

# Some copper sulphide parageneses from the Raipas formation of Northern Norway

BY

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With 3 plates and 8 text-figures.

## Contents:

	Page		Page
Abstract .....	74	Copper paragenesis .....	81
Introduction .....	75	The Ulveryggen deposit .....	81
Raipas formation — general geology .....	77	Grade of deposit .....	82
Repparfjord window — general geology .....	77	The ore .....	82
Copper sulphide deposits in the Repparfjord window .....	78	Mineralogy .....	84
Pyritic paragenesis .....	78	Paragenesis .....	95
Bratthammer mine .....	79	Temperatures .....	96
The Porsa mines .....	79	Chemistry .....	96
		Raipas mine, Alta .....	96
		Other deposits .....	104
		Summary and conclusions .....	105

## Abstract.

The Precambrian Raipas formation of Northern Norway contains copper deposits showing two distinct parageneses. The first is a type common in the Scandinavian Precambrian and Caledonian ores, i. e. chalcopyrite-pyrite-pyrrhotite (the «pyritic paragenesis»). The other is much less common and consists of the association bornite-chalcopyrite-neodigenite-(chalcocite). This is termed the «copper paragenesis».

The mineralogies of deposits showing both these paragenetical types from Raipas areas in Vest-Finnmark are described, with the greatest emphasis on two deposits showing the «copper paragenesis». Especial attention is given to the question of the origin of the  $Cu_2S$  mineral. It is concluded that this is mainly neodigenite and most probably of hypogene origin, an important point when

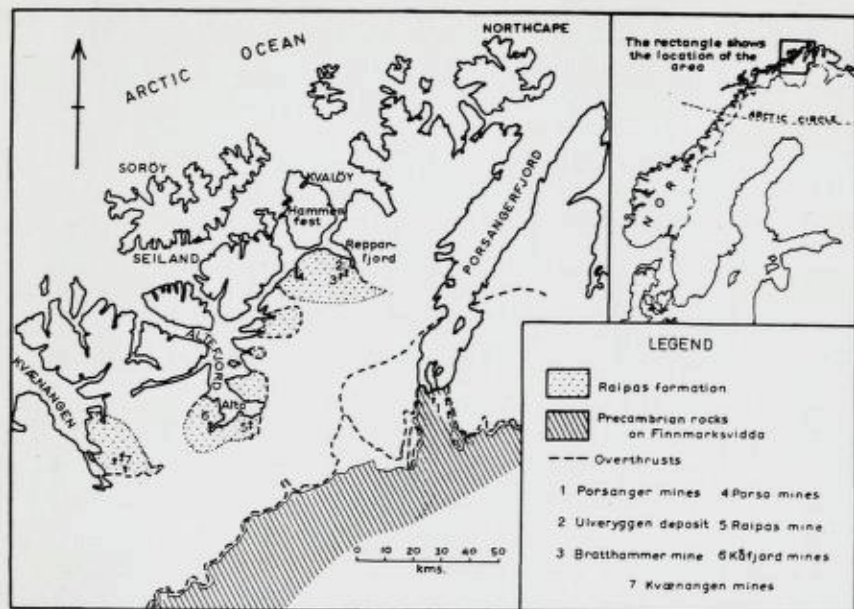


Fig. 1. Map showing the outcrops of the Raipas formation in Finnmark and the locations of the mines mentioned in the text. Geology after Holtedahl and Dons, 1953.

*Kart som viser kjente områder med Raipas-formasjon i Finnmark og beliggenheten av gruvene som nevnes i teksten. Geologien er tatt fra Holtedahls og Dons kart, 1953.*

considering the continuation of the ores in depth. The relations between the two parageneses are briefly discussed, and different origins are suggested. The occurrence of a cobalt sulphide in the ore at Raipas mine, Alta, indicates that the ores of the copper paragenesis belong to the world-wide group of Cu-Co-U ores and it is suggested that the possible occurrence of the third metal should not be overlooked.

### Introduction.

Some time ago the writer's attention was attracted by reports in the archives of the Geological Survey of Norway concerning a deposit of copper sulphide minerals which appeared to be unique for the country, and perhaps for Scandinavia as a whole. On the other hand it seemed to have great mineralogical, lithological and stratigraphical affinities with some of the economically important

ores of the Northern Rhodesian «Copperbelt», of which the writer had had recent first-hand experience.

The deposit in question was that at Ulveryggen, west of Repparfjord, in the northernmost county of Finnmark (latitude  $70^{\circ} 26' N$ , longitude  $24^{\circ} 18' E$ , see map, Fig. 1). The mineral association bornite, neodigenite, chalcopyrite, covellite occurs as a weak to moderate impregnation in feldspathic sandstones and quartzites of the Precambrian Raipas formation.

In March—April 1954, the writer examined the disused copper mine of Raipas, just south of Alta, also in Finnmark. Here the paragenesis is the same as at Ulveryggen, though the deposit consists of breccia-veins in dolomite.

The paragenesis exhibited by these two deposits is shared by a number of others (see below, p. 104) and is quite distinct from the usual pyrite-pyrrhotite-chalcopyrite paragenesis which is normal for the economically important Caledonian ores, and for numerous others of apparently Precambrian age.

The writer proposes to refer to the Ulveryggen—Raipas paragenesis as «the copper paragenesis», and to the other one as the «pyritic paragenesis».

In the present paper only those deposits occurring within Raipas formation rocks will be treated in any detail since it seems that the close juxtaposition there of deposits showing both the copper and pyritic parageneses gives the best chance of deducing the relationships between them.

It is not suggested these relationships can be solved in such a preliminary treatment of the problem as the present one, but it is hoped that it may suggest further work which can be taken up at a future date. The study of the copper paragenesis in some detail is in itself a new contribution to the knowledge of Norwegian ore deposits.

The writer has not visited the Ulveryggen locality. Mineralogical examination of specimens collected by colleagues on the staff of the Geological Survey of Norway was carried out in the Survey's laboratories at the Geologisk-Mineralogisk Museum of the University of Oslo.

The writer is grateful to P. Padget, G. McCandless and P. Reitan for the collection of specimens and for the opportunity of discussing problems arising from the study. Dr. H. Neumann

kindly placed at the writer's disposal specimens of Raipas ore in the University Museum's collections. He also gave much appreciated advice and criticism during the preparation of the manuscript.

The writer is grateful to Mr. S. Føyn, Director of the Geological Survey of Norway for permission to publish the paper.

### **Raipas formation — general geology.**

The Raipas formation is exposed in the northern counties of Troms and Finnmark as a series of tectonic windows appearing from below the overthrust metamorphic rocks of the Caledonian mountain chain. The formation consists of little metamorphosed supracrustal rocks, comprising both sediments and extrusive and intrusive igneous rocks. The most comprehensive descriptions are to be found in the writings of O. Holtedahl (1918, 1953). The map, Fig. 1, is taken from the general geological map of Norway published by Holtedahl and J. A. Dons in 1953. On this are shown several tectonic windows of Raipas formation. Mapping carried out by P. Reitan of the Geological Survey in 1956 seems to indicate that the area covered by the northernmost Raipas window is much larger than shown on the present geological map. However, since Reitan's work is in its very early stages, the present writer will treat the Raipas geology on the basis of pre-1956 knowledge.

Of greatest interest in the present connection is the northernmost of the Raipas outcrops, in the area of Finnmark lying on the mainland south of Kvaløy and west of Repparfjord (see Fig. 1). For convenience this area may be termed the Repparfjord window.

### **Repparfjord window — general geology.**

Apart from the general information on the Raipas formation contained in the two publications of Holtedahl cited above, T. Strand (1952) has published an account of the relations between the Raipas rocks and the overthrust Caledonian schists along the eastern border of the window, south and southeast of Repparfjord.

The lower division of the Raipas sequence consists of volcanic and sedimentary greenstones and greenschists which are followed by a light sandstone and a dark, somewhat sandy, shale. The upper division consists of coarse-grained feldspathic sandstone

(sparagmite) overlain by a conglomerate with a greenish schistose matrix, both deposits of a post-orogenic molasse type. There exists an unconformity (according to P. Reitan tectonic) between these and the underlying rocks. The Raipas rocks show a low grade of metamorphism, but contain intrusions of gabbroic and ultrabasic rocks (serpentinites).

### **Copper sulphide deposits in the Repparfjord window.**

In an unpublished account by Prof. J. H. L. Vogt (1907) there is given a classification of the copper-bearing deposits found in the Repparfjord window (see Fig. 1 for location of these). Within this comparatively small area Vogt was able to distinguish three different types of mineralization. His classification is based in the geological (morphological) appearance of the deposits, but as will be seen, it coincides with the paragenetical classification adopted in this paper.

The three types are:

a). Typical lodes. Calcite-quartz lodes carrying chalcopyrite and pyrite, as at the Bratthammer mine and the Porsa mines.

b). So-called «slate-lodes». Impregnations of sulphide minerals in zones of slate. No further information is given of this type, which is probably of subordinate importance.

c). So-called «sparagmite-ore». Impregnations in sandstone, conglomerate and sparagmite. Minerals are mainly bornite, chalcopyrite and neodigenite. This type occurs only in the deposits along Ulveryggen, west of Repparfjordbotn.

Thus Vogt's types a). and probably (?) b). show a mineralization of the pyritic type (pyrite, chalcopyrite) while the «sparagmite ore» at Ulveryggen has a copper-type mineralization.

### *Pyritic paragenesis.*

The deposit at Bratthammer will be taken as an example of this type. It lies only about 1 kilometre SW of the Ulveryggen deposits yet shows a completely distinct morphology and mineral paragenesis. The mineralogy of specimens from the Porsa mines in the west of the Repparfjord window will also be treated.

*Bratthammer mine.* This disused deposit lies about 5—6 kilometres WSW from the head of Repparfjord. According to Vogt (op. cit.), the deposit is an «ore-vein» having a dip of about  $30^\circ$  to the SE and cutting obliquely the schistosity of the enclosing rocks which dips at about  $85^\circ$  to the SE. The vein has been developed along a strike length of about 50 to 60 metres to a depth (measured along the dip) of about 40 metres. It shows widths of 0.6—0.8 metre in its central part, but thins out in both directions along the strike to 10 to 20 cms.

Vogt describes the vein as being composed of calcite and quartz carrying chalcopyrite and pyrite. Ore with up to 7 % Cu had been produced by hand-sorting. In all it seemed a very limited and insignificant deposit and in Vogt's opinion did not warrant further attention from an economic point of view.

Some few specimens of the ore were collected by Padget and McCandless in 1955 and have been examined by the writer. The specimens show a massive, compact sulphide ore with very little gangue visible macroscopically. In one of them the sulphides enclose a large piece of greyish calcite, which seems to represent a breccia-fragment.

Microscopical examination under reflected light shows that the ore is very simple mineralogically, containing pyrite and chalcopyrite, with small amounts of calcite as gangue. The pyrite occurs as rounded or sub-rounded, corroded grains, between 0.5—5 mm in diameter set in an even groundmass of chalcopyrite. The carbonate occurs as irregular grains and groups of grains which could be contemporaneous with the copper mineral, or more likely, could represent partly digested fragments of early-formed mineral.

There is a clear age difference between the two sulphide minerals. The pyrite is extensively embayed by the copper sulphide along the grain boundaries. In many cases the chalcopyrite sends long, irregular veinlets into the pyrite. In extreme cases all that remains of an original pyrite grain is a group of very small, ragged fragments.

No other sulphide minerals were revealed, magnetite was observed occasionally as small, euhedral crystals (octahedra) set in the chalcopyrite and apparently unaffected by any replacement

*The Porsa mines.* These mines, which are now disused, are situated in the western part of the Repparfjord window (see Fig. 1).

Chalcopyrite and pyrite occur in narrow quartz-calcite veins (1—10 metres wide) in greenstone. Mining was carried out here from 1890 to 1910 and from 1929 to 1931. According to Adamson and Neumann (1951) the grade during the last working period was about 1% Cu. They put the reserves at a few thousand tons in terms of metal content.

Specimens from the dumps at Porsa were collected for the writer by P. Reitan. The following notes are the result of a macroscopic examination of the specimens.

The specimens of compact sulphides show great similarity to the Bratthammer ones, except that pyrite is less abundant. It occurs as rounded cubes up to 2 mm diameter in a fine-grained ground-mass of chalcopyrite. Calcite occurs as irregular patches in the sulphides, often with granular magnetite. The latter mineral is more conspicuous in thin bands or streaks parallel to one particular direction in the ore. In some specimens the magnetite content becomes considerable and the mineral occurs as large coarse-grained patches in the chalcopyrite.

Less rich specimens show a manded country-rock, the bands consisting of a schist rich in fibrous green hornblende, coarse-grained calcite and quartz, and medium-grained, granular magnetite. Chalcopyrite and pyrite occur as individual grains and as patches up to about 1 cm across, scattered at random throughout this rock. In the granular magnetite bands the pyrite has often crystallized as euhedral individuals, cubes or pyritohedrons, up to 3—4 mm dimensions. This would seem to indicate that the pyrite crystallized simultaneously with, or earlier than the granular magnetite. The copper mineral on the other hand occurs as very irregular patches, often infilling between the magnetite grains, showing that as in the Bratthammer specimens it is the youngest mineral in the ore.

Specimens from the Bachke mine, three kilometres north of Porsa mine, show identical features to those from this latter locality. The country-rock at both localities seems to have been a hornblende-rich schist or amphibolite which became tectonically sheeted in the ore-zones. Calcite predominantly, and calcite-quartz veins were then deposited between the sheeted zones producing the typical «ribbon-structure» seen in many of the specimens. The metallic minerals were deposited, probably after renewed fracturing, as bands of more solid ore and as metasomes in the schist and calcite bands.

The succession of crystallization seems to have been pyrite and magnetite, followed by chalcopyrite.

The above evidence establishes the presence of an epigenetic pyrite-chalcopyrite-magnetite mineralization in a dominantly carbonate gangue at three different deposits within the Repparfjord window of Raipas formation.

During the programme of geological mapping of the Precambrian rocks of Finnmarksvidda undertaken by N.G.U., several small occurrences of almost identical type were found. These are described and discussed in a publication summarizing the results of this work up to the end of the 1955 field season (Holmsen et al., 1957).

The pyritic paragenesis is therefore widespread in the Precambrian of Northern Norway. It characteristically occurs in deposits of small dimensions, related to fracture zones, especially in the greenschist and greenstone formations. The mode of occurrence is in sharp distinction from that of the copper paragenesis in the feldspathic sandstones of Ulveryggen.

#### *Copper paragenesis.*

*The Ulveryggen deposit* lies about 40 kms SE of Hammerfest in somewhat rough, hilly country at an altitude of 250—300 metres above sea level. The mineralization occurs in a formation of arkosic sandstone (sparagmite) towards its southern border with an underlying greenstone and green schist formation (see Strand, op. cit., p. 23). The strike of the beds is roughly SW—NE, with a steep dip to the northwest (Vogt, op. cit.).

Strand describes the beds on Ulveryggen as being massive and thick-bedded sparagmites with unrounded feldspar grains several millimetres in diameter and with occasional layers of fine conglomerate. Cross-bedding shows that the succession is normal.

Vogt, in his report, points out that although he was originally responsible for the ore being called «sparagmite-ore», arkose is not the dominant rock type in the area, and much of the ore could well be called «sandstone-ore». He puts the thickness of the formation at 250 metres, as a minimum.

Microscopic observations by the present writer of specimens of the ore showed that the country rocks consist chiefly of clastic



grains of quartz and quartzite, ranging in dimensions from about 10 mm to less than 1 mm and showing marked strain extinction. Feldspar, mostly plagioclase, is a minor constituent and in several of the specimens does not show the 25 % content necessary to class them as an arkose. They may be termed feldspathic quartzite. Sericite and some chlorite occur as thin wisps and shreds interstitial to the clastic grains. The sericite appears to be due to an authigenic crystallization from detrital clayey material; there is no evidence that it is the result of any alteration processes connected with the sulphide deposition. Often it can be seen that the sulphides have filled in between the mica flakes, showing a later age of deposition.

*Grade of deposit.* The mineralization along Ulveryggen can be followed along a zone over 1½ kilometres long and up to 130 metres wide. Within this zone richer parts occur, typically lens-shaped, with the long axes of the lenses parallel to the strike of the beds. Vogt gives the average copper content of the poor impregnation ore as 0.20 %, whereas in the richer lenses grades of up to 3 % Cu are met with. Intermediate values occur in the ground surrounding these richer parts.

*The ore.* The dominant texture of the «sparagmite ore» is one where the sulphides occur as scattered patches, «spots» or grains interstitial to the clastic grains of the country rock. The sizes of these patches vary considerably, from about 5 mm or so, down to very small fractions of a mm. In the specimens examined the average grain size of the sulphide spots seemed to lie between 0.5 mm and 0.1 mm.

Microscopic examination in both transmitted and reflected light showed that the disseminated sulphides are, in their present forms, of a later age of formation than the minerals of the enclosing sediment. They have been introduced into the interstitial spaces between the rock grains and in places ragged grain boundaries seem to show that the sulphides have replaced the silicates to some extent.

The amount of sulphides contained in these dissemination ore types is usually quite small, always under 5 % and often around 1 %, though the number of specimens examined was not sufficient to arrive at an average figure. The copper values given elsewhere also show the generally low-grade nature of the copper mineralization.

Relatively larger concentrations of sulphide minerals occur in the form of veins and veinlets cutting in all directions through the sparagmite. In the specimens examined these veins were fairly common though not abundant. Their widths were usually of the order of 0.5—1 cm. In most of them a considerable amount of specular hematite was associated with the copper sulphides. The veins represent infillings of joints or shear planes in the sparagmite; along the surfaces of some of these planes there occurred weak slickensiding, evidence of slight movements probably associated with the folding of the country-rocks. In one or two cases such movement-planes did not carry a central sulphide veinlet, but for distances up to a centimetre on either side there was a marked impregnation of sulphide patches and «spots».

Such evidence seems conclusive of an epigenetic origin for the Ulveryggen mineralization, one which was controlled to a large extent by the presence or absence of joints or other planes in the sparagmite. It shows that the sulphides were introduced later than (perhaps simultaneously with) the folding movements under which the country-rocks assumed their present steep dips. The conclusion that the copper mineralization is epigenetic at Ulveryggen is in agreement with that put forward by J. H. L. Vogt in his 1907 report. In this he strongly discounts a sedimentary origin and regards the «fine streaks of ore-minerals» which are seen intersecting each other in every direction as a criterion indicating an introduced origin. The mineralizing solution had penetrated fairly evenly in between the mineral grains in the porous sediment. Parts were found which were richer than the general body of the mineralization. These parts took the form of lenticular bodies, with their long axes parallel to the bedding planes of the enclosing rocks. When followed along strike or down dip any one particular lens would disappear but new ones would come in at slightly different levels within the general zone of mineralization.

Vogt considers that a considerable depth of mineral-bearing rock (he states «several kilometres») has been eroded away since the minerals were deposited in the sediments. The mineralization would have no relation at all to the present surface of erosion and it would be reasonable to consider that it would continue to a considerable depth under this surface.

In any future field-work on these deposits it seems that attention

should be concentrated on areas showing increased incidence of joints and planes of weakness, as these would be most likely to offer areas of richer mineralization. (However, a report written by P. Padget after a visit in 1955 includes the statement that marked fracture-zones are lacking.)

*Mineralogy.* The following minerals, excluding the rock-forming silicates have been identified in the Ulveryggen ore:

Bornite .....	$\text{Cu}_5\text{FeS}_4$
Chalcopyrite .....	$\text{CuFeS}_2$
Neodigenite .....	$\text{Cu}_9\text{S}_5$
Covellite .....	$\text{CuS}$
Hematite .....	$\text{Fe}_2\text{O}_3$
Magnetite .....	$\text{Fe}_3\text{O}_4$

In addition, green and blue carbonates and silicate of copper occur as secondary products. These will not be dealt with here.

The microscopic examination has given quite clear evidence as to the paragenesis of the sulphide minerals, except the relation between bornite and chalcopyrite.

*Bornite* is the most abundant of the sulphides seen in the Ulveryggen specimens. It occurs disseminated throughout the feldspathic sandstone as specks, spots and patches of very variable dimensions, ranging in size from 0.01 mm to about 1 or 2 mm. Since it occurs interstitially to the rock-forming silicates the shapes of the grains are very irregular. It «fills in» between the clastic grains and also has partly replaced the sericitic and chloritic cementing substance between these grains. In the latter instances its grain boundaries are irregularly embayed.

The bornite patches present an even appearance and do not show any internal texture. The mineral varies in colour according to the degree of tarnish from pale to deep pink. Under oil immersion the colour is markedly deeper. The mineral is quite isotropic.

The patches and grains of bornite are almost invariably replaced to a greater or lesser extent by neodigenite and, at times, by covellite. The degree of replacement varies considerably from specimen to specimen. On occasions patches of bornite were seen which were unaffected by the alteration. The textures produced by this replacement are described under *neodigenite* and *covellite*, below.

Bornite shows a definite tendency to occur in veinlets or oriented «streaks» cutting at random through the country rock. These are mostly quite narrow; the maximum width of the veinlets observed was about 1 cm. Often micaceous hematite occurs in these veinlets (see below).

Bornite occurs in some specimens in a lattice texture with chalcopyrite (see under the latter mineral), but otherwise little can be said of the relation between these two minerals.

Bornite would appear to be primary in the Ulveryggen ore, and one of the earliest copper sulphides to be deposited, probably penecontemporaneously with the chalcopyrite.

*Chalcopyrite* also appears to be a primary copper sulphide in the Ulveryggen ore, and occurs, like the bornite, in irregular patches, grains and «spots» interstitial to the rock-forming minerals. In the specimens examined no definite veinlets or «streaks» of chalcopyrite were observed; on the other hand the patches of this mineral in the quartzite tended to be of larger dimensions than those of bornite. The average size was between 2 and 4 mm. Microscopic examination showed that, unlike the bornite, the chalcopyrite was practically unaffected by replacement processes, neither did it show any association with other primary metallic minerals. The patches and grains of chalcopyrite show even, flat fields under the microscope, without any deciphérable texture.

There would thus seem to have been, in parts of the deposit at least, a surge of mineralization leading to the deposition of chalcopyrite. Bornite, by itself, was not observed in contact with the chalcopyrite, though patches of the two minerals were seen in close proximity in the same specimen.

In some specimens from the Hans mine locality the chalcopyrite grains showed invariably a thin, even rim of a dark grey mineral with dark wine-coloured internal reflections. This is most probably limonite. It forms a thin rim around nearly all the chalcopyrite grains from this particular locality and is due to a supergene replacement of the copper mineral inwards from the grain boundaries. Fig. 2 a. shows a typical rim. Under high magnification it can be seen that the rims are composite and that the replacement «front» is always convex toward the chalcopyrite. In composite grains of chalcopyrite and neodigenite the limonite rim occurs solely at the



Fig. 2. Replacement rims of secondary limonite (li) around grains of chalcopyrite (cp). Note the absence of such rims at the grain-boundaries of the neodigenite (nd). Finely stippled areas in the neodigenite are replacement remnants of bornite.

*Fortrengnings-rand av sekundær limonitt (li) rundt kopperkis korn (cp). Merk at disse ikke finnes omkring neodigenitten (nd). Fin-prikkete områder i neodigenitten er fortrengnings-rester av bornitt.*

borders of the chalcopyrite, never at those of the other sulphide. (Fig. 2 b.) This is to be expected since Fe is absent from the  $Cu_2S$  mineral and its weathering could not produce limonite.

Chalcopyrite also occurs extensively in characteristic intergrowths with the bornite. In this latter mineral it occurs as

minute spindle-shaped lamellae mostly no more than 0.1 mm. long. The density of the spindles varies considerably, mostly just one or two of them appear in an area of bornite; at times these are parallel to a common direction, at others they cross each other at all angles. This would indicate that they occur in particular crystal planes of the bornite. At times the density of the spindles increases markedly and they form an intersecting mesh in the bornite. An extreme example of this was observed in specimens of fairly rich ore which appeared slightly crushed. In these the chalcopyrite lamellae had increased to form about 50 % of the area of the composite grains, and they took the form of a beautiful, closely intersecting lattice texture (see Plate 1).

Such textures seem to be identical with those first investigated by Schwartz (1931) who showed them to be due to the unmixing of the two minerals from solid solutions above  $475^{\circ}C$ . Such textures have since been described from several ore-deposits and have been taken as indicating a high-temperature origin (around  $500^{\circ}C$ ).

In the case of the Ulveryggen sulphides there seem to be certain difficulties in the way of accepting this «orthodox» explanation. It would seem reasonable to suppose that, if the mineralized zone had originally been invaded by sulphide-bearing solutions at or above 500°C, the rocks in this zone would have become heated up to a temperature approaching this. This condition would have been necessary for the individual droplets of sulphides to take up their positions within the quartzite, crystallize there and then unmix at a temperature around 475°C. Either that, or the small droplets must have possessed an unacceptably large degree of superheat so that they could have reached their «resting places» in the comparatively cool country-rock without having cooled themselves below, say, 500°C.

This heating-up of the ore-zone rocks *should* have produced a detectable amount of thermal metamorphism. This, however, cannot be detected. The country-rocks, both in the ore-zone and away from it, are in a very low state of metamorphism. The minerals in the matrix between the quartz and feldspar grains are predominantly sericite and a little chlorite. In one or two specimens a little dull olive-green biotite had begun to form. This association would place the rocks rather accurately on the borderline between the greenschist and epidote-amphibolite facies. (Barth, 1952, p. 337.)

The temperature to which the rocks have been subjected are thus considerably less than those necessary if the lattice textures between chalcopyrite and bornite had formed due to unmixing from solid solution.

Moreover, once having been heated up to this temperature, the ore-zone rocks would cool relatively slowly, for they represent a considerable volume. Schwartz (op. cit.) showed that when specimens showing lamellar intergrowths between bornite and chalcopyrite were cooled slowly from the unmixing temperature, the two minerals segregated into a granular intergrowth. Thus it seems that even if the two minerals had formed a lattice intergrowth at a high temperature, this would have been destroyed in the cooling-down process and the ores today would only show granular intergrowths of bornite and chalcopyrite.

The specimens of Ulveryggen ore examined in this investigation are too few to enable these incompatibilities to be resolved. However in the case of the similar ore at Raipas mine, Alta, there

is evidence strongly supporting an alternative origin for the lamellar textures between chalcopyrite and bornite. It could be that this explanation (see pp. 100—2) could also apply to the Ulveryggen ore and that a more representative suite of specimens would provide the necessary evidence.

In any case, the Raipas evidence gives a warning against placing too great a reliance on the textures of these minerals as indicating any one particular process in their formation.

The bornite-chalcopyrite intergrowth has been partly replaced by neodigenite and covellite, especially along the grain-boundaries of the sulphides and along cleavages and other cracks in them. Both minerals of the intergrowth are eventually replaced, but it can be seen that the later minerals have attacked the bornite in between the chalcopyrite lamellae first, giving a very complicated form to the «replacement front».

In the cases where the chalcopyrite lamellae occur only sparingly in the bornite it can be seen clearly that the neodigenite replacement attacks the host preferentially, often isolating individual lamellae from it, before these, too, are eventually swallowed up. However, as has been stated above, the areas of pure chalcopyrite in the ore never show replacement by the copper sulphides.

Thus we may conclude that there are two generations of chalcopyrite in the ore. The first never occurs with other minerals, but as pure, irregular grains, spots and patches in the sedimentary country rock. It may be of approximately the same age as the bornite, but since the two minerals were not seen in contact, their relative ages could not be determined. This seems to raise an interesting question to be solved by any future investigation. Are parts of the ore characterized by chalcopyrite as the primary copper mineral and other parts by bornite? That is to say, has there been a primary mineral zoning in the deposits?

The second generation of chalcopyrite would appear to occur as the lamellae in the lattice intergrowth with bornite. The relation between these two generations is not clear.

*Neodigenite.* There occurs in the ores, replacing bornite to varying degrees, a pale sky-blue, isotropic copper sulphide which optically and paragenetically corresponds to the so-called «isotropic blue chalcocite». The writer has followed Ramdohr (1943) and

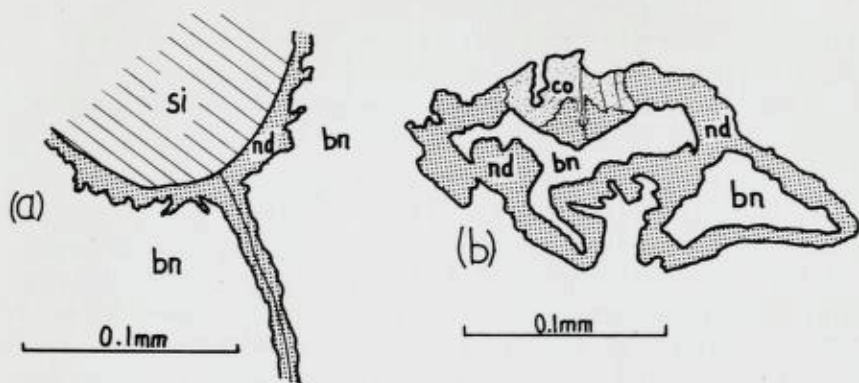


Fig. 3. a). Neodigenite (nd) replacing bornite (bn) along its grain-boundaries with a grain of gangue (si) and on either side of a micro-fracture. b). Sketch of typical rim-replacement of bornite (bn) by neodigenite (nd). Covellite (co) is in its turn replacing the neodigenite.

a). Neodigenitt (nd) som fortrenger bornitt (bn) langs korn-grensene mot et kvartskorn (si) og langs en mikrosprekk i bornitten. b). Bornitt (bn) er fortrengt langs randen av neodigenitt (nd). Covellin (co) fortrenger i sin tur neodigenitten.

Uytenbogaardt (1951) in using the name *neodigenite*. The name *digenite* was proposed by Buerger (1941), who first established the existence of the form and showed it to have the formula  $Cu_9S_5$ .

Etching with 1 : 1  $HNO_3$  brings out the cleavage pattern very clearly. It shows a series of closely-spaced parallel cleavage cracks, with a subsidiary, though well-defined set at right angles. The two sets divide the mineral into square or rectangular «blocks». No instances were seen of the octahedral etch cleavage which is regarded as being characteristic of the isometric neodigenite.

However, X-ray powder patterns confirmed the identification of the mineral as the isometric form of  $Cu_2S$ .

Neodigenite occurs solely as a replacement product of bornite, it was not observed as an independant mineral in the ores. The degree of replacement varies considerably from specimen to specimen and between different bornite patches in the same specimen.

The most common texture is a «rim replacement» of the bornite grain by the neodigenite, starting from the grain boundaries of the former mineral. The «rim» may vary from a mere film surrounding the bornite to an almost complete replacement of it, leaving only very irregular remnants to show the original nature of the grain.



The replacement has proceeded very unevenly and the «fronts» normally show the most intricate and embayed forms.

No dependence on the structure of the bornite, e. g. the cleavage, could be observed, but replacement veinlets of neodigenite were often seen following fairly irregular cracks in bornite. In other cases intricate replacement patches of the blue sulphide occurred at random in the bornite grains. Examples of the textures formed by the two minerals are given in Fig. 3. Plate 2, Fig. 1, illustrates a beautiful semi-graphic texture seen occasionally, which represents an extreme stage of the replacement of the bornite.

The amount of bornite replaced by the neodigenite must be quite considerable, in many specimens probably about a third was so affected, but the average is probably less. The net effect of the alteration is an increase in the copper content of the ore, there being a loss of iron and sulphur from the bornite.

The nature of this replacement is discussed below.

The larger areas of neodigenite formed by the replacement of bornite show often a well-marked cleavage (see above). The cleavage cracks are often filled with a later mineral, in some cases a green secondary copper mineral (carbonate). The cleavage cracks are so fine that certain identification of the late mineral is difficult. The cracks have also acted as loci for the secondary replacement of the neodigenite by the covellite (see below).

An extremely important question is the origin of the neodigenite replacing the bornite. Is it supergene or hypogene? The answer to this question would have a considerable bearing on the possible economic importance of the Ulveryggen deposit. If the alteration is supergene (secondary enrichment) one would expect a falling-off of values in depth as the protore is reached. In view of the fact that the ore exposed at the surface and in the shallow workings is itself not of very high grade, any such falling-off in depth would make the deposit of doubtful economic worth.

However, it seems from a study of the relevant literature that the replacement has been of a hypogene character. It has been mentioned that neodigenite is the mineral which was termed in older publications «isometric blue chalcocite». It was thought that there were two modifications of chalcocite, one orthorhombic and one isometric. Of these, the latter was established as having a temperature of formation above 91°C. On cooling, this modification inverted

to the orthorhombic form, but it was thought that if more than 8 % of CuS were in solid solution the inversion was inhibited.

In the earlier literature dealing with the copper sulphides the isometric form of  $\text{Cu}_2\text{S}$  was considered to be diagnostic of hypogene conditions of deposition. For example, Emmons (1933), in a general discussion of copper sulphide enrichment, states that «a chalcocite that is isometric or that is a paramorph after isometric chalcocite may be taken as evidence of hypogene origin» (p. 406).

Again, Bateman and Lasky (1932) in a discussion of the copper deposits at Kennecott, Alaska — «most of the . . . . chalcocite has been found to be isotropic and therefore isometric. Consequently it is the high temperature form and is definitely of hypogene origin.»

However, the restudy of the system  $\text{Cu}_2\text{S}$ —CuS by N. W. Buerger (1941) showed a rather more complicated state of affairs. He established three compounds in the system, i. e.

Chalcocite (ideally  $\text{Cu}_2\text{S}$ )  
Digenite  $\text{Cu}_9\text{S}_5$  — here termed Neodigenite  
Covellite CuS.

These compounds exhibit four phases:

High chalcocite  
Low chalcocite  
Digenite  
Covellite.

A study of the phase diagram established by Buerger (op. cit., p. 35) shows that (neo)digenite, having the composition  $\text{Cu}_9\text{S}_5$ , is stable at all temperatures from 20°C upwards. Above 78°C this mineral is able to take increasing amounts of either chalcocite or covellite into solid solution. A (neo)digenite with greater than 20 atomic percent CuS forming at elevated temperatures, would on cooling, unmix to give an intergrowth of neodigenite (of composition  $\text{Cu}_9\text{S}_5$ ) and covellite. On the other hand, with less than 20 atomic percent CuS, there will result an intergrowth chalcocite and covellite, which was referred to in the older literature as an intergrowth of «white and blue chalcocite».

Most of the neodigenite in the Ulveryggen specimens occurs by itself — a very minor proportion only occurs intergrown with

the so-called «abnormal covellite» (see below, p. 93) in a manner suggesting contemporaneous crystallization. There is no conclusive evidence to show that either chalcocite or covellite has unmixed from the neodigenite and thus the original composition was probably not far from  $\text{Cu}_9\text{S}_5$ . According to Buerger's diagram such material could have originated at either high or low temperatures, and it therefore cannot be used to decide supergene or hypogene origin.

Among the more recent contributions to this problem, P. Ramdohr (1943) came to the conclusion that the cubic mineral (neodigenite) in the system  $\text{Cu}_2\text{S}$ — $\text{CuS}$  was *a priori* no geological thermometer, since its occurrence was exclusively governed by the excess or deficiency of sulphur in the ore-forming media. In a table (op. cit., p. 309) Ramdohr gives his interpretation of the various «chalcocite» minerals occurring in natural ores. «Blue isotropic chalcocite as the older mineral» is to be interpreted as neodigenite formed above  $78^\circ\text{C}$ . The same mineral occurring cementatively, mostly after bornite, is neodigenite formed under  $78^\circ\text{C}$ , i. e. secondary.

Ramdohr later (1950) discusses at length the interpretation of Buerger's results in terms of the textures exhibited by the  $\text{Cu}_2\text{S}$  —  $\text{CuS}$  minerals in nature. Here he is of the opinion that «neodigenite is *mostly* formed at higher temperatures» (p. 288).

Thus it can be seen that the question of the temperatures of formation of the  $\text{Cu}_2\text{S}$ — $\text{CuS}$  minerals is far from being solved. The weight of *opinion* in the literature seems to be in favour of a high temperature origin for the cubic mineral, neodigenite.

Of the graphic and subgraphic replacement intergrowths between bornite and neodigenite (Pl. 2, Fig. 1), Schwartz (1932) states that the weight of evidence seems to indicate that they are commonly a result of hypogene processes, but that the texture, as such, is unreliable as a criterion. Lindgren (1930) discussed the textures under the name of «pseudo-eutectic intergrowths» and concluded they were due to hypogene replacement.

A negative piece of evidence against secondary alteration in the Ulveryggen ore is the complete absence from it of the so-called «sooty chalcocite», which is the only form which is regarded as being absolutely diagnostic of supergene origin.

More general considerations make it unlikely that supergene enrichment has affected the Ulveryggen deposit. The complete lack

of pyrite would mean that any secondary leaching processes would have been slow in the extreme. Most students of secondarily enriched copper deposits are agreed that sulphuric acid generated by the oxidation of pyrite is vitally important for the processes of secondary enrichment.

The absence of an upper, leached, low-grade zone or capping is not evidence against secondary enrichment since this could quite well have been removed by the strong erosion occurring during the Quaternary glaciation.

*Covellite* is a minor component of the bornite-bearing parts of the ore, but one which is unmistakable on account of its very characteristic effects under the microscope. It occurs very largely in forms indicating that it is replacing the neodigenite. More infrequently it seems to have replaced the bornite directly without an intervening neodigenite stage. It was never observed attacking chalcopyrite when this mineral occurred alone.

Optical properties indicate that there are two types of covellite present:

a) the more common type shows very strong and characteristic pleochroism, O:deep inky blue, E:bluishwhite, in air. Under oil immersion the pleochroism is greatly accentuated, O becomes a deep violet to purple-red, while E is somewhat darker blue. Anisotropism is marked and distinctive, from a fiery orange to dark brown.

b) the less common type shows much less distinctive pleochroism in shades of light and dark blue. Under oil immersion the only noticeable effect is a slight accentuation of the colour differences. Anisotropic effects are very much toned-down as compared with type a).

These two types are well-recognized in the literature. Uytendogaardt (1951) refers to the second type as «anomalous covellite» and regards it as the less common of the two.

Ramdohr (1950, p. 472) also describes the different optical properties of «normal» and «abnormal» covellite, his descriptions corresponding exactly with those just given. The abnormal covellite has been observed from many localities, including Rio Tinto and Chucquicamata, as well as from some of the American «porphyry copper» deposits (e. g. Morenci). In a number of cases the normal

and abnormal covellites were seen together in the same polished section, with the latter type mostly appearing as being formed the later of the two. Nearly always the abnormal covellite occurred intergrown with chalcocite in tabular forms parallel to the (001) direction.

The covellite-types from Ulveryggen show certain similarities with Ramdohr's description.

a) «Normal covellite» appears in very irregular minute patches within, or on the borders of, the areas of neodigenite. These patches have very complicated textures, being made up of feather- or flame-shaped individuals, often arranged in a sub-parallel radiating pattern.

The patches sometimes appear enclosed in a larger area of neodigenite, but mostly they are located at grain boundaries and along the well-marked cleavages of this mineral (see Plate 2, Fig. 2). From these points the covellite appears to have worked its way irregularly into the neodigenite, not following any crystallographic directions.

Examination under high magnification shows the cleavages of the neodigenite to be filled with a dull grey, non-sulphide mineral, sometimes giving coloured internal reflections. It is not clear if the covellite is genetically connected with this infilling of the cleavage cracks.

b) The «abnormal» covellite occurs as larger areas, sometimes lamellae-shaped, in the areas of neodigenite. In some cases it seems to have «flooded» irregularly into the neodigenite as though replacing it. In other cases the broadly lamella-shaped patches seem to be intergrown with the neodigenite as though the two minerals were contemporaneous. However, nothing resembling a regular lattice intergrowth was seen, and it is doubtful if the covellite could have exsolved from the neodigenite.

The covellite is in except a very few cases clearly a product of replacement of the neodigenite, but it is not clear whether this is supergene or hypogene. From the general mode of occurrence of the mineral, a supergene origin would be indicated.

*Hematite.* Micaceous specularite occurs extensively in the Ulveryggen deposit. Characteristically it occurs coating the joint surfaces of the rocks as an interlocking mesh of platy crystals, up to

2—3 mm in diameter. In other cases it occurs as isolated, tabular crystals or groups of crystals scattered irregularly throughout the rock.

The hematite always shows regular crystal outlines towards the copper sulphides, when these occur together. The latter appear to be «moulded» around the iron oxide and the evidence is that the latter is everywhere older than the sulphides.

In one specimen a composite oxide-sulphide vein was observed cutting through the bornite-impregnated sandstone. The vein was  $\frac{1}{2}$ —1 cm wide and along one of the walls occurred a fairly continuous growth of regular platy hematite, with crystals about 1 mm in dimension. The rest of the vein was filled bornite and neodigenite, the latter strongly replacing the former. The sulphides had clearly «filled-in» against the hematite crystals and represented deposition in the vein after the formation of the hematite along one wall.

The hematite crystals, especially the larger, less regular ones showed numerous very small inclusions of a grey-brown isotropic mineral. The inclusions were mostly very irregular and ragged, often occurring in groups which suggested the remnants of an originally much larger grain. These relationships show they are replacement residuals in the hematite. The optical properties indicate that the mineral is *magnetite*.

In other specimens irregular veinlets of specularite were seen intersecting the country-rock. The mineral was present as thin micaceous lamellae intersecting in all directions. The lamellae showed a fine twinning at high angles to their longest dimensions. Magnetite was present in larger proportions in such veinlets, often in well-formed, octahedral crystals.

This oxide paragenesis must be regarded as separate from, and much earlier than, the sulphides, and most probably of a higher temperature of formation.

*Paragenesis.* The evidence given in the description of the different minerals shows the following facts regarding the order of succession. Firstly the sulphides are later than the oxide minerals. Secondly there is the clear replacement succession: bornite—neodigenite—covellite, where the first replacement is probably hypogene, the second more probably supergene. Thirdly there is the lattice

intergrowth in parts of the ore between bornite and chalcopyrite, showing (?) contemporaneity between these two minerals in certain cases. Fourthly no evidence has come to hand regarding the age relationship between the main parts of the chalcopyrite and the bornite.

*Temperatures.* The presence of the lattice intergrowth texture between chalcopyrite and bornite could be interpreted as meaning that in parts at least of the deposit the temperature of the introduced sulphides attained a minimum of 475°C, but there are objections to this interpretation, as set out on pp. 86—88. The neodigenite probably replaced part of the bornite at a temperature around 100°C.

*Chemistry.* The ore at Ulveryggen is chemically simple, with Cu, Fe and S as the main introduced constituents. A spectrographic investigation\* of a sulphide concentrate from the ore showed the following «trace» elements:

Ag, order of size	.....x/100 %
Cr, —	.....1/100 %
Mn, —	.....1/100 %
Ni, —	.....x/100 %
Pb, —	.....x/100 %
V, —	.....1/100 %
Zr, —	.....1/100 %
Zn, (trace)	.....(1/10 %)

These figures would seem to indicate that very little in the way of valuable by-products could be expected from a copper concentrate from the Ulveryggen ore.

The absence of Co is surprising, and disappointing, in view of the occurrence of a cobalt mineral in the mineralogically similar ore of the Raipas mine, Alta, (see below).

*Raipas mine, Alta.* This disused copper mine lies in rocks of the Raipas formation, but in a separate tectonic window from that containing the above-described deposits (see Map, Fig. 1). The mine produced small quantities of high-grade copper ore in the middle of the 19th Century. The present writer made an under-

\* Analyst: Sentralinstitutt for industriell forskning, Oslo.

ground examination of the mine in March—April 1954, and later published a short account of the general geology and vein structures (Vokes, 1955).

The deposit consisted of breccia-veins which cut almost at right angles the N—S-striking dolomites and mudstones of the Raipas formation in this Alta window.

The rich sulphides occurred mainly cementing and partly replacing the fragments of the country-rock breccias (Plate 3, Fig.1). They comprised mainly chalcopyrite and bornite, with lesser amounts of tennantite and the cobalt-nickel sulphide, siegenite. Neodigenite, chalcocite and covellite are quantitatively minor constituents.

This is the first recorded instance of the presence of siegenite in a Norwegian ore deposit, and the properties, mode of occurrence and paragenesis of the mineral are treated in a separate publication. Tennantite is also uncommon in Norwegian ore deposits. It has previously been found in the cobalt deposits of the Modum district.

Microscopic examination of the specimens of Raipas ore revealed many features in common with those from Ulveryggen, but there also occurred new features which indicated that the two deposits have had somewhat different mineralogical histories. Particular emphasis will be laid on these new features in the following discussion.

It was possible to obtain a clear idea of the relations between the *chalcopyrite* and *bornite* in the Raipas ore; this important information was lacking from the Ulveryggen specimens. Together, the two minerals formed over 95 % of the sulphides in the ore. Their proportions varied considerably from specimen to specimen, but on the average chalcopyrite was dominant over the bornite in the ratio of about 3 : 1.

When present together, the two minerals are intimately intergrown in a very characteristic texture. In this the boundaries between the bornite and the chalcopyrite are smooth and curved, but *always* convex towards the bornite. Thus, patches of bornite within the chalcopyrite appear as cusped remnants, often very elongated in one dimension. On the other hand, the chalcopyrite always appears as rounded forms within the larger areas of bornite. Typical views of this texture are shown in Fig. 4.

At first this texture gives the impression that the bornite is the



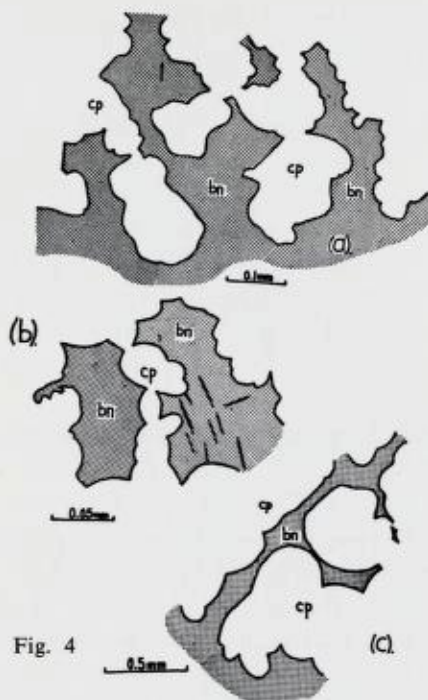


Fig. 4

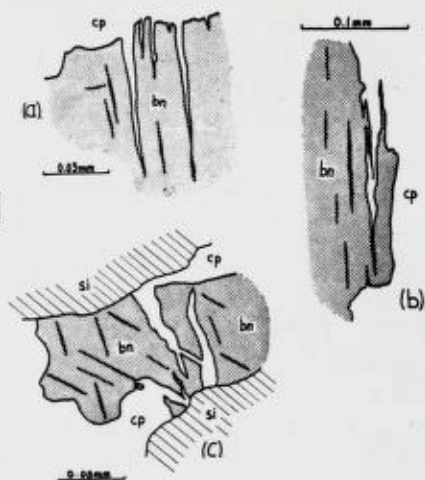


Fig. 5

Fig. 4. Sketches from polished sections of Raipas mine ore showing typical «caries-texture» between chalcopyrite (cp) and bornite (bn) which shows that the former is replacing the latter. In (b), the thick black lines are chalcopyrite lamellæ.

Skisser fra polerslip av malm fra Raipas gruve som viser typisk «caries-struktur» mellom kopperkis (cp) og bornitt (bn). Denne struktur viser at kopperkisen fortrenger bornitten. De tykke sorte linjer i (b) er lameller av kopperkis.

Fig. 5. Sketches from polished sections of Raipas mine ore showing how the main generation of chalcopyrite (cp) has penetrated earlier bornite (bn) along its cleavage directions. Within the bornite, lamellæ of «secondary» chalcopyrite (black) also lie parallel to its cleavage.

Skisser fra polerslip av Raipas malm som viser hvordan hoved-generasjonen av kopperkis (cp) trenger inn i eldre bornitt (bn) langs spalte-retningene. Lameller av «secundær» kopperkis (sort) finnes også inne i bornitten parallelt med spaltereningene.

younger mineral and has filled interstices between the chalcopyrite grains. However, certain textures to be described below indicate clearly that the chalcopyrite is definitely the younger mineral. Also one has not to search long in the literature to find that the chalcopyrite—bornite texture shown in the Raipas specimens is identical

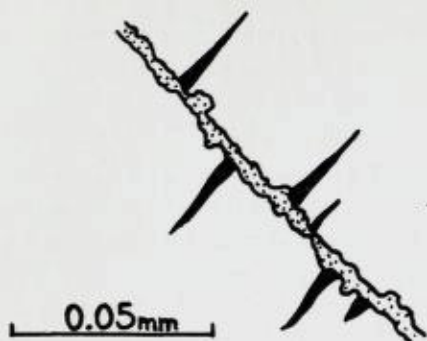


Fig. 6



Fig. 7

Fig. 6. Lamellæ of «secondary» chalcopyrite (black) growing out from a replacement veinlet of neodigenite (stippled) along the cleavage directions of bornite (white).

*Lameller av «secundær» kopperkis (sort) som vokser ut fra en fortrensnings-gang av neodigenitt (prikket) langs spalte-retninger i bornitt (hvitt).*

Fig. 7. Neodigenite «worms» in bornite (white) along both sides of a neodigenite replacement veinlet (stippled). Lamellæ of «secondary» chalcopyrite shown in black.

*«Ormer» av neodigenitt langs en fortrensnings-gang av samme mineral (prikket) i bornitt (hvitt). Kopperkis lameller tegnet sort.*

with one that is well-recognised as a replacement texture. This has been given the name «caries texture» by Lindgren because of the strong resemblance to dental caries. The mineral exhibiting the convex forms is interpreted as replacing the other one, and the cusped forms are remnants showing an extreme stage of the replacement (e. g. Fig. 4 c).

The «caries texture» indicates that the bornite has presented a uniform resistance to replacement by the chalcopyrite; the latter has «bitten into» the bornite without paying any attention to its cleavage. However, there frequently appeared textures showing that the chalcopyrite often had followed structural directions in the bornite during its attack. These textures are illustrated in Fig. 5. This figure shows how the chalcopyrite penetrates deeply into the bornite in long «spear-like» forms. As can be seen, these spears are parallel with the chalcopyrite lamellæ which appear as a crystallo-

graphic intergrowth in the bornite (see below). The chalcopyrite has thus penetrated the bornite along its cleavage directions, which are clearly marked by the lamellar texture.

The textures described above present good evidence of an age difference between the two main copper minerals in the Raipas ore. However, one important mineralogical problem must remain unsolved and that is whether there was any systematic change in the proportions between chalcopyrite and bornite with depth.

The lamellar texture between bornite and chalcopyrite mentioned above is fairly common where the two minerals occur together. A number of specimens, however, showed bornite as the only copper-iron sulphide and in these the lattice texture was absent.

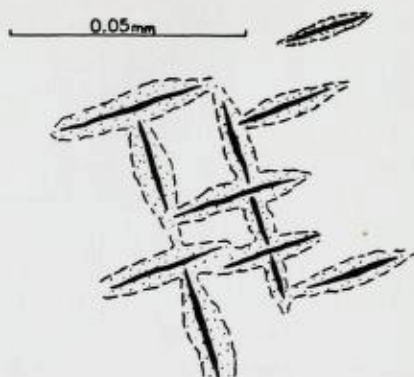
The similar textures occurring in some of the specimens from the Ulveryggen deposit have already been described above (pp. 86—87). However, in the Raipas specimens no parallel has been noted of the close lattice-texture in which bornite and chalcopyrite occur in about equal amounts (Plate 1) and which was interpreted as possibly being an exsolution texture.

The chalcopyrite lamellae in the Raipas bornite are much thinner than in the Ulveryggen examples, and show a much more uneven distribution. Although they occur in two of the crystallographic directions of the cubic mineral they very seldom intersect each other, which means that a true lattice-texture is not developed. The lamellae also show increased incidence in bornite along each wall of the numerous replacement veinlets of neodigenite which often intersect the bornite (Plate 3, Fig. 2). In several cases it could be seen that the chalcopyrite lamellae branched out from the sides of the neodigenite veinlets, as illustrated in Fig. 6. In such cases there would seem to be an undoubted genetic connection between the veinlets and the lamellae. Under high magnification it can be seen that the bornite along the walls of neodigenite veinlets is often completely «riddled» by minute hair-like «worms» of neodigenite, (Fig. 7) as though the bornite had been crushed and the neodigenite had been formed on either side of the microscopic cracks. Within these areas, too, the chalcopyrite lamellae were usually more abundant.

Also, high-power magnification showed that often the bornite on either side of the chalcopyrite lamellae was of a distinctly lighter colour than usual and that this lighter-coloured patch was bordered on the outside by a line of thin neodigenite «worms», (Fig. 8).

Fig. 8. Lamellæ of «secondary» chalcopyrite (black) in bornite (white). Each lamella is surrounded by an area of bornite of an apparently different composition (stippled) which is separated from the rest of the bornite by a line of neodigenite «worms» (short black lines).

*Lameller av «secundær» kopperkis (sort) i bornitt (hvit). Disse lameller omgis av bornitt som øyensynlig har en forskjellig sammensetning fra hovedmassen. På ytter-kanten av denne bornitten finnes en rekke små «ormer» av neodigenitt (korte sorte linjer).*



This evidence would suggest that the formation of the lamellæ of chalcopyrite in the bornite was in some way connected with the alteration bornite—neodigenite.

Zies, Allen and Merwin (1916) produced similar lamellæ of chalcopyrite in the crystallographic directions of pieces of bornite by immersing them in a 2½ % solution of  $H_2SO_4$  at 200°C for periods of 2 and 8 days respectively. These authors interpret the mode of formation thus: «The acid first attacked the surface of the bornite, altering it to cupric and cuprous sulphides; ferrous sulphate and hydrogen sulphide being formed at the same time. The interior thus became protected from the direct action of the relatively strong acid and the small amount of acid which did penetrate was greatly weakened by reacting with the bornite. Under these conditions we have found that ferrous sulphate, cupric or cuprous sulphide, and hydrogen sulphide will react to form chalcopyrite. The most likely place for the chalcopyrite to develop will be of course along the lines of fracture and cleavage since they afford to the acid the readiest means of ingress.»

The above workers also found blades of chalcopyrite «seemingly following the cleavage cracks in the original bornite» after the sample had been immersed for one day in cupric sulphate at 200°C. Sulphuric acid was detected in the solutions at the end of this experiment, so the mode of formation of the chalcopyrite was probably identical with that in the first experiment, using sulphuric acid alone.

Edwards (1954) figures and describes a case where minute spindles of chalcopyrite developed in bornite as a temporary phase at the edge of a chalcocite replacement veinlet. This author considers that the chalcopyrite spindles dissolve as the replacement proceeds and that new ones are precipitated at the loci of replacement. He gives the equation for the change as



The textures observed in the Raipas ore would indicate that some, at least, of the chalcopyrite lamellae owe their formation to processes which also led to the formation of the neodigenite veinlets and «worms».

The microscopic work indicates that most of the  $\text{Cu}_2\text{S}$ -mineral at Raipas is the same as that at Ulveryggen — i. e. it is the isotropic, and therefore isometric, mineral neodigenite. In the case of the Ulveryggen deposit it was concluded that this mineral had formed under hypogene conditions, and there seems to be no reason to change that conclusion in the case of the Raipas ore.

In one specimen the  $\text{Cu}_2\text{S}$  mineral occurred in larger patches, full of bornite replacement remnants. A good deal of the mineral in these patches showed a weak but distinct anisotropism. This may be interpreted as showing that part of the originally isometric neodigenite has inverted to the lower temperature, orthorhombic chalcocite (see also p. 109).

The evidence would indicate therefore that a hypogene replacement of bornite to neodigenite had caused the formation of chalcopyrite lamellae in exactly the same manner that the action of sulphuric acid produced it in the experiment of Zies, Allen and Merwin.

This brings one to the question of the relation of the main body of chalcopyrite in the ore to that in the lamellae within the bornite. The main generation of chalcopyrite is, as shown above, replacing the bornite. It is also demonstrably older than the neodigenite. For instance, micro-veinlets of neodigenite sometimes follow the bornite-chalcopyrite contacts. Also, the cracks in the bornite, which were the loci for the neodigenite replacement veinlets, are present in the chalcopyrite too. While the latter mineral has clearly not been replaced by the neodigenite, this mineral has often been deposited in these cracks for short distances from the bornite contact.

The evidence therefore indicates that the «main» generation of chalcopyrite is older than that which forms the lamellae in the bornite. Thus the spear-like forms of chalcopyrite penetrating into the bornite, as figured in Fig. 5, must be interpreted as being independent of the chalcopyrite lamellae within the body of the bornite. The fact that they are parallel is due to their being also controlled by the cleavage directions of the bornite.

The blue copper sulphides are quantitatively minor in amount. *Neodigenite* occurs in thin replacement veinlets which traverse the bornite in all directions. The locus of replacement was in each case a micro-fracture in the host mineral. The junctions of the bornite with the country-rock fragments also usually show a thin replacement rim of neodigenite. The occurrence of *chalcocite* has already been noted above (p. 102). *Covellite* was very scarce in the specimens examined. Its brilliant anisotropic effects showed it to be present as minute specks in some of the wider neodigenite veinlets.

*Tennantite* is widespread in the Raipas ore in subordinate amounts. Under the microscope it is light-grey in colour and quite isometric; it was only distinguished from sphalerite by its X-ray powder diagram. The mineral occurs as rounded, anhedral grains, mainly in the chalcopyrite fields and its mode of occurrence gives little indication of its place in the paragenesis. It could either be contemporaneous with, or older than, the chalcopyrite.

A seventh mineral in the Raipas ore could not be definitely identified due to its extremely fine state of division and minute quantity. It occurs as microscopic rim and patch replacements at the grain boundaries of the tennantite and, to a lesser extent, the bornite. It is silver-white in colour, soft and as far as can be seen, isotropic. From its paragenesis and optical properties it could be galena, though none of that mineral's characteristic cleavage was seen.

In the specimens of Raipas ore examined during this investigation there appeared no evidence to show that any non-sulphide gangue-minerals have been deposited in the veins. Dolomite occurs as breccia fragments derived from the wall-rocks, and it would be difficult to distinguish fragments from patches of introduced carbonate earlier in age than the sulphides. Attention should be drawn to the occurrence of large quantities of *barite* in one of the vein structures at Raipas; the relation of this mineral to the sulphides is not known.

The *paragenesis* at Raipas would appear to be thus:

siegenite  
bornite  
chalcopyrite and (?) tennantite  
neodigenite, chalcocite, covellite  
«secondary» chalcopyrite (lamellae)  
unknown sulphide — position uncertain.

None of the textures or minerals can be used to give any indications of the *temperatures* at which they were deposited.

West of Raipas mine, around Kåfjord, are situated a number of old mines. These worked vein-type deposits in greenstones of Raipas age. The ore here showed the pyritic paragenesis. The differences between Raipas mine and the Kåfjord mines are, therefore, comparable to those between the Ulveryggen deposit and, say, the Porsa mines.

*Other deposits.* The copper paragenesis is widespread in rocks of Precambrian age in Norway. The deposits are mostly of minor economic importance; none are being worked at the moment, very few have been exploited in the past. In the majority of cases the copper sulphides occur in quartz veins or pegmatite bodies and no parallel to the «sparagmite-ore» of Ulveryggen appears to have been found.

*Porsanger, Finnmark.* S. Foslie (1933) mentions the extensive low-grade copper mineralization at Porsanger (see Fig. 1), some of which must be classed in the copper paragenesis. The deposits, according to Foslie are remarkable for their great extent. Numerous deposits are scattered over an area of about 150 square kilometres, where the rocks are amphibolites with subordinate belts of quartzite and dolomite. The copper minerals, mainly bornite and chalcocite, have partly impregnated the amphibolites, partly they occur in veins and veinlets of quartz within this rock.

In the same area it appears that there also occurs extensive mineralization of the pyritic type. Pyrrhotite, pyrite and a little chalcopyrite occur as impregnations in schist over long zones following the schistosity. (See C. W. Carstens, 1931 and J. Færden, 1952).

These deposits have not been worked.

*The Sjangeli copper mines* would also come into this group according to Foslie's description. They are situated in the Precambrian rocks of the Rombak window, due east of Narvik, on both sides of the Norwegian—Swedish border.

The Swedish deposits in this group have been briefly described by Per Geijer (1923).

*The Ofoten area.* Foslie (1941) describes small bornite-chalcocite-covellite deposits occurring in the rocks of the Caledonian orogenic belt in the Ofoten area of Northern Norway. These are, apparently, the only recorded instances of the copper paragenesis in rocks later in age than Precambrian.

T. Gjelsvik (1957) has discussed a small area of bornite-chalcocite mineralization in the Precambrian rocks of western *Finnmarksvidda*, near the Finnish border. He has tentatively identified linnaeite as an accessory mineral in some of the specimens from here.

In *Southern Norway* there occurs a well-defined mineralized province in the Telemark formation (Precambrian). The copper deposits within this province are also characterized by the absence of pyrite and pyrrotite, and thus may be classed in the copper paragenesis. Most of them occur within a broad zone along the border of a massif of younger granite. They are typical quartzveins with chalcopyrite, primary bornite and some chalcocite. The main deposits are the Åmdal mine and the Hovin group. A small representative of this group, at Straumsheia 35 kms SW of Åmdal, has been described in some detail by H. Neumann (1955). Here the copper minerals occur in pegmatites and consist of chalcocite and bornite, with malachite and chrysocolla as secondary products.

### Summary and conclusions.

The Raipas formation in northern Norway shows, in relation to its area of outcrop, a fairly strong metallization. Further geological work may show that the Raipas rocks can be linked with similar Precambrian rocks now being investigated further to the south, on *Finnmarksvidda*. If this proves to be the case the deposits of Ulve-ryggen, Porsa, Raipas, Kåfjord (and Kvænangen, further south-west) will be referable to a metallogenetic province comprising most of



the Precambrian areas east of about longitude 22°E. This province seems to be characterized by epigenetic sulphide ores in which the metal of economic interest is copper.

The above account has shown that the copper can occur in deposits showing two distinct mineral parageneses, often in close proximity to each other.

So far no evidence has come to hand which would indicate any age-difference between the two types of copper ores. Both must be assigned, provisionally, a Precambrian age, but there is always the possibility that they are the results of two different metallogenetic epochs in the Precambrian.

(It might be objected that these ores, of both types, could be of Caledonian age, but emplaced in Precambrian rocks. If this were so, however, we would expect to find deposits of the two types in Caledonian rocks too. Such is not the case. The Caledonian pyritic ores, though similar to those of the sulphide paragenesis, do not show the marked calcite-quartz gangues of the Precambrian pyritic ores, and their morphology is different. Only one instance of the copper paragenesis has been reported from a Caledonian area, the Tysfjord area of Nordland, as mentioned on p. 105. However, in this area there is a large formation of basal granite («bunnganit») which could be rejuvenated Precambrian, so there may not be a strictly Caledonian environment here.)

Mineralogically, an obvious difference is the presence of free iron sulphide (pyrite or pyrrhotite) in the pyritic paragenesis. The ores showing this paragenesis are almost identical mineralogically and texturally with many of the economically important ores of the Caledonian mountain chain. A close association with volcanic greenstones is also a feature common to both these types.

The copper paragenesis, on the other hand, shows marked differences from the Caledonian ores, both mineralogically and in its environment. The iron-poor and iron-free minerals bornite and neodigenite and/or chalcocite appear as primary minerals, while covellite is present, apparently as a result of supergene action.

The ores of this class show no constant association with any particular type of rock and their mode of occurrence can be as varied as breccia-fillings on the one hand and sparse disseminations on the other.

These chemical-mineralogical differences seem to indicate two

different origins for the two types of ore. It is suggested that the iron-rich ores (pyritic paragenesis) are derived from rocks of a basic character. Elsewhere the present writer (Vokes, 1957) has suggested that the origin of the Caledonian pyritic ores is to be found in processes which involved the mobilization, during orogeny, of Fe, Cu and S contained in sediments and basic volcanic rocks previously laid down or extruded in the geosyncline. It may be not unreasonable to suggest a similar origin for the Finnmark pyritic ores, during a Precambrian orogeny.

An igneous source for the copper-type ores is not easy to detect, yet they are clearly epigenetic.

In a discussion of the association of mineral deposits with various kinds of igneous rock, Buddington (1933) shows that copper deposits having the paragenesis bornite, chalcopyrite, chalcocite exhibit a marked genetic association with the rock types quartz-dolerite, dolerite-granophyre or dolerite-syenite. Buddington cites, as an example of this association, the native copper, bornite, chalcocite and subordinate barite, mineralization connected with the quartz-dolerite sills of the «Palisades disturbance» in eastern North America. From western North America, also, he gives examples of chalcopyrite, bornite, chalcocite mineralization in intrusive dolerite.

However, the Raipas paragenesis shows considerable similarity to that exhibited by the ores of the Butte district. Minerals in common are bornite, chalcocite (neodigenite), tennantite and chalcopyrite. The Butte ores are genetically related to the final stages of the Tertiary Boulder batholith (quartz-monzonite) and are believed to follow-closely the injection of quartz-porphyry dikes.

Thus this mineral association shows genetic relations to a variety of different igneous rocks. In Africa the origin of the mineralogically similar ores of the Northern Rhodesian Copperbelt is the subject of a sharp controversy. Here as in Finnmark, no suitable igneous rocks are exposed near enough to be considered as the source.

It is thus clear that the question of origin of the copper paragenesis ores is a very open one, and one which needs a very considerable amount of further investigation.

As regards the economic possibilities of the ore, no deposit showing the copper paragenesis has yet given any significant amount

of ore, yet this may be due to their not having been investigated in the light of modern mining requirements. In the past the rich, compact sulphide ores of the pyritic type of deposit were of greatest interest, since they could be easily hand-sorted to give a directly smeltable ore. Now the emphasis has changed to large-tonnage ores which can be treated by flotation to produce a copper concentrate. The Ulveryggen ore seems in the light of present knowledge one which gives promise of providing a basis for a low-cost, large-tonnage operation. The grade would be low, but if mining were on a sufficient scale it might prove an economic proposition. It certainly warrants a closer investigation directed towards such a goal.

The Porsanger deposits also indicate the possibility of finding large, low-grade copper bodies.

Of considerable economic interest is the discovery of siegenite in the Raipas ore and of linnaeite on Finnmarksvidda (Gjelsvik, op. cit.). It may be that further investigation will reveal a cobalt content in other ores showing the copper paragenesis. The situation seems to be similar to that in the Northern Rhodesia-Katanga copper region, where several of the bornite-chalcopyrite-chalcocite ore-bodies carry economic cobalt values, the cobalt mineral being linnaeite,  $\text{Co}_3\text{S}_4$ , which is isomorphous with siegenite  $(\text{Co},\text{Ni})_3\text{S}_4$ .

The African copper-cobalt ores are often accompanied by a third metal of great interest at the present moment, namely uranium. So far this has not been reported from any of the mineralogically similar Norwegian ores. A brief scintillometer survey in Raipas mine failed to reveal any noteworthy radioactivity. However, the possibility of finding this third member should be kept in mind if these ores are investigated in the future.

C. F. Davidson (1954) regards the paragenesis Cu-Co-U as being of world wide extension; thus «the association of copper, cobalt, uranium . . . . . is characteristic in every way of hydrothermal lode fields such as Cornwall, the Erzgebirge, or the Singhbhum district of India». Later in the same discussion Davidson draws attention to the «fundamental similarities» between the mineralization of the Copperbelt, the Witwatersrand of S. Africa, Rum Jungle in Northern Australia, and the Plateau country of western America.

In Sweden bornite-chalcocite ores are apparently not considered favourably by the mining interest. Geijer (op. cit., p. 3) states that many engineers will not look at a copper deposit if it is known to

contain bornite. He suggests that this is due to the fact that the paragenesis «hints at the possibility of secondary enrichment». Geijer is not able to make any definite conclusions as regarding the origin of the Swedish chalcocites, except in two ores. Here the presence of both octahedral and orthorhombic etch cleavage is taken to mean that the chalcocite was originally isometric (i. e. neodigenite in the terminology of this paper) but that part of it suffered conversion to orthorhombic form. These facts indicate a hypogene origin in these two cases.

The evidence presented previously in this paper indicates that the Ulveryggen neodigenite is most probably of hypogene origin, so that the above objections are invalid. However, only an investigation in depth will really prove or disprove this.

### **Sammendrag.**

#### *Noen kopper-mineralparageneser fra Raipasformasjonen i Nord-Norge.*

Denne avhandling beskriver noen forekomster av koppersulfid-mineraler som ligger i bergarter tilhørende Raipasformasjonen i Finnmark. Mineralene forekommer i to forskjellige assosiasjoner: den ene består av kopperkis, svovelkis (magnetkis), (av forfatteren kalt «kisparagenesen» eller «pyritic paragenesis»), den annen av bornitt (broget kopper), kopperkis, neodigenitt, litt kopperglans, og covellin (av forfatteren kalt «kopperparagenesen» eller «copper paragenesis»).

Eksempler på disse to parageneser (mineralselskaper) fra Raipasområdet i Vest-Finnmark er beskrevet, særlig to forekomster som viser «kopperparagenesen», nemlig: Ulveryggen forekomst, Repparfjord og Raipas gruve, Alta. Mineralene, deres strukturer og opprinnelse er behandlet for begge forekomster.

Av særlig interesse i Ulveryggen-forekomsten er at  $\text{Cu}_2\text{S}$ -mineralet er neodigenitt (som har regulær krystallstruktur), ikke kopperglans som er rombisk). Dette tyder på at mineralet ikke skyldes sekundær anrikning. Det er derfor rimelig at kopperverdien vil holde seg i dypet.

Av interesse fra Raipas-forekomsten er tilstedeværelsen av kobolt-nikkelsulfidet: siegenitt. Tilstedeværelsen av en mulig kobolt-nikkelgehalt i disse malmer frister til en systematisk leting etter eventuelle forekomster av samme type i Raipasformasjonen.

Opprinnelsen av, og forholdet mellom, de to mineralparageneser er diskutert. Mineralparagenesene i malmer av «kopperparagenese»-type indikerer at de hører til en gruppe som er nokså velkjent over hele verden. I denne gruppe er de viktigste metaller kopper, kobolt og uran. Kopper og kobolt er funnet i de beskrevne forekomster i Finnmark. Det turde ikke være umulig at det tredje element kanskje kunne finnes ved en mer intensiv undersøkelse av Raipasområdene.

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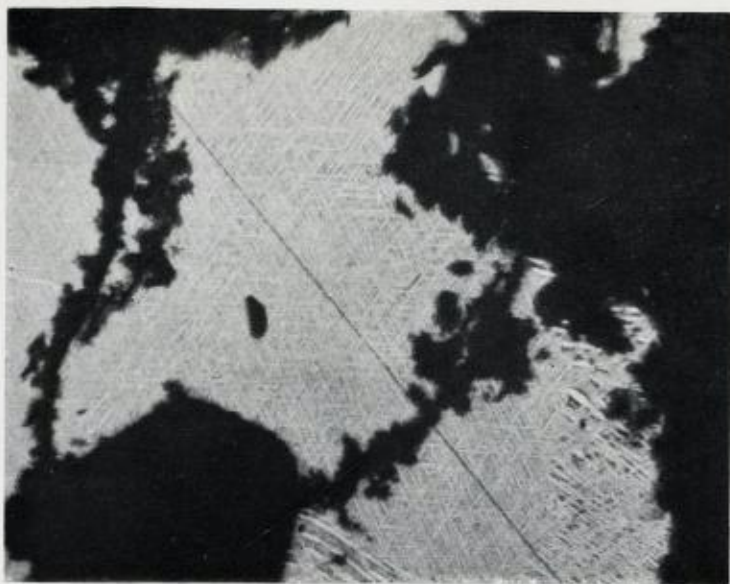


Plate 1, Fig. 1. Lattice texture between chalcopyrite lamellæ (light) and bornite ground-mass (dark) with irregular replacement veinlets of covellite (very dark grey). Gangue fragments black. Ulveryggen. Reflected light. X250.

*«Gitter struktur» mellom kopperkis lameller (lys) og en grundmasse av broget kopper (mørk). Covellin opptrer som uregelmessige små fortrennings-ganger (meget mørk grå). Kvartskorn er sorte. Ulveryggen. Reflektert lys. X250.*

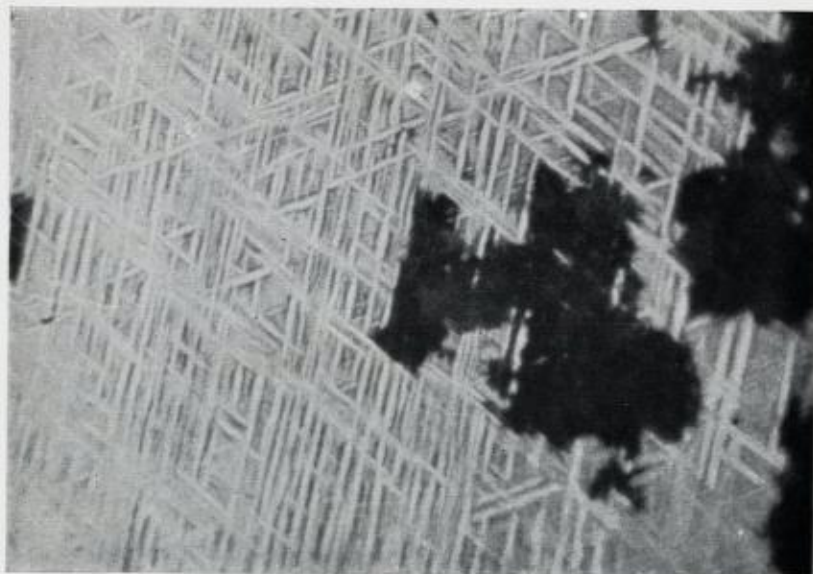


Plate 1, Fig. 2. Chalcopyrite-bornite lattice texture with irregular replacement patches of covellite (dark grey). Ulveryggen. Reflected light. X1000.

*Kopperkis og broget kopper i en «gitter struktur» med uregelmessige fortrennings-legemer av covellin (mørk grå). Ulveryggen. Reflektert lys. X1000.*



Plate 2, Fig. 1. Subgraphic replacement texture between bornite (light grey) and neodigenite (dark grey). The latter mineral also forms a replacement rim along the border between the bornite and the quartz fragments (black, internal reflections).  
Ulveryggen. Reflected light. X280.

«Subgrafisk» fortrennings-struktur mellom broget kopper (lys grå) og neodigenitt (mørk grå). Neodigenitt fortrenger også bornitten langs grensen mot kvarts-kornene (sort, med indre reflekser). Ulveryggen. Reflektert lys. X280.

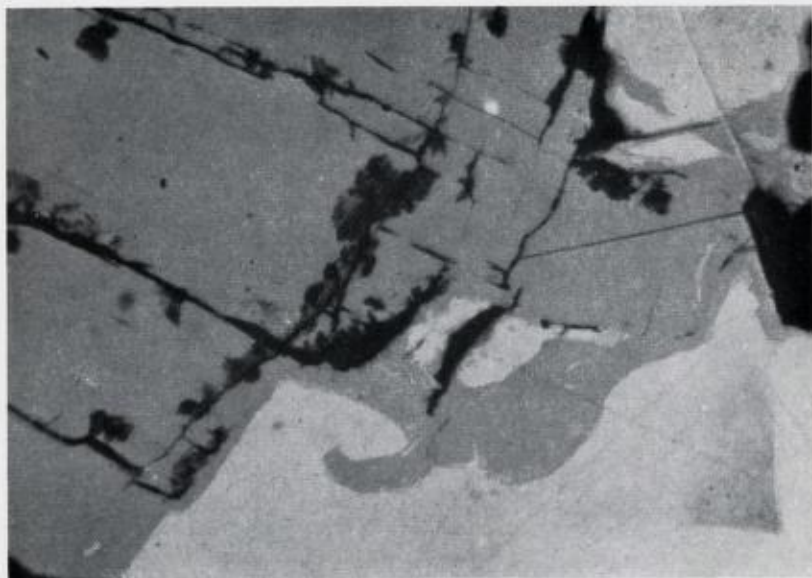


Plate 2, Fig. 2. Covellite (dark grey, mottled) replacing neodigenite (grey) along the latter's well-marked cleavages. Bornite (lighter grey) is being replaced by the neodigenite. Ulveryggen. Reflected light. X230.

Covellin (mørk) fortrenger neodigenitt (grå) etter spalte-retningene. Broget kopper (lys grå) fortrennes av neodigenitten. Ulveryggen. Reflektert lys. X230.



Plate 3, Fig. 1. Photograph of a piece of ore from Raipas mine in the mineral collections of the University of Oslo's Mineralogisk Museum. The breccia consists of pieces of dolomite and mudstone cemented by chalcopyrite and bornite. Natural size.

*Foto av malm-stykke fra Raipas gruve. Brudstykker av dolomitt og leirsten er sementert av kopperkis og broget kopper. Fra Geologisk Museum, Tøyen. Naturlig størrelse.*



Plate 3, Fig. 2. Lamellæ of chalcopyrite (white) in bornite (dark grey) on either side of a veinlet of neodigenite (diagonal from top left to bottom right). Raipas mine. Reflected light. X200.

*Kopperkis lameller (hvit) i broget kopper langs en liten gang av neodigenitt. Raipas gruve. Reflektert lys. X200.*



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