

SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C.

Avhandlingar och uppsatser.

N:o 321.

ÅRSBOK 17 (1923) N:o 2.

SOME SWEDISH  
OCCURRENCES OF BORNITE  
AND CHALCOCITE

BY

PER GEIJER



*Pris 1,00 kr.*

STOCKHOLM 1924

KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER

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## Introduction.

Bornite and chalcocite (copper glance) have contributed very little to Sweden's production of copper, chalcopyrite being utterly predominant as a copper ore. In the one big copper mine, Falun, credited with about 80 per cent, or more, of the total copper production of our country, neither bornite nor chalcocite has been recorded. In many of the other, smaller mines, however, these two minerals have been observed, generally as exceptions but locally in enough quantities to give them a little importance economically. It is impossible to state with any degree of precision the proportion, in the total production, of copper won from these richer sulphides. One may guess that the figure is less than 5 per cent, even when not counting Falun.

Broadly considering, it may be stated that the richer copper sulphides are restricted to deposits of small — generally very small — dimensions. They are known to our mining men as «unreliable», and when a prospect is reported to contain bornite or chalcocite, the presence of these minerals is almost considered discrediting. This may be, in a way, only another expression for the experience that the minerals in question are more characteristic for small deposits, but it may also contain other facts. It hints at the possibility of secondary enrichment as a factor in the development of those deposits that carry the richer sulphides. Truly, there have been very strong reasons to doubt that remnants of pre-glacial enrichment zones are present in any noteworthy extent, but the problem has needed an investigation. One clear case had already been noted by the writer (12, p. 282).<sup>1</sup>

The primary purpose of this study, therefore, has been to ascertain the origin of the bornite and the chalcocite in their main types of occurrence in Sweden. There have also been obtained certain other data on the geological history of our ore deposits, and a number of new contributions to

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<sup>1</sup> The first number in the paranthesis refers to the list of works cited, in the end of this paper. To avoid confusion in cases where several works are quoted together, reference to a given page is made as above.

that interesting chapter of mineralogy, the characters and mutual relations of the copper sulphides.

The occurrences of the minerals in question in Sweden may be grouped as follows:

A. Archæan deposits.

1. In northern Sweden (Nautanen-Svappavaara group, Sjangeli, and a few isolated occurrences).
2. In Central Sweden.
3. In south-eastern Sweden.

B. Post-Archæan deposits in western south Sweden (veins in the provinces of Dalsland and Värmland).

Only the Archæan deposits are considered here. Of the post-Archæan group, the writer has had no field experience of his own, and the published data are much too meagre to serve as the basis for a study of specimens in mineral collections. Furthermore, this group, veins with a gangue of quartz, often also carbonates and fluorite, and in many cases containing argentiferous galena and locally zinc blende or tetrahedrite, is radically different from the Archæan deposits and is instead related to vein types that have been studied in detail in many foreign districts. The veins are supposed to be of late pre-Cambrian age. For the reasons given, this investigation has been limited to the occurrences of Archæan age.

Of many among the deposits considered here, the writer has already published descriptions. These deposits are again considered, with special emphasis on the relations of the richer copper sulphides, and referring to the results of chalcographic<sup>1</sup> studies. Some other deposits, like Lattevara and Vähävaara, not previously described, have needed more space. Further, a few deposits not visited but closely related to types studied in the field by the writer, are described from the data published by others, and from chalcographic examinations of museum specimens. Also at several localities where the writer has undertaken field studies, the occurrence of bornite or chalcocite has been so local in character that recourse had to be made to old museum specimens for their study. Several old collections have furnished material of great value in this respect, notably those of the National Museum of Natural History (Naturhistoriska Riksmuseum, here abbreviated R. M.), the University of Uppsala (U.), and the School of Mines in Stockholm.

At a very early stage in this work, the writer was given the opportunity to take part in a short course in the methods of chalcography, led by Prof. H. Schneiderhöhn. It is a great pleasure to record here the value of this instruction for the investigation now presented. For the preparation of specimens for microscopical examinations, and for the photographic work, the writer is indebted to Messrs. G. Larsson and A. Hj. Olsson, respectively.

<sup>1</sup> Following Brauns, Schneiderhöhn, and others, the term chalcography is here used for «the microscopical examination of opaque minerals in reflected light».

## Occurrences in northern Sweden.

### Lattevare.

Lattevare<sup>†</sup> is a hill at Lattelahti, a bay on the northern shore of the easternmost part (Kortolahti) of the lake Torne Träsk, about 13 km ENE of the railway station Torneträsk. The occurrence of copper minerals at Lattevare was discovered by the Lap J. O. Turi, well known as a prospector, hunter and author. Some prospecting work was done, but the deposit proved to be without any commercial value. The geological relations were studied by the writer during a brief visit, in 1916, and were found to offer several points of interest.

The ore-bearing rock is a gabbro. Gabbro bodies occupy considerable areas of the Archæan around the eastern end of Torne Träsk. Within a zone south of the copper prospect there is much pyrite disseminated in the gabbro. Sometimes it is concentrated in small feldspar »pockets». The largest pyrite bodies are streaks about 1 meter long and 10 to 15 cm wide. The gabbro is quite unaltered, and the pyrite appears to have been concentrated during the crystallization of the rock enclosing it.

The rock at the copper prospect is a massive gabbro with purplish gray feldspars. The size of grain varies irregularly and rather abruptly. Microscopic examination shows a normal uralite gabbro. The chief components are an andesine feldspar ( $Ab_{65}An_{35}$ ) and a light brownish green hornblende, of a type commonly occurring as uralite. There is also some biotite, rather much magnetite with thin coatings of titanite, and a little apatite. The plagioclase is quite fresh. The most salient textural feature is the spot-wise variation in the size of grain, from about 5 to 10 mm down to 0.20 or 0.30 mm. The texture is that of a granular gabbro, ophitic development of the uralitic hornblende appearing only locally.

A peculiar variety of the gabbro has evenly rounded, greenish white, 10 to 20 mm large spots. A thin section shows that such a spot is an aggregate of strongly altered plagioclase grains, with a great amount of magnetite in small grains. Also the surrounding mass, a normal fine-grained gabbro, is rich in magnetite, but in larger crystals.

The copper minerals are chalcopyrite (predominating), and bornite. At least the chalcopyrite occurs here and there in the gabbro, in small »pockets» of coarse feldspar, hornblende, etc. Chiefly, however, the copper minerals occur in more or less clearly defined veins, generally a few dm wide, which further consist of crystalline magnetite and varying quantities of a dark green hornblende.

From the feldspar »pockets» in the gabbro there are transitions to pegmatitic veins, a few cm wide, of feldspar, quartz, hornblende, magnetite, chalcopyrite and bornite. The ore minerals and the quartz seem to exclude

<sup>†</sup> Sometimes erroneously spelled Lahtivare.

each other. There are also larger veins or dikes, varying in texture between aplitic granite and pegmatite. These dikes cut the copper-bearing magnetite veins. In one aplite dike there was observed a feldspar pocket, in which the interstices between the feldspars were filled with bornite and chalcopyrite. It is uncertain whether these dikes, that consist of microcline, albitic plagioclase, and quartz, belong to the differentiation products of the gabbro magma. The examination in the field gave the impression that they are connected with the small pegmatitic veins already described, which, in turn, belong to the gabbro, but no decisive chain of evidence could be produced.

A typical pocket in the gabbro, about 5 cm in size, was examined microscopically. The chief components are plagioclase and hornblende, both of the same general character as in the normal gabbro, but in larger grains. Further there is magnetite and chalcopyrite — generally associated, with chalcopyrite as the later mineral to form — and several large grains of apatite.

A thin section from one of the pegmatitic veinlets that carry copper minerals has also been studied. The vein, about 5 cm thick, consists of pinkish feldspar in grains a few mm in size, and between them a subordinated mass of hornblende, magnetite, chalcopyrite, and bornite. The thin section shows that the feldspar is an albite (about  $Ab_{95}An_5$ ), with the irregular lamination so frequently observed in pure albite, here grading into an irregular spottedness. The most salient textural feature is the irregular, sutured character of the contours of the albite grains. I have observed this feature also in other albitic rocks. Besides those constituents that are already visible to the naked eye, the microscope shows orthite and titanite.

The ore veins proper consist, as already mentioned, of magnetite, hornblende, chalcopyrite, and bornite. The proportions between the constituents are varying, but the copper minerals are, on the whole, subordinated. The hornblende is dark green (very pale green in thin sections), and generally forms short-prismatic grains, 1 to 2 mm in length. The ore minerals are »squeezed in» between these hornblende grains, but have corroded them to some extent. This corrosion makes it impossible to identify any original crystal faces in the hornblende. What evidence there is points to a primary hornblende, not a uraltic one.

The characters of the ore minerals, and their mutual relations, are best brought out by the chalcographic examination. The magnetite appears to be entirely homogeneous. Etched sections do not show any intergrowths of hematite or ilmenite. The bornite, when examined at low magnifications, is homogeneous, although with a peculiar colour. Higher power, and particularly the use of the immersion objective, reveals a most regular and beautiful intergrowth of chalcopyrite as fine lamellæ, arranged in three directions, probably corresponding to directions of octahedral parting in the bornite (fig. 5, Pl. I). It has been impossible to discern whether these

lamellæ, as in some analogous cases that will be described in the following, are bordered by chalcocite.

The magnetite shows more or less well-defined idiomorphic (euhedral) outlines against the copper minerals (fig. 5, Pl. I). In the areas made up of the latter, the bornite chiefly lies along the borders or in the corners, while the centre of the field is occupied by chalcopyrite with only isolated patches of bornite. In general, the chalcopyrite exhibits convex outlines towards the bornite, and appears to replace it. The texture is more like those brought about through corrosion in an igneous rock (corrosion embayments) than the usual replacement relations between sulphides. Sometimes, however, there is seen a tendency towards the development of relations analogous to those of the common intergrowths of chalcocite and bornite.

Curved cracks cut both chalcopyrite and bornite. In the latter, covellite is developed along them (fig. 5).

The above description shows that the aggregates of ore minerals (magnetite, chalcopyrite, bornite), whether they occur in pegmatitic pockets or veinlets, or in ore veins free from feldspar but rich in hornblende, must have formed at high temperatures in connection with the crystallization of the gabbro. Furthermore, it is evident that they belong to an end phase, and represent substances that were concentrated in those fractions of the magma that were the last to crystallize. Terms aiming at a more precise characterizing of the stages between »magmatic» and »pneumatolytic» mineral-forming processes have been introduced by Graton and Mc Laughlin (17). The Lattevaré veins composed of hornblende and ore minerals are, in all probability, to be designated as pneumotectic in the sense of the authors just quoted, *i. e.* they differ from the products of the magmatic (orthotectic) crystallization by the fact that volatile constituents played an important part in their development. The interaction between the constituents — corrosion of hornblende by ore minerals, of bornite by chalcopyrite — is comparable to processes that take place also in orthotectic crystallization. Therefore, these phenomena do not justify the term pneumatolytic, as restricted by Graton and Mc Laughlin to cover processes characterized by the interaction of volatile magma constituents and already existing mineral aggregates (contact metasomatism is a typical case of pneumatolytic action in this restricted sense). It is probable that also the ore-bearing pegmatitic veinlets were formed through pneumotectic processes.

As already recorded, the ore minerals show the sequence: magnetite, bornite, chalcopyrite, covellite. The covellite must be a product of recent (post-glacial) secondary enrichment on an insignificant scale, but the other minerals are clearly of primary origin. The order bornite-chalcopyrite is uncommon, but so is also the general character of the deposit. The occurrence of chalcopyrite lamellæ in the bornite will be discussed in the following. It may be mentioned at once, however, that the writer is inclined to regard these lamellæ as segregations from a mixed crystal (solid

solution) that was homogeneous at higher temperatures. The combination of bornite with chalcopyrite segregations and free chalcopyrite is regarded as analogous to the association of perthitic potash feldspar with free albite or plagioclase, which is so common in igneous rocks.

#### Veins in Kiirunavaara.

Within the iron ore body of Kiirunavaara and in its immediate foot wall rock there have been found a few narrow veinlets of bornite and chalcocite (11).

*Veins of southern Kiirunavaara (Professorn ridge).* In the foot wall rock of the iron ore, a syenite-porphiry, there have been observed in the open cuts two or three veins of bornite, none of them more than a few cm wide. Besides the bornite, a little chalcopyrite is also observed as a primary component. There is some white quartz with needles of black tourmaline. The microscopic examination further shows much biotite in some sections. This mica is strongly pleochroic and occurs in prismatic individuals of the »roll of money» type. Plagioclase, apatite and rutile also occur, but may belong to the wall rock. Partly, at least, the veins are formed by replacement of the porphyry.

The veins are strongly oxidized, chrysocolla being the chief product formed, with some limonite, a little malachite and possibly melaconite.

The chalcographic examination of these veins reveals a beautiful case of the replacement of bornite by chalcocite. Generally, the chalcocite is somewhat subordinate in amount. The bornite is seen to vary somewhat in colour, ranging from orange to red with a decided bluish tinge. By using an immersion system, one may sometimes discern small lamellæ of chalcopyrite in the bornite. These lamellæ are often curving or irregular, but may locally show an evident octahedral grouping. Mostly they are few and rather unevenly distributed, and then there is nothing comparable to the beautiful intergrowth described above from Lattevere. In one section, however, the intergrowth is much more conspicuous. Fig. 6 (Pl. I) shows a typical part of this section. The areas of intergrowth are separated from the homogeneous bornite by veins of oxidation products. The homogeneous bornite shown in fig. 6 has decidedly more yellow in its colour than the bornite in general in these veins.

The intergrowth is a very regular one (fig. 7, Pl. II), the chalcopyrite lamellæ showing the same octahedral grouping as in the Lattevere bornite. In the Kiirunavaara mineral, however, the intergrowth is coarser, and gives us the possibility of a more detailed study. It has exactly the pattern generally exhibited by lamellæ of a segregated substance in a crystal belonging to the cubic system. Each lamella of chalcopyrite is accompanied on both sides by a border of chalcocite (not quite well shown in fig. 7).

The chalcocite very clearly replaces the bornite. Sometimes it forms a network of veins of the type shown by fig. 8 (Pl. II), where both the larger

relations and the textural details give evident proofs that replacement has taken place. The smaller bornite remnants are remarkably angular. In other cases, the chalcocite veins are made up of larger grains, and the boundary line against the bornite is more irregular in its larger features, but less complicated in detail. Quite locally, a tendency to a graphic intergrowth of bornite and chalcocite is observed.

The chalcocite is mostly of the »white» variety. Blue chalcocite also occurs, however, mainly as stripes parallel to one of the orthorhombic cleavage directions and alternating with white chalcocite. In other grains one sees irregular streaks of blue chalcocite in the white mineral — apparently a common mode of occurrence for blue chalcocite (compare 56). The ordinary orthorhombic cleavage of the chalcocite is often visible also in unetched sections.

In some specimens, part of the chalcocite grains contain much covellite in the form of stripes and blades elongated parallelly to the chalcocite cleavage lines. Generally, the covellite is intergrown with the chalcocite in such a way that all the covellite patches within each grain of chalcocite have the same orientation. This is particularly well brought out by the use of polarized light (compare fig. 9, Pl. III, which also shows the shape of the covellite areas). The intergrowth can be due to later enrichment, but the covellite patches do not show any dependence of the cleavage cracks, although orientated parallelly to one cleavage direction. It seems more probable, then, that they have been segregated from a blue chalcocite that originally held some cupric sulphide in solid solution.

The oxidation products form systems of fine veins that very often follow the middle of the chalcocite veins. In general, there is chrysocolla next to the chalcocite, and limonite in the centre of the vein, but this pattern is not always followed.

*Veins of northern Kiirunavaara.* In the part of the ore mountain that was in former days called Geologen (now removed by mining), the writer found a few loose fragments of copper ore in an open cut bench (II, p. 123). The vein appears to have been up to 1 dm wide, or perhaps more. It is not clear whether it has occurred in the magnetite body, or in an inclusion of the foot wall porphyry. The constituents are bornite, chalcocite, and a light green hornblende. The microscopic examination shows how the hornblende, occurring in prisms up to a few mm in length, is corroded by the sulphide mass. The texture is somewhat similar to that of the Lattevaara veins, but the amphibole prisms are more slender in the Kiirunavaara specimens. Chalcocite and bornite are present in approximately equal amounts. They occur in large pure grains and in beautiful graphic intergrowths. There are also small replacement veins of chalcocite in the bornite, frequently connecting with the chalcocite of the intergrowths.

The bornite is homogeneous. The chalcocite is mostly white but partly blue, the latter variety occurring in very much the same way as in the veins of southern Kiirunavaara. There is always a deep blue border on

the bornite, when bordering on chalcocite. When etched with KCN, part of the chalcocite exhibits the regular, sparsely spaced, »triangular» or octahedral etch cleavage (fig. 10, Pl. III). Other grains, however, show the ordinary etch cleavage of orthorhombic chalcocite, with the very fine striation parallel to the basis beautifully developed. Sometimes one system in the triangular pattern is much more closely spaced than the other two, and thus takes on the appearance of the orthorhombic basal cleavage.

The »triangular» etch pattern has been much discussed (15, 56, 2, and other papers). At first explained as »inherited» from replaced bornite, it seems now to be regarded by most observers as indicating an original isometric nature of the chalcocite. Bateman and Mc Laughlin, in discussing the origin of the Bonanza (Kennecott) chalcocite (2), mention the co-existence of octahedrally and orthorhombically etching grains, and refer it to original differences in the amount of dissolved cupric sulphide (compare 39). It seems most probable that a similar explanation must be applied to the occurrence now in question.

In one of the first years of mining on Kiirunavaara, a remarkable copper vein was encountered in the northernmost part of the mountain (Vaktmästaren). A specimen was preserved by one of the engineers, and later given to Stutzer, who has described it (52, p. 293). The ore is reported to be fine-grained and to consist of plagioclase, augite, biotite, bornite, chalcocite and apatite, with a little tourmaline and garnet. The sequence is 1) apatite, tourmaline, garnet, biotite, and augite, 2) plagioclase, 3) ore minerals. The copper minerals have corroded the other constituents.

*Origin of the Kiirunavaara copper veins.* The mineral association and the texture indicate that the veins have been formed at high temperatures. In the papers quoted above, both Stutzer and the present writer have characterized them as magmatic. With the present more restricted meaning of this term, however, it can hardly be used, except perhaps for the vein at Vaktmästaren. The Geologen vein is probably a pneumotectic one, like the veins at Latteväre. If the interpretation of the etch cleavage that was quoted above is right, then the chalcocite of this vein must belong to the primary (hypogene)<sup>1</sup> mineralization. The textural relations of chalcocite and bornite will be discussed in a following section.

As to the veins of southern Kiirunavaara, they show a combination of features that points to a partly pneumotectic and partly pneumatolytic origin.

The connection between the copper veins and the magnetite ore body may perhaps be due to a chemical influence of the latter on copper-bearing solutions. If so, the copper was probably derived from the same sources as the copper deposits of the Nautanen-Svappavaara group, to be described below. It is also possible, however, and perhaps even more probable, that

<sup>1</sup> The terms »hypogene» (»formed from below») and »supergene» (»formed from above») have been introduced by Ransome (40, p. 152) to avoid the misunderstandings easily encountered when using *primary* and *secondary* in the discussion of sulphide deposits.

the combination with the iron ore is of a much earlier date geologically, the copper compounds having accompanied the iron ore in the earlier stages of magmatic differentiation, to be finally segregated as veinlets in the margins of the magnetite body, or injected in its wall rock.

*Secondary (supergene) processes.* As stated already in an earlier paper by the writer (12, p. 282), the copper veins of southern Kiirunavaara form a typical case of »secondary enrichment». The much more detailed description above contains sufficient proofs.

There can be no doubt about the pre-glacial age of these phenomena. The few thousand years that have elapsed since the Pleistocene ice sheet left the Kiruna region can hardly have been sufficient for such changes, particularly as the climate has been very unfavourable. In southern Sweden, with a longer post-glacial period and better climatic conditions, there is no case known of post-glacial enrichment on any comparably scale. It must be admitted that the position of the Kiirunavaara veins, in the high ridge of the ore mountain, has favoured supergene processes, but this can hardly have offset the unfavourable influence of the other factors. Furthermore, the copper veins are not the only examples of a deep-going oxidation in the southern part of Kiirunavaara. While the more or less altered copper veins have been observed down to a depth of at least 15 meters below the surface of the ore ridge, other related phenomena reach much deeper levels. Not far north of the copper veins, the immediate foot wall rock of the iron ore body is porous, »chalky», and strongly impregnated with limonite. The iron ore along the foot wall is mainly a fine-grained specular hematite, instead of the ordinary magnetite, and contains drusy cavities lined with red, probably hydrous, oxide of iron. It has been pointed out already in another paper (11, p. 102) before any chalcographic examination had been undertaken, that this hematite ore was probably secondarily formed from magnetite (martitization). Under the reflecting microscope, the various stages of the martitization process can be studied. The oxidation generally proceeds along the octahedral cleavage planes of the magnetite (fig. 11, Pl. IV). When the alteration is nearly complete, there remain of the magnetite only small patches in the hematite mass, always bounded by lines of the octahedral pattern. This ore variety is now mined between the top of the ridge and the 60 meters level, but smaller quantities have also been encountered in the railway adit on the 220 meters level, only slightly above the level of the lower country surrounding the mountain. The iron phosphates described by Kœchlin (26, 27) were probably found in the same part of the mountain. The locality is not known, as the minerals were noticed in an ore shipment at its place of destination, but the few other discoveries of these phosphates have mainly been in this part. It seems probable that the movements of the phosphorus illustrated by these occurrences of secondary phosphates have contributed to the rather low phosphorus percentage of the hematitic ore.

All these phenomena characteristic of southern Kiirunavaara, the oxidation

and sulphidic enrichment of the copper veins, the limonitic alteration of the foot wall rock, the large-scale martitization of the magnetite, and the development of secondary iron phosphates, must be regarded as the results of a deep-going oxidation in pre-glacial times.

As to the veins in the northern part of the mountain, there are no direct proofs of any secondary changes. The different textural appearance and etch cleavage of the chalcocite in the southern veins and in the vein of Geologen forbid us to extend to the latter the conclusions reached with regard to the former.

### The Nautanen-Svappavaara group.

Under this heading may be comprised a number of copper deposits, most of them very small and without economic value, that are closely related to each other genetically, and are scattered over a wide portion of northern Lapland, chiefly east of the iron ores of the Kiruna-Gellivare group. The longer axis of the metallogenetic province in question appears to run in a direction a little west of north from Snipberget in the Råneå parish<sup>1</sup> to Svappavaara, a distance of about 150 km. The maximum width, between Risbäck (on the Gellivare—Kiruna railway line) in the west and Maunuvaara (Pajala) in the east, is 78 km. Copper minerals with the same mode of occurrence have been noted also in several places outside of this tract, but only in quite insignificant amounts.

Copper mining at Svappavaara was started in 1644 and carried on intermittently during the seventeenth and eighteenth centuries, but the total copper production reached only about 45 metr. tons. Nautanen, east of Gellivare, was not discovered until 1898. Mining operations were soon begun there, as well as on neighbouring deposits, but were given up in 1908. The copper production in the district appears to have been only some few hundred tons. In 1916, a geological study of this district was undertaken by the writer (13). Referring to this work for details, the general geological characters may be summarized as follows.

The main rock units of the province in question are the leptite formation and the granite. The former is a series of crystalline schists, mainly leptites and amphibolites, with some mica schist and quartzite. Evidently it is a surface formation in a highly metamorphic habit. The granite, represented by a number of large intrusions, is accompanied by great numbers of pegmatite dikes. Those farthest away from the granite are rich in tourmaline. With one exception, the ore deposits lie in rocks belonging to the leptite formation, generally at a distance of several km from any exposed granite. Even pegmatite dikes are rare within the ore-bearing areas. A broader consideration of the geological relations, however,

<sup>1</sup> Snipberget has not been visited by the writer. Specimens in the Survey collections (F. Svenonius) show desmine veins with bornite, a paragenesis that leaves little doubt as to the connection with the Nautanen-Svappavaara group.

has led to the conclusion that the deposition of the ores must have been one phase of the action exercised by the granite on the intruded formation.

The ore deposits are of many different types, which grade into one another. In highly scapolitized leptite with some tourmaline one encounters disseminated chalcopyrite and magnetite. There are also lean replacement zones with the same ore minerals, accompanied by garnet and tourmaline; more compact replacement bodies of quartz, magnetite, chalcopyrite, pyrite and tourmaline; tourmaline-bearing quartz veins with chalcopyrite, and accompanied by an intense tourmalinization of the wall rock; scapolitic veins with chalcopyrite, bornite, magnetite; quartz veins with bornite (sometimes together with chalcopyrite), or with chalcocite, magnetite, hematite, zeolites and free gold; veins or impregnations of chalcopyrite, pyrite, magnetite, hornblende, and apatite.

We shall here confine our attention to those deposits that contain bornite or chalcocite, and select for description the following representative types:

- 1) Scapolitic veins with bornite and chalcopyrite, Nietsajoki (Ferrum) near Nautanen.
- 2) Vein with bornite, Risbäck.
- 3) Quartz veins with bornite and chalcopyrite, Svappavaara.
- 4) Veins with bornite and molybdenite, Vähävaara.
- 5) Replacement vein system of bornite and chalcocite, Liikavaara.
- 6) Quartz and zeolite veins with chalcocite and gold, Fridhem.

The bornite veins of *Nietsajoki*<sup>1</sup> are small patches in a leptite almost completely altered to an aggregate of scapolite, tourmaline and hornblende. The width appears generally not to surpass 2 or 3 cm. They consist of bornite with scattered lumps of chalcopyrite, and also sometimes of a little feldspar, scapolite and calcite, surrounding the sulphides. The textural relations point to replacement of the chalcopyrite by the bornite. The chalcographic examination gives the same impression. It also shows, however, that the bornite is not homogeneous but contains a great quantity of very fine lamellæ of chalcopyrite, in octahedral grouping. The size is of the same order of magnitude as in the Latteväre bornite. In one section, the inclusions appear more like elongated drops than tabular bodies. The bornite areas are bordered by a narrow fringe of chalcocite, and are crossed by a few veinlets of the same mineral.

To judge from the associated minerals, the sulphides were formed at high temperatures through reactions in which volatile compounds took part, the bornite being somewhat later than the compact chalcopyrite and formed by replacing it. Only the chalcocite is ascribed to supergene processes.

The occurrence of copper minerals near *Risbäck* is mainly in the form of a weak impregnation of chalcopyrite in scapolitized leptite. Among

<sup>1</sup> Most of the copper in this mine, or rather prospect, is in the form of chalcopyrite in quartz-tourmaline veins.

drift boulders there has been found, besides boulders of this type, also one containing a narrow vein of bornite with a little quartz. This bornite proved to be interesting from a mineralogical point of view. A freshly broken surface shows the normal colour of bornite, and then takes on the ordinary bluish tarnish. The chalcographic examination reveals its composite character. At a magnification of 100, there appear scattered chalcopyrite lamellæ, with covellite borders, arranged in three directions, probably octahedrally. The main mass of the bornite appears homogeneous, but has an orange yellow colour. Only in some parts of a section there can be distinguished chalcopyrite lamellæ of a finer size. When examined with an immersion objective, however, the whole mass is found to be full of chalcopyrite lamellæ, with covellite borders, octahedrally arranged (fig. 12, Pl. IV). It must be left an open question whether the bornite of the interstices is really homogeneous, or whether this apparent homogeneity is only due to the limited power of the microscope. The specimens also show secondary veins of malachite and limonite, with a little chalcocite and more covellite. This covellite is not connected with the linings on the chalcopyrite strips, but is sometimes seen to cross them as a distinctly later formation.

The Risbäck bornite is the only occurrence encountered in this investigation that permitted the isolation of pure material for analysis of a bornite known to be extremely rich in lamellæ of the segregation type. The analysis was carried out in the laboratory of the Geological Survey, by Dr. A. Bygdén. The result obtained was the following.

*Bornite, Risbäck, Gellivare.*

	I	II	III	Average	Calculated on material dried in exsiccator
Cu . . . . .	56.60	56.59	—	56.60	56.64
Fe . . . . .	13.11	13.15	—	13.13	13.14
S . . . . .	—	—	30.02	30.02	30.05
Gangue (insoluble in aq. reg.) . . . . .	—	0.10 <sup>†</sup>	—	0.10	0.10
H <sub>2</sub> O (in exsiccator) . . . . .	—	—	0.08	0.08	
				99.93	99.93

The conclusions that can be drawn from this analytical result are given in a later section of this report.

The *Svappavaara* copper mines are immediately adjacent to the large iron ore deposit of the same name (38). The copper deposits are quite evidently related to those of the Nautanen district, while the iron ore appears to belong to the Kiruna-Gellivare group. Therefore one has no reason to suspect so close a relation between iron and copper ore as was suggested above in the case of Kiirunavaara, and it is more probable that

<sup>†</sup> 0.09 p. c. are SiO<sub>2</sub>.

the iron ore is older and has, by chemical influence, contributed to the deposition of the copper minerals in the adjacent leptitic rocks.

Part of the ore is chalcopyrite in scapolitized leptite,<sup>1</sup> but the richest ore consisted of narrow bornite-chalcopyrite veins with a gangue of quartz. Free gold has once been found in one of these veins, and also in a similar vein at Nautanen. The bornite of the veins contains lumps of chalcopyrite, in the same way as has been described above from Nietsajoki. Also in this case, the chalcographic examination shows that the bornite contains chalcopyrite in a lamellar intergrowth, but the quantity is less than in the Nietsajoki bornite. The relations between the bornite and the larger particles of chalcopyrite are also analogous to those in the same veins, but the Svappavaara specimens show more clearly how the latter is replaced by bornite. There are secondary veinlets of chalcocite and covellite combined. Seams of malachite and limonite sometimes follow their centres.

From the general geological relations it seems probable that the bornite of the veins is formed at moderately high temperatures. The relations to the chalcopyrite indicate that the bornite belonged to a later stage of the original (hypogene) mineralization. The chalcocite and covellite are clearly secondary, as are, of course, also the malachite and the limonite. A bluish-black coating, probably consisting of covellite and chalcocite, is often seen also on the chalcopyrite.

*Vähävaara* is one of the most interesting mineral prospects that belong to the Nautanen-Svappavaara group. The following description is based upon a brief visit by the writer and Dr. B. Högbom, in august, 1922, and upon material collected at this opportunity.

*Vähävaara* is a low hill situated 40 km south-east of Gellivare. The surrounding country is covered by a thick and continuous mantle of glacial drift (moraine), partly also by extensive peat bogs, and exposures are few, and generally restricted to the summit portions of the hills that rise to heights of 100—200 meters above the average level of the surrounding more level country. To judge from these exposures and from the drift boulders, the bed-rock is leptite, cut by very numerous and sometimes large dikes of pegmatite (mostly tourmaline-bearing), and also intruded by granite bodies that are outliers of the greater masses in the north. On Suoravaara, 3 km NNE of *Vähävaara*, there are outcrops of pegmatite dikes with big tourmaline prisms which reach up to 7 cm in cross-section.

The prospect that takes its name from *Vähävaara* is situated in the top of a lower hill 1 km east of *Vähävaara*. Just on the top there is a group of outcrops of pegmatite, with small areas of leptite between them. The ore minerals — molybdenite and bornite — occur in the pegmatite and (mainly) in a vein that follows in a general way the contact with leptite.

<sup>1</sup> There is also desmine, some tourmaline, magnetite and molybdenite. In one specimen of this type (R. M.) in the collections of the old Mining Department (Bergscollegium) there is a badly developed crystal, 1 cm in size, of a cobalt mineral, probably cobaltite. The label gives the locality as "Abrams Skierpning" at Svappavaara. Cobaltite is also reported from a vein in the Nautanen district (R. M., specimen collected by G. Löfstrand).

To judge from the drift boulders, there is an area of granite in the immediate neighbourhood. This granite belongs to the same group as the other granite bodies in the metallogenetic province of the Nautanen-Svappaavaara group (»Lina granites»), but differs from the ordinary type by containing amphibole instead of biotite. It has an intermediate potash-soda proportion, and consists of perthitic microcline, albite, quartz, and moderate quantities of amphibole, titanite and magnetite. The amphibole is black, and in thin sections shows a very deep colour. The absorption scheme is:  $a$  light yellowish brown;  $b$  very dark bluish green;  $c$  bluish green; the relative absorption is unusual, with  $b > c > a$ ; the  $b$  absorption being extremely strong, so that the mineral appears almost opaque even in a thin section less than 0.03 mm in thickness. Our possibilities to judge the composition of an amphibole from its optical properties are very limited. In the present case, it can only be concluded that there must be a high content of iron. The rock also contains a little zircon, and small grains resembling orthite. The composition of the plagioclase, which is pure albite (symmetrical extinction  $-18^\circ$ ), and the character of the amphibole give to this granite a more "alkaline" character than is usual in the Lina granites, the plagioclase of which normally does not surpass 88 per cent. Ab.

The pegmatite of the outcrops is of the same type as generally in this region, consisting of white feldspar, light gray quartz, black tourmaline, some muscovite, and in places small red garnets. The feldspar has been identified as albite, but there may also be microcline present. The tourmaline content is lower than in the Suoravaara dikes. As usual in this region, the tourmaline occurs mainly in the quartz. Graphic intergrowths of these two minerals are not uncommon. The texture of the pegmatite varies from pegmatitic to aplitic, often in a pronounced banding. In the pegmatitic phases, graphic intergrowths appear, but it also happens that the feldspar forms idiomorphic crystals several dm in length, enclosed in the quartz.

The leptite is dark gray and consists of plagioclase and biotite, a common type in the south-eastern border of the great ore-bearing region of northern Lapland. There is no well-marked parallel texture. The signs of strike and dip in fig. 1 refer to a coarse and irregular jointing that appears to be roughly parallel to the weakly developed schistosity, where such a one can be clearly discerned.

In the prospecting trench no. 3 (fig. 1) there is pegmatite, but leptite may be present along the north-western side. In the pegmatite are some segregations, 1 or 2 dm in length, of the ordinary gray quartz, with apatite in the form of thick green prisms, mostly 1 or 2 cm long.

In fine-grained and drusy patches in the pegmatite, much molybdenite and some malachite is seen. Within the pegmatite there is also a vein, up to 6 dm wide, of quartz with moderate quantities of molybdenite and bornite and finely crystalline magnetite as streaks up to 1 dm in length. The vein, where exposed, runs entirely within the pegmatite, but loose

pieces indicate that towards SW it soon follows the contact with the leptite. There is in this part a border zone, sharply defined against the leptite, less so against the vein quartz, and generally 5 cm wide, of feldspar, muscovite and some biotite, as elongated individuals perpendicular to the contact, and carrying the three ore mineral: molybdenite, bornite, magnetite. There are some patches of a similar character also in the pegmatite mass.

In trench no. 5, the vein is again exposed. At first it is similar to the part exposed in no. 3, but further to the SW the quartz part disappears. The vein follows the contact, and finally turns a little into the leptite (this may be only a branch, however). In part, the vein matter is a somewhat drusy mass of white feldspar, partly in fine-grained aggregates, some quartz, green apatite grains up to 3 or 4 cm in lengths, micas, and the three ore minerals. The whole character is then that of the fine-grained and drusy patches in the pegmatite. A microscopical examination shows that the feldspar is albite.

The vein in leptite is only 5 cm wide, and is identical with the border zone of the quartz vein as described above: the chief constituent is feldspar, in a columnar mass arranged at right angles to the vein plane, further there are large plates of muscovite and smaller ones of biotite, with the same orientation of apatite, molybdenite, bornite, and magnetite. Thin sections show that the feldspar is a calcic plagioclase. It is often zonally built, with frequent repetitions. The variations appear to fall within the range of labradorite, but even homogeneous grains may be so

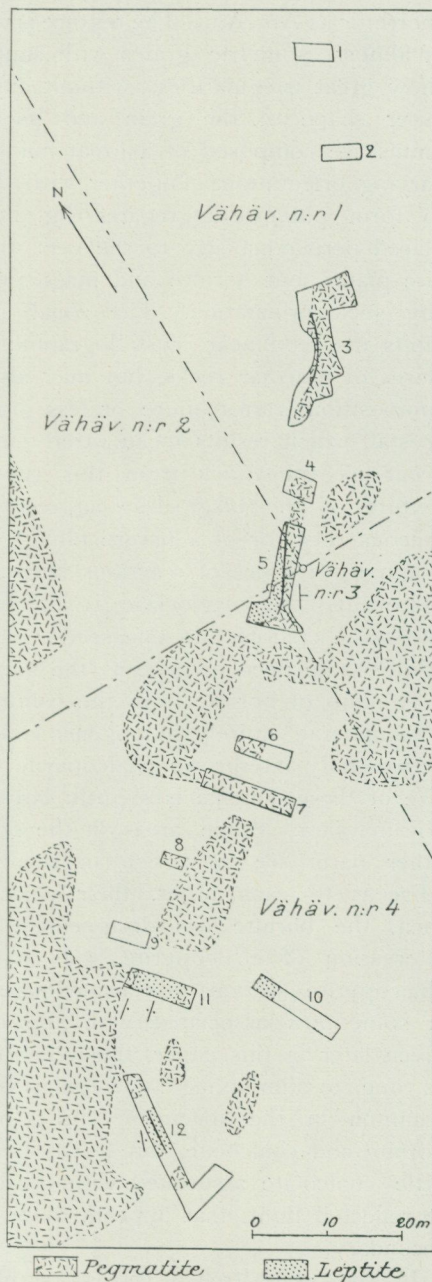


Fig. 1. Sketch map, 1 : 1000, of molybdenite prospect at Vähävaara.

2—240327. S. G. U. Ser. C, nr 321. Geijer.

anorthitic as  $Ab_{45}An_{55}$ . The texture is very peculiar: partly there are aggregates of almost isometric grains with simple outlines, but the "columnar" parts show great irregularities, without any distinct correspondence between the outer shape of the grain and its crystallographic orientation. Most columns are composed of a great number of plagioclase grains with somewhat varying orientation. Together with the micas, these plagioclase grains tend to form plumose aggregates (fig. 13, Pl. V). The apatite grains are also placed perpendicularly to the vein walls, in some degree also the molybdenite plates, but bornite and magnetite, as isometric minerals, do not show any such orientation. The zonal structure of the plagioclase mostly exhibits the rectilinear crystallographic contours common in the zonal plagioclases of igneous rocks, but may also be more irregular. Very often, the composition varies more or less gradually, from spot to spot, within one crystal, which results in an utterly irregular variation in extinction. There occur all transitions from this type to the regular zonal structure. The texture of the plagioclase aggregates does not correspond to that of an igneous rock, or of a fissure filling. Instead, the whole aspect suggest an origin by a series of reactions between solutions and solid crystals.

Locally the plagioclase is altered to scaly aggregates of a light mica, and some epidote. In one section, a little amphibole was observed. It is of the same peculiar type as the amphibole of the granite.

A lump of bornite from the columnar vein was studied chalcographically. The mineral, entirely homogeneous to the naked eye, was found to contain octahedrally intergrown chalcopyrite lamellæ with chalcocite borders. The size of these lamellæ is slightly larger than in the similar intergrowth from Kiirunavaara. Some areas in the bornite are free from such lamellæ, but other parts are very rich in them. The lamellæ often lie immediately adjacent to each other, their chalcocite borders uniting. In these parts, then, the bornite has disappeared, and its place is taken by a striped alternation of chalcopyrite and chalcocite. The lenticular form of the chalcopyrite sections is conspicuous in these aggregates. A little covellite is sometimes associated with the chalcocite. For reasons that will be given later in this paper, the writer is inclined to regard these phenomena as due to "unmixing". Irregular veins of covellite, of ordinary type, are common in the specimen. As is mostly the case, the covellite replaces bornite and chalcocite, but leaves the chalcopyrite intact. There is also a little chalcocite associated with the covellite, and a mineral, grayish white in reflected light, that appears to be melaconite. These veinlets are clearly secondary.

In the same trench (no. 5) a little molybdenite was observed in the normal pegmatite. This is the case also in no. 8. In no. 12 there is a drusy vein in the leptite, containing molybdenite, bornite and apatite, and similar to the pegmatitic part of the vein in no. 5. In this case, part of the vein, which is about 1 dm wide, is a normal although fine-grained pegmatite or aplite, with bornite and apatite.

The leptite in trench no. 10 contains impregnations, in the form of stripes or veinlets, of dark amphibole and biotite, with some bornite and molybdenite. The microscope also shows quartz and a little tourmaline. The amphibole belongs to the type that from its colour in thin sections is often characterized briefly as bluish green hornblende. It is not at all so strongly coloured as the previously described variety. A chalcographic study of the opaque minerals showed that there are two varieties of bornite in this occurrence. One, the most common form, is entirely normal. The other, occurring as independent areas, is orange yellow with a fairly uniform colour up to about a magnification of 100, but with higher systems discloses an intergrowth similar to that of the Lattevaara bornite. There is a striking difference in the effects of supergene processes on the two different forms. The normal bornite is largely replaced by covellite, growing out from the surrounding gangue grains or from fissures as rows of inward-pointing blades (fig. 14, Pl. V). The chalcopyritic bornite, on the other hand, is being replaced by a more irregular and fine-grained aggregate, in which there is some covellite, but mainly hydrous iron oxides and some malachite.

It is evident that the Vähävaara veins are high-temperature deposits, very closely connected with the pegmatite. They are, in fact, partly nothing but phases of pegmatitic offshoots. The intimate relation is further illustrated by the occurrence of the characteristic vein minerals, molybdenite, bornite and green apatite, in segregations in the larger pegmatite dikes. A small but significant detail as the local appearance in the main vein of the characteristic amphibole of the granite. The main vein, and that exposed in trench no. 12, are certainly to be designated as pneumatitic. The small veinlets in no. 11, on the other hand, may have been formed, wholly or in part, through a pneumatolytic alteration of the leptite.

The differentiation of the vein-forming substances from the pegmatite magma presents several points of interest. Thus it is surprising to find no tourmaline, except a very small quantity in the veins of trench no. 11, which otherwise in their mineral composition are most remote from the pegmatite. Most peculiar, however, is the calcic character of the plagioclase in the "columnar" vein in trench no. 5. The granite and the pegmatite contain albite, and this feldspar is also found in the other textural form of the ore-bearing vein. The occurrence of labradorite in this relation is contrary to all our experience of magmatic differentiation, according to which the late-magmatic and particularly the pneumatitic fractions are lower in anorthite than their parent magma, and seldom, particularly in the case of granite derivatives, contain any other plagioclase feldspar than albite. It seems almost certain, however, that the Vähävaara vein is only apparently an exception, the explanation being that the labradorite is not a primary product, but formed from *scapolite*. The occurrence of a calcic scapolite in a vein connected with granite is quite normal, as illustrated by the Laurinkari scapolite (6). Already the megascopical appearance of

the columnar vein suggests scapolite. The peculiar microscopical characters described at some length above are easily explained in this way, but hardly in any other. Feldspar forming from scapolite as the result of a pneumatolytical or hydrothermal "after-action" has been described from various places (8, 18). In some places micropertthite has been found, but more common is albite with or without contemporaneous epidote. The forming of albite and epidote is simple and easily explained. The transformation of scapolite to labradorite is somewhat more complicated,<sup>1</sup> but still less so than the alteration to micropertthite. The forming of labradorite, instead of a separation into albite and epidote, must depend upon local conditions. It is probable that a temperature not far below that of pegmatite crystallization was a necessary requirement.

The connection thus proved between granite, pegmatite and mineralization at Vähävaara means a decisive confirmation of the writer's views on the source of the copper deposits of the Nautanen-Svappavaara group (13). It may be noted that magnetite is very often associated with the copper sulphides, molybdenite likewise (Svappavaara, Särkivaara) and apatite occurs abundantly in some deposits at Nautanen. Quartz veins with bornite and a little molybdenite, at Sakakoski, between Vähävaara and Gellivare, are perhaps the best analogies to the main vein of Vähävaara.

The effect of supergene processes is illustrated by the covellite that replaces the Vähävaara bornite, and by the associated oxidic minerals. This alteration may be of pre-glacial age, but there are no cogent reasons for such a view, it can also be post-glacial. It is to be noted that the specimens studied were taken from the uppermost 1 or 2 dm of the outcrops.

The main deposit of *Liikavaara* near Nautanen, called Nya Fyndet ("the new discovery"), was about 40 m in length and up to 4 m in width. It is one of the very few deposits of bornite-chalcocite ores in Sweden that could be worked with a profit. The total production was small, however, amounting to less than 3000 metr. tons<sup>2</sup> of hand-sorted ore, presumably of a high average grade. In depth, the workable ore ended very soon, probably in about 30 meters, or even less. The ore body follows the strike and vertical dip of the enclosing leptite, and can be described as a system of replacement veinlets and patches in this rock. Streaks consisting of small garnets, some biotite and calcite are common in the ore body. Of ore minerals, only bornite is visible to the naked eye, forming the veinlets just mentioned, which seldom surpass one or a few cm in width, and partly concentrated in larger masses. Quartz is often seen with the bornite, apparently replacing the leptite between the ore streaks. A thin section of typical ore also shows tourmaline, some

<sup>1</sup> The rare epidote in the Vähävaara vein is an alteration product of the labradorite, and does not belong to the process now considered.

<sup>2</sup> The total production of Liikavaara is given as 2859 metr. tons. Of this quantity, up to a few hundred tons may have come from the smaller prospects.

epidote and a considerable quantity of apatite in small grains. As already stated, tourmaline and apatite are characteristic of many deposits of the Nautanen-Svappavaara group.

The chalcographic examination reveals much chalcocite with the bornite. In fact, the two minerals are present in about equal amounts. There is also much magnetite in an intimate association with the copper minerals. This magnetite is largely altered to specular hematite (martite).

The veins and patches of ore minerals are often bounded by concave outlines that suggest deposition after that of the replacements quartz. The magnetite is mostly found along the edges of the areas of the copper minerals, and turns idiomorphic (euhedral) faces towards the latter (fig. 15, Pl. VI). The alteration to hematite starts from the margins and proceeds inward, preferably following the octahedral cleavage planes of the magnetite (fig. 16, Pl. VI).

The bornite is generally homogeneous, although chalcopyrite intergrowths are sometimes noticed. In some cases, different colour varieties of bornite are seen together, some varieties having a more pronounced orange tinge than ordinary bornite. The chalcocite is white or light bluish. In general, the boundaries between the two varieties within one grain are quite straight, and one often sees an alternation of parallel bands recalling the twinning of plagioclase. Etching with KCN brings out exactly the same types of cleavage as in the chalcocite from Geologen, Kiirunavaara (compare above, p. 10), that is, partly the triangular pattern supposed to mean isometric ( $\alpha$ ) chalcocite, and partly the closely spaced basal cleavage of the orthorhombic form ( $\beta$ ). It has not been possible to state definitely that the areas showing the former type are optically isotropic.

There are areas of bornite and of chalcocite, with simple, slightly curving boundaries, and to some extent also narrow veins of chalcocite in bornite, but considerable portions of the sulphide mass are made up of the most beautiful "graphic" intergrowths of the two minerals. These intergrowths are about as complicated as any of the same kind that have been described from other localities, but contain no new textural features. With immersion, small lamellæ of chalcopyrite may sometimes be seen in the bornite, particularly bridging portions where the bordering chalcocite areas come close to each other. It is a striking fact that the chalcocite of the intergrowth is mostly — but not always — of the white variety. It is not unusual to find that the blue component of a composite grain stops as soon as the mass changes from compact chalcocite to a graphic intergrowth with bornite. There are also conspicuous exceptions to this rule, however, and it may be noted that Laney (29, p. 77) found the opposite rule in the Virgilina copper veins. Secondary (supergene) covellite appears in a small quantity in the Liikavaara ore.

The bornite-chalcocite deposit of Liikavaara can be interpreted only as a replacement deposit in the leptite, formed at moderate or high temperatures.

*Fridhem.* This locality, a few km distant from Nautanen, Liikavaara and Nietsajoki, is a gold prospect, but no regular production has taken place. The country rock is leptite. The ore minerals occur in a system of quartz veins, one of which is reported to reach a width of 2 meters, including bands of country rock. Probably it is a vein zone rather than one vein. Most of the veins do not reach more than one dm or less in width. The walls are sharply defined. The immediate wall rock, to a distance of one cm or so, and thin slabs of leptite enclosed in the vein filling, are often very strongly tourmalinized. With the tourmaline is also much scapolite, magnetite and biotite. Most of the veins consist mainly of quartz, but in some of them there is also much calcite and zeolites (desmine and chabazite). The other vein minerals are chalcocite, a little bornite, specular hematite, magnetite, biotite, some actinolite, and free gold. Tourmaline needles are seen to project from the wall into the vein filling, but are never found wholly within the latter. The gold occurs in several associations, but the best specimens are of veins with comparatively little quartz but much zeolites, calcite, and ore minerals. In one case it forms plates between thinly tabular crystals of specular hematite. Mr. L. Björkqvist, the discoverer and owner of the deposit, mentions that when panning crushed vein filling he found a heavy white mineral, possibly scheelite.

The veins are drusy, with radial aggregates of desmine, about one cm in diameter or less. Special search was made for chalcocite crystals in the cavities, but none were found. A remarkable textural feature, observed in several cases, is the idiomorphy of radial aggregates of desmine against chalcocite.

The chalcographic examination shows that there are more analogies to the Liikavaara ore than could be expected. The magnetite is partly changed to hematite, but this alteration has proceeded quite irregularly. Also primary specular hematite, recognized as such from its crystal forms, is associated with the magnetite. The copper sulphides generally fill the interstices between the iron minerals. The bornite, which is entirely subordinated in amount, is replaced by the chalcocite. The bornite areas have a bluish border which clearly belongs to them and not to the surrounding chalcocite. There are also narrow and indistinct bands of the same bluish bornite enclosed in the chalcocite, probably representing the final stages in the replacement process. Etching of the chalcocite brings out a cleavage pattern similar to that of the Liikavaara chalcocite, but much more closely spaced and with some irregularities.

The paragenesis of these veins suggests deposition within a rather wide range of temperature. The alteration of the wall rock to tourmaline and scapolite, and the forming of crystals of magnetite and of specular hematite belong to processes that are supposed to take place at rather elevated temperatures, while the zeolites, and consequently also the chalcocite, must be much lower down on the scale. Exact data on the temperature range of the zeolites in question are wanting, but a conside-

ration of their known paragenetical relations in other localities points to deposition probably somewhere between 100° and 200° in this case. As the chalcocite, in part at least, is later than the desmine, but is never found to surround the chabazite in a similar way, the textural relations may be interpreted as showing how the deposition of the copper sulphide continued after that of the desmine had ended, but probably stopped before the crystals of chabazite were formed. It is probable that the temperature, for the chalcocite, was nearer to 100° than to 200°. The relations between chalcocite and zeolites also give a superfluous but conclusive proof that also the former was deposited from aqueous solutions.

*Origin of the bornite and chalcocite of the Nautanen-Svappavaara group.* The broader relations of these copper deposits have been treated in the writer's previous report on the Nautanen district. Only the special problems connected with the occurrence of bornite or chalcocite are further considered here. In connection with the above descriptions, some of the conclusions that suggest themselves have already been pointed out, but some general remarks may be added.

Supergene changes appear to have been of very little consequence in these deposits. Veinlets of covellite, observed in several cases, are certainly due to such changes. It is uncertain whether they are of pre-glacial or post-glacial age, but their rather wide-spread occurrence, in association with some oxidic minerals, favours the latter alternative. The same explanation must apply to the chalcocite that is associated with the covellite, as at Svappavaara, and probably also to the veinlets and borders in the Nietsajoki bornite.

The bornite appears to be a primary (hypogene) mineral in all the cases considered. Its paragenetical relations are significant: it is absent from the quartz-tourmaline veins with chalcopyrite, but is much more common than this sulphide in the quartz veins without tourmaline. While the chalcopyrite is always plainly earlier than desmine in those veins where they are associated,<sup>1</sup> bornite is sometimes contemporaneous with the zeolites (Snipberget) or, like the Fridhem chalcocite, distinctly later (one observation at Nautanen). Also when bornite replaces chalcopyrite, as at Nietsajoki and Svappavaara, there is nothing indicating that this replacement is due to superficial (supergene) processes.

The chalcocite presents a more difficult problem, supergene chalcocite being recorded from several localities, as stated above. However, the absence of any noticeable chalcocitization in pyrite and chalcopyrite ore, and the very weak influence on bornite in such cases as Svappavaara, Nietsajoki and Vähävaara, give us reasons to believe that occurrences so entirely different from them as Liikavaara and Fridhem are of a hypogene ("primary") origin. One arrives at the same result when considering the paragenesis, in the way just applied to the bornite. Taking into account

<sup>1</sup> Desmine sometimes occurs in druses in the quartz-tourmaline veins with chalcopyrite.

the various forms of deposits, there stands out among the copper sulphides a sequence: chalcopyrite, bornite, chalcocite. This is largely a function of temperature, with chalcopyrite as the characteristic mineral in those deposits that were probably formed at the highest temperature, bornite for the intermediate range, and chalcocite for the lowest, but there can be exceptions due to other causes, as illustrated by the Vähävaara bornite. The absence of the combination chalcopyrite-chalcocite is characteristic of hypogene mineralization, bornite forming instead. The results of this chalcographic study confirm the views about the generally hypogene origin of the bornite and chalcocite of the Nautanen district that the writer had previously arrived at from less complete observational evidence (13, p. 100).

A remarkable feature in the Nautanen-Svappavaara group is the appearance of magnetite throughout almost the entire temperature range of the copper minerals. It is associated with chalcopyrite in many of the deposits at Nautanen, always as the older mineral. The occurrences with bornite and chalcocite have been described here. Veins of finely crystalline calcite and magnetite are known from Nautanen and Sorvanen. The oxidation of magnetite to martite, and the deposition of primary hematite appear to be connected with the occurrence of chalcocite. We shall return to this association in a later section. It is not comparable to the co-existence of martite and supergene chalcocite in southern Kiirunavaara.

### Sjangeli.

The copper deposits of Sjangeli, close by the Norwegian boundary line SW of Torne Träsk, probably represent the largest concentration of copper as bornite and chalcocite that has been encountered in Sweden. They have never been regularly worked, however, due partly to their position in a remote mountain region and partly to their mode of occurrence and grade. The district has not been visited by the writer. It appears to present certain special problems not met with in the other deposits treated here, and it is impossible for anybody not familiar with its field geology to form any more definite idea of its geological relations. When, nevertheless, Sjangeli has been included in this report, it is because a paper on the Archæan occurrences of bornite and chalcocite of our country would be too incomplete without at least a brief reference to this field.

The geology of the country around Sjangeli has been described by W. Petersson (37). The ore deposits belong to an Archæan<sup>1</sup> area exposed within the Cambro-Silurian region of the Scandinavian mountain chain. The Archæan rocks are mica schists, amphibolite and diorite, dolomite, anthophyllitic schists with serpentine, gneiss and granite. The ore deposits are always connected with the amphibolite ("Sjangeli schists"), and are widely

<sup>1</sup> The formation is very distinctly pre-Cambrian, and shows no features that suggest a late pre-Cambrian age, therefore it may be classed as Archæan.

distributed in the zones occupied by this rock. Petersson describes the copper ores as follows. They consist mainly of bornite and chalcocite, often intimately mixed with magnetite, as layer-like deposits, on a whole following the strike and dip of the containing rock. Bornite occurs also as veins, while bornite and chalcocite very often form small lenses and disseminated deposits in the amphibolite. Chalcopyrite occurs only in subordinated quantity.

Under the microscope, much tourmaline was found in one thin section, but this appears to be exceptional, the minerals associated with the ores generally being amphibole, biotite, epidote, plagioclase, and quartz, more or less intimately belonging to the normal character of the amphibolite. A chalcographic study of some specimens in the Geological Survey collections has been undertaken by the writer. Specimens of copper ore with magnetite show a fine-grained mass of gangue silicates (mostly amphibole), magnetite, specular hematite, bornite and chalcocite. The magnetite is largely martitized, and is accompanied by a great quantity of primary specular hematite. The iron minerals are sharply idiomorphic against the copper sulphides, and the amphibole is less pronouncedly so. The magnetite often shows crystal faces against the primary hematite. The textural relations of bornite and chalcocite are characterized by simple outlines and in general "mutual" contours, but simple intergrowths of a graphic character are also observed. A specimen of massive bornite showed martite inclusions and small veinlets and streaks of covellite with a little chalcocite, probably of supergene origin. In another bornite specimen, a most peculiar phenomenon was encountered. The bornite forms areas hemmed in by amphibole stalks. Associated with it there is a quite subordinated quantity of covellite, occurring in somewhat the same way as with the Kiirunavaara chalcocite (p. 9, and fig. 9, Pl. III), that is, as interlocking covellite individuals — generally two in each case — in grains with the cleavage and habit of chalcocite. The appearance is one that might be expected if covellite replaced chalcocite grains — partly in the Kiirunavaara specimen, completely in that from Sjängeli. The covellite also occurs in beautiful graphic intergrowths with the bornite, of entirely the same pattern as the common bornite-chalcocite intergrowths. Also in this case the covellite component is generally built up of two individuals, interlocking stripewise.

For reasons already given, it is impossible to try any explanation of the phenomena just related. It may be pointed out, however, that the copper ore rich in iron minerals bears important resemblances to the Nya Fyndet ore of Liikavaara. Yet, when considering the Sjängeli ores we probably ought to reckon with the possibility of more secondary processes, supergene or otherwise, than in the case of the majority of the deposits treated in this investigation.

### Occurrences in Central Sweden.

For the present purpose, the occurrences of copper minerals in Central Sweden may be placed into three groups. One group comprises those cases where the copper minerals form part of larger replacement deposits of purely or at least dominantly sulphidic ores. In this group, bornite and chalcocite are rare, and the quantity of copper occurring in these forms is entirely insignificant in comparison to the amount that is contained in chalcopyrite. To a second group may be referred the cases where copper minerals appear in the replacement magnetite ores, generally, when present at all, as rather wide-spread but quantitatively little important constituents. In these cases also, chalcopyrite is the most common copper mineral, but appears in much smaller quantities than pyrite. Bornite and chalcocite are extremely rare. The third group comprises local deposits of copper minerals in the stratified, generally quartz-banded iron ores commonly supposed to be of sedimentary origin. In this group, the proportions are quite different. Bornite is there found quite as frequently as chalcopyrite, and may perhaps surpass the latter in quantity. Chalcocite is also observed in a number of cases, but is less common than bornite.

### Occurrences in the sulphide deposits.

The typical sulphide deposits of the Archaean of Central Sweden may be briefly characterized as replacement deposits formed at high temperatures. When occurring in limestone and dolomite, they mostly exhibit all the characteristics of contact deposits in mineral composition and texture ("skarn ores"). When in quartz-feldspar rocks, as leptite, they are accompanied by an alteration resulting mainly in quartzitic rocks with silicates of Al, Mg and Fe, as cordierite, andalusite, anthophyllite, almandite garnet, etc. There are compact ore bodies as well as lean impregnations.<sup>1</sup>

*Falun.* In the famous copper mine of Falun, credited with a production of about 500,000 metr. tons of copper, chalcopyrite (partly disseminated in pyrite) is the only copper sulphide recorded, with the exception of a very small quantity — to judge from the description (51) a few pounds of copper at most — represented by the sub-species of tennantite known as fredricite. Cleve (9), however, gives Falun as the locality for one of those specimens of bornite, the analyses of which formed the basis for his paper on the composition of bornite. The material used has not been identified, and there are reasons to doubt the authenticity of the label. The only bornite claimed to be from Falun that the writer has seen is a small specimen in the School of Mines collections, Stockholm, labelled »Falun.

<sup>1</sup> For further data, see nos. 12 and 14 in the list of works cited in this paper. An abstract of no. 12 and other literature on the same subjects is published in *Economic Geology*, 1921, p. 279—288.

Liljenbergs gång». However, the characters of the specimen make it highly probable that in this case also there has been some mistake with the label.<sup>1</sup> In older mineralogical works, reference is sometimes made to certain ore varieties at Falun in words that have caused certain later readers to interpret them as meaning bornite and chalcocite. According to a communication from Dr. N. Zenzén who has studied this question and will publish some data on it, it is possible to prove that these interpretations are due to misunderstandings of the older mineral names. This fact is important, for it shows that also the rich copper ore of earlier mining at Falun was in the form of chalcopyrite, and it reduces almost entirely the possibility of supergene enrichment. The writer thinks it most probable, from the data available, that the veinlike »sköl» ores of hypogene origin contributed much to the richness of the ore production.

*Garpenberg.* The sulphide deposits are partly »fahlband»-like zones in a quartzitic mica schist (altered leptite) with almandite, andalusite, staurolite, and partly amphibole skarn ores. Copper values are chiefly in the former type, which is predominating, lead and zinc ore in the latter (compare also no. 12 and 55 in the literature list). From one mine, bornite and chalcocite are reported (Hisinger, 24, p. 118). Hisinger speaks of the locality as Biskopsgruvan; the label of one of his specimens (R. M.) has Lilla Biskopsgruvan. It is not quite clear, however, whether these minerals have not also been encountered in the neighbouring mine Stora Biskopsgruvan. At the time of Hisinger's visit, in the last quarter of the eighteenth century, the chalcocite ore could be found only as loose fragments on the ground around the mine. His note that rich chalcocite ore had been mined there, must imply that the quantity was of some importance, at least as copper ore production was at that time.

The material studied by the writer has been only 4 specimens (R. M. and U.). The gangue is mostly quartz and mica, and the ore forms a phase of the ore-bearing mica schist. A little calcite is associated with the sulphides. In thin sections, the mica shows pleochroism in light green to yellowish shades.

The ore minerals are bornite, chalcocite, galena, zinc blende, magnetite and hematite (specularite), and also traces of chalcopyrite. The zinc blende is dark brown, but shows yellow in thin sections, instead of the deep red colour commonly observed in the blende of the ore deposits in Central Sweden. Apparently there is but little iron in it. The specularite is in part martite (pseudomorphic after magnetite) but part of it is primary, showing the outlines of tabular hematite crystals.

The textural development of the iron minerals is mostly quite irregular, although in places both magnetite and specularite may show a tendency

<sup>1</sup> The bornite is accompanied by a drusy mass of feldspar and some quartz. There is also much malachite, a mineral not observed in such amounts anywhere underground in the mine, while the label must be interpreted as meaning that the specimen comes from the 260 meters level or thereabout.

to idiomorphic outlines. Veinlets of these minerals, of almost microscopic dimensions, are often observed in the calcite of the gangue. The iron minerals appear to be older than all the sulphides. The local occurrence of veins that cut areas of bornite is explained by the fact just mentioned that such veins occur in the calcite. Apparently, the surrounding calcite has been replaced by bornite, but the magnetite-specularite vein has been left untouched.

Among the sulphides, the oldest mineral is the zinc blende, largely appearing as grains up to a few mm in size and with fairly well developed idiomorphic outlines. A broad and regular twinning lamellation is often brought out by etching. A few specks of chalcopyrite have been noted, enclosed in quartz or in zinc blende, and in the latter case often associated with a little bornite. The galena also appears to be older than the bornite, but is plainly later than the zinc blende. The bornite appears homogeneous, but high magnifications show the same regular intergrowths of chalcopyrite lamellæ that have already been noted from so many bornite occurrences in northern Sweden. The outlines of the various sulphides are smooth and but little complicated (fig. 17, Pl. III), and the whole association strongly recalls the aggregate of the same minerals from a Siberian mine that has been figured by Graton and Murdoch (15, fig. 24; 32, Pl. I, fig. 4) as a typical primary structure. The picture is not much changed when chalcocite also appears. Its relations to the bornite are clearly those of replacement, however, the bornite forming remnants in the chalcocite mass. The outlines of these remnants are fairly simple; there are no intricate vein systems of chalcocite, and only slight tendencies to graphic intergrowths. The bornite remnants always have a fuzzy bluish border, evidently the phenomenon so often reported from replacements of bornite by chalcocite. The other ore minerals are not attacked, and the gangue shows no change.

*Mårtanberg.* This little copper mine differs in more than one way from the related deposits in Central Sweden. The country rock is a gneissic granite, with very numerous inclusions of amphibolite. The ore has mainly occurred in a quartzite with a monoclinic amphibole, the optical properties of which point to a ferromagnesian species. This quartzite, then, belongs to one of the types of metasomatically altered rocks that are the normal associates of the sulphide ores in Central Sweden. Its original character is unknown. It may represent an altered inclusion of leptite, but it may also be an altered phase of the granite itself, as the surrounding granite shows signs of partial alteration, quartz, almandite garnet and ferromagnesian amphibole forming as new minerals at the expense of the feldspar (plagioclase). Chalcopyrite and pyrite are the ore minerals of the quartzite, and the former has also been noted in the altered granite. In one of the mines (Lundins gruva), most of the ore appears to have occurred in veins of biotite, chlorite, and some hornblende («skölar»).<sup>1</sup>

<sup>1</sup> For further details about the Mårtanberg mines, compare a previous description by the writer (12, p. 211).

Bornite and chalcocite have occurred in some quantity at Mårtanberg, but it is extremely difficult to form a clear idea of their paragenetical relations, as they have to be judged from some notes in old descriptions, chief among which is the one accompanying Swab's mine map of 1783 (54), and from a limited number of specimens in old collections. One of these specimens (R. M.) appears to belong to the quartzitic ore. To the unaided eye it shows finely crystalline pyrite, and bornite, in a quartzy gangue. The chalcographic examination shows the good idiomorphic development of the pyrite crystals. Together with the bornite, almost as much zinc blende is seen. The blende contains very numerous inclusions of chalcopyrite, of the type often observed in this mineral (32, 47, 48), and interpreted by Schneiderhöhn (47, 48), as due to the unmixing of a solid solution. The relations between blende and bornite are similar to those observed in the Garpenberg ore,

although the outlines of the blende in the Mårtanberg specimen are often more irregular. When the aggregates of bornite and blende are in contact with pyrite, they form a filling between the pyrite crystals. Sometimes, however, the pyrite exhibits what is known as the »exploding bomb structure» (15), the crystal being crushed and the fragments separated a little from each other. Also in these cases the sulphides, or at least the zinc blende, occupy the interstices between the pyrite grains. There is some chalcocite with the bornite. The simple outlines of the chalcocite areas do not directly point at an origin by replacement of the bornite, but do not exclude this possibility.

The other bornite specimens (R. M. and U.) belong to the »sköl» ores. They show solid chalcopyrite, up to 5 cm in width, but sometimes the whole width of the »vein» is made up pyrite. The sulphides are surrounded by mica or chlorite, with a little hornblende.<sup>1</sup> The chalcopyrite portions are bordered by bornite, and replacement veinlets are often seen to branch off into the chalcopyrite of the centre (fig. 2). No bornite is associated with the pyrite. One specimen of the »sköl» ore (U.) shows chalcocite instead of bornite. With the reflecting microscope, bornite and pyrite are also seen. The pyrite occurs as scattered pieces in the chalcocite, apparently representing a late stage in the *replacement* of »exploding bombs». (In the case described above, where zinc blende fills the interstices in crushed pyrite aggregates, there were no signs of replacement.) The bornite forms irregular replacement remnants in the chalcocite mass, often with a tendency



Fig. 2. Copper ore in a »sköl», Mårtanberg.  $\frac{3}{4}$  nat. size. Black is bornite, dotted chalcopyrite, short lines indicate »sköl» matter (amphibole and chlorite).

<sup>1</sup> These varieties of the Mårtanberg ores appear to be closely analogous to the »sköl» ores of Falun.

to graphic development. In a few cases, small pieces of pyrite that are enclosed in bornite were found to be surrounded by halos of chalcopyrite, only vaguely defined against the surrounding bornite. These halos appear to be segregations from the bornite. It is probable that the replacement shown in the shape of the pyrite grains was affected by the bornite, and that later the chalcocite in turn replaced the bornite, without much changing the pyrite that was left from the earlier stage. Etching brings out a coarse orthorhombic cleavage in the chalcocite; no signs of a triangular pattern are observed.

Pieces of calcite veins in granite were found by the writer on the dumps. They contain chalcocite in tabular individuals, presumably badly developed orthorhombic crystals. These veins may represent either the last stages of hypogene mineral deposition, or, more probably, re-arrangements of later date, but can hardly be the products of descending acid solutions.

Else, there are at Mårtanberg particular reasons to reckon with the influence of supergene processes. Thus chrome ochre with cuprite is reported by Hisinger (24). Therefore, when first describing the replacement shown in fig. 2, the writer was inclined to regard it as a case of supergene enrichment. In view of the cases already described above, where bornite is formed from chalcopyrite by *hypogene* replacement, the view just quoted can hardly be upheld any more. A further discussion will be given in the following (p. 33).

*Kallmora at Norberg.* In the important iron mining district of Norberg, bornite and chalcocite have been observed in several places. Some of these occurrences belong to the type of local secondary deposits in iron ores, and will be considered in the next section of this paper. The other deposits are, partly at least, more independent sulphide deposits.

The Kallmorberg or Kallmora mine works a cluster of iron ore bodies of rather small size, representing a wide variation of types. There are magnetite ores in limestone and dolomite, or accompanied by an amphibole skarn (more rarely garnet), and quartz-banded specular hematite or magnetite ores. The surrounding leptites are in part altered to almandite- or gedrite-quartzites. Copper ores have been encountered on several levels. The best ore body, around the 230 meters level, is a rich chalcopyrite ore, with fluorite and quartz as the chief gangue minerals, but intimately associated with a magnetite ore in amphibole skarn (12, p. 236). Several examinations of ore faces underground and of ore stored at the mine have failed to show any other copper mineral than chalcopyrite. On another level (180 meters), however, an occurrence of bornite was studied. It appears to have no connection with the chalcopyrite ore. The bornite ore forms a vein-like strip, up to about 2 dm in width, in a quartzitic (metasomatically altered) leptite, and contains lenses of quartz and stripes of sericitic rock. Evidently it is related to the »sköl» ores. Besides the bornite, a little chalcopyrite also occurs. With the reflecting microscope there is also seen magnetite and some specularite (martite?). The bornite varies

greatly in colour. In one section, there are observed together three grains of different colours: one is a little more bluish purple than the normal colour of bornite, one is brownish orange, and one orange-coloured. In all the three of them, occasional blebs or lamellæ of chalcopyrite are seen, the latter exhibiting the usual octahedral pattern. In the polished section, the first-named variety soon takes on a typical bornite tarnish (blue), while the others remain bright.

From the same mine, G. Nordenström (34) has described a specimen of bornite that he thought proved »the isomorphism of bornite and magnetite». To judge from the specimen, which has been identified in the School of Mines collections in Stockholm, the minerals mentioned have been associated with some actinolite skarn, possibly in a vug. The supposed isomorphism is based on the fact that octahedral crystal surfaces of magnetite are found to cover cores of bornite, and sometimes appear within bornite grains. This relation between two isometric mineral is hardly surprising, although unusual. Obviously, it does not prove isomorphism in the present meaning of the term. Chalcographic examination reveals another interesting phenomenon. There are patches and streaks of chalcopyrite and another, gray mineral enclosed in the bornite. The gray mineral is not attacked by the common etching agents, and appears to be tetrahedrite or some related copper compound. Towards the chalcopyrite it shows mutual boundaries, although partly approaching graphic intergrowths. The two minerals, with the supposed tetrahedrite predominant, also form straight lines in the bornite, following at least two different directions. It is probable that they, like the magnetite, form covers on octahedral surfaces in the bornite.

The »Kallmora silver mine», at a distance of about 500 meters from the mine just mentioned, has worked a deposit of argentiferous galena. The geology has been described by Beck (4) and commented upon by the present writer (12, p. 238), who differs from Beck's opinion with regard to some of the paragenetical relations. The mine has been idle for several years. The mine maps and notes, and the study of material on the dumps and in the remnants of ore heaps give the following picture of its geology. In most of the ore, the galena, with its gangue of andradite garnet and fluorite, replaced limestone that occurred alongside of a bed of quartz-banded specular hematite ore. There is some magnetite associated with the sulphides. Fluorite, garnet, magnetite and sulphides very clearly belong to the same period of deposition, and have followed each other with inconsiderable intervals in the order named. Part of the ore has had the character of lepidite with disseminated galena.

Galena is the only sulphide of importance, but chalcopyrite, pyrite, and arsenopyrite also occur. Bornite appears to have been very rare. One piece was found by the writer. The bornite is associated with chalcopyrite, a little galena, and magnetite. It replaces the chalcopyrite, penetrating it as irregular and branching veinlets, as shown in fig. 3. Its relation to the galena are less clear.

*Läggesta*.<sup>1</sup> This little copper mine, situated in the neighbourhood of Askersund, appears to have carried bornite as its most important ore mineral. Both chalcocite and chalcopyrite are also reported (5, p. 48). Specimens (R. M.) show bornite in a gangue of skarn silicates, chiefly garnet (probably andradite) and actinolite.

In one specimen, the chalcographic examination shows bornite and chalcopyrite in »mutual» textural relations. Locally there are some chalcopyrite lamellæ in the bornite, visible only with high magnifications. Associated with the chalcopyrite occur small quantities of the same mineral that was also encountered at Kallmora and tentatively classed as tetrahedrite. An-

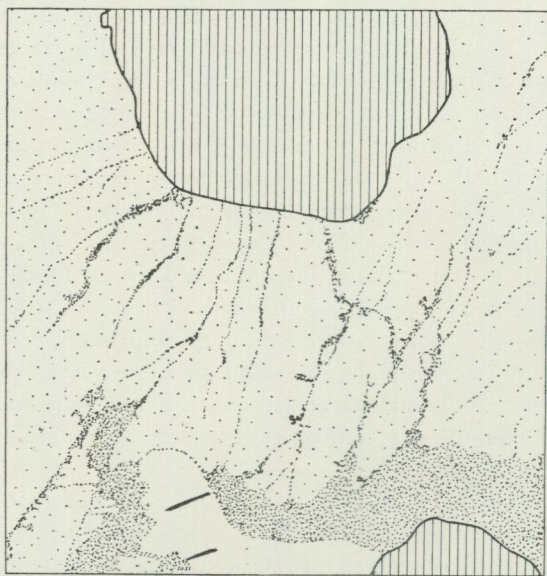


Fig. 3. Bornite, Kallmora silver mine. Drawn from a photogr. of a polished section,  $\times 55$ . Closely dotted is bornite, sparsely dotted chalcopyrite, white galena (with black cleavage grooves), hachures magnetite.

other specimen shows a plain case, easily studied already in the hand specimen, of the replacement of bornite by chalcopyrite. The alteration proceeds along a system of parallel planes, and is seen in all stages from the first beginning to the complete replacement. The proportions exclude the possibility that it is a case of unmixing.

*Tunaberg*.<sup>1</sup> At the old copper and cobalt mines, best known among mineralogists as a locality for cobaltite crystals and cubanite, bornite and chalcocite have been found, but chalcopyrite is, as usual, the chief copper mineral. The sulphides occur in limestone with or without a skarn sili-

<sup>1</sup> Not visited by the writer.

cate gangue. A. Erdmann, in his list of the Tunaberg minerals (10, p. 90—91), mentions bornite and chalcocite as occurring rarely, in the De Besche mine. Only one bornite specimen (U.), has been studied by the writer. It shows the same replacement by chalcopyrite as in the last-mentioned specimen from Läggesta. The main mass of the specimen is a coarsely crystalline marble with scattered grains of pyroxene.

*Origin of the bornite and chalcocite in the sulphide deposits.* For most of the cases described here, the hypogene origin of the bornite is evident. The bornite ore studied underground in the Kallmora mine is a local occurrence without any connection with copper minerals in the upper levels of the mine. Also the total quantity of copper higher up has been quite small, and cannot have supplied material for supergene actions at this depth, through largely massive rocks. At Läggesta and Tunaberg, the replacement of bornite by chalcopyrite is probably hypogene; in any case it excludes the possibility that the bornite should be supergene. The Garpenberg bornite forms part of an association that is typically hypogene. The association with zinc blende and galena illustrates the fact, encountered also in the Nautanen-Svappavaara group, that the bornite belongs to a lower stage of temperature than the chalcopyrite. Further examples are the combination with zinc blende at Mårtanberg, and with the supposed tetrahedrite at Kallmora and Läggesta.

The Mårtanberg ores present several difficulties. The bornite associated with the zinc blende is undoubtedly hypogene. When it has formed by replacement of chalcopyrite, as in the case shown above in fig. 2, the possibility of a supergene origin must be taken into account, although the replacement in itself is no *proof* of supergene processes. Swab's description (54) also suggests a supergene origin. According to Swab, the gangue in one part of Lundin's mine was so loose that it could be dug out with a spade. When the gangue took on this character, the ore changed from chalcopyrite to irregular lenses of chalcocite and bornite. It is quite possible, however, that the change in the gangue was from quartz to chloritic, that is, from hard ore to »sköl» ore, and it is not necessary to regard the richer sulphides in this case as supergene. With so little known about their modes of occurrence, their origin cannot be stated with certainty. This doubt does not affect the conclusion about the bornite associated with the zinc blende, which is undoubtedly hypogene.

The Garpenberg chalcocite is very probably of hypogene origin. Compared to the chalcopyrite of the same mining field, it represents, as to chemical and physical conditions of deposition, a further step in the same direction as the bornite, towards lower temperature and accompanying conditions. As in the Nautanen-Svappavaara group, the chalcocite is separated, paragenetically, from the chalcopyrite by bornite. The hypogene origin of this bornite permits the same conclusion for the chalcocite. The chalcocite associated with the hypogene bornite at Mårtanberg is analogous, but otherwise the origin of the chalcocite from this locality is uncertain.

The bornite at the Kallmora silver mine is probably hypogene, but too little is known about it to allow a definite conclusion.

### Occurrences in the iron ore deposits.

Small concentrations of the richer copper sulphides are often encountered in the iron mines of Central Sweden. As already mentioned, they belong to the sedimentary iron ores, while chalcopyrite is practically the only copper mineral encountered in the iron ores formed by replacement. One case of chalcocite belonging to the latter type, the only one known to the writer, is here included with the occurrences in sedimentary ores (V. Åsgruvan at Norberg). The copper sulphides seem to be restricted to magnetite ore bodies, never appearing in purely hematitic ores. The copper minerals are chalcopyrite, bornite, and chalcocite. As already mentioned, the richer sulphides are much more common in this group of deposits than in the preceding one. A few examples will be described here.

*Norberg.* The occurrence of bornite in sulphidic ores of Kallmora in this district has already been described. There are also some quite small deposits in the iron ores, apparently localized by the occurrence of magnetite. One is the mine Bondgruvan. The material examined was gathered on the dumps, no underground study has been undertaken. The iron ore is quartz-banded, mostly specular hematite but in part magnetite. The copper occurs as bornite, with a little chalcopyrite. These minerals appear as impregnations and streaks in the magnetite ore. The bornite is often associated with fluorite, forming granular aggregates that are seen to cut across the banding of the iron ore. There is also a skarn of brown garnet, a very light bluish green amphibole,<sup>1</sup> and fluorite, probably replacing limestone bands in the iron ore. Some magnetite has been dissolved and has formed new crystals of larger size, often an inch across. The mineral association shows certain analogies to the Kallmora silver mine, although galena is entirely lacking. The magnetite associated with the bornite is in part martitized. This is a common feature in ores of this type, however, and is not necessarily dependent on the deposition of copper minerals.<sup>2</sup>

From Västra Åsgruvan, a skarn iron ore in limestone, a chalcocite specimen is known (R. M.). The copper sulphide is seen to replace »exploding bombs» of pyrite. There is also magnetite, slightly martitic. Little can be said of this occurrence, as it has to be judged from one isolated specimen. It seems to have been the pyrite rather than the magnetite that

<sup>1</sup> This amphibole is strikingly similar to the one that is associated with fluorite and chalcopyrite in prospect no. 112 in the Korphytte field at Riddarhyttan (14, Pl. 3).

<sup>2</sup> The altered iron ore of Bondgruvan, with its secondary fluorite, presents features recalling the ore of the mine Bäckgruvan near Västanfors. It seems doubtful if this latter mine really, as once suggested by the writer (14, p. 131) belongs to Myrback type of Riddarhyttan. It may, instead, have the same character as Bondgruvan.

localized the deposition of chalcocite. The possibility of a supergene origin is not excluded.

At Hedbergsgruvan, Norberg, an ore body of the quartz-banded type, bornite, chalcocite and a little chalcopyrite have been found together, according to a specimen in the School of Mines collections, Stockholm. The associated gangue is granular quartz and a little biotite. According to the label, the copper sulphides occurred at a depth of 120 feet (40 meters) as a lenticular body, 3 feet long, 2 feet deep and 1 foot wide, in the iron ore body and close by its foot wall.

*Ingelsgruvorna (Linde parish).* These mines work a series of ore bodies of finely banded iron ore of the Stripa type. While most of the ore contains the iron as specular hematite, there are marginal zones of magnetite ore in the various ore bodies, particularly at the ends. The copper minerals occur locally in this magnetite, sometimes in such quantities that hand sorting has been directed not only to keep the iron ore free from copper but also to pick out the richer copper ore. There is slightly more chalcopyrite than bornite, but it is probable that most of the copper occurs in the latter form. No chalcocite was observed. Small quantities of calcite and quartz accompany the copper minerals. The quartz occurs as prismatic crystals up to 15 mm in length, a rather unusual type in a replacement deposit. One often sees big crystals of magnetite enclosed in the copper sulphides, pointing at solution and re-deposition of part of the magnetite ore. As at Bondgruvan, fluorite rock also occurs. There are bands up to 10 cm in width, and perhaps more, of light greenish fluorite in grains of a few mm, with bornite and some chalcopyrite in regular distribution, the sulphides being hemmed in between the isometric fluorite grains. The chalcographic examination of copper ore from these mines shows either mutual boundaries of bornite and chalcopyrite, or gashes of the latter that appear to replace the bornite. The magnetite is only slightly martitic, but there are bunches of tabular hematite crystals growing from magnetite grains out into the bornite.

At the Gullblanka mine, 5 km NW of Ingelsgruvorna, the relations of iron ore varieties are similar, but the magnetite is rich, without quartz bands, while at Ingelsgruvorna it has the banding and approximately the same quartz content as the hematite phase. At Gullblanka, the change to magnetite appears to have been connected with a thorough alteration of the original, quartz-banded ore. Gullblanka is mentioned here as a case of secondary copper sulphides, *without* the development of bornite or chalcocite. There is some chalcopyrite, and also much pyrite.

*Riddarhyttan.* In this district, sulphide ores — chalcopyrite, pyrite, pyrrhotite, cobaltite, and some molybdenite — are associated with magnetite in replacement deposits of various types (14). Bornite and chalcocite are conspicuously absent in these associations. The only two occurrences known in the district are in quartz-banded iron ores, which otherwise are very poor in sulphides. At the Stora Stripa mine, a little bornite and

chalcopyrite have been noted. At Bastnäs, in one of the mines on quartz-banded iron ore (Stora Bastnäsgruvan), chalcocite and bornite have been encountered in few cases as vein-like or lenticular deposits up to 0.35 m in width, evidently similar to the occurrence at Hedbergsgruvan described above. They are reported to cut obliquely across the strike and dip of the iron ore.<sup>1</sup> One specimen only (R. M.) has been examined. It shows scattered grains of specular hematite, quartz and mica — remnants of the original iron ore — in a mass of chalcocite with remains of bornite. The replacement of bornite by chalcocite results in intergrowths that locally take on a graphic character.

*Pershyttan.* Several specimens from the Old Field at Pershyttan (R. M. and U.) are of chalcocite, similar to that from Bastnäs at Riddarhyttan, including the content of hematite and gangue. The bornite is separated from the replacing chalcocite by a fuzzy border zone of bluish colour, consisting of blue lamellæ in the white chalcocite. The reaction of the bornite when etched is unusual. With nitric acid it takes on the deep yellow colour generally shown by chalcopyrite in the same case, with a »cracked porcelain» surface, and a quite distinct boundary towards the outer, more normally coloured portion of each bornite area. The chalcocite partly shows a triangular etch pattern.<sup>2</sup>

*Utö.* Also the iron ore deposits of Utö belong to the quartz-banded type. Part of the iron occurs as specular hematite, associated with reddish gray quartz to form a jaspilitic ore, and part of it as magnetite, generally with gray quartz. Sulphide ores, mainly argentiferous galena, have been mined on a quite small scale in a mine in one end of the workable iron ore bed, and also in prospects in the rocks farther away from the iron mines (compare 25). There is not the slightest doubt that the sulphides are much later than the iron ore.

In old mineral collections, specimens from Utö that show bornite and chalcocite are not uncommon. Many of them also contain native silver. Unfortunately, no detailed notes of the mode of occurrence are preserved, neither the particular mine nor the depth being given.

Examination of a number of these specimens (R. M. and U.), partly with the aid of the reflecting microscope, has brought out that the native silver is invariably associated with bornite and chalcocite, in particular with the bornite. There is both magnetite and hematite in these specimens, but no sign of a local martitization. The gangue is quartz and some actinolite. With the copper sulphides, there appear in some specimens galena and zinc blende. The paragenesis, therefore, is similar to that of the Garpenberg chalcocite. The textural relations, as far as the sulphides are con-

<sup>1</sup> According to notes left by Mr. C. D. Tideström, for many years manager at Riddarhyttan.

<sup>2</sup> There were observed also several grains of a mineral that could not be identified with certainty. It is creamy white, of medium hardness, not brittle, and is not attacked by the reagents commonly used in etching. It appears to be optically isotropic. The chalcocite replaces it as narrow veinlets.

cerned, are also the same as there. The chalcocite replaces the bornite, and small patches of the latter are often enclosed in the chalcocite grains. No other mineral appears to be affected by the chalcocite. The silver is always seen in either bornite or chalcocite, and generally in bornite (fig. 18, Pl. VII).

*Origin of the bornite and chalcocite in the iron ore deposits.* The views that were put forth when discussing the richer copper sulphides of the sulphidic ore deposits apply also to the local occurrences in the iron ores. One argument for a hypogene origin can be added in this case: the absence of any sources from which a supergene enrichment could derive its copper. The only doubtful case is that of Västra Åsgruvan at Norberg. It is characteristic that this is the only case known to the writer of a rich copper sulphide in an iron ore body formed by replacement. It emphasizes the extreme rarity of the richer sulphides when copper was deposited by the same high-temperature mineralization as iron.

The purely sulphidic ores of Central Sweden are numerous and widely scattered, pointing to a wide-spread penetration of the leptite formation by copper-bearing solutions. This probably took place during the period of folding and intrusion of the older Archæan granites (12, p. 275). The copper minerals in the stratified iron ores may, therefore, and because of many analogies to the sulphidic ores, be interpreted as probably derived from the same sources as the latter, and belonging to the same period of mineralization.

The metamorphic processes accompanying the development of the sulphidic ores have been shown to lead to a change of hematite into magnetite (14, p. 134), probably because of the higher temperature involved. It is not probable, however, that the occurrence of the copper sulphides just in the magnetite phases is due to a combined magnetitization of the hematite and deposition of the sulphides. Instead, the magnetite may have been formed in consequence of the more regional metamorphism during the same orogenetic period. The association of magnetite and sulphides, then, must be due to the chemical composition of the former, its ferrous iron acting as a strong reducing agent. The same factor may also have determined the high proportion of bornite and chalcocite, as will be shown presently.

The difficulties encountered when trying to picture more in detail the chemical forces controlling the deposition of the copper sulphides are great indeed, but some tentative conclusions can be drawn, as a guide for further study. The mineralogical difference between the copper minerals in the purely sulphidic ores on one hand, and the occurrences in the iron ores on the other, may be chemically expressed either in the higher proportion of copper to iron in the latter, or in the preponderance of cuprous copper, with correspondingly low sulphur. By laying stress on the former side of the difference, one is led to assume that the ratio iron: copper in the solutions has gradually changed, and that in the case of the deposits

in iron ores, which for many reasons may be supposed to have formed at lower temperatures than the pyritic chalcopyrite deposits,<sup>1</sup> there should have been proportionately less iron than in the case of the latter. Similar points of view could be applied in the interpretation of the Nautanen-Svappavaara group. Yet, in both cases there are iron minerals present, belonging either to an earlier phase of the same mineralization (Liikavaara and Fridhem in the Nautanen district) or to a much older one. The solution and recrystallization of magnetite that has been reported above from Norberg (Bondgruvan) and Ingelsgruvorna, also shows that iron must have been present in considerable quantities in the copper-bearing solutions during the reactions.

Lack of sulphur is another possible factor, and one that deserves serious consideration. For good reasons it has been generally assumed that copper-bearing hydrothermal solutions contain much sulphur also in the form of alkali sulphides, and some as hydrogen sulphide,  $H_2S$ . The former are supposed to determine the solubility of the copper sulphide. There are no direct proofs that these compounds, as well as  $H_2S$ , were present also when the occurrences now considered were formed, but it is probable that they were. A more probable explanation than lack of sulphur is, in fact, found in the regular association with magnetite, and with martitization. If, as seems evident, the deposition of the copper sulphides was caused by the reducing action of ferrous iron in the magnetite, which was oxidized to martite, it is only natural that this action has also brought much of the copper to the cuprous stage, thereby making possible the formation of bornite and even chalcocite. The details of the process cannot be determined. The sulphides replace gangue minerals rather than magnetite or hematite. The fluorite encountered in several deposits of this type shows that the reduction of the copper, which may have been the initial action, disturbed the equilibrium of the copper-bearing solutions and started reactions of a much more complicated character.

The same association of chalcocite, and in a less pronounced degree bornite, with magnetite and martitization was encountered also in such deposits as Liikavaara, Fridhem, Sjangeli and Garpenberg — all cases where the magnetite probably belongs to an earlier phase of the same mineralization as the copper sulphides. It is striking that no martitization takes place when magnetite and copper sulphides meet under conditions indicating higher temperature than in the cases just quoted. So at Lattevere, in the chalcopyrite-magnetite ores of Nautanen and the Riddarhyttan district, etc. In the latter cases no mineral containing cuprous copper is formed, which emphasizes the importance of martitization or similar reactions for this process. At Lattevere, bornite occurs, but the order in relation to chalcopyrite is an unusual one, and factors may have influenced that cannot be identified.

<sup>1</sup> As they are quite local deposits, and are not accompanied by the metasomatic alteration typical of the pyrite-chalcopyrite deposits.

The association of chalcocite with pyrite at Västra Åsgruvan, and the same combination, although not quite comparable, at Mårtanberg, cannot be quoted as *proving* a supergene origin of the chalcocite in these cases. Also in hypogene deposits, pyrite and chalcocite are sometimes deposited together (44, p. 1610), showing that the reactions are not controlled only by the proportions of Cu, Fe and S in the solutions.

The Utö ore presents a special problem: the origin of the native silver. It is evident that the silver was deposited through reactions with bornite and chalcocite. The power of these minerals to precipitate silver from its solutions is amply demonstrated (23, p. 523; 36). Bastin and Palmer (36) describe and figure small veinlets of bornite, chalcocite and silver that are interpreted as supergene replacements in an altered pyroxenite. These veins appear to have much in common with the silver-bearing aggregates in the Utö ore. Yet for the latter a supergene origin cannot be claimed, at least not for the bornite, the relations of which are typically hypogene. Of course, it is possible that the silver alone may be supergene. The textural relations do not favour this view, however, for one should then expect some more signs of the action of supergene solutions.

### Occurrences in southeastern Sweden.

(Östergötland—Småland.)

In the southern part of the province of Östergötland and in northeastern Småland there is a number of copper deposits, generally small although one of them, the Åtvidaberg-Bersbo district, has probably produced more than 7,000 metr. tons of copper.<sup>1</sup> The larger deposits carry chalcopyrite chiefly, but both in them and particularly in the smaller ones there is bornite, and sometimes chalcocite.

*Åtvidaberg.*<sup>2</sup> Together with magnetite, pyrite, gangue silicates (biotite, tourmaline), and quartz, the copper ore occurs mainly as replacement veins in a gneissic granite, apparently formed in a close connection with the solidifying of this rock (53). In this case the copper is generally in the form of chalcopyrite, but bornite is also known. One specimen (R. M.) from a depth of about 180 meters in the most important mine, Mormorsgruvan, shows the bornite associated with chalcopyrite, pyrite and magnetite. The bornite replaces the chalcopyrite, with little complicated outlines. In places, minute lamellæ of chalcopyrite appear in the bornite. The presence of pyrite grains in the bornite is a rather unusual feature in the deposits considered in this investigation. It is met with also in another mine in the same district (Malmviksgruvan), and at Mårtanberg, as already men-

<sup>1</sup> There is some uncertainty about this figure, as the production has to be judged from smelter statistics.

<sup>2</sup> The Bersbo mines, with a different geology, have not carried any bornite or chalcocite, and are therefore omitted here.

tioned. To judge from several specimens (U.), bornite has occurred also as a megascopically evident replacement of chalcopyrite, particularly in quartz lenses. This phenomenon, closely paralleling the relation shown above in fig. 2 (p. 31), is known both from Mormorsgruvan and Garpa. One specimen of bornite from the Garpa mine (U.), in quartz<sup>1</sup> shows a very high content of minute chalcopyrite lamellæ in the usual orientation. Veinlets of covellite and some chalcocite replace the bornite. A little chalcocite is also megascopically visible. It is of interest to find that there is also some zinc blende in this specimen (duly noted on the old label). The appearance of this mineral (not otherwise recorded from the Åtvidaberg group) is a new example of the association of zinc blende and bornite.

Among the other deposits of this metallogenetic province, none of which have been visited by the writer, some may be briefly mentioned. Bornite specimens from the copper and cobalt mines of *Gladhammar* (U.) show the mineral in a gangue of dark green actinolite, together with chalcopyrite, magnetite and some specular hematite. Chalcographic examination shows that the textural relations of bornite and chalcopyrite are of the »mutual» type with simple outlines, although here and there the chalcopyrite forms gashes in the bornite. At a magnification of 100, the bornite appears quite homogeneous, but the immersion system brings out a very delicate network of chalcopyrite intergrowths in the usual pattern. The copper sulphides fill the interstices between magnetite crystals. These are not martitized at all, but locally they project from them, into the bornite, sheaves of lamellar crystals of hematite, recalling the bornite-bearing iron ore of Ingelsgruvorna. With high magnifications, a very narrow zone of chalcocite is seen along the boundaries between bornite and gangue.

Bornite specimens from the *Skrikerum* mine (U.), best known as the locality for the rare selenium minerals berzelianite, crookesite and eukairite, show the bornite, with some chalcopyrite, in a gangue of hornblende, quartz and mica. Evidently the bornite belongs to a paragenesis entirely different from that of the selenium minerals, which occur in a vein of coarsely crystalline calcite. The relations between bornite and chalcopyrite are similar to those in the Gladhammar ore, and the regular chalcopyrite intergrowths in bornite were observed in one of the specimens studied.

*Sunnerskog* shows the following list of metallic minerals: chalcopyrite, bornite, chalcocite, malachite, native copper, native silver (31). Little is recorded about the geological relations, but Nordenskjöld (33, p. 671) states that the deposit »is probably a true vein with cavities filled with sulphide ores and other minerals». The mineral list certainly suggests supergene mineralization. A peculiar chalcocite from Sunnerskog was analyzed by Lindström (30), who found the »carmenite» composition  $\text{Cu}_2\text{S}\cdot\text{CuS}$ . Chalcographic examination of the type material (R. M.) shows a normal »white» chalcocite, with irregular veinlets of finely crystalline covellite. This mineral also occurs as occasional stripes parallel to one direction in the ortho-

<sup>1</sup> At this mine, quartz is by far the predominating gangue mineral (53, p. 89).

rhombic cleavage of the chalcocite, as in part of the Kiirunavaara chalcocite. The total quantity of covellite that is visible is too small to account for the composition shown by the analysis. Of course there may be some cupric sulphide still contained in the chalcocite, but if so it has no influence on its colour. The covellite of the veins is plainly supergene. Independent of the origin of the chalcocite — hypogene, or supergene from an earlier period (pre-glacial) — the covellite occurring as orientated stripes in it must be interpreted as either formed at the same time as the containing chalcocite, or at first kept in solid solution and later segregated.

## Discussions.

### The composition of bornite.

The most striking feature in the occurrences of bornite treated in this investigation is the very frequent appearance of chalcopyrite lamellæ in a regular crystallographic intergrowth with the bornite. They have been noted, sometimes as a normal feature in the bornite, sometimes rather as exceptions, in the following localities: Lattevare, Kiirunavaara, Nietsajoki, Risbäck, Svappavaara, Vähävaara, Garpenberg, Läggesta, Åtvidaberg, Gladhammar, Skrikerum. At Liikavaara there are some tendencies towards the same phenomenon, and likewise at Kallmora. No such intergrowths have been noted in the specimens from Fridhem, Sjangeli, Mårtanberg, and from the five localities in iron ore deposits in Central Sweden that have been studied.

In some rare cases, the chalcopyrite appears to form short rods, or »elongated drops», in the bornite. Generally, however, and independent of the quantity of chalcopyrite, and of the size, the pattern is the one that is best shown by fig. 7, Pl. II: the chalcopyrite appears as spindle-shaped bands that evidently are cross-sections of flat discs, arranged generally in three directions, and by the frequent occurrence of a clearly octahedral pattern indicating that they probably always follow the octahedral cleavage planes of the bornite. There is also, when the intergrowth is coarse enough, seen a rim of chalcocite or covellite on both sides of every chalcopyrite spindle.

This form of intergrowth has long been known, but it is uncertain whether the total number of occurrences previously known is equal to that described here. Graton and Murdoch (15, fig. 18), Tolman (56, figs. 18—20), Overbeck (35, fig. 8) and Uglow (57) have described and figured it. The variations in size appear to be fully as great as among the Swedish examples. The entire appearance is the same as in the Swedish cases, including the rims of chalcocite or covellite on the stripes of chalcopyrite. The authors quoted interpret the intergrowth as due to supergene replacement of bornite by chalcopyrite. Schneiderhöhn, on the other hand, who had to judge from the descriptions and figures, means that the chalcopyrite has separated out as the result of an »unmixing» of a solid solution (47, p. 524). The »orange» and »purple» bornites are regarded by Schneiderhöhn

as probably containing in solid solution an excess of chalcopyrite or chalcocite, respectively (49). Recently, Schneiderhöhn has described some related phenomena, to which he applies the same interpretation. In this case, the chalcopyrite appears to follow cleavage planes, but the chalcocite the boundaries between the bornite grains. With regard to the intergrowths described above, the present writer finds the explanation suggested by Schneiderhöhn the only possible one. The reasons for this are several, as will be seen.

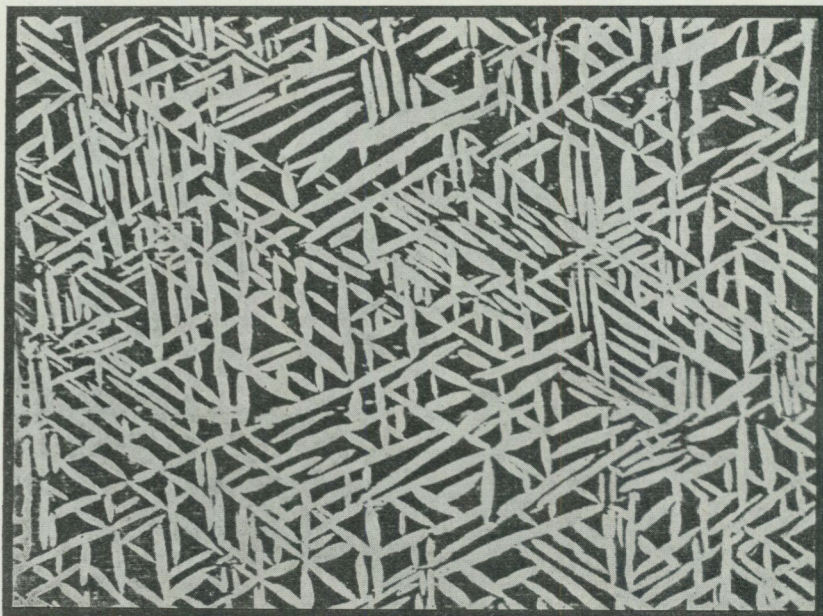


Fig. 4. "Typical segregate." Microphoto. of polished section of a nickel-silicium alloy,  $\times 70$   
After Guertler and Tamman.

Characteristic of the intergrowth is the combination of two features: the octahedral arrangement of the chalcopyrite lamellæ, and their spindle-shape in cross-sections, particularly their tapering when crossing each other. These features are exactly those that are most characteristic of a structure known positively from experimental work to have been formed by the segregation of one component out of a »mixed crystal» or »solid solution». In Guertler's metallographic handbook (20, p. 224) there is shown as »a typical segregate» of this character the micro-photograph which is here reproduced as fig. 4. A comparison with fig. 7, Pl. II, ought to be sufficient. An intergrowth as crystallographically arranged lamellæ is not alone a proof of segregation, as illustrated by the examples of martitization that have been described above.<sup>1</sup> It is only when the spindle-shape of the chalcopyrite sections is added that the conclusion can be drawn.

<sup>1</sup> It is excluded that these could represent cases of unmixing. The martite ore of Kiiruna-vaara is particularly clear, in its association with other oxidation phenomena, and its contrast to the normal character of the ore body.

In the few cases encountered by the writer where chalcopyrite in the form of veinlets is seen to replace bornite, the chalcopyrite stripes generally start from the periphery of a bornite area, or from a gangue inclusion, and taper inwards in the bornite (Ingelsgruvorna, Gladhammar). An arrangement regulated by the cleavage of the bornite has been observed in a specimen from the fissure vein region of southwest Sweden,<sup>1</sup> but there are more irregular gashes associated, and the typical spindle-shape is absent.

This characteristic spindle-shape of the segregated portions is easily understood. The thickest parts must represent those points where the segregations started, afterwards growing out in all directions on the same cleavage plane. The analogy to the form of tension veins in rocks may be noted.<sup>2</sup> For the present we shall leave out the chalcocite or covellite linings on the chalcopyrite stripes, to return to them later on.

Not only are there very strong positive reasons to regard the phenomenon in question as due to segregation (unmixing). Negative evidence, that excludes an origin by replacement, may also be produced. Thus the intergrowth is observed also in the bornite that *replaces* chalcopyrite, as at Nietsajoki. Further, when the bornite with intergrown chalcopyrite is replaced by chalcopyrite in larger and irregular aggregates, there is a well-marked hiatus between the two forms of chalcopyrite. There are no structural transitions between them.<sup>3</sup> Compare fig. 6 from Latteväre, or fig. 19 in Tolman's paper (56). As formulated above, the two appearances of chalcopyrite correspond to the forms of albite feldspar in a granite: part of it formed originally as free albite, but a certain amount was taken up in solid solution by the potash feldspar, to be later segregated as perthite. An argument against a supergene origin is also found in the common occurrence of the intergrowth in question in Sweden, where so few traces of supergene mineralization have been found.

The fact that segregations of this kind are so much more numerous in the Swedish occurrences than in bornite from other localities is probably dependent upon the fact that the occurrences here considered appear to be generally formed at high temperatures, which would mean an increased solubility of foreign compounds, and consequently an increased probability of their segregation at lower temperatures. The absence of segregations in the bornite of the iron ores, believed for other reasons to belong to a

<sup>1</sup> For this specimen, from Änimskog, the writer is indebted to Mr. J. Eklund. Megascopically there are seen veins of chalcopyrite in bornite. The chalcographic examination shows that these veins are really zones of small veins or stripes of the type just mentioned, together with independent veins of covellite.

<sup>2</sup> Overbeck has noted the salient feature in this kind of intergrowth, as is evident from his words (35, p. 162): »It is interesting to note that the gashlike replacement or alteration bands become narrow where two bands cross, instead of broadening out as should be expected if ordinary replacement were taking place.» Overbeck concludes, however, that the structure is due to supergene replacement.

<sup>3</sup> The dependence of the chalcopyrite lamellæ on the larger areas of the same mineral, as reported by Uglow (57), may be due to the fact that the larger units have had an inoculating influence.

comparatively low temperature range, is perhaps significant. It is also possible, however, that the mechanical straining that these minerals must have experienced, particularly as many of them appear to have formed in the course of folding processes (12, p. 275; 13, p. 89), has given an impetus to the segregation of compounds that would otherwise have been kept in solid solution indefinitely.

There remain to be considered the chalcocite or covellite linings on the chalcopyrite spindles. From the standpoint of the supergene replacement hypothesis the interpretation is obvious: a later replacement of the bornite by cuprous or cupric sulphide has followed the boundaries of the chalcopyrite lamellæ, but has, as is so often the case, not changed the chalcopyrite. Schneiderhöhn, who describes a related but structurally somewhat different phenomenon (49) explains it as a breaking up of bornite into chalcocite and chalcopyrite. The possibility of such a change is suggested by the bornite formula if written  $2\text{Cu}_2\text{S}\cdot\text{CuS}\cdot\text{FeS}$ .

Several examples here described, particularly those from Kiirunavaara and Vähävaara, show that portions of the bornite grains have, in fact, changed to aggregates of chalcopyrite and chalcocite. The fairly regular proportions between the chalcopyrite spindles and the accompanying chalcocite linings, and the absence of chalcocite in any other form of occurrence, seem to the writer to constitute strong arguments for the extension of the segregation hypothesis to cover also the chalcocite. In all the cases described here, however, the amount of chalcocite is too small to have once with the chalcopyrite formed a mineral  $2\text{Cu}_2\text{S}\cdot\text{CuS}\cdot\text{FeS}$ . Without entering into further argumentation, there may only be presented here what appears to the writer the most probable explanation. An excess of  $\text{CuS}\cdot\text{FeS}$  can be taken up in solid solution by the bornite under certain conditions. With a change in the physico-chemical environment, probably chiefly a decrease in temperature, this solid solution becomes unstable, and a segregation takes place, perhaps aided by mechanical influences. We do not yet know the crystal structure of bornite, but that of chalcopyrite (19, and Burdick, Ellis and Wherry, quoted in 3, p. 153), which contains the atoms Cu, Fe and S, so that the formula can be written  $\text{CuS}\cdot\text{FeS}$ . It is therefore possible that bornite is built on similar lines. When the dissolved  $\text{CuS}\cdot\text{FeS}$  begins to segregate as chalcopyrite aggregates on the cleavage planes, a process is started which by inoculation may lead to a segregation also of CuS and FeS units belonging to the bornite itself. This forming of chalcopyrite sets free the  $\text{Cu}_2\text{S}$  of the bornite that is broken up. The amount of chalcocite, therefore, corresponds only to that part of the segregated chalcopyrite that belonged stoæchiometrically to the bornite. This hypothesis explains both the textural and the quantitative relations. The possibility of a spontaneous segregation of bornite into chalcopyrite and chalcocite, without the impetus given by an excess of either of these constituents, is not to be denied, but the material described here gives no example that can be so interpreted.

The covellite linings present another problem. They are best represented in the Risbäck bornite, but it is possible that they occur also in other localities, the very small dimensions making a decision difficult. Obviously, the explanation given must be somewhat different from that applied to the chalcocite, but still contain in principle similar views. The analysis of the Risbäck bornite furnishes a starting-point. It is clear from the microscopic examination that the covellite linings on the chalcopyrite segregations are entirely independent of the quite irregular vein system of supergene covellite. Leaving out the 0.10 per cent of gangue, the analysis is as follows:

Cu . . . . .	56.64 % . . . . .	0.8910
Fe . . . . .	13.14 » . . . . .	0.2353
S . . . . .	<u>30.05 » . . . . .</u>	<u>0.9370</u>
	99.83	

Allotting first enough S to Fe as FeS, the proportion between Cu<sub>2</sub>S and CuS is determined by the available sulphur. The amounts of FeS, CuS and Cu<sub>2</sub>S are then combined into bornite (2Cu<sub>2</sub>S·CuS·FeS), chalcopyrite (CuS·FeS) and covellite (CuS), the three minerals observed as components of the segregation intergrowth. The weight percentages obtained are:

FeS . . . . .	20.69	2Cu <sub>2</sub> S·CuS·FeS . . . . .	47.51
CuS . . . . .	49.00	CuS·FeS . . . . .	25.81
Cu <sub>2</sub> S . . . . .	<u>30.14</u>	CuS . . . . .	<u>26.51</u>
	99.83		99.83

It must be admitted that several per cent of covellite can be due to supergene alteration, but not more. With this covellite are intimately associated the malachite and limonite veinlets. As all pieces containing such veins were carefully avoided for the analysis, and a large portion of the material used was examined chalcographically and found to contain very little supergene minerals already before this separation, it is safe to conclude that only a small portion of the 26.51 per cent. of covellite can be of supergene origin. It appears, therefore, that bornite may take up in solid solution not only more than 25 per cent. chalcopyrite, but also, at the same time, more than 20 per cent. covellite. Again may be remembered the combination of CuS and FeS in chalcopyrite. The segregation of the covellite has probably been called forth by the segregation of a portion of the dissolved CuS in the form of chalcopyrite. No breaking up of the stoichiometric bornite has taken place. The proportions between chalcopyrite and covellite, as observed under the microscope, appear to agree very well with the explanation given, but the small dimensions have prevented accurate measurements and only a rough estimate could be made.<sup>1</sup>

<sup>1</sup> It may be noted incidentally that these proportions also exclude the old formula Cu<sub>3</sub>FeS<sub>3</sub> for the bornite. This formula would give 26.51 per cent. CuS as in the above calculation, but reduce the chalcopyrite to only 8.40 per cent.

It must be admitted that a solution of CuS beyond the quota for chalcopyrite is a rare feature in bornite. No analysis in the diagram constructed by Rogers (42) shows so much CuS as the one from Risbäck.

In summary, the material here described confirms the view that the formula of bornite is  $\text{Cu}_5\text{FeS}_4$ , as indicated by Cleve (9) and more definitely stated by Harrington (22) and by Allen (1). The variations from this formula, also in material that appears homogeneous under the microscope, is due to the presence of various substances, taken up in solid solution at the crystallization of the bornite. The gradations observed from the fairly coarse intergrowth of fig. 7 down to the minutest spindles suggest that also in many apparently homogeneous bornites of peculiar colour a segregation has already taken place, but the segregated portions are so small as to be invisible. In the Swedish bornites, chalcopyrite is the substance that is normally dissolved in the bornite and afterwards segregated, but covellite is locally found with it. An excess of chalcocite was not encountered, but this is no reason to doubt Schneiderhöhn's view that this compound also can be taken up.

#### **The criteria of hypogene chalcocite.**

While bornite has offered a special interest in the question of its chemical composition, the most prominent problem with regard to chalcocite concerns its origin. In the case of few minerals, if any, the paragenetical relations have been so much studied and discussed of late as have those of the chalcocite. The chief reason for this, of course, is the economic importance of a possibility to decide whether the chalcocite in a certain deposit is hypogene and will be found also in greater depth, or supergene and of limited extension vertically.

When a full understanding of the importance of supergene process had been arrived at, the tendency was first to ascribe all chalcocite to supergene alteration. By and by, however, facts were discovered that indicated the existence also of primary or, to use a less ambiguous terminology, hypogene chalcocite. These facts concerned the characters of the chalcocite itself, its paragenetical associations, the textural relations to other minerals, notably the graphic intergrowths with bornite, and local geological conditions.

The clearest case of hypogene deposition of chalcocite on a great scale, the Butte district, has been interpreted more from geological than from mineralogical facts, the relations of the chalcocite to various forms of rock alteration, its age in relation to certain faults, the physiographic requirements for deep oxidation, etc., being the chief factors considered (44). The paragenetical relations have also counted, however. In this treatment of the Swedish occurrences, paragenesis and geological environment have furnished most of the evidence.

Such methods, however, do not permit a decision for every single specimen, if supergene chalcocite also occurs in the deposit. In this respect, the characters of the chalcocite itself as revealed by the etch cleavage, and the intergrowths with bornite, have given certain promises of more decisive criteria, but these promises have been fulfilled only in part.

The use of the etch cleavage is based on the dimorphism of  $\text{Cu}_2\text{S}$ , which is isometric above  $91^\circ$  and orthorhombic below this temperature, no inversion taking place if the isometric  $\text{Cu}_2\text{S}$  contained 8 per cent., or more, of  $\text{CuS}$  in solid solution (39). Two different types of etch cleavage are encountered in chalcocite. One is »triangular», showing cleavage lines in three directions that may be seen to intersect in angles of  $60^\circ$ . This is the normal, octahedral cleavage of isometric  $\text{Cu}_2\text{S}$ . However, it has also been interpreted as the preserved cleavage of replaced bornite (15, 56, and other authors). It is difficult to judge the cases so interpreted from descriptions and figures only, but it seems to the writer as if the best examples did not show the rather sparse cleavage lines of isometric chalcocite, but instead the »lattice» type.<sup>1</sup>

The orthorhombic etch cleavage, on the other hand, shows a fine striation parallel to (001), a more sparsely spaced one following (010), and a weakly developed system following (100). In two cases described above (northern Kiirunavaara, and Liikavaara) the triangular and the orthorhombic etch pattern are seen in adjacent grains, which is interpreted as indicating that the chalcocite was originally isometric, but part of it suffered conversion into the orthorhombic form.

It remains to consider the graphic intergrowths of chalcocite and bornite. When first described by Lancy (28), they were regarded as absolutely reliable proofs of a contemporaneous and hypogene deposition of the two minerals. Later, new observations were made that led several authors to doubt the validity of this interpretation. Thus Rogers (43) presented strong evidence for an origin of the intergrowth in such a way that the bornite should have been partially replaced by chalcocite through the action of ascending

<sup>1</sup> The »lattice» chalcocite of American writers, and the »lamellar» chalcocite of Schneiderhöhn (45, 48) are described as practically identical. Schneiderhöhn regards it as a paramorphose of orthorhombic after isometric chalcocite; the small bornite areas often enclosed between the octahedrally arranged chalcocite lamellæ are interpreted as segregations. The »lattice» or »reticulating» intergrowths of chalcocite and bornite, on the other hand, are described as replacements of bornite by chalcocite, the latter following the octahedral cleavage planes of the bornite (15, 16, 41, 56, 58). Indubitably there are many close analogies between these two phenomena, and it is probable that some cases described as belonging to one of them ought to be referred to the other. Yet the obvious analogies to the structural relations between magnetite and hematite strongly suggest that there are really two different phenomena, and not only different interpretations of one and the same thing. The reason for considering this problem here, where no chalcocite of this type has been reported, lies just in this analogy. It has been shown repeatedly in this report how the change of magnetite to hematite follows the octahedral cleavage of the former. The same phenomenon has also been described from other localities (7). On the other hand, it is well known that the titaniferous magnetite contains most of its titanium in the form of segregated plates of ilmenite in octahedral arrangement. These two different forms of octahedral intergrowths in magnetite have already been contrasted by Broderick (7, p. 362), but the analogy to the »lattice» or »lamellar» chalcocite has not been emphasized.

solutions. More evidence for an origin by replacement was produced by Ray (41), and Whitehead (58). The latter regards the replacement as a supergene process. Guild (21) points out that also segregation at the unmixing of a solid solution may be expected to produce graphic structures under certain conditions. The example immediately in view was one of other minerals, however (galena and stromeyerite). Schneiderhöhn (46) has made an interesting attempt to distinguish between those graphic intergrowths that are due to hypogene replacement by presumably alkaline solutions, and those of supergene origin from acid solutions. It is held that the crystallographic orientation of the bornite exerts a stronger influence in the latter case.

In his monograph on the Virgilina district (29), Laney, in 1917, gives a more detailed account and discussion of the graphic intergrowths. While presenting a strong combination of evidence for an origin by simultaneous crystallization, Laney also objectively points out the facts that indicate replacement.

It is evident that the graphic intergrowths do not have the diagnostic value that was once attributed to them, but they still present much of interest. One important point that appears to have been largely overlooked is the difference in origin from the products of eutectic crystallization. As stated concisely by Guild (21, p. 313), the graphic aggregate, »since it is a deposition from solution cannot in any way be looked upon as a true eutectic«. One must also consider the fact that graphic aggregates are encountered also in ore deposits that were formed by the replacement of older rocks, not by deposition in open waterways.

However, these very important differences from the conditions of eutectic crystallization do not change the main conclusion of Laney and his followers: the intergrowths may still be regarded as indicating *contemporaneous* growth. It is interesting to note that the structural similarity is equally great when comparison, instead of with the eutectic structures, is made with the group of intergrowths that are called by Sederholm (50) symplektites, and are typically represented by the myrmekite. Sederholm's valuable survey of these structures shows that no general interpretation has been found, but the main conditions of origin are evident: replacements, particularly in the form of interaction between adjacent grains of different minerals, partly in connection with the final stages of magmatic crystallization, partly perhaps during conditions of regional metamorphism. In some cases, the replacement may have been mainly a re-arrangement, as suggested in Guild's interpretation of certain sulphide intergrowths (compare above). The bornite-chalcocite intergrowths appear to be more comparable with the symplektites arising from contemporaneous replacement of a third mineral (or several minerals) than with the eutectic intergrowths. If changed conditions allow the chalcocite to form also after the deposition of bornite has ceased, one might expect it to replace the latter, locally at least. Bateman (3) has given a similar interpretation of the relations be-

tween bornite and chalcocite in the Bristol mine, Connecticut, on what appears to be very good reasons.

The application of these ideas to the intergrowths described in this paper does not imply any opposition to the views of Schneiderhöhn and Whitehead that structures similar or only slightly different may also arise through supergene replacement.

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### Explanation of plates.

**Plate I.** *Fig. 5.* Ore vein, Lattevarre. Microphoto., refl. light, oil immersion,  $\times 280$ . White is chalcopyrite, black is hornblende (Co covellite), B bornite (with chalcopyrite lamellæ), M magnetite.

*Fig. 6.* Copper vein, Professorn, Kiirunavaara. Microphoto., refl. light,  $\times 55$ . B is bornite, B + Cp bornite with chalcopyrite lamellæ (white), dark-coloured areas are oxidation products (malachite, limonite).

**Plate II.** *Fig. 7.* Bornite, Professorn, Kiirunavaara. Microphoto., refl. light, oil immersion,  $\times 550$ . White is chalcopyrite, gray (B) is bornite, darker gray (Cc) is chalcocite, black oxidation products.

*Fig. 8.* Copper vein, Professorn, Kiirunavaara. Microphoto., refl. light,  $\times 50$ . Bornite (B) is being replaced by chalcocite (Cc), veins of limonite, malachite and chrysocolla (dark gray) follow the middle of the chalcocite veins.

**Plate III.** *Fig. 9.* Copper vein, Professorn, Kiirunavaara. Microphoto., refl. light, obliquely crossed nicols,  $\times 70$ . B is bornite, Cc chalcocite, white is covellite intergrown with the chalcocite. Note the similar orientation of the covellite blades in each grain of chalcocite!

*Fig. 10.* Copper vein, Geologen, Kiirunavaara. Microphoto., refl. light,  $\times 55$ ; specimen etched with KCN. B is bornite, Cc1 chalcocite showing triangular etch lines, Cc2 chalcocite with typical orthorhombic etch cleavage, B + Cp is intergrowth of bornite and chalcocite, H is hornblende.

**Plate IV.** *Fig. 11.* Martitized magnetite ore, Landshövdingen, Kiirunavaara. Microphoto., refl. light, oil immersion,  $\times 300$ . Shows how the hematite (light gray) is developing along the cleavage planes of the magnetite (dark gray); black areas are holes in the porous ore.

*Fig. 12.* Bornite, Risbäck. Microphoto., refl. light, oil immersion,  $\times 550$ . Shows three sets of chalcopyrite lamellæ (white) with covellite linings (black) in bornite.

**Plate V.** *Fig. 13.* Ore vein, Vähävaara. Microphoto. of thin section in transmitted light, crossed nicols,  $\times 13$ . Shows the irregular columnar or plumose aggregates of plagioclase (with micas) supposed to indicate pseudomorphs after scapolite.

*Fig. 14.* Copper ore, Vähävaara. Microphoto., refl. light,  $\times 55$ . Shows bornite (B), covellite (Co), and gangue, chiefly hornblende (H).

**Plate VI.** *Fig. 15.* Copper ore, Liikavaara. Microphoto., refl. light,  $\times 55$ . Area of bornite (B) and chalcocite (Cc), partly in graphic intergrowths, is bounded by crystals of magnetite (M), peripherically altered to hematite (lighter gray); some quartz (Q).

*Fig. 16.* Martitized magnetite in copper ore, Liikavaara (same specimen as fig. 15). Microphoto., refl. light, oil immersion,  $\times 280$ . (Section polished to show the copper minerals, therefore the magnetite surface pitted). Magnetite (dark gray) with hematite (white) developing along its cleavage planes.

**Plate VII.** *Fig. 17.* Copper ore, Biskopsgruvan, Garpenberg. Microphoto., refl. light,  $\times 55$ . Shows bornite (B), galena (G), zinc blende (Z) and quartz (Q).

*Fig. 18.* Copper sulphides and native silver in iron ore, Utö. Microphoto., refl. light,  $\times 55$ . Bornite (B, dark gray), chalcocite (Cc, light gray) and native silver (white), in a mass of quartz (black) with scattered grains of magnetite (gray).

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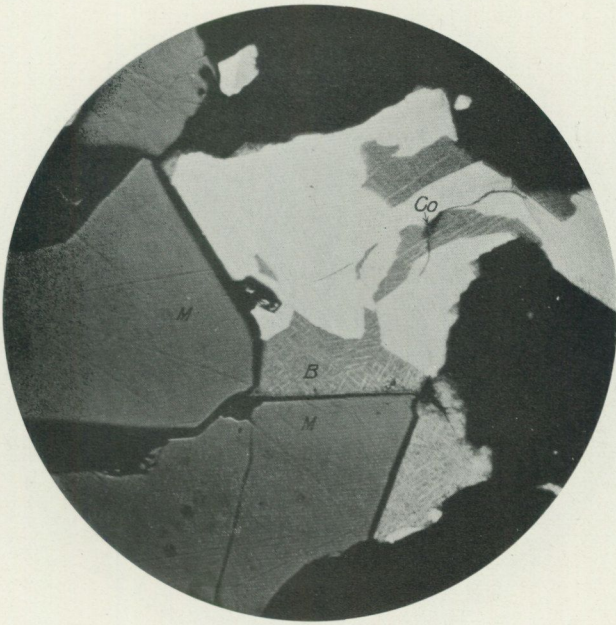


Fig. 5.

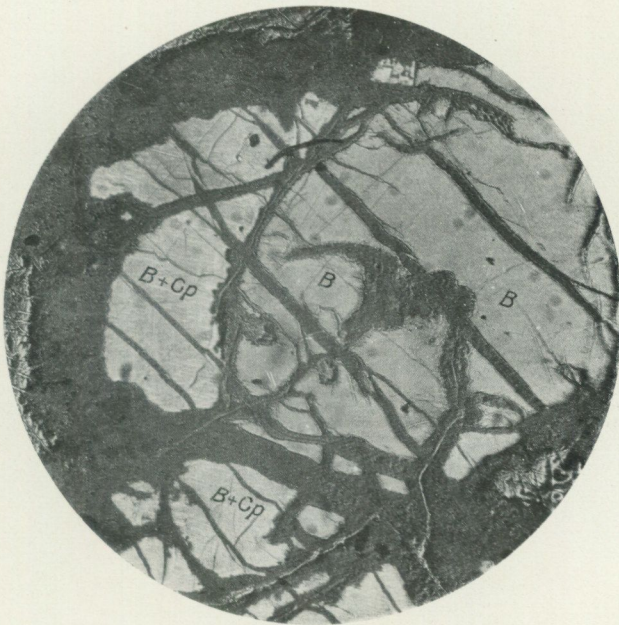


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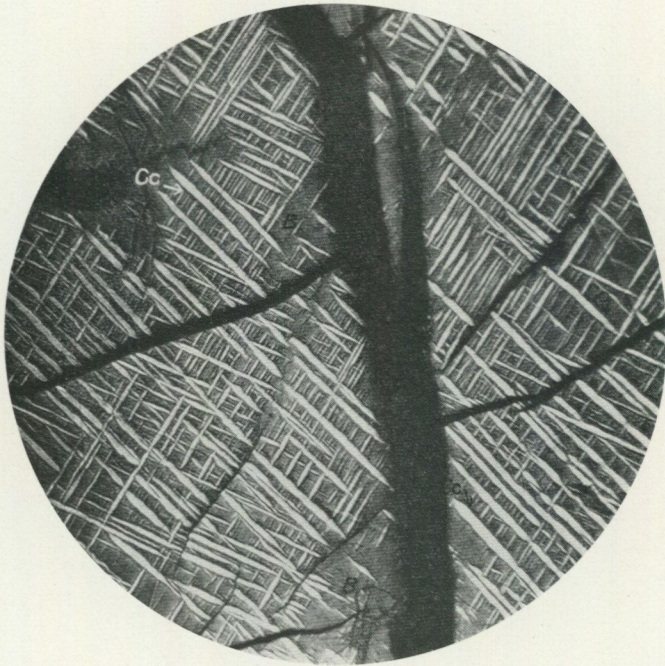


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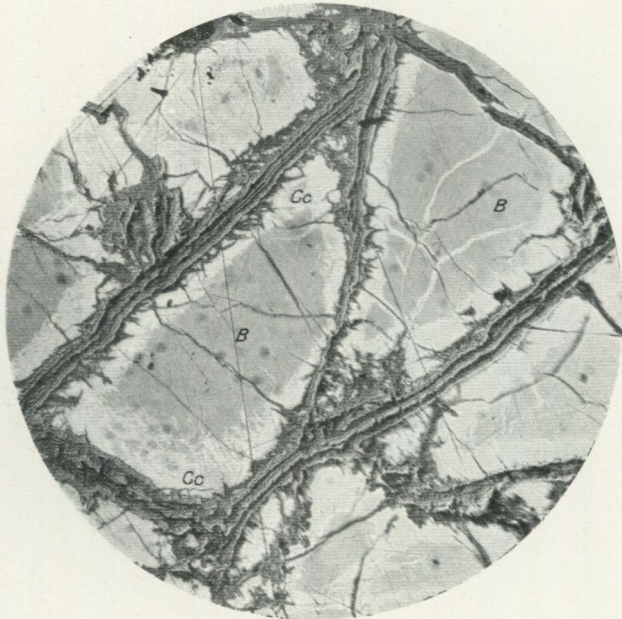


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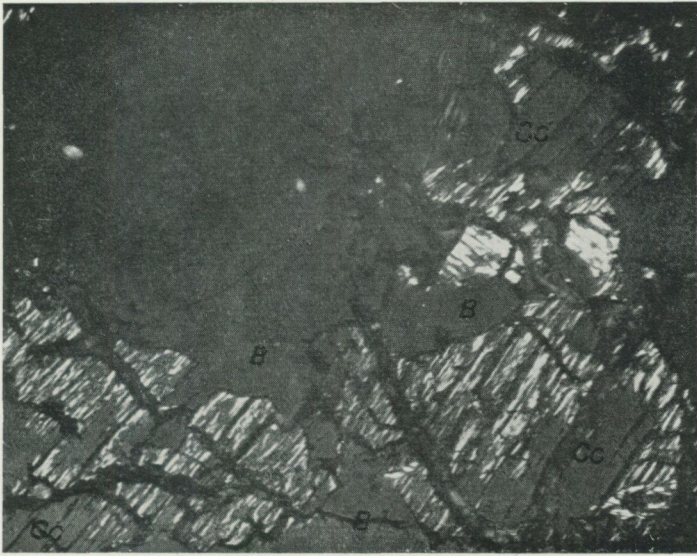


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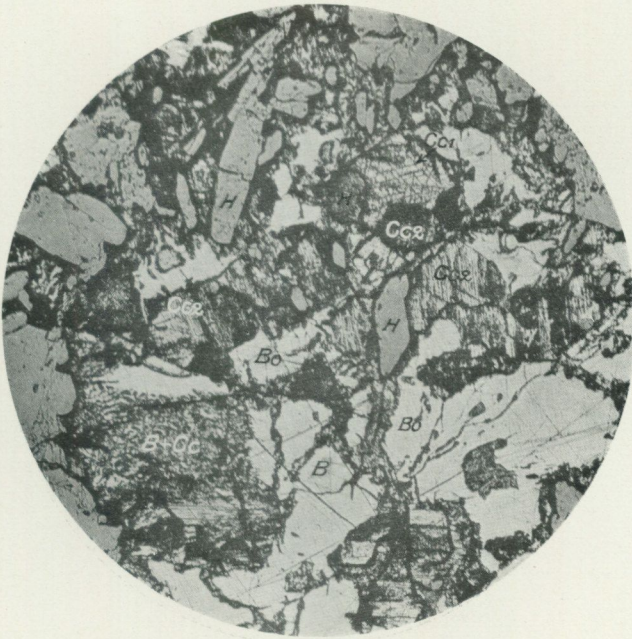


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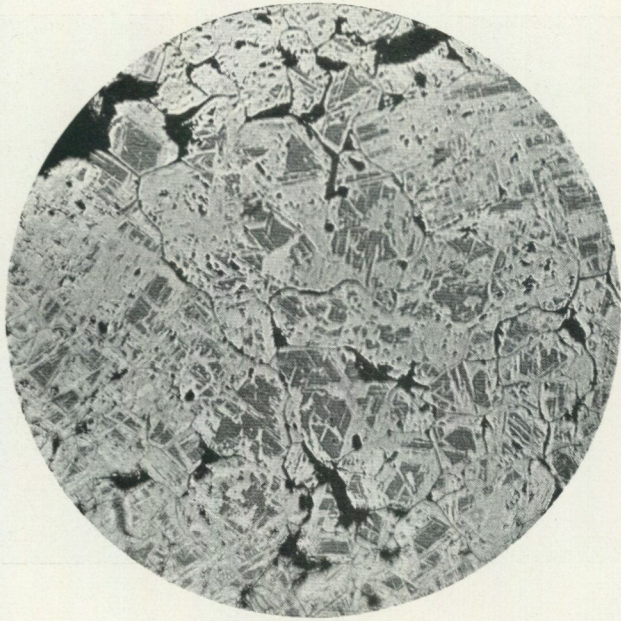


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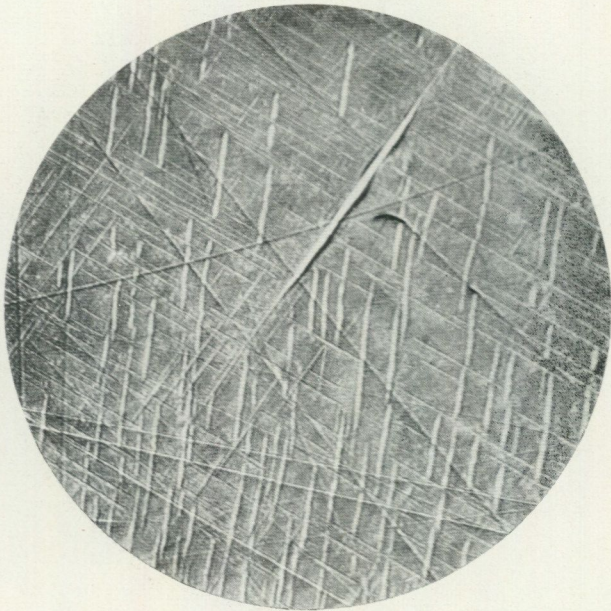


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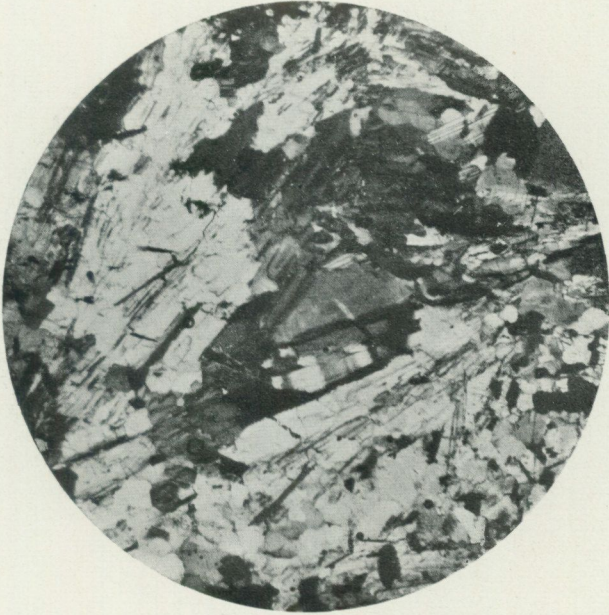


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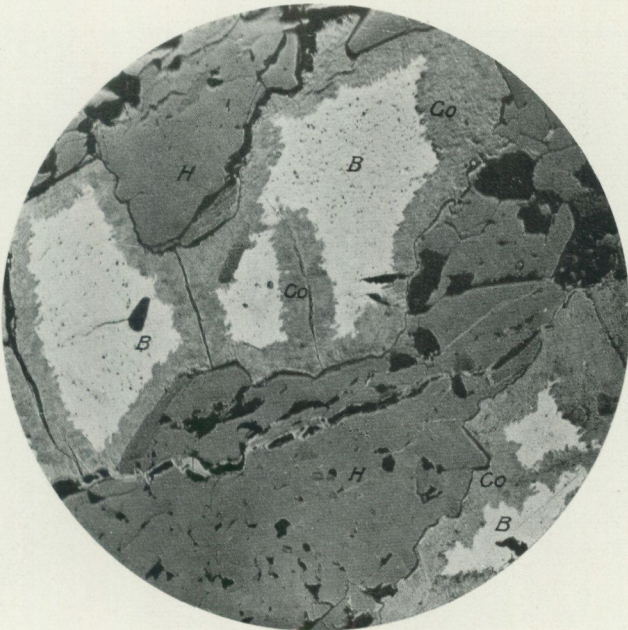


Fig. 14.

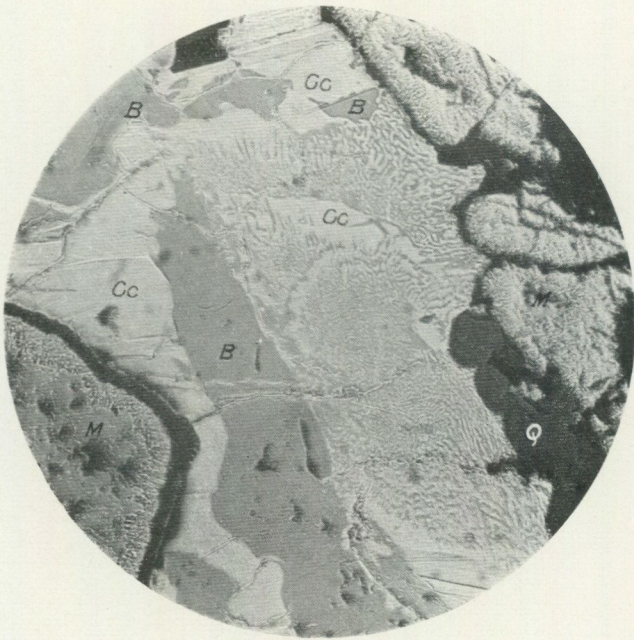


Fig. 15.

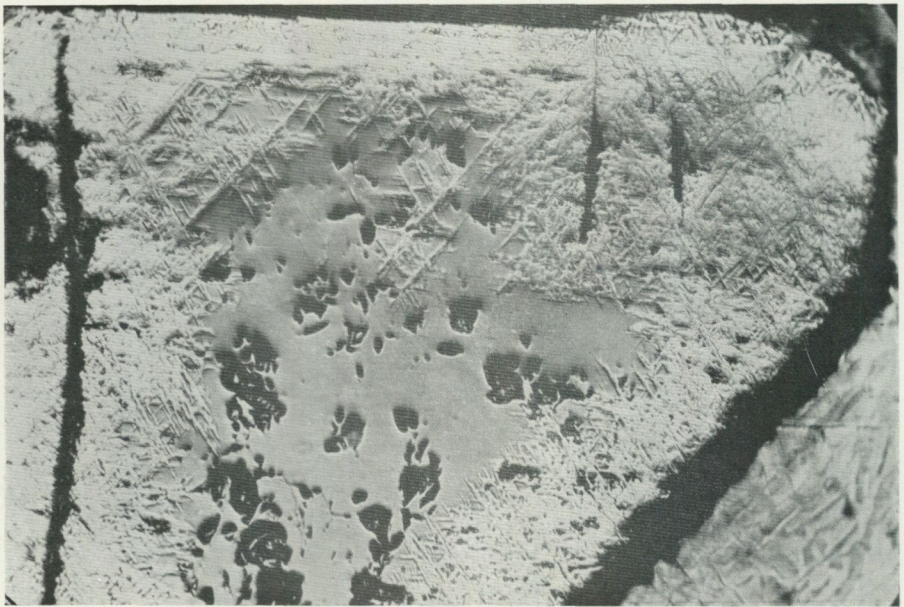


Fig. 16.

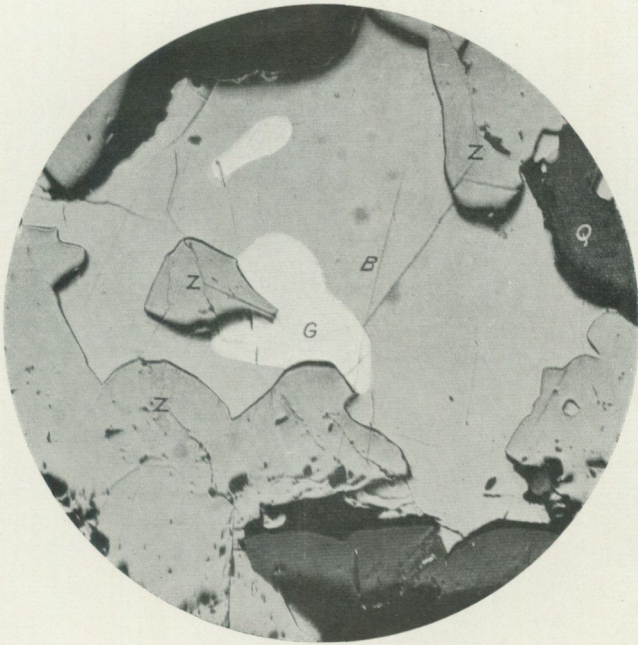


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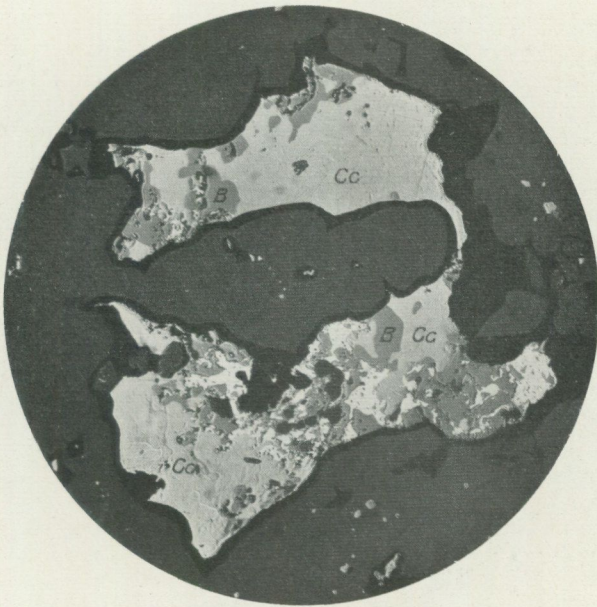


Fig. 18.

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