556
1...	1.483	1.485	412		—
2...	1.456	1.452	332	1	1.451
2...	1.425	1.420	323	1	1.435
3...	1.363	1.361	510		—
5...	1.320	1.327	224		—
3...	1.249				
1...	1.227				
2...	1.209				
6...	1.157				
2...	1.139				
3...	1.114				
4...	1.100				
2...	1.021				
3...	1.004				
2...	0.987				
4...	0.966				
5...	0.941				

against sulphides (Pl. IV, 1 and V, 1) but in irregular shapes against gangue (Pl. IV, 2). The core of many grains, essentially those enclosed in sulphides, is occupied by a very fine grained and sometimes finely banded mixture of sulphides and uraninite (Pl. IV, 3 and Pl. V, 1).

Several coffinite pseudomorphs enclosed in gangue in one polished section were rather homogeneous, containing relatively few sulphide inclusions. One of the pseudomorphs was isolated for single crystal examination. Only x-ray powder lines, not diffraction spots, were recorded on the Weissenberg films. On this basis it is concluded, that the apparent homogeneous mineral grains (disregarding naturally the fine sulphide disseminations) actually represent aggregates of submicroscopic coffinite. A Debye Scherrer powder pattern on material representing a few of the pseudomorphs from the same polished section gave relatively sharp diffraction lines (Table 1). All the coffinite lines listed in the ASTM file (card no. 8-304) were recorded on the film. In addition to these, several lines were recorded which on the basis of the cell dimensions of the mineral could be referred to coffinite. Only one line with low intensity ( $d_{hkl}$ : 4.16) has not been identified.

The light grey mineral intergrown with sulphides and contained in the core of some of the coffinite pseudomorphs has been identified as uraninite on the basis of the microprobe scanning photographs Pl. V, 2 and 3. The area examined in these photographs is framed on Pl. V, 1. The photographs show that the mineral forming the core contains no silicon, whereas the uranium content is equal to that of the coffinite dominated area. Relatively more sulphides are contained in the core than are disseminated throughout the coffinite area. The grey mineral present in the core thus contains more uranium than the coffinite and is therefore assumed to be uraninite. The reflectivity and reflection colour of the mineral support this assumption.

Microprobe examination of four coffinite pseudomorphs present in the same polished section from which the mineral was isolated for x-ray examinations unfortunately gave poor quantitative results. These pseudomorphs were without the uraninite-sulphide core and contained only few visible sulphide inclusions. In addition to uranium and silicon the following elements and their compositional ranges were recorded: S = 0.8 – 4.3 percent, Bi = 2.7 – 6.4 percent, Pb = 7.3 – 15.4 percent, Cl = 1.6 – 4.3 percent and Ca, Th and Fe = less than one percent each.

The sulphur values no doubt reflect very fine sulphide inclusions within the analyzed areas. The X-ray scanning photographs Pl. V, 4-6 show the distribution of lead, bismuth and sulphur in the coffinite, in the uraninite-sulphide intergrowth and in adjacent gustavite. From these photographs it is clear that the major portion of lead within the coffinite area is contained in the coffinite structure. Only a minor portion along with the low erratic bismuth occurs together with sulphur as sulphide. It is therefore concluded that all bismuth and small amounts of lead recorded in the analyses may occur combined with sulphur as a silver-free sulphide. Another unusual feature reflected in the analyses is the presence of

considerable amounts of chlorine. The small amounts of thorium, iron and calcium need not attract attention.

The presence of other minerals than coffinite, uraninite and sulphides within the pseudomorphs studied cannot be demonstrated. The Ivigtut coffinite therefore must contain chlorine in place of oxygen, and lead together with small amounts of thorium, iron and calcium in place of uranium. Unfortunately the analytical results were too poor to permit the proposal of a reasonable formula for the mineral.

The following description of the mode of formation of coffinite pseudomorphs with and without uraninite enclosed areas is suggested: "An unknown mineral crystallized as an - to euhedral crystals from local concentrations of very small amounts of uranium and chlorine. Formation of a crystal proceeded from outside toward its centre and as such actually crystallized from fluids entrapped in itself (Pl. IV, 1). This may explain the great abundance of the fine sulphide disseminations. The formation of some of the crystals was interrupted at an early stage due to the removal of silicon from the enclosed mineralizing fluids. Consequently these fluids crystallized as a mixture of uraninite and sulphides. Some crystals were fractured before the enclosed fluids had crystallized, as shown by the fact that fractures are filled with sulphides from outside and sulphide-uraninite material from inside (Pl. IV, 1). At some stage during the crystallization of the mineral suite the original uranium-silicon mineral became unstable and recrystallized as submicroscopic coffinite".

#### Gustavite and phase X

Gustavite ( $\text{Bi}_{11}\text{Pb}_5\text{Ag}_3\text{S}_{23}$ ) and phase X ( $\text{Bi}_{10}\text{Pb}_7\text{Ag}_2\text{S}_{23}$ ) have been described by KARUP-MØLLER (1970), and only a summary will be given here. Gustavite is tabular and contains phase X, which has exsolved as submicroscopic blebs (KARUP-MØLLER, 1970, figs 1-16). The chemical composition of the two phases is based on 25 individual microprobe analyses (op. cit. fig. 18). It was concluded that the two phases form members of a solid solution series with  $\text{Pb}_3\text{Bi}_2\text{S}_6$  and  $\text{PbAgBi}_3\text{S}_6$  as possible end members. The possibility of a solid solution series between gustavite and andorite ( $\text{PbAgSb}_3\text{S}_6$ ) is suggested due to the similar cell dimensions and the same space group possibilities for these two sulphides.

Gustavite from other mineral deposits has recently been described by the author (1972).

#### Berryite

Berryite ( $\text{Pb}_3\text{Bi}_7(\text{Ag}_{1.5}\text{Cu}_{3.5})\text{S}_{16}$ ) from Ivigtut was described by the author (1966). Data on beryite from localities in U.S.A. and Sweden were published simultaneously by NUFFIELD & HARRIS (1966) who gave

the formula  $(\text{Pb}_2(\text{Cu}, \text{Ag}_3\text{Bi}_5\text{S}_{11}))$ . Berryite from still another locality has recently been described by the author (1972).

### Mineral A

Mineral A ( $\text{Ag}_2\text{Cu}_3\text{Bi}_6\text{Pb}_9\text{S}_{20.5}$ ) occurs as fine exsolution laths in galena and has been described by the author (1971). Its fine grain size prevented a complete mineralogical investigation and hence no new mineral name has been suggested.

### Cosalite

Cosalite is irregularly shaped although elongated in its prismatic direction. Each grain is "polycrystalline", composed of a large number of very small and lamellar grains with almost parallel orientation (Pl. VI, 3). In some grains a distinct cleavage is developed parallel to their prismatic direction. The mineral is weakly pleochroic in air, distinctly so in oil. The reflectivity of cosalite when placed in its darkest position is slightly higher than that of galena. Colour ranges from white to a slight grey-white when compared to that of galena. The anisotropic effect is strong in both air and oil, and the anisotropy colour is dark red-brown. The polishing hardness is higher than that of both balena and gustavite. A greyish brown precipitate develops on the mineral after etching for 1–2 second with concentrated nitric acid (Pl. VII, 4). Cosalite, gustavite and galena react differently to treatment with the nitric acid and can therefore easily be distinguished from each other in etched polished sections.

A representative microprobe analysis of a cosalite grain is:

	Wt. %	Mol. %	Ideal composition
Pb .....	34.8	17.7	22.2
Bi .....	42.6	21.4	22.2
Ag .....	3.3	3.2	—
Cu .....	1.8	3.0	—
S .....	16.7	54.7	55.6
Total .....	99.2	100.0	100.0

The presence of both silver and copper in the cosalite structure is a characteristic feature of the mineral from many sulphide deposits. The two elements appear essentially to have taken the place of lead in the lattice. The ideal cosalite formula is  $\text{Pb}_2\text{Bi}_2\text{S}_5$ .

### Aikinite

Aikinite grains are generally equidimensional and only very rarely elongated. The average grain size is around a quarter of a millimetre.

The grains are isolated or present in aggregates. No cleavage has been observed. The pleochroism is weak in air but distinct in oil, and colours range from cream to lemon-yellow. The reflectivity is higher than that of gustavite, cosalite and galena, but similar to that of berryite. Anisotropy colours are vivid. The polishing hardness is less than that of gustavite and berryite. The reflection colours of aikinite from Ivigtut were found to be brighter and the anisotropy colours more vivid than those of aikinite from other localities including the type location at Berezowsk in the U.S.S.R.

Microprobe analyses confirmed the formula  $\text{PbBiCuS}_3$  for the mineral. A silver content varying from 0.5 to 0.7 percent was recorded.

### **Galena**

Microprobe analyses on 10 galena grains present in one polished section along gustavite grain boundaries or as inclusions in this mineral gave silver values in weight percent ranging from 1.1 to 1.6, averaging 1.4 and bismuth contents ranging from 2.9 to 3.6 with an average of 3.3.

The intimate intergrowth between galena and gustavite has prevented isolation of either mineral for X-ray investigation. However, the galena and gustavite lines on powder films could easily be distinguished from each other. The first three galena lines (111), (200) and 220) from five Guinier films, gave a cell dimension of  $a = 5.929 \pm 0.004 \text{ \AA}$ . This value is slightly lower than that of pure galena which is  $5.9362 \text{ \AA}$  (ASTM card 5-0592). The lower value is considered to be due to the content of silver and bismuth in the galena structure (VAN HOOK, 1959; CRAIG, 1967).

### **Matildite and argentite (?)**

A few galena grains in one polished section were found with exsolved matildite lamellae.

Electron microscope studies using the plastic technique by BRADLEY (1954) have shown the presence of a cubic or pseudocubic mineral enclosed in Galena (KARUP-MØLLER, 1970, figs. 8 and 13). The cubic mineral is irregularly distributed and occurs with random orientation. Presumably it has exsolved from the host mineral. Because of its fine grain size, it cannot be identified positively. Due to its cubic shape it is assumed to be argentite.

### **Gold**

Chemical analyses on sulphide material from Ivigtut have shown the presence of gold but the existence of free gold has first been discovered in the present mineral suite (Pl. IX, 1 and X, 3). It is easily identified due



to its characteristic optical properties. A possible silver content of the mineral has not been investigated.

### **Sphalerite**

Sphalerite is light grey and characterized by numerous internal light yellow-brown reflections. This suggests that the iron content is rather low.

### **Pyrite, native bismuth, chalcopyrite, pyrrhotite and marcasite**

The properties of these minerals are well known and no new data have been gathered on them. Therefore, a description of them has been omitted here.

## V. MINERAL RELATIONSHIPS

### Relationships of the matrix gangue minerals

The relationships of the matrix gangue minerals are best illustrated by a description of the rock specimen shown on Pl. I, supplemented with observations from thin section studies of other specimens.

The centre portion of the specimen on Pl. I is dominated by topaz-fluorspar material (dark) disseminated with gustavite, cosalite, galena and associated sulphides (grey white) flanked on both sides by the matrix gangue minerals. A narrow band of sulphide-free topaz-fluorspar material occurs to the right of the sulphide-disseminated area. The contact between the two areas is poorly defined due to the gradual disappearance of the sulphides. The relationships between the two gangue minerals within both areas are similar. Very fine topaz in a structureless mass of rosettes occurs as host for irregularly shaped fluorspar (Pl. II, 2). A few small weberite aggregates are enclosed in the sulphide-free topaz-fluorspar material but none are present in the sulphide-disseminated material.

Towards the three weberite areas in the bottom middle portion of the specimen a vague development of fluorspar and topaz in concentric layers has taken place. Similarly shaped areas, developed in a much more spectacular fashion, have been observed in other specimens (Pl. III, 1). The central portion of the "cauliflower head"-shaped area shown on this photograph is characterized by a structureless aggregate of granular fluorspar as host for topaz rosettes, minor amounts of sulphides and rare weberite. The crystallization of this aggregate was followed by precipitation of alternating topaz-rich and fluorspar-rich bands. The adjacent minerals are mainly muscovite, acting as host for pyrite. The shape of the topaz-fluorspar area against the muscovite-pyrite material suggests that the latter crystallized last. Rhythmic precipitations of topaz and fluorspar in irregularly shaped areas are shown in Pl. II, 3 at the bottom left. Such material has, very rarely, been found in contact with irregularly shaped aggregates of quartz containing abundant fine grained muscovite-disseminations.

A row of several relatively large weberite areas occurs across the centre portion of the specimen shown on Pl. I. A few unreplaced remnants

of the early dark purple fluorspar lie along the contact between these and the sulphide-free topaz-fluorspar material. On the right side of this row of weberite aggregates the mineralogy of the gangue minerals is strikingly different from that on the left side. Topaz has disappeared and muscovite is present instead in amounts equal to those of the fluorspar. A gradual but short transition zone between the two gangue association exists just right of the weberite aggregates.

Fluorspar and muscovite form a rather heterogeneous intergrowth. In muscovite-rich areas small fluorspar inclusions have generally been corroded by the host mineral. In fluorspar-rich areas muscovite occurs in enclosed aggregates and sometimes the host fluorspar shows rhythmic or colloform banding concentric around the enclosed muscovite material. Corrosion of the fluorspar host has taken place. A certain portion of the muscovite within both fluorspar-rich and fluorspar-poor areas thus appears to have crystallized later than the fluorspar, although the major portion may have crystallized penecontemporaneously with it.

Aggregates of weberite are enclosed in fluorspar-muscovite material. Some of these aggregates are partly surrounded by early dark purple fluorspar. Both fluorspar varieties are in places cut by the weberite. The dark purple fluorspar is colloform. It contains no muscovite inclusions. It is conformably surrounded by late fluorspar which shows that no sharp distinction in age exists between the two fluorspar generations here.

Corrosion of early dark purple fluorspar by weberite and late fluorspar-topaz material in other specimens is a common feature. The photographs Pl. II, 3 and Pl. III, 2 show layers of late pale fluorspar precipitated around earlier dark purple fluorspar remnants. On Pl. III, 2 the weberite is partially separated from the early fluorspar by a very thin layer of late colourless fluorspar. Similarly corroded early fluorspar also occurs in the sulphide-disseminated fluorspar material shown on the plate.

The mineralogy of the matrix gangue minerals in the specimen on Pl. I is quite different on the left side of the sulphide disseminated topaz-fluorspar material from that on its right side. The contact here between sulphide-disseminated and sulphide-free fluorspar-topaz material is similar to that on the right side of the sulphide-disseminated area. The sulphide-free gangue minerals occur in contact with a relatively large elongated area of early fluorspar. On the left side of this a three centimetre wide deformation zone has developed. Early dark purple fluorspar and sulphide-free fluorspar-topaz material have been intensively brecciated. The deformation was accompanied or followed by the crystallization of weberite, muscovite and pyrite. Weberite forms a monomineralic area. The pyrite, shaped as crystals ranging from half a

millimetre to rarely more than two millimetres in size, occurs in aggregates containing as much as 90 percent of the sulphide. The matrix mineral for the pyrite is muscovite.

In Pl. II, 3 fluorspar, topaz and weberite were broken up and imbedded in muscovite. In other specimens early muscovite together with all the other gangue minerals present were brecciated and imbedded in late muscovite. The final stage in the formation of the mineral suite is muscovite-filled fractures cutting the specimen.

In summary the following crystallization sequence has taken place:

The coarse grained, colloform and dark purple fluorspar crystallized first. It was often intensively corroded before formation of the two mineral pairs, fluorspar-topaz and fluorspar-muscovite which form the bulk of the matrix gangue minerals. These two mineral associations crystallized penecontemporaneously except for a portion of muscovite which crystallized later than the associated fluorspar. Most of the weberite present is of the same age as the fluorspar, topaz and muscovite, apart from that portion of the mineral which crystallized late from entrapped fluids. Muscovite and some weberite crystallized late along deformation zones, which are host to the major portion of the pyrite present. Thin muscovite - filled fractures represent the final stage in the formation of the matrix gangue minerals.

#### **Relationships between the sulphide disseminated topaz-fluorspar material and the matrix gangue minerals**

The sulphide disseminated topaz-fluorspar material often occurs in contact with intensively corroded dark purple fluorspar belonging to the matrix gangue minerals (Pl. III, 2). The mode of occurrence of the pale purple fluorspar in the matrix gangue and in the sulphide-disseminated material show that the mineral in both areas is of the same age but have crystallized in different environments. A similar age relationship exists between topaz in the two areas. Topaz in homogeneous area belonging to the matrix gangue may extend into the sulphide-disseminated areas. Topaz and pale purple fluorspar of the matrix gangue minerals thus belong to the same generation as fluorspar and topaz of the sulphide-disseminated material.

It is therefore assumed that crystallization of the sulphide-disseminated topaz-fluorspar material and crystallization of the matrix gangue minerals took place penecontemporaneously over a certain period of time.

Crystallization of the sulphide-disseminated topaz-fluorspar material began with formation of the gangue minerals but was soon accompanied by that of the sulphides which to various extents replaced already

crystallized gangue. Deformation of solidified material has taken place in particular during the final phases of crystallization. Fracture zones cutting the matrix gangue minerals sometimes extend into the sulphide-disseminated material. These features are described in more detail in the section following.

### **Relationships between sulphides and host topaz-fluorspar material**

#### **A. General relationships**

The sulphide disseminated topaz-fluorspar material (Plate I at centre) forms a massive, structureless aggregate of rather evenly distributed minerals. The average ratio of gangue to sulphide is estimated by the naked eye to be 3:1. The major portion of the sulphides forms areas up to a few millimetres in size isolated in gangue. As these areas increase in number and in size they join up and develop into an interrupted sulphide network. Rarely the sulphides dominate and they then appear as host for the gangue minerals.

Rather equal amounts of topaz and fluorspar are estimated to be present. In areas with little or no sulphides fluorspar generally occurs as irregularly rounded grains or aggregates of these enclosed in topaz (Pl. II, 2). No observations suggest anything but simultaneous crystallization of the two gangue minerals.

The sulphide-fluorspar and the sulphide-topaz contact relationships are differently developed due to the entirely different habits of the two gangue minerals. The contact between sulphides and fluorspar is always sharp but irregular. Since topaz is very fine grained and occurs as needles arranged in rosettes the contact between topaz and sulphides is always transitional and poorly defined. Towards the sulphide areas these rosettes gradually become more and more disseminated with sulphides (Pl. II, 1), and finally topaz occurs as isolated needles in the sulphides (Pl. VII, 4).

Both gangue minerals, but mainly topaz, are disseminated throughout the sulphides. Richly topaz-disseminated sulphide grains may lie in contact with sulphide grains of similar mineral species containing no gangue at all. Such disseminated areas are then very well defined. However, disseminated topaz needles may also occur as poorly defined "clouds" in the sulphides without being restricted or controlled by the individual host grains. Naturally, gradations exist between poor and well defined areas. The presence of such topaz disseminations suggests that the gangue mineral occurred suspended in the fluids from which the sulphides later crystallized.

Minor amounts of the two gangue minerals crystallized penecontemporaneously with late sulphides. Abundant topaz as fine needles

has been found associated with late galena, which as veinlets have penetrated and replaced gustavite (Pl. III, 3). Fluorspar associated with the same late galena occurs frequently as lamellar inclusions in gustavite and both minerals are considered to have crystallized from solutions entrapped in already crystallized gustavite (Pl. III, 3 and VII, 4).

### **B. Replacement of gangue by sulphides**

Replacement of gangue by sulphides has taken place throughout the mineral suite. Replacement of fluorspar by sulphides is most obvious when fluorspar occurs as relatively large grains adjacent to sulphide-rich areas.

Groups of irregularly shaped fluorspar grains imbedded in sulphides are often considered to be replacement remnants of much larger and more homogeneous dark purple fluorspar. Intense replacement of the marginal areas of large fluorspar grains is a common feature. In the central portion of such grains sulphides have crystallized along fine fractures and intensively corroded the gangue walls. Present in the same fluorspar grain are bands of sulphide grains (Pl. IV, 4). These may occur along the extension of sulphide-filled fractures or independently of them. The sulphide tablets possibly crystallized during replacement of the gangue host from solutions which penetrated along invisible fractures. Alternatively the tablets may represent recrystallized sulphide-filled fractures, although no substantial proof for this assumption can be demonstrated.

The fluorspar-topaz association with or without interstitially crystallized sulphides sometimes are cut by sulphides which occur along irregular veins. The crystallization of one unusually large gustavite grain along such a vein is shown in Pl. VI, 1. The gustavite grain is developed with its lamellar direction oblique to the direction of the vein. This "lamellar" direction is marked by the lamellar shaped fluorspar which projects into the sulphide grains as protuberances from irregularly shaped fluorspar grains imbedded in the topaz matrix. The lamellar fluorspar grains are all aligned parallel to the lamellar direction of the gustavite host. They are therefore considered to be replacement remnants of larger irregularly shaped fluorspar grains of which portions are preserved in the adjacent topaz. Their lamellar shape presumably resulted from the crystallization force of the gustavite host grain after one of its crystallographic directions. These relationships imply that the sulphides crystallized during replacement of the gangue. They were probably introduced by solutions which initially followed very fine fractures in the gangue.

The sulphide vein in Pl. VI, 2 is considered to have formed in a similar way. It is obvious from the photograph that the sulphides along the vein are distinctly younger than those interstitially related to the topaz cut by it.

Richly disseminated topaz areas have sometimes been cut by gangue-free sulphides, the majority of which formed as fracture fillings. The contact between such gangue-free sulphides and sulphide-disseminated topaz is sharp in contrast to the generally gradual transition shown on Pl. II, 1.

Replacement of gangue by sulphides thus is a general characteristic of sulphide-rich areas. However, when the gangue minerals dominate and contain the sulphides in small disseminated areas, then only minor replacement if any at all of gangue by sulphides has taken place. The gradual transition from sulphide-free topaz, via topaz-disseminated sulphides to gangue-free sulphides is considered to have developed when sulphides crystallized interstitially to already crystallized gangue and not during replacement of gangue by sulphides. For instance, the delicate topaz rosettes in sulphides shown on Pl. II, 1 could hardly be interpreted as "unreplaced topaz remnants".

### C. Deformation of the mineral suite material

The mineral suite has been exposed to deformation both early and late during its period of crystallization. Such deformation has resulted in the development of different sulphide-gangue relationships, depending upon when the deformation took place.

One large polished section was found to be cut by a straight one to one and a half millimetre thick and more than four centimetre long fracture filled with sulphides (Pl. VI, 4). The gangue adjacent to the fracture is evenly disseminated with sulphides. These occur in small aggregates which either are isolated in the gangue or join up with numerous sulphide filled short veins. All veins being oriented parallel to the major fracture filling has caused a distinct foliated texture. The fractures formed after crystallization of the gangue minerals but before that of the sulphides. As the fractures developed the fluids entrapped in gangue penetrated along the fractures and corroded the walls of these. First then the sulphides crystallized. This pattern of formation explains the irregular shape of the veins, their parallel orientation with the major sulphide-filled fracture and the presence of apparently only one sulphide generation. Similar, but randomly oriented, sulphide-filled fractures occur throughout the sulphide disseminated topaz-fluorspar material.

The presence of deformation zones observed in a few specimens is evidence of intense mechanical stress during the crystallization of the mineral suite. These zones vary in width from a fraction of a millimetre to half a centimetre and can be followed for several centimetres before they gradually disappear. The most characteristic feature of the zones is the mechanical and possibly also chemical decomposition of the two major gangue minerals (Pl. VII, 1). The disintegrated gangue appears as

extremely fine grained material disseminated in sulphides. Areas with such material occur with sharp boundaries against gangue-free sulphides but have both gradual and sharp boundaries with gangue. Although the deformation zones may cut across previously crystallized sulphides no mechanical deformation of these adjacent to the zones can be recognized. Such features may have been obliterated by subsequent recrystallization. Sometimes the fine grained gangue-sulphide areas are themselves cut, fractured and intruded by later gangue-free sulphides (Pl. VII, 2).

#### **D. Summary of sulphide-gangue age relationships**

On the basis of the gangue-sulphide mineral relationships observed it is concluded that in the first place most gangue crystallized with the sulphide components in interstitially entrapped fluids. These fluids often intensively corroded and replaced their host gangue. Minor amounts of gangue crystallized penecontemporaneously with even late sulphides. Mechanical stress took place during the crystallization of the mineral suite. This resulted in the formation of simple fractures filled with sulphides but also in the development of deformation zones characterized by intense crushing of the gangue minerals.

### **Sulphide relationships**

Sulphides occur disseminated in topaz-fluorspar material, along deformation zones cutting this material and in minor amounts disseminated throughout the matrix gangue minerals.

#### **A. Sulphides disseminated in massive topaz-fluorspar material**

##### **1. Gustavite, phase X and galena**

Gustavite with exsolved phase X is the major sulphide and occurs as randomly oriented laths. Gustavite is always associated with galena. The major portion of the galena present is considered to have crystallized during replacement of gustavite. This galena occurs enclosed in gustavite or along gustavite grain boundaries. Galena enclosed in gustavite varies in habit from irregularly shaped grains to rather well shaped laths. The laths are always oriented parallel to the lamellar direction of the gustavite host. Unreplaced gustavite remnants sometimes occur in the galena (KARUP-MØLLER, 1970, fig. 6). Rarely galena dominates and is then the host for numerous unreplaced gustavite remnants (Pl. VII, 3). Galena along the gustavite grain boundaries has penetrated the gustavite grains parallel to its lamellar direction but not across it (Pl. VII, 4). This galena is shaped as triangular grains.

Simultaneous crystallization of galena and gustavite has resulted in myrmekitic intergrowth between the two minerals. Such intergrowths



are generally enclosed between galena-free gustavite laths, indicating that they have crystallized from fluids entrapped between these (Pl. VIII, 1). Partly idiomorphic gustavite laths in a matrix of galena have been observed rarely (KARUP-MØLLER, 1970, fig. 5). These laths presumably developed suspended in fluids which later crystallized as galena. Galena entrapped between gustavite laths is considered to have crystallized from similar fluids.

## 2. Cosalite

Cosalite is present in most of the polished sections studied. It occurs as irregularly shaped polycrystalline grains elongated along their prismatic direction (Pl. VI, 3). Single grains are enclosed in gustavite. Cosalite infingers with gustavite as fine lamellae when the two minerals are in parallel orientation (Pl. VII, 4 at bottom right). In other orientations their mutual contact is more stumpy (Pl. VII, 4 at top right). Partial replacement of isolated cosalite grains by gustavite has been observed only in very rare cases. This textural relationship suggests that here, crystallization of cosalite began before that of gustavite. In general, however, the two sulphides appear to have been formed more or less simultaneously.

## 3. Aikinite and berryite

The distribution of aikinite and berryite varies considerably. The two minerals are absent in many sections, are sparsely present in some and dominate in a few. Rarely one is present without the other. They often form mutual contacts. Berryite may rarely project into aikinite while aikinite is never enclosed in berryite. Gustavite in general is the host mineral except in very aikinite- and berryite-rich areas where it may be absent. Galena is always present. When present in small amounts, which generally is the case, then aikinite and berryite together with galena and gustavite often are host for pyrite. When pyrite dominates, then the other sulphides are developed interstitially to it. Pyrite may, although rarely, be found in gustavite and galena without aikinite and berryite being present. Pyrite is generally absent or only represented in accessory amounts in very aikinite- and berryite-rich sections.

Aikinite and berryite have never been found in contact with cosalite or within a few millimetres distance from this mineral.

Aikinite occurs as equidimensional grains. The only mineral enclosed in it is galena, which has crystallized along aikinite grain boundaries. Rarely the two minerals form myrmekitic intergrowth, which suggests simultaneous crystallization.

Regularly shaped berryite laths are enclosed at random orientations in gustavite (KARUP-MØLLER, 1966, figs 1-6). The laths are sometimes

developed across gustavite grain boundaries without being distorted. When present in large amounts the laths may be grouped in bunches. Galena is always associated with berryite and is younger than this mineral. It occurs along berryite-gustavite grain boundaries and may penetrate into berryite across its platy direction. Fine galena laths, oriented parallel to the host, often represent protuberances from transgressing galena. This galena variety is identical to that present as replacement laths in gustavite. Galena has sometimes crystallized from fluids entrapped between relatively big berryite laths and may contain inclusions of relatively small and partially idiomorphic berryite crystals.

The thin berryite lath in Pl. VIII, 2 which extends away from the large berryite lath presumably crystallized suspended in such fluids which later crystallized as galena and partially replaced the large berryite lath.

Gustavite laths may contain irregularly shaped berryite in myrmekitic intergrowth with galena (Pl. VIII, 3). The galena may either have exsolved from the berryite; or more likely the intergrowth is the result of simultaneous crystallization of fluids entrapped in the host gustavite, thus resembling the myrmekitic gustavite-galena intergrowth shown on Pl. VII, 1.

#### 4. Mineral A

Mineral A occurs as rare exsolution lamellae in galena closely associated with berryite and aikinite (KARUP-MØLLER, 1971, fig. 1).

#### 5. Pyrite

Minor amounts of pyrite are present throughout the sulphide disseminated topaz-fluorspar material, either isolated or in aggregates. The mineral is generally idiomorph when present in contact with gangue minerals, but anhedral when imbedded in sulphides. The pyrite crystal on Pl. VIII, 4 was originally idiomorphic against the gangue but was later replaced along its margin by gustavite and cosalite. The crystal must therefore have formed earlier than the replacing minerals, possibly simultaneously with the gangue host.

Pyrite enclosed in other sulphides has often been intensively replaced by them. Such pyrite may contain numerous inclusions of the same minerals that replaced it. This suggests that pyrite enclosed numerous small pockets of fluids as it crystallized. These fluids later crystallized as sulphides, possibly at the same time as the host fluids for the pyrite crystallized and partially replaced the pyrite. No indications that the enclosed minerals should have developed from fluids which had penetrated the pyrite along fine fractures can be demonstrated.

Most of the pyrite present occurs in aggregates, either at random or arranged in a regular pattern. Four examples which illustrate the dif-

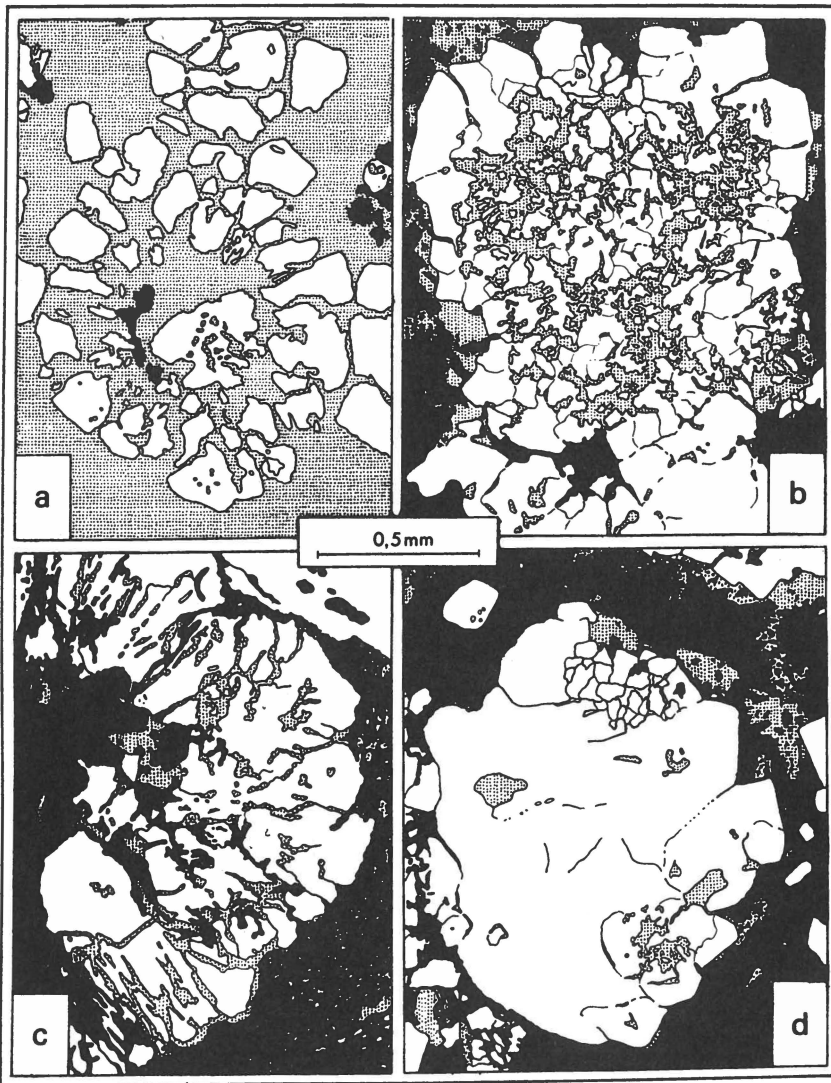


Fig. 3. Sketch showing four stages in the growth of a pyrite aggregate. In fig. 3a pyrite grains (white) in gustavite (dotted) are isolated from each other but in spite of this they form a regular circular shaped aggregate. In fig. 3b the individual pyrite crystals have joined up, but considerable gustavite is still contained in the central area of the aggregate. The black phase is gangue. The content of gustavite is less in the aggregate in fig. 3c (of which only half has been shown) but considerable gangue is present. In fig. 3d the pyrite aggregate contains almost no other sulphides at all.

A few gustavite wisps mark the boundary between the individual pyrite grains.

ferent stages in the growth of such regularly developed aggregates are sketched after photographs on fig. 3. A general feature is the circular to ellipsoid shape of the aggregates. All pyrite in fig. 3a occurs as isolated

grains enclosed in gustavite. In fig. 3b and 3c a more advanced stage in the crystallization of similar aggregates has been reached. Here the individual pyrite grains have partly joined up, but abundant gangue and other sulphides are still present within the aggregates. A very advanced stage in the growth of an aggregate is reached in fig. 3d where pyrite is almost the only mineral present. The outline of the individual grains is marked either by a mineral film or by remnants of other sulphides.

#### 6. Chalcopyrite, sphalerite, pyrrhotite and marcasite

Chalcopyrite and sphalerite are present in insignificant amounts. They may occur in gangue but are generally located along the gangue-sulphide boundary. Both minerals are often idiomorphic when in contact with gangue minerals, but the mutual boundary with other sulphides is smooth. Chalcopyrite, sphalerite and associated bismuth also occur as individual grains enclosed in galena. Very fine fractures filled with chalcopyrite cut both gangue and sulphides. In rare cases chalcopyrite along these fractures joins up with irregularly shaped chalcopyrite grains in gustavite. One fine fracture was found to be composed of chalcopyrite, pyrrhotite, marcasite (secondary after pyrrhotite), sphalerite and unidentified gangue, and represents the only location where pyrrhotite and marcasite have been observed.

#### 7. Bismuth

Bismuth occurs as mentioned above, as grains in galena, but also as very small, irregular grains in gustavite. One relatively large bismuth grain was found in myrmekitic intergrowth with galena (Pl. IX, 2).

### **B. Mineralogy of the deformation zones**

As described above, the mineral suite is cut by fracture zones up to half a centimetre in width and with a length rarely in excess of two centimetres. In general the zones are less than one millimetre wide and they are characterized by an intense crushing of the gangue minerals. The sulphides apparently have completely recrystallized. No indications have been found to suggest that material was introduced along the zones. An exception is two major deformation zones, the mineralogy of which differs from that of the adjacent mineral assemblages. These two zones referred to as zones a) and b), are described in some detail below.

*Deformation zone a* extends across the boundary between the matrix gangue minerals and gustavite-cosalite-galena disseminated topaz-fluorspar material. The sulphides along the deformation zone are galena, aikinite, pyrite and minor berryite, sphalerite, chalcopyrite, bismuth, gold and possibly mineral A.

Pyrite was one of the first minerals to crystallize and is developed as idiomorphic crystals against areas of aikinite and galena disseminated with abundant fine grained gangue. This pyrite was later replaced along its margin by galena, aikinite and fluorspar. Some berryite laths occur enclosed in the galena. Pyrite has been crushed, and fractures have been filled with fluorspar and small amounts of all the other sulphides present along the deformation zone, including some gold grains.

Abundant bismuth occurs as irregularly shaped grains in a few galena grains enclosed either in gangue or between aikinite grains (Pl. IX, 3). Similar intergrowth has developed between bismuth and sphalerite and between bismuth and chalcopyrite. Again, the host mineral in general is aikinite although some intergrowth have also been observed along fractures in pyrite. Sphalerite rarely occurs in direct contact with gangue but is separated from it by a very thin layer of galena. Sphalerite also occurs within galena-rich areas disseminated with abundant very fine gangue, (Pl. IX, 4).

Galena intergrown with aikinite contains, very rarely, very fine lamellae of a mineral which closely resembles aikinite. These undoubtedly formed as a result of exsolution.

The host sulphide for finely crushed gangue is either galena with a few berryite laths or galena and aikinite. Gangue-disseminated areas have been fractured parallel to the direction of the deformation zone and the fractures have been filled with gangue-free galena. Numerous fine berryite lamellae are enclosed in this late galena.

*Deformation zone b* cuts topaz-fluorspar material mineralized with gustavite, aikinite, berryite, and galena. The dominant minerals along the zone are pyrite, aikinite and galena associated with berryite, chalcopyrite, bismuth, rare sphalerite and gold. Gustavite is absent here.

The most interesting feature of this zone is the growth pattern of pyrite. When this mineral crystallized enclosed in gangue-free aikinite and galena it developed as very irregularly shaped crystals containing abundant inclusions of these two sulphides (Pl. X, 1). However, pyrite present in gangue-disseminated aikinite and galena is idiomorph and contains only small but numerous sulphide inclusions and abundant gangue. Pyrite crystals straddle the boundary between gangue-free and gangue-rich sulphides. That portion of the pyrite which lies within the gangue-disseminated sulphides resembles the pyrite grains completely isolated in the material. However, that portion which extends into the gangue-free sulphides resembles pyrite in these environments. The limit of the gangue-disseminated area at this particular place thus appears to be independent of the sulphides throughout which it extends. The fine gangue therefore is considered to have been present as a "cloud" in the fluids when the sulphides crystallized.

However, sulphide grains only very rarely straddle the boundary of the gangue-disseminated areas. The same sulphides generally occur on both sides, but grain size and mineral proportions may differ considerably. Rarely the gangue-disseminated areas are slightly foliated (Pl. VII, 1) and the grain size of aikinite and galena here is very fine. Locally the gangue appears to lie along sulphide grain boundaries. Crystallization of the sulphides may have taken place simultaneously with slight movement of the sulphides.

The pyrite-rich aggregate shown on Pl. X, 2 is considered to have crystallized from a pocket of fluids entrapped in very gangue-rich fluids. The original outline of the pocket is marked by the stippled line. Within this, pyrite crystallized in a way similar to the pyrite in gangue-free sulphides shown on Pl. X, 1. After the crystallization of the central aggregate or "core" was completed, pyrite, possibly due to its relatively great force of crystallization, continued to develop into the gangue-rich area. Most gangue and sulphides here were removed but some were included as very fine grained material.

Pyrite may dominate locally along the gangue-free portion of the deformation zone and here form an almost homogeneous granular aggregate. Minor galena, aikinite and rare gold mark the boundary between the individual pyrite grains (Pl. X, 3).

### C. Sulphides disseminated in the gangue matrix minerals

The gangue matrix minerals are disseminated with an estimated 3 percent sulphide, dominated by pyrite. The other minerals are chalcopyrite, galena, aikinite and berryite. Chalcopyrite, but not the three others, is always closely associated with pyrite. Gustavite and cosalite have not been observed.

Pyrite occurs mainly in several centimetres large aggregates developed along breccia zones (Pl. I at left). Chalcopyrite is enclosed in and concentrated along pyrite grain boundaries (Pl. X, 4). At a later stage in the crystallization of pyrite only very few remnant chalcopyrite "stringers" are present.

Aikinite, berryite and galena occur as fine disseminations in the gangue. The relationships of the three minerals resemble those of the same three minerals present in the sulphide disseminated topaz-fluorspar material.

## VI. P-T-CONDITIONS OF FORMATION OF THE MINERAL SUITE

The cryolite deposit and therefore also the gustavite-bearing mineral suite are considered to have formed at a depth of a few kilometres corresponding to a load pressure of about 1000 bars or less.

PAULY (1960) assumes that the maximum temperature of formation of the siderite-cryolite was around 510–590° C. However, mineralizing processes are known to have taken place locally at temperatures as low as 200° C (OEN ING SOEN & PAULY, 1967).

Both primary and secondary fluid inclusions are contained in the early and in the late fluorspar of the gustavite-bearing mineral suite. The primary dominate and have a diameter of 0.001 to 0.01 millimetres. At room temperature they represent two-phase gas-liquid inclusions. Preliminary studies of the primary inclusions were undertaken on a modified Leitz heating-cooling stage. The early purple fluorspar homogenized at 473–480° C, the late pale fluorspar at 275–300° C. A pressure correction based on aqueous fluid inclusions gave minimum temperatures of formation of approximately 500 °C and 300° C respectively.

Native bismuth melts at 269° C at a pressure of one atmosphere. The temperature is slightly lowered by increase in pressure. Therefore bismuth present in minerals which have crystallized at temperatures above the melting point of bismuth generally contains this mineral as droplet-shaped inclusions. Bismuth expands when it crystallizes from molten material, and fractures may therefore developed in the host grain around the enclosed bismuth (RAMDOHR, 1960, fig. 318).

The relationships between bismuth and the two host minerals gustavite and galena, suggest that bismuth and therefore also the host minerals crystallized at temperatures below the melting point of bismuth.

The mode of occurrence of bismuth and the studies of the primary fluids enclosed in the late, pale purple fluorspar thus suggests that crystallization of gustavite and associated sulphides first began at temperatures around 275–300° C.

It is only possible to speculate at what temperature crystallization of the sulphides was completed. Matildite lamellae have excolved from a very few galena grains, a process considered to have taken place at

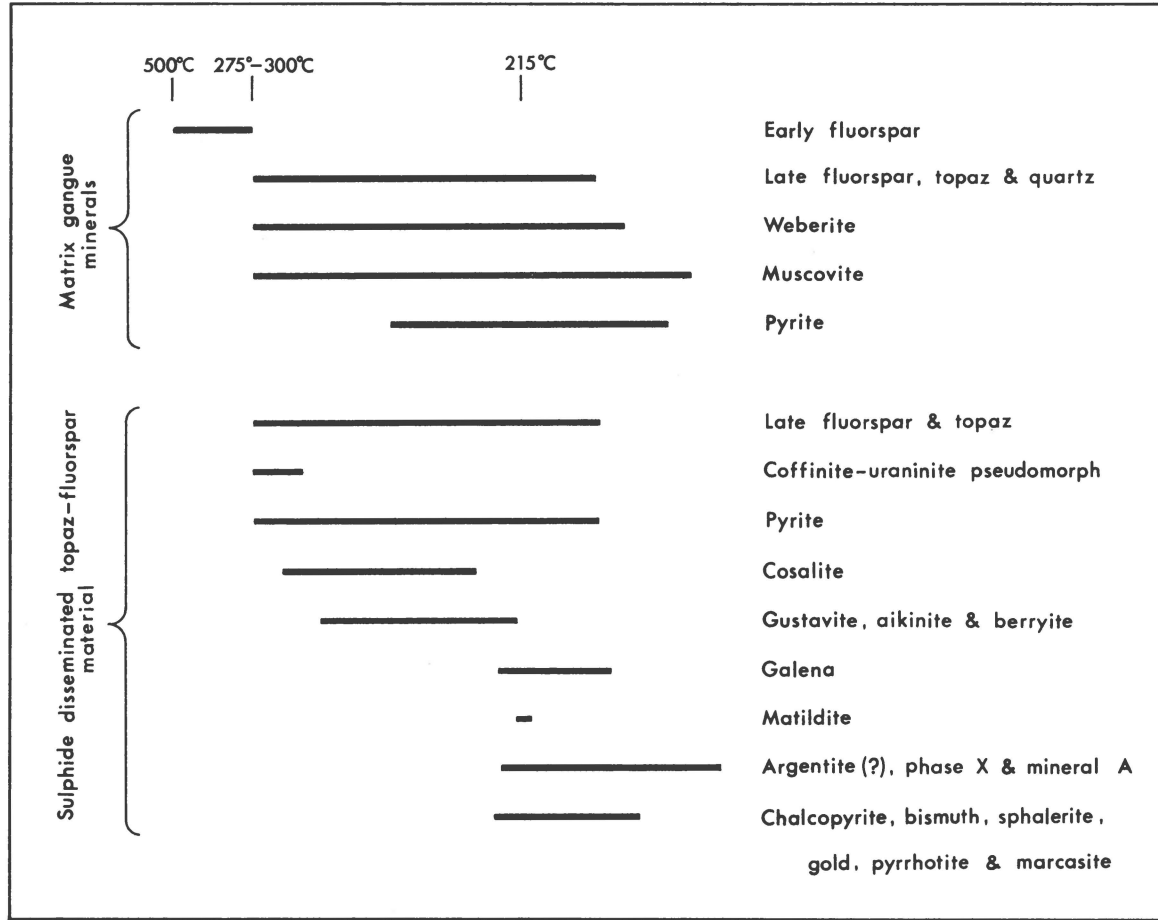


Fig. 4: Diagram showing mineralogical sequence and temperatures of formation.



temperatures around 215° C (CRAIG, 1967). Although galena crystallized in very silver- and bismuth-rich environments only some five mol. percent  $\text{AgBiS}_2$  were dissolved in its lattice. Total miscibility between  $\text{PbS}$  and  $\text{AgBiS}_2$  exists at temperatures above 215° C. The low  $\text{AgBiS}_2$  content of the galena thus suggests that the mineral, or at least the major portion of it, crystallized at temperatures below 215° C as shown on fig. 4. Naturally, the possibility cannot be excluded that galena crystallized above 215° C, but due to the composition of the mineralizing solutions it only crystallized with about 3.5 mol. percent  $\text{AgBiS}_2$  dissolved in its structure.

## VII. FORMATION OF THE MINERAL SUITE

### Physical state of the mineralizing fluids

The textural relationships between sulphides and gangue clearly show that all minerals have crystallized from relatively stagnant fluids. The various replacement patterns observed, often accompanied by relatively mild fracturing suggest only small local movement of the fluids during formation of the minerals. These features indicate, that the sulphides may have crystallized from a sulphide melt. The existence of sulphide melts at temperatures around 300° C have not experimentally been demonstrated to exist. Possibly high fluorine and carbon dioxide pressure combined with the presence of small amounts of other elements apart from lead, silver, bismuth and sulphur may have considerably lowered the melting temperature. Hopefully, this assumption may be confirmed by laboratory experiments sometimes in the future. Thus, due to our limited knowledge of the mineralizing media, the neutral term "fluids" has been employed throughout the paper.

### Crystallization sequence

The crystallization sequence is sketched on fig. 4. The first mineral to crystallize was the dark purple fluor spar, which was subsequently fractured and corroded by both sulphide-rich and sulphide-poor fluids.

The crystallization sequence of the matrix gangue minerals has been summarized on page 20 and need not be repeated here.

Topaz and fluor spar within the sulphide-disseminated area are considered to have crystallized penecontemporaneously with the matrix gangue minerals. A considerable portion of the two minerals crystallized before crystallization of the sulphides began. However, a minor amount of both minerals also crystallized simultaneously with late sulphides as illustrated on Pl. III, 3.

Pyrite began to form either simultaneously with the gangue minerals or at a later stage. The most part of the pyrite is considered to have formed earlier than the other sulphides, because it is extensively replaced by them. Cosalite started to crystallize before gustavite, but most

of it is believed to be contemporaneous with gustavite. The formation of cosalite was probably completed before that of gustavite. Both berryite and aikinite crystallized simultaneously with gustavite.

Crystallization of galena started during the final stages of the gustavite and berryite formation, possibly from fluids entrapped in already crystallized sulphides and gangue, and resulted in the partial replacement of gustavite and berryite. Formation of the major sulphide-filled deformation zones may coincide with the formation of the major breccia zone cutting the matrix gangue minerals. The pyrite present along this is not considered to have crystallized from the same fluids from which gustavite and associated sulphides crystallized. However, mixing of the two types of fluids may have taken place along major sulphide-filled deformation zones.

### **Changes in the composition of the fluids as crystallization progressed**

The trend of crystallization outlined above reflects the following possible changes in the composition of the fluids as the crystallization progressed:

The initial crystallization of pyrite has significantly lowered the iron content of the fluids. The subsequent formation of cosalite slightly enriched the residual fluids in silver. Continuous crystallization of both cosalite and gustavite caused little change in the silver and lead content but gradually lowered the bismuth content. After the formation of cosalite was completed, and as a result of the continuous crystallization of gustavite, the fluids gradually became depleted in both silver and bismuth. Finally, the formation of gustavite ceased and was succeeded by the formation of galena.

Local concentration of berryite, aikinite and sometimes also pyrite is undoubtedly the result of an irregular distribution of copper and iron in the mineralizing fluids. However, the distribution and crystallization of aikinite and berryite may locally be controlled by the differing ability of copper to dissolve in the lattice of gustavite and cosalite.

Microprobe analyses have shown that up to 1.8 percent copper was dissolved in cosalite but less than 0.2 percent in gustavite and galena. During crystallization of cosalite all the available copper was dissolved in the lattice of this mineral and therefore no copper-bearing minerals crystallized associated with cosalite. Very little copper was able to dissolve in the gustavite lattice. When gustavite and cosalite crystallized together, the amount of copper which could not dissolve in gustavite was tied up in adjacent crystallizing cosalite. In areas where no cosalite developed, excess copper crystallized in aikinite and berryite, the former

of these possibly in a relatively silver-poor, the latter in a more silver-rich milieu.

The amount of copper which could not be dissolved in the galena lattice, when this mineral crystallized, combined with iron as chalcopyrite. The very minor amounts of sphalerite associated with chalcopyrite reflect the enrichment of zinc in the residual fluids from which this mineral crystallized.

As described above, the considerable amount of pyrite present along the breccia zones cutting the matrix gangue minerals is considered to have crystallized from solutions which are not genetically related to those from which the gustavite and associated sulphides crystallized.

### **Exsolution minerals**

Instability of galena and gustavite after their formation has resulted in the exsolution of various minerals. The exsolution of phase X-blebs from gustavite and mineral A from galena has been described by the author (1970) and (1971). Additional minerals which exsolved from galena are argentite (?) and very rare matildite.

## VIII. ORIGIN OF THE MINERALIZING FLUIDS

Galena constitutes slightly less than half a percent of the cryolite deposit. The mineral contains about  $\frac{3}{4}$  percent silver and  $1\frac{1}{2}$  percent bismuth dissolved in its lattice.

The sulphides belonging to the gustavite-bearing mineral suite are composed of the same major elements as those forming the common Ivigtut galena. However, the elements are present in strikingly different proportions. A characteristic dissimilarity is the complete absence from the mineral suite of several rare tin-tellurium-silver-antimony minerals which in trace amounts have been found by H. PAULY in the common Ivigtut galena.

Extensive reactions took place between late crystalizing fluorspar-zone material and adjacent rock types. (Personal communication by H. PAULY). This suggests that the fluorspar-zone crystallized over a considerable period of time.

The gustavite-dominated sulphides occur within a restricted area of the fluorspar zone. The only other sulphide present in the fluorspar-zone is small amounts of rather evenly distributed pyrite. The lack of other sulphide-disseminations thus questions the possibility that the material which crystallized as gustavite, cosalite, galena and associated sulphides formed a portion of the fluorspar-zone material before it reacted with siderite-rich material and other rock types as well. An alternative origin of the mineralizing fluids thus is suggested.

During the extensive reactions between the fluorspar zone material and the adjacent rock types, sulphides in the latter must have been mobilized and crystallized elsewhere. The gustavite-bearing mineral suite, contained in gangue characteristic of the fluorspar zone, was found at a very short distance from the sulphide disseminated siderite-zone. It is therefore possible that the mineral suite may have crystallized from material derived from mobilized silver-bismuth-bearing galena in the siderite-zone. This material may have been kept mobile over a sufficiently long time to be concentrated locally and have its bulk composition considerably changed from that of the common silver-bismuth-bearing Ivigtut galena.

## IX. CONCLUSION

The present paper represents the completion of the study of a mineral suite from the cryolite deposit dominated by the sulphides gustavite, cosalite and galena. This suite is unique in several respects. It has contributed four new sulphides, namely gustavite, berryite, mineral A and phase X. Unfortunately the data on the two latter were not sufficient to permit the proposal of new mineral names. The discovery of gustavite promoted the author to investigate old museum specimens which might contain related minerals. This resulted in the discovery of gustavite at four additional localities and berryite at one, all located in the U.S.A. (KARUP-MØLLER, 1972).

The mineral suite is unique in another respect. It is considered to have crystallized from stagnant fluids, possibly a sulphide melt, at temperatures slightly below 300° C. This suggests that sulphide melts do exist at such low temperatures although this has not been demonstrated experimentally. The suite crystallized in a closed system from fluids, the metal ratio of which is represented by the analysis on page 10. Thus the mineral suite formed under conditions attempted in the synthesis laboratory.

The chemical similarities between the bulk compositions of the mineral suite sulphides and that of the common Ivigtut galena suggest that genetic relationships exist. The sulphides are considered secondary in origin having crystallized from mobilized common Ivigtut galena. Such mobilization took place when material belonging to the fluorspar zone reacted with the sulphide-disseminated siderite-rich material. The composition of the mobilized metal-bearing fluids must have changed considerably before the crystallization of the gustavite-bearing mineral suite.

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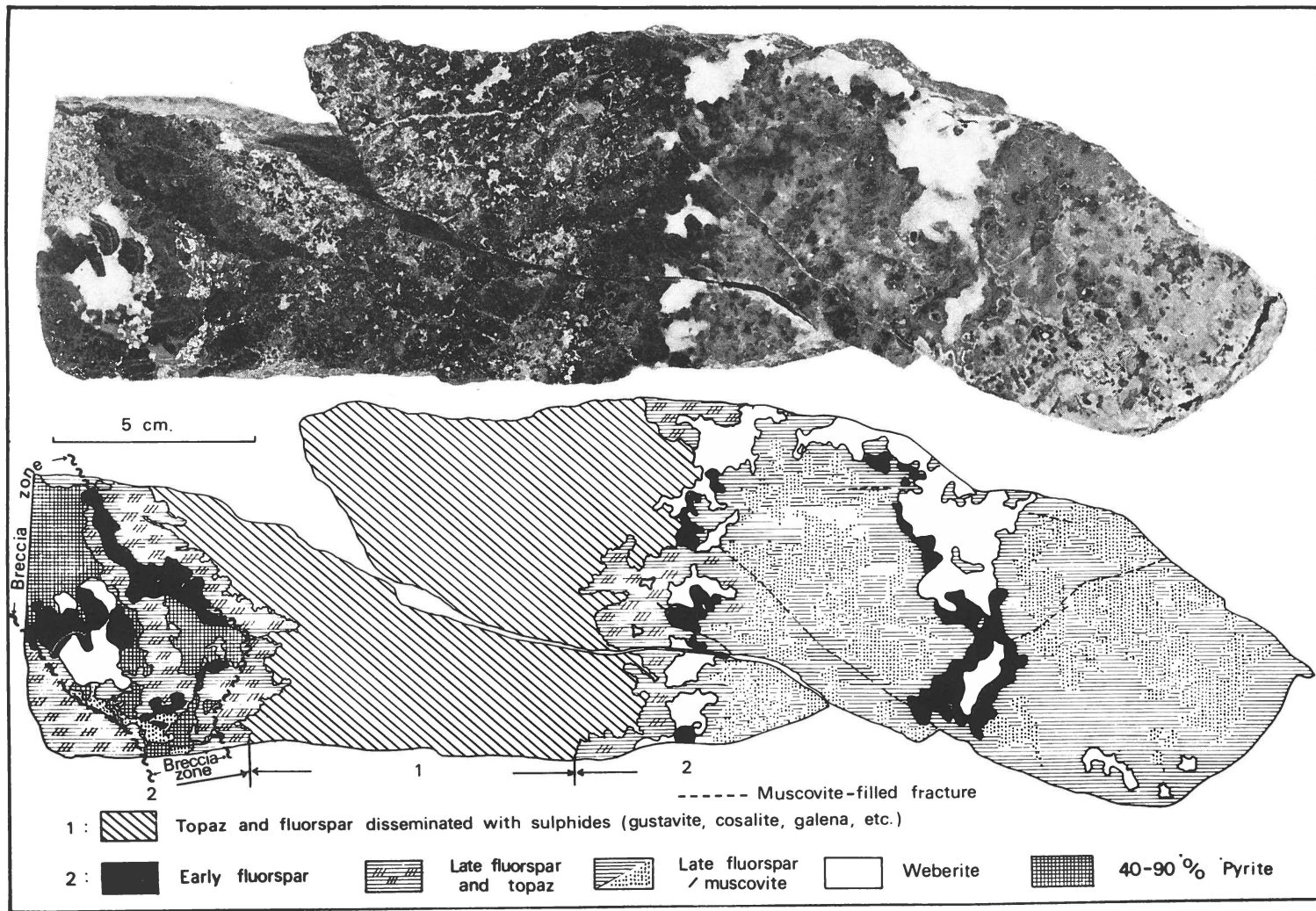
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## PLATES

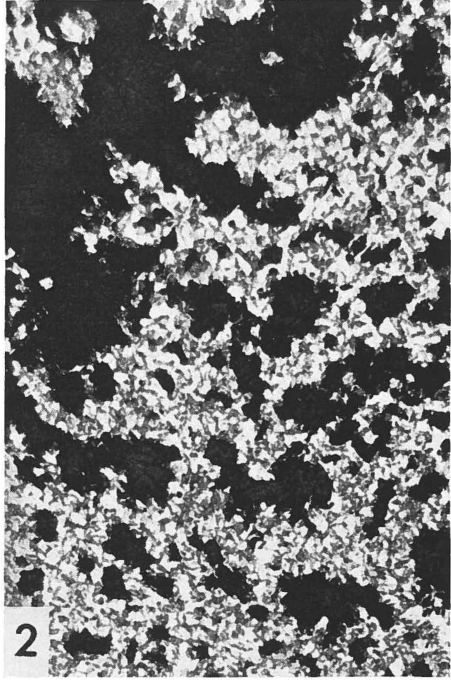
### **Plate I**

Photograph and sketch of rock specimen representing a cross section of the exposed mineral suite. For details see the description page 18 to 20.



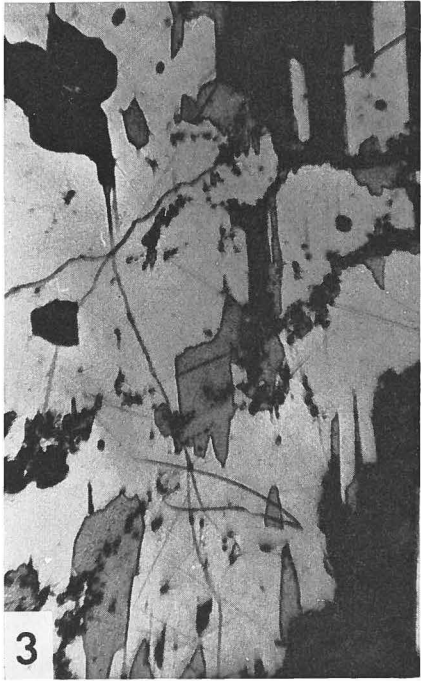
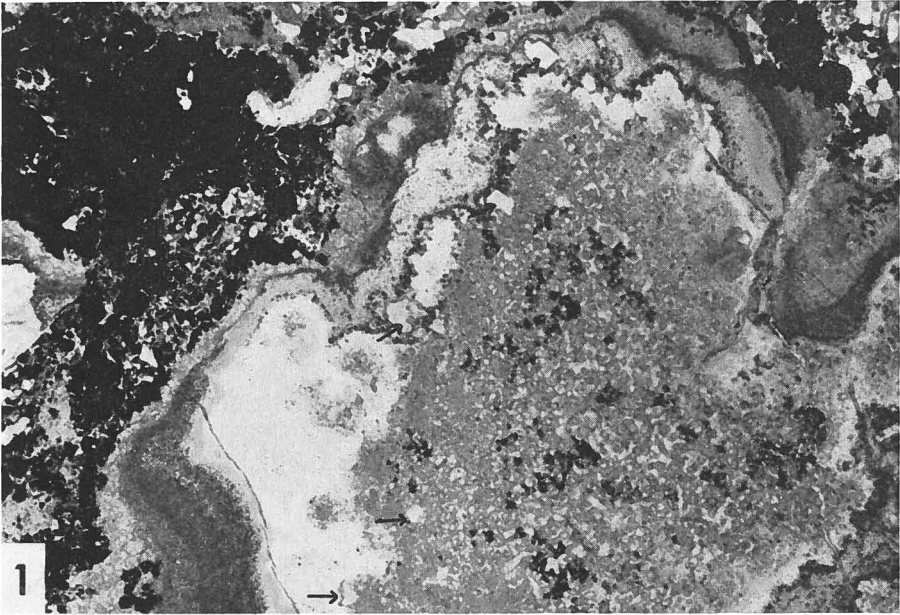
## Plate II

- Fig. 1. Aggregate of topaz rosettes (dark grey) and irregularly shaped fluorspar (black) in gustavite (white). (110 X. Oil immersion).
- Fig. 2. Massive aggregate of topaz rosettes (white) as host for fluorspar (grey) and sulphides (black). (50 X. Transmitted light. Crossed nicols).
- Fig. 3. Colloform, dark purple and early fluorspar corroded and surrounded by several layers of pale purple, late fluorspar. Alternating layers of late fluorspar (grey) and topaz (white) are present at bottom left. Weberite (w) occurs in aggregates of a few grains. Fractures in the early fluorspar are filled with sulphides, late fluorspar and outside the photograph also weberite. Muscovite (m) was introduced late during a phase of deformation. (7 X. Transmitted light. One nicol.).



### Plate III

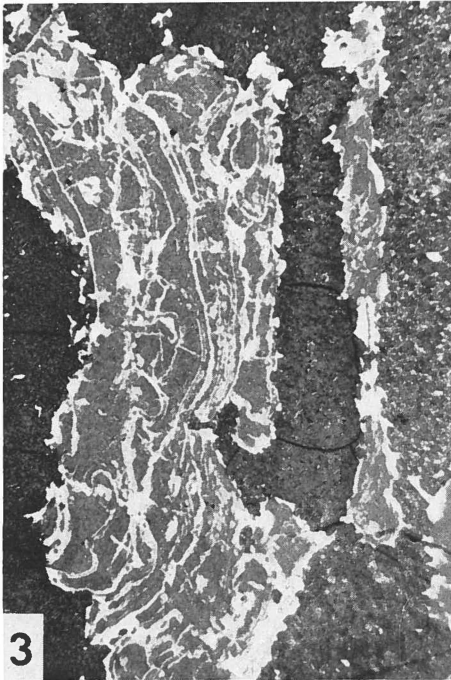
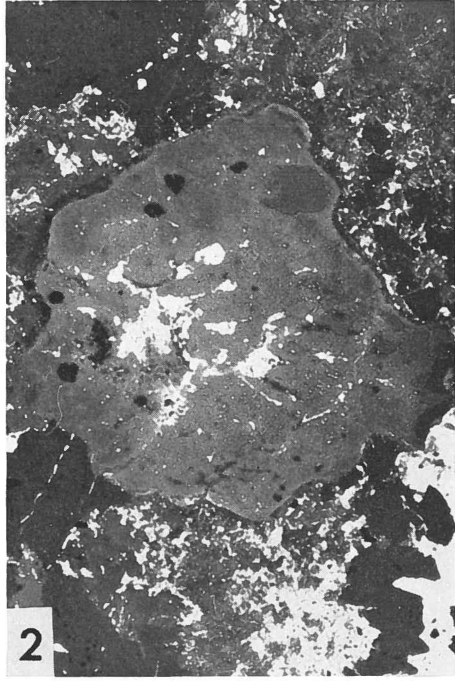
- Fig. 1. "Cauliflower head" shaped topaz-fluorspar aggregate. The central area, occupied by a mixture of granular fluorspar (grey), topaz rosettes (white), a few weberite grains (at arrows) and sulphides (black) are surrounded by alternating layers of topaz (white) and fluorspar (dark grey). Sulphides, mainly pyrite, at left and upper right contain interstitial fluorspar and muscovite. The weberite aggregate (white) at middle far left occurs in contact with a few alternating fluorspar and topaz layers. (6 X. Transmitted light. Oil nicol.).
- Fig. 2. Weberite (white), in part separated from corroded, colloform, dark purple, early fluorspar by light purple, late fluorspar, occurs in contact with sulphide-disseminated topaz-fluorspar material. (The contact between weberite and late fluorspar is dotted). Remnants of corroded dark purple fluorspar occur at upper right in the sulphide-disseminated topaz-fluorspar material (7 X. Oil immersion).
- Fig. 3. Large gustavite grain (white) is cut by replacing galena containing fine topaz disseminations (black). The large black gangue inclusions are fluorspar. (140 X. Oil immersion. Etched 1-3 secs. with conc.  $\text{HNO}_3$ ).



#### Plate IV

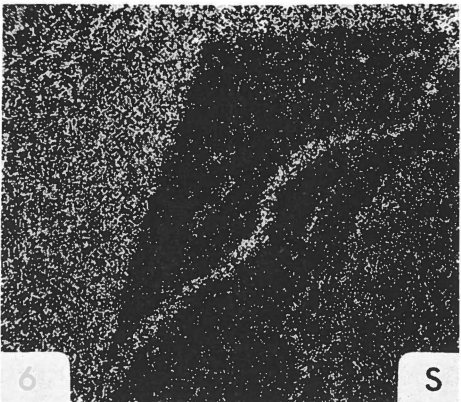
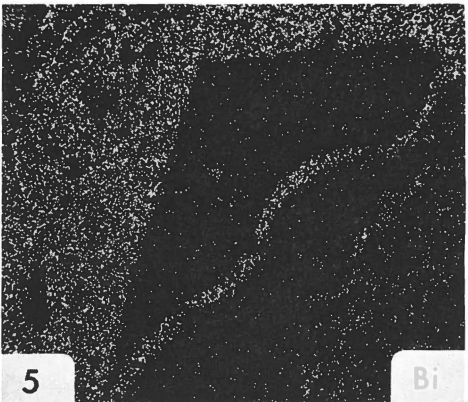
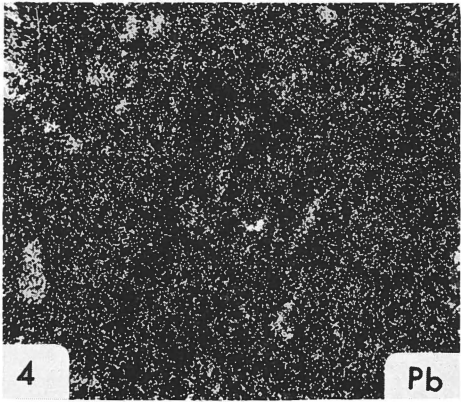
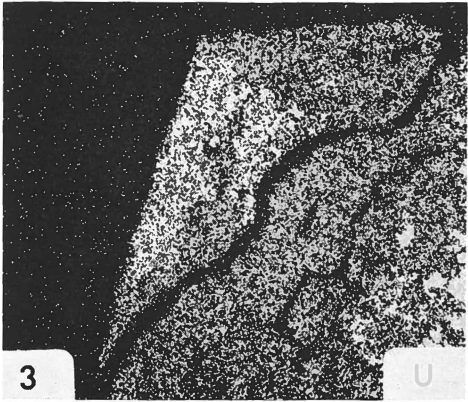
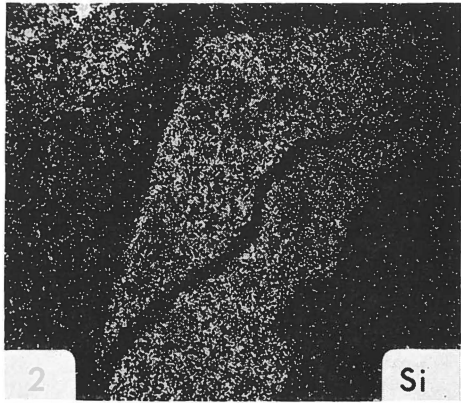
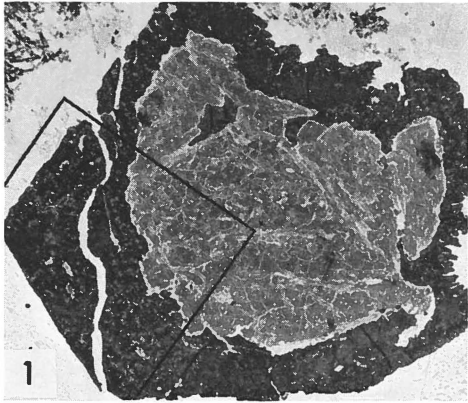
- Fig. 1. Pseudo-idiomorph coffinite aggregate with the central area characterized by a heterogeneous intergrowth of sulphides and uraninite. (160 X. Oil immersion).
- Fig. 2. Irregularly shaped coffinite pseudomorph in gangue containing abundant sulphides. (80 X. Air).
- Fig. 3. Portion of a relatively large coffinite pseudomorph characterized by an enclosed area of mixed uraninite (light grey) and sulphides. The finely banded texture within the area suggests rhythmic precipitation of uraninite and sulphides from entrapped pockets of fluids in the host coffinite. Extremely fine sulphide occurs as disseminations throughout both uranium minerals. (500 X. Air).
- Fig. 4. Band of sulphide grains, presumably gustavite, in fluorspar. Darker gangue mineral at upper right is weberite. (105 X. Oil immersion).





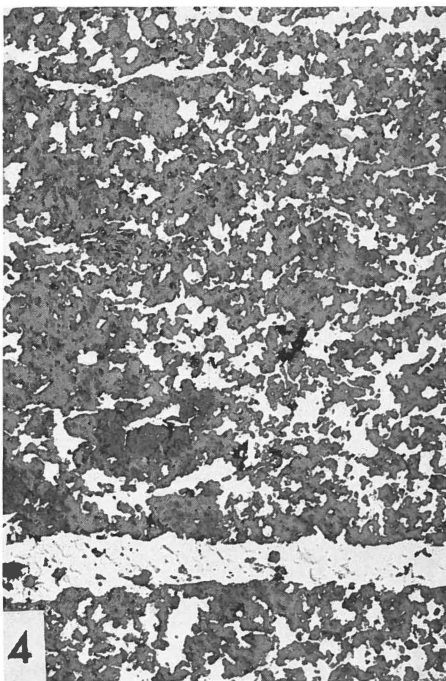
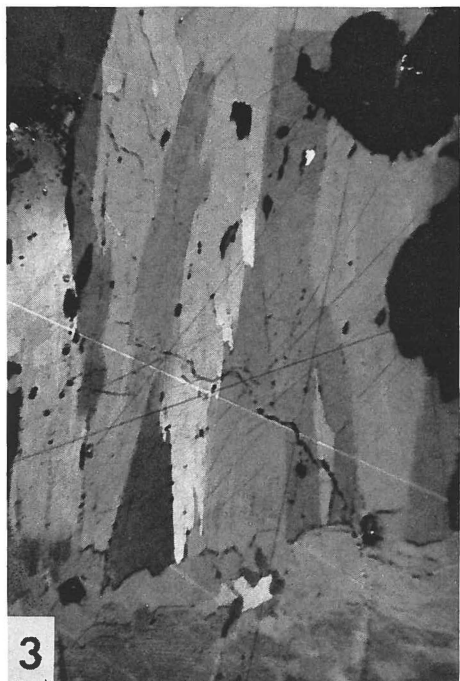
### Plate V

Fig. 1-6. Partly idiomorph coffinite pseudomorph with numerous fine sulphide inclusions and its central area occupied by uraninite and sulphides. Distribution of elements within the framed portion of the figure is illustrated in the X-ray scanning photographs 2-6. (Fig. 1: 155 X. Air. Figs 2-6: 270 X.).



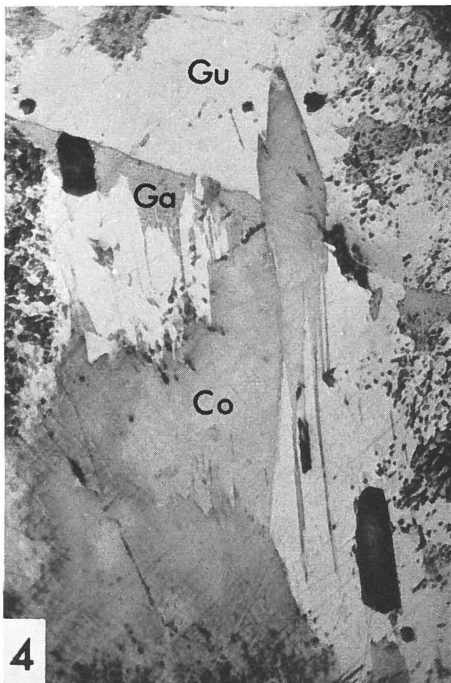
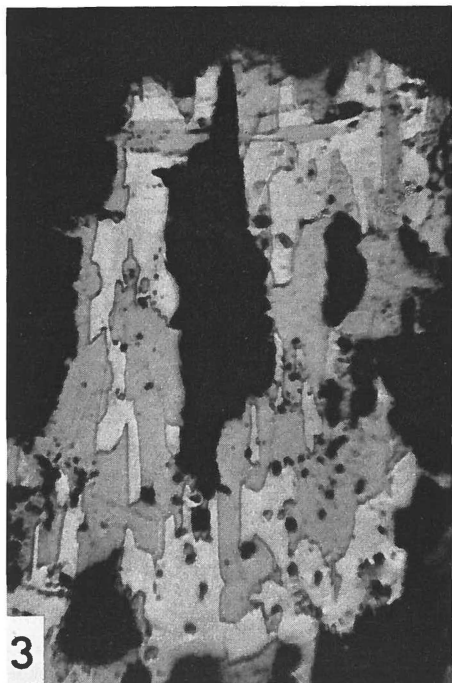
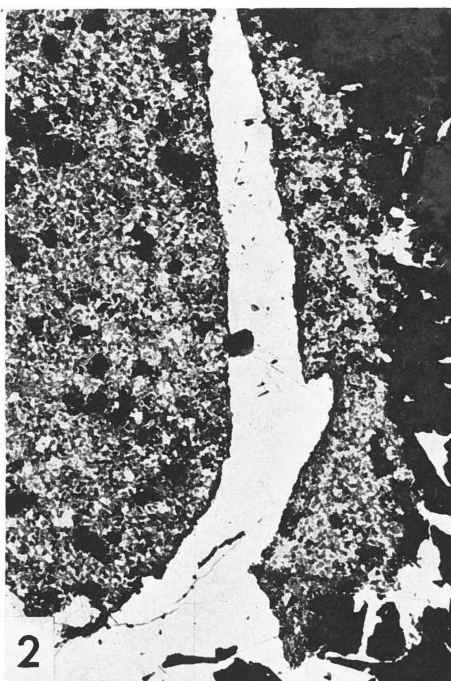
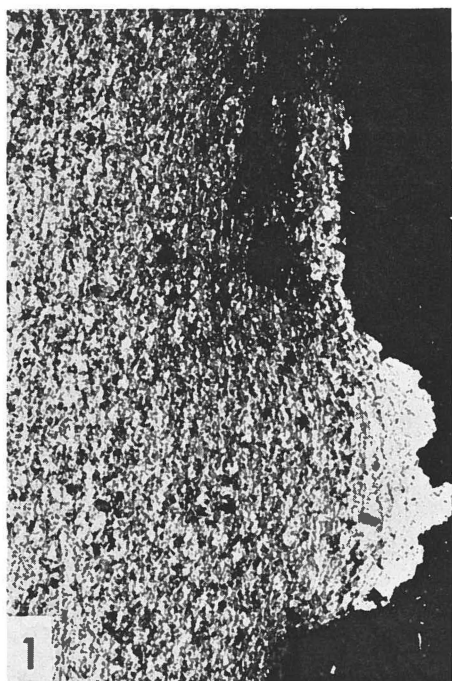
## Plate VI

- Fig. 1. Relatively large gustavite grain developed along a sulphide replacement vein across an almost sulphide-free fluorspar (dark grey)—topaz (light grey) area. The lamellar shaped fluorspar grains in the gustavite grain form extensions from larger irregularly shaped fluorspar grains in the topaz rosettes. They are all oriented parallel to the lamellar direction of the host mineral grain. (35 X. Air.).
- Fig. 2. Gustavite and minor galena present along a replacement vein extending across an area of fluorspar and sulphide-disseminated topaz. (70 X. Air.).
- Fig. 3. Polycrystalline cosalite grain characterized by numerous small grains oriented almost parallel to their prismatic direction. (115 X. Oil immersion. Nicols crossed at  $88^\circ$ ).
- Fig. 4. Topaz-fluorspar material disseminated with sulphides present as small patches some of which gradually change into fine, irregularly shaped sulphide-filled fractures. These are all oriented parallel to one major, at least four centimetre long and very regular sulphide-filled fracture. (12 X. Air.).



## Plate VII

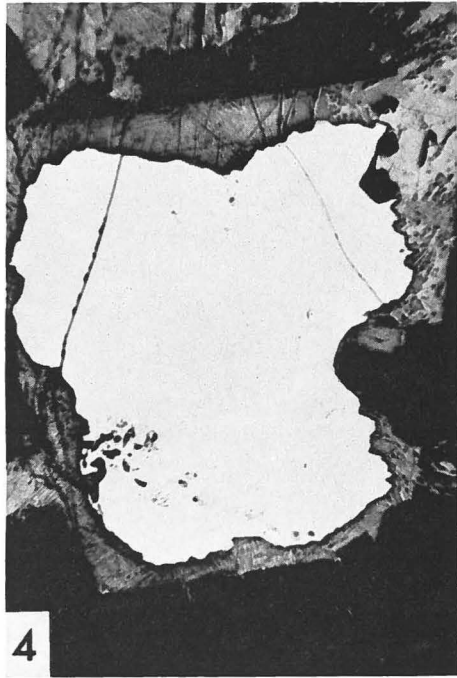
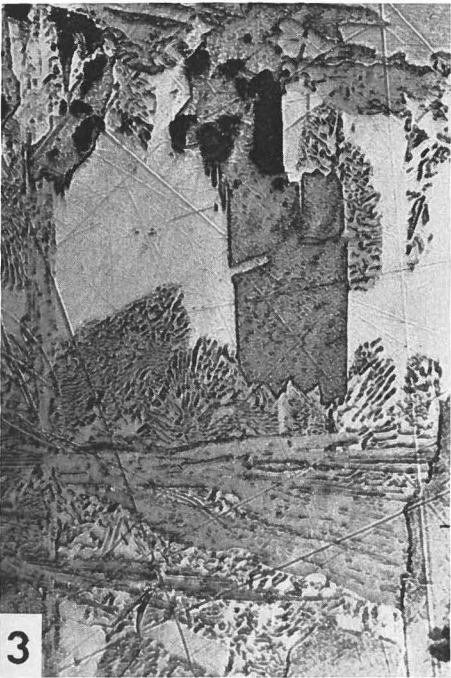
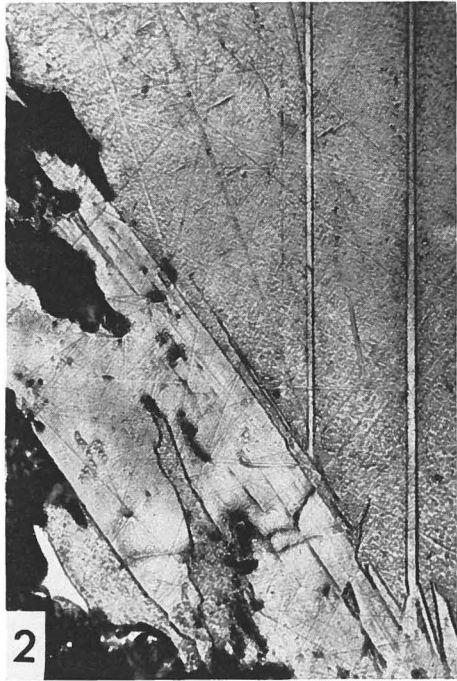
- Fig. 1. Portion of sulphide-filled deformation zone characterized by finely crushed gangue smeared out in the sulphides. (55 X. Air.).
- Fig. 2. Portion of old deformation zone, characterized by finely crushed gangue in sulphides, has later been cracked and fractures have been filled with younger sulphides, here gustavite with minor amounts of galena and berryite. (50 X. Air.).
- Fig. 3. Gustavite grain (white) in fluorspar (black) partially replaced by galena (grey). (145 X. Oil immersion. Etched 1–3 seconds with conc.  $\text{HNO}_3$ ).
- Fig. 4. Intergrowth between cosalite (Co), galena (Ga) and gustavite (Gu). The cosalite grain at right on the photo straddles the boundary between two differently oriented gustavite grains. A delicate interfingering intergrowth has developed between the gustavite grains which is oriented with its lamellar direction parallel to that of the cosalite grains. The cosalite grain is stumpy against the other gustavite grain (at top on photograph) which occurs with its lamellar direction almost angular to that of the cosalite grains. Galena grains lie along the contact between two gustavite grains at upper left on photograph. They penetrate one of the gustavite grains parallel to its lamellar direction, but not the other grain across the lamellar direction of this. Relatively large black grain at upper left and at lower right is fluorspar. The fine grained gangue is topaz. (85 X. Oil immersion. Etched 1–3 seconds with conc.  $\text{HNO}_3$ ).



### Plate VIII

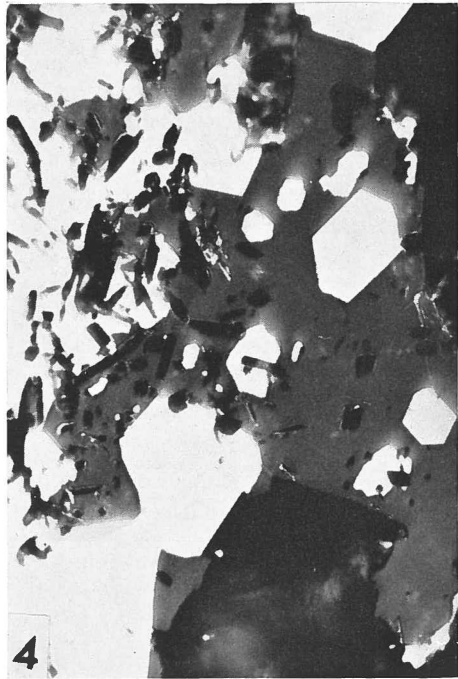
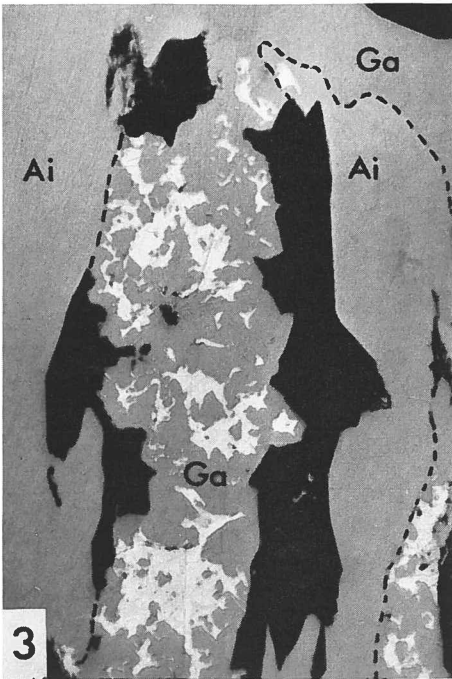
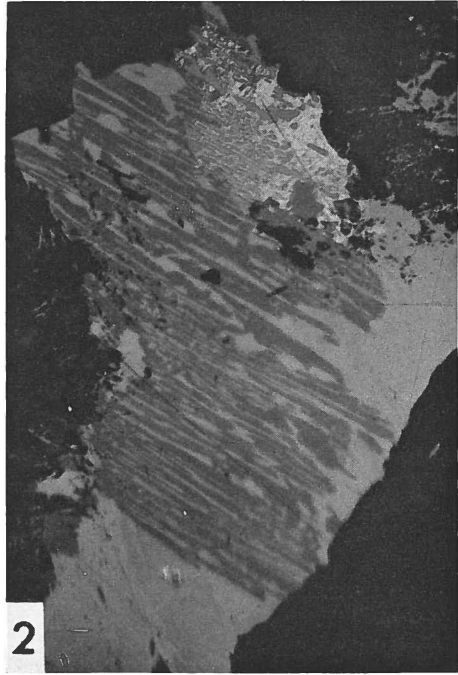
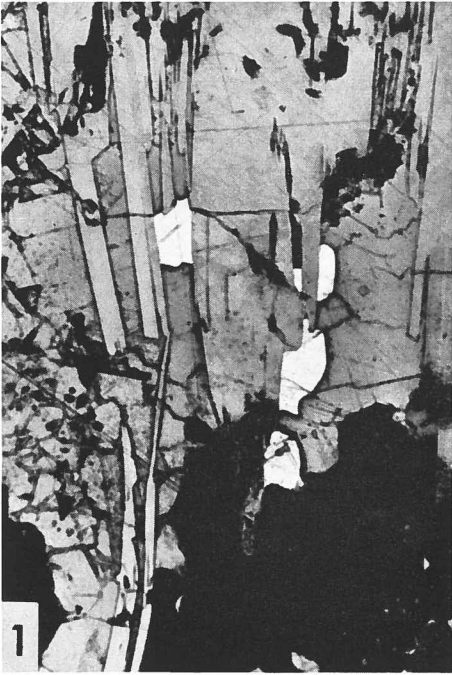
- Fig. 1. Myrmekitic intergrowth of galena (grey) and gustavite (white) has developed interstitially to galena-free gustavite grains. (125 X. Oil immersion. Etched 1–3 seconds with conc.  $\text{HNO}_3$ ).
- Fig. 2. Fine berryite laths (light grey) in galena (dark grey) project away from large berryite lath which is slightly replaced by galena. (540 X. Oil immersion. Etched 1–3 seconds with conc.  $\text{HNO}_3$ ).
- Fig. 3. Intergrowth between gustavite (white), galena (dark grey) and randomly oriented and irregularly shaped berryite laths (medium grey) containing very fine inclusions of galena. (610 X. Oil immersion. Etched 1–3 seconds with conc.  $\text{HNO}_3$ ).
- Fig. 4. Idiomorph pyrite crystal in gangue replaced along its margin by gustavite, cosalite and galena. (80 X. Oil immersion. Etched 1–3 seconds with conc.  $\text{HNO}_3$ ).





## Plate IX

- Fig. 1. Gold grains (bright white) associated with galena (dark grey) shaped as lamellae intergrown with gustavite (grey). (110 X. il immersion. Etched 1-3 seconds with  $\text{HNO}_3$ ).
- Fig. 2. Myrmekitic intergrowth between gustavite (dark grey) and galena (light grey) lie in contact with galena in myrmekitic intergrowth with bismuth (bright white). (85 X. Oil immersion. Nicols crossed at  $88^\circ$ ).
- Fig. 3. From deformation zone a. Galena (Ga) containing irregularly shaped bismuth grains is enclosed in sphalerite (black) and all are enclosed in aikinite (Ai). The galena-aikinite boundary is marked by the dotted line. (550 X. Oil immersion).
- Fig. 4. From deformation zone a. Sphalerite containing galena (white) and needles of topaz. (710 X. Oil immersion).



## Plate X

- Fig. 1 .From deformation zone b. Idiomorph pyrite crystals in gangue-disseminated aikinite-galena intergrowth containing abundant very fine inclusions of gangue, aikinite and galena. The pyrite crystals in the gangue-free aikinite-galena intergrowth contain numerous and relatively large inclusions of only the two host sulphides. Some pyrite crystals straddle the boundary between gangue-free and gangue-disseminated aikinite and galena. That portion developed on the gangue-disseminated side resembles the pyrite crystals present here, while that in the gangue-free aikinite-galena intergrowth resembles the pyrite crystals enclosed in these two minerals. (55 X. Oil immersion).
- Fig. 2. From deformation zone b. Pyrite-aikinite-galena aggregate in sulphide-disseminated gangue, presumably crystallized from an enclosed pocket of fluids. The original outline of this pocket is marked by the stippled line. After the entrapped fluids had crystallized as sulphides resembling the mineral intergrowth in the bottom portion of Pl. X, 1 pyrite continued to crystallize into the sulphide-disseminated gangue. Here it enclosed abundant very fine gangue, aikinite (Ai) and galena (Ca). It developed with idiomorph outline against the sulphide-disseminated gangue and as such resembles the pyrite crystals in the upper portion of Pl. X, 1. (75 C. Oil immersion).
- Fig. 3. From deformation zone b. Almost homogeneous pyrite aggregate with remnant aikinite (Ai), galena (Ga) and free gold along the pyrite grain boundaries. (130 X. Oil immersion. Etched 1-3 seconds with conc.  $\text{HNO}_3$ ).
- Fig. 4. Pyrite grains in matrix gangue minerals containing numerous chalcopyrite inclusions. Abundant chalcopyrite has crystallized along the pyrite grain boundaries. (55 X. Oil immersion).

