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IGDLUKÚNGUAQ NICKELIFEROUS PYRRHOTITE

TEXTURE AND COMPOSITION
A CONTRIBUTION TO THE GENESIS OF THE ORE TYPE

BY

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WITH 5 FIGURES IN THE TEXT
AND 20 PLATES

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Abstract.

Because of the very remarkable phases and structures it contains, the only nickeliferous pyrrhotite so far known in Greenland is given a very thorough ore-microscopic description.

The locality where this block of ore—about 28 tons—was found by Steenstrup in 1872 is situated on the Northeast coast of the island of Disko, which in turn lies off the West coast of Greenland.

The ore was contained within a dike rock belonging to the basalt complex which i. a. forms the main part of Disko and the neighbouring regions of the Greenlandic coast.

The ore itself, although it has the composition of normal nickeliferous pyrrhotite rich in nickel, presents a remarkable variety of phases and exsolution structures. It is the author's belief that these components form an almost unbroken chain of evidence covering the whole range, from the first consolidated sulphides to exsolution phenomena representing temperatures of under 200° C.

The following exsolutions were found in the ore:—

1. Chalcopentlandite, i. e. a pentlandite containing about 10 per cent. of chalcopyrite. Formed at near 850° C.
2. Chalcopyrite in rectilinear lamellae following $(ho\bar{h}o)$, formed at around 700° C.

2a. Chalcopyrite in rectilinear lamellae along $(ho\bar{h}l)$, formed at around 700° C.

2b. Chalcopyrite in rectilinear lamellae following $(ho\bar{h}l_1)$, likewise formed at near 700°.

3. Chalcopyrite in flame-like lamellae corresponding to about 550° C.

3a. Chalcopyrite in flame-like lamellae of another type.

4. Pentlandite sparks formed at near 550 C.
5. Pentlandite flames of the well-known type formed at 310° C.
6. Pyrrhotite α—β lamellae formed at around 140° C.

The study of the compact ore showed that development of the ore comprised three stages:

An initial stage, from which the primary oxides came as a result of gases originally held within the molten sulphide mass.

The main stage, where consolidation of the sulphides took place together with the solidification of oxidic material.

The third stage was dominated by processes of hydrothermal character. The formation of both sulphidic and oxidic phases took place widely at the expense of earlier-formed compounds.

The wealth of new observations which the author was able to make during his work on the Greenlandic ore is described in detail, after brief mention of historical data, in pages 27—65. Chemical analyses of rocks and ore will be found on pages 21 and 25.

On page 65 is a list showing the mineral content of the ore. The following pages, 66 to 101, contain a discussion of the microscopic observations; the second half of that discussion deals especially with the significance of the gases originally held within the sulphide mass. Water and carbon dioxide seem to have played an important rôle in the forming of the ore, not as carriers of the ore material but as participants in the chemical reactions.

Comparison of Canadian, African, Scandinavian and Australian occurrences with several new observations made by the author is followed by a chapter devoted mainly to summing up and placing the nickeliferous pyrrhotite in relation to other geological phenomena.

The last pages contain a brief discussion of a possible relation between nickeliferous pyrrhotite and the well-known occurrence of native iron in the Greenlandic plateau basalts.

THE IGDLUKÚNGUAQ ORE

> It loomed up in the world of speculation, immediately open to interpretation in the light of rational experiments with other products of nature; it was enveloped in no veil of tradition created by miners of remote times.

Introduction.

Little more than a hundred years have elapsed since nickeliferous pyrrhotite was first utilized industrially and only about 10,000 tons had been produced until near the close of last century. The growing interest in this type of ore is naturally reflected in the figures of the annual outputs. It was only as the new century approached that there appeared more intimate descriptions of the deposits as well as hypotheses on the genesis of the ore. At that time petrography was beginning to work experimentally and this particular ore was soon compared with products that were familiar from ore smelting. The magmatic origin of the ore-bearing rock was beyond discussion, and the ore itself fitted so well into the imaginary picture of nature's matte process that its validity was not seriously contested for many years. Notwithstanding subsequent—and radically deviating—opinions on the genesis of the ore, it is fairly safe to say that it remains one of the "most magmatic ores" in existence.

However, as time went on and more and more detailed studies of the deposits within this type appeared, some of them seemed to embody contradictions of various kinds. Structural features of the ore-bearing rocks and the placing of the ore in them seemed irreconcilable with the ideas which had necessarily to be formed if for example the ore were the result of a gravitative precipitation in a true magma. Several different theories were set up regarding the genesis of nickeliferous-pyrrhotite ore, and among them hydrothermal processes are accepted as the most probable by several geologists.

A. Bateman (4)¹) summarized the position in these words:—

> "Two explanations remain: either the ores were introduced by hydrothermal solutions of a rather pecular nature, as seems probable, or they represent late magmatic injections of a sulphidic melt which, because of lower freezing temperature, remained mobile until after the consolidation of the main norite and the later intrusions."

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¹) The number in brackets after an author's name refers to the bibliography page 167.

The discussion on the origin of the ore has also occupied itself with the nature of the rocks bearing it; attention has been given to the results of analogous melts in the laboratory; the various phases of ore processing have been included; the structural conditions in the rocks in which the ore occurs; the placing of the ore in the rocks and the particular variations in the rocks in conjunction with the occurrence of the ore, have likewise formed sections within the framework of the discussion. But the relations inside the sulphidic body itself have received less attention. Naturally, as far as was possible these relations of the ore minerals have been studied, but these studies could not be effective until into the 'twenties, and really thorough investigations could not be made until the development of the technique of ore microscopy in the 'thirties. As the studies of nickeliferous pyrrhotite ores were made mostly in the 'twenties, it follows that ore microscopy played no great part in them.

Among the literature on microscopic studies of nickeliferous pyrrhotite ore published in the 'thirties are several excellent works treating of various forms of this type of ore. Perhaps one of the most thorough—and richest in details—is SCHOLTZ's work (35) on the ore of East Griqualand and Pondoland. In addition to the geological and petrological examination of the rocks the work presents a really splendid microscopical study in connection with the occurrence of the sulphides. The description, which includes many detailed observations, is accompanied by numerous good and illustrative photographs.

The particular feature of SCHOLTZ's work, however, is its wealth of ore-microscopic observations combined with excellent observations of the petrographic details, all forming one collective, natural whole. SCHOLTZ's theory of the ore's magmatic origin harmonizes well with the other sections of the work, and what must be noted specially is the weight which he attaches to the late-magmatic products and, particularly, the relation of the gases to the sulphides. The very significance of that relation is of greatest importance. On the whole, the work excels by its praiseworthy integrity. On points where the present writer has been unable to accept SCHOLTZ's interpretation of the phenomena, it has been possible to try to reach other interpretations on the basis of his descriptions and illustrations.

However, there is a break in the continuity of the magmatic development of the ore minerals. We can observe certain relations between the minerals that are capable of being attributed to high temperatures, actually very close to the melting point of the sulphides as demonstrated by various laboratory tests. But then there is a marked temperature jump to the next phase, indicated by the mineral relations in the ore, for it must be looked for in the interval between 400 and 200°. It would seem that the materials examined microscopically have not embodied any possibility of establishing even a fairly continuous series of temperature-indicating mineral structures in order to form a reasonable connection between the products of the highest temperatures and the stable combinations set up in the various cooling phases.

No doubt there are several different explanations of this, but it seems important to point out the relations, discussed inter alia by A. B. Edwards (12), between the temperature of the ore-carrier and the temperature of the surroundings into which the ore is brought; moreover, it is certainly very important to note the time factor in the evolution of the ore within a particular temperature environment. In other words, we must differentiate between the formation temperature of the ore and its characterizing temperature. The former is actually what we understand by formation temperature, the temperature at which consolidation begins, whilst the latter is the temperature or temperature interval at which the ore has mostly remained stable. The characterizing temperature is really the one which has most chance of being reflected in the internal state of the ore, provided that the temperature interval lies in such a position that the physico-chemical processes can take place.

The continuity from the highest to the lowest temperature stages must be broken radically if the ore secures the opportunity of remaining for a suitable time at about 200°; but experience seems to show that a few traces remain even from the first developed textures in the ore. This may be caused by pseudomorphoses, for instance, retaining the originally formed structures whereas in their material combinations, new to the ore, they satisfy the requirements of the characterizing temperature.

The possibility of drawing conclusions along a fairly unbroken chain to the original temperature of the ore—the temperature of formation—seems very slender when we consider the general formation of nature's products. The very fact that all known deposits of this type of ore are hundreds of millions of years old, and that moreover they occur in rock masses of such thickness that it is a reasonable assumption that the placing of the ore proceeded at a relatively great depth, where geothermal measurement permits us to assume temperatures of 100°, and perhaps more likely 200°, makes it hard to believe it possible to find an ore which clearly has retained even a more or less continuous series of evidences leading right back to the formation stage.

In itself this is not particularly encouraging. If then we take the laboratory experiments into consideration, we must a priori adopt a highly pessimistic view of the sulphide ores as a whole. These experiments show, for example, how it is possible with copper and iron sulphides easily and in a very short space of time—hours and days—to homogenize heterogeneous phases and, conversely, in a suitable cooling period to obtain complete separation of the phases. The temperatures employed lie between 200° and 400°.

However, experience with many different ores and ore types shows that it is not at all so unusual as may be thought from the above to find temperature indications showing a plurality of temperature equilibria reflected in minerals and mineral combinations within one ore. The cause of this is hard to tell. In a few cases it is thought possible to indicate the presence of special elements which presumably caused a certain tardiness in the transformation of the structures of minerals representing higher temperatures, but as a general rule one must abstain from any explanation. In actual fact there is something of a paradox in the existence of these temperature-indicating phases. Its incomprehensibility becomes almost complete when we consider all the experiments in which naturally occurring ores have been used for demonstrating exsolutions and homogenizations within their various components.

There is so much the more reason for calling attention to this problem because my studies of the nickeliferous pyrrhotite ore from the basalt deposits in the northern part of Disko island in West Greenland have demonstrated the presence of a number of exsolution structures which, in point of temperature, must be placed between the temperature indicators hitherto known in the region of 200—400° and the few known indicators that are assumed to correspond to processes close to the transition of the ore melt to solid form. It would seem that with this ore it has been possible more than anywhere else to set up an "evolution series" showing the course of the cooling processes reflected in the various components of the ore.

In the following I shall give a description of the deposit as known from earlier records, more recent research, and observations which I was able to make during a very brief visit to the locality. Principal importance, however, is attached to the analysis of the components of the ore body itself as they appear in the samples of the sulphide mass. My concentration on the ore's own structure, prompted by its unusual character, naturally enough engendered the impulse to search the literature for parallels in other deposits. Some were found, others are merely suspected. In a number of instances it has been possible to analyze samples from other localities along the same lines as those which the Greenlandic ore described in the following had induced me to follow. In several cases the samples were of such a character that I was able to observe in them hitherto unnoticed structures and mineral relations, whereby correlation between the Greenlandic ore and the ores of the same type previously known was extended to some of the newly observed exsolution structures.

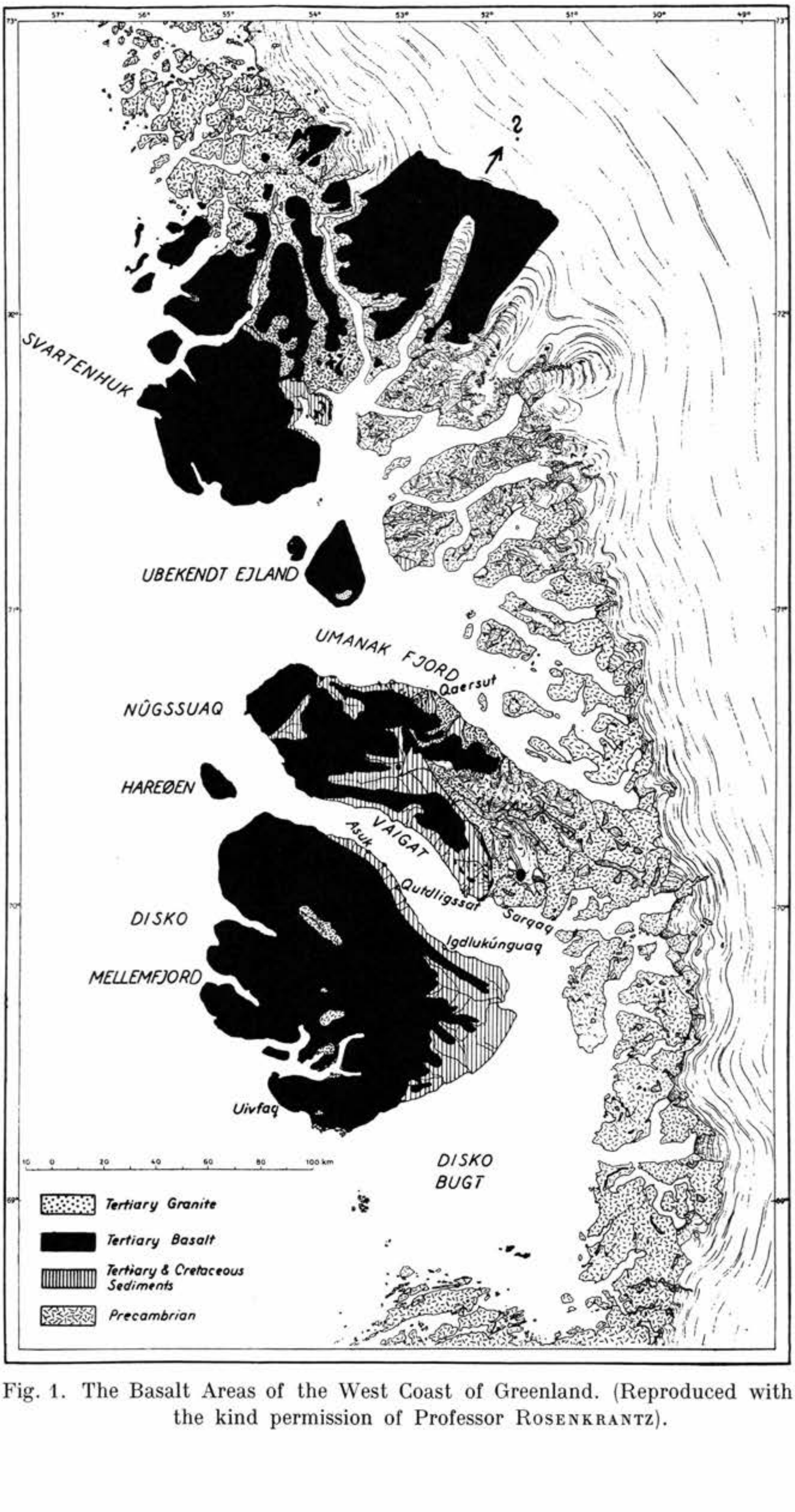

Fig. 1. The Basalt Areas of the West Coast of Greenland. (Reproduced with the kind permission of Professor ROSENKRANTZ).

The analysis of the Greenlandic ore is followed by a short examination of other deposits, based partly on the literary sources and partly on my own researches.

The Ore Deposit at Igdlukúnguaq.

The nickeliferous pyrrhotite at Igdlukúnguaq[1] was first discovered by Fritz Jørgensen, the manager of the store at Ujarasugssuk, not far from the deposit. Steenstrup (46) records that when Nordenskiöld in 1870 (26) visited the place, Jørgensen showed him the locality. Nordenskiöld had just time to go there and collect a few samples and then proceed on his journey. Later, on arriving at another place, he threw some of the pieces away, saying that they were only pyrrhotite. Steenstrup found them there a year later and wrote the first description of the deposit. It appears as a footnote in his work (43) page 88 and reads as follows in translation:

> "The most remarkable of the basalt dikes I saw is at Igdlokunguak on the Waigat [a sound, see fig. 1]. It is situated a few hundred feet from the beach, about 250 feet above sea level, is from 10 to 16 feet wide and can be followed for a distance of about 900 feet in the direction from N. 40° W. to S. 40° E. This dike provides incontrovertible evidence that the Greenlandic basalt also had a very high temperature when it extruded through the coal-bearing formations, because it baked the surrounding sand into a hard, quartzite-like sandstone which has split into beautifully angular columns up to more than a foot long, exactly like the well-known sandstone columns from blast-furnaces. Though this marked action on the basalt in the surrounding deposits is unique among the fifty or more basalt dikes which I have had the opportunity of examining closely along the Waigat shores, basalt action is nevertheless observable at most places and is far from being so imperceptible as one should think from the remarks of one or two recent travellers. The most remarkable feature of this dike, however, is that at the spot where it is cut through by a little brook it contains a very large block of nickeliferous pyrrhotite. Besides as small pellets in the basalt this mineral lies in the middle of the dike in the form of a big lump whose visible dimensions are: breadth 5 feet, length 10 feet and thickness 4 feet, so that it has a volume of at least 200 cubic feet."

A year later Steenstrup (44) mentions the deposit again, but only briefly, adding that there is presumably 28,000 kg of ore.

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[1] Old spelling: Igdlokunguak.

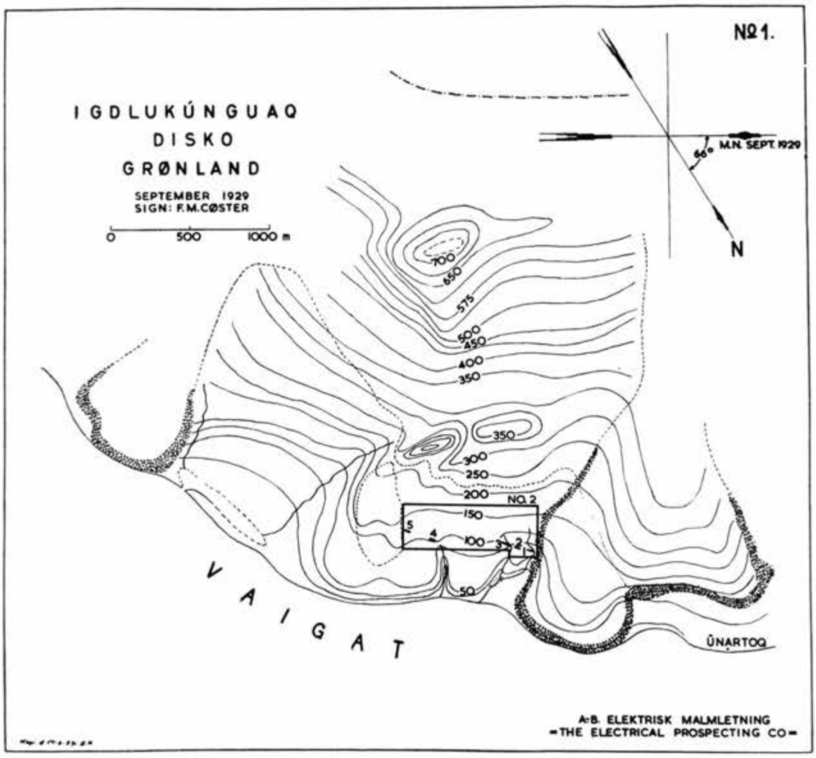

Fig. 2.

In 1898 Steenstrup was again at the locality, and he informs us (46) that its appearance had undergone a very radical change owing to weathering. Now, he says, it is impossible to take a non-weathered sample as one could in 1871. Everything is a rusty red or dark with a green coating of Cu and Ni compounds, and it looks quite different to what it did when every stroke of the hammer resulted in bright, shiny surfaces with a handsome crystalline structure. Weathering had proceeded rapidly in the intermediate 27 years and Steenstrup concludes that the ore must have become exposed very shortly before 1870. He adds, by the way, that the samples also weather quickly in the museum

Steenstrup's description and references to the deposit are all that the literature contains. In Mineralogia Groenlandica they are given but very brief mention, and Bøggild (8, 9) thereafter writes a description of some of the minerals found at the locality: zaratite, in the form of a green coating on the ore, crystals of magnetite and siderite, occurring in many cavities in the ore together with a chlorophaitic mineral (hisingerite). Less frequently there are cavities containing crystals of

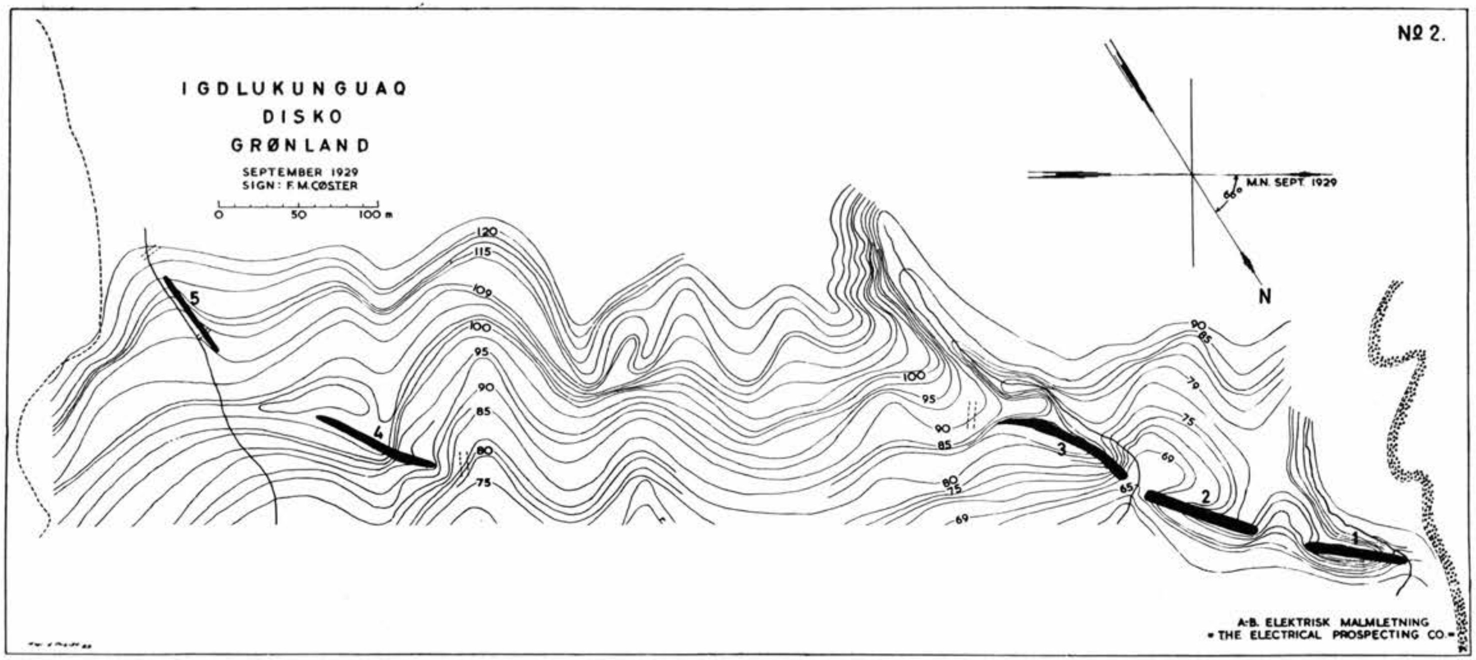
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Fig. 3.

pyrrhotite—1 to 3 mm in size—with the following developed faces: (0001), $(10\bar{1}0)$, $(20\bar{2}1)$ and $(11\bar{2}0)$.

ARTHUR SCHWANTKE (36) in his work on the basalts of Northwest Greenland referred to Igdlukúnguaq pyrrhotite as an important deposit which he proposed to discuss more thoroughly in a subsequent work; but apparently it was never published.

No further description seems to have appeared in the literature between 1906 and 1940, though in 1923 SYDNEY H. BALL (1) recapitulated what was known of the deposit until then.

However, interest in the deposit was not quite dormant. Disturbances in the reception of wireless telephony between land and ship stations in the waters off the coast where the dike is situated awakened renewed interest in the ore, as appears from reports to the Greenland Administration (58) from Telegraph Superintendant HOLTEN MØLLER in 1927 and later. Preparatory work was carried out by LAUGE KOCH, and in 1929 this was followed up with a geological reconnaissance by F. CÖSTER with the object of examining the possibility of employing geophysical methods in the search for further ore deposits. The results of the latter work are given in a report to the Greenland Administration 1929 (58). CÖSTER's description of conditions at Igdlukúnguaq is quoted below. Fig. 2 and 3 are reproductions of his maps, showing the stretch of coast and the immediate surroundings of the actual locality. Numbers and terms refer to these maps.

> "The Tertiary sediments at Igdlokunguak are interspersed by a basalt dike which is exposed at five places along a stretch of 800 metres (see figs. 2 and 3). In one of these outcrops is the nickel-copper-ore described by STEENSTRUP. The area southwest of the southern outcrop, No. 5, consists of a bed of basalt, probably a subsided part of the basalt plateau higher up. The valley-plain lying immediately southwest of this basalt area has been searched without discovering any outcrops of this dike rock. Southwest of the valley-plain a dead glacier reaches down to the water. The moraine, which covers the ice completely, consists of basalt blocks, some of large size. No block of the character of the basalt dike was found there. The ground just north of Exposure No. 1 comprises a lobe of moraine-covered dead ice extending from the basalt slope to the water and northwards extending to the brook which has its mouth near the settlement of Unartok. The moraine consists of blocks of basalt and tuff. The area close by Exposure No. 1 is obviously older than the other parts of the moraine and practically all the fine-grained material has been washed out.
>
> "In all probability the dead ice under the area is not particularly thick. In the part of the glacier more to the north and north-

east the ice may have a thickness of 25 to 50 metres, but the moraine covering is so thick that the ice is not exposed anywhere. The ground surface between Exposures 1 and 5 is covered with the usual arctic vegetation; often it is waterlogged, and solifluction phenomena are to be seen here and there. At places where excavations were made the tæle begins at a depth of 50—60 cm.

"Description of the outcrops:

"*No. 1.* The length is 50 m, the width 5—5$^1/_2$ m. One end is much weathered. The east part is dike rock in situ. The dip is steep (85° to E). Sandstone occurs, partly in situ in the footwall. A fist-size lump of ore was found in the hangwall about a half metre from the east wall. On the whole the dike is not visibly mineralized. There is a coal-bearing coarse-grained sandstone in the northern part. The dike rock is surrounded by a contact zone, $^1/_2$ to 1 m in width, on the footwall side. The hangwall is normal dike rock.

"*No. 2.* The length is 75 m, the width 5$^1/_2$ m, the dip steep, probably to E. There is sandstone on both sides of the dike, which is much weathered. No mineralization observable here. The width of the contact zone is 1 m.

"*No. 3.* The length of this outcrop is 90 m, the width at the north end 5$^1/_2$ m, the dip 80° to W. The northeast end is mineralized along a length of 15 m. The width of the mineralized part is 2 m. The ore was found in this mineralized part. The dimensions of the ore-body are, as far as can be seen: length 3 m, breadth $^1/_{10}$ m and depth 0.95 m; probably it extended 3 m more to the south in the direction of the dike strike.[1]) A trench was cut for the purpose of discovering a possible continuation of the ore. Two weathering zones were observed in the trench: an upper, rust coloured zone with fist-size lumps of relatively pure ore at the bottom, and a lower zone situated in the permafrozen part of the soil, containing nickel salts. Mineralized basalt in situ was reached at a depth of 1$^1/_2$ m.

"This outcrop with the ore-body lies at about 400 m from the beach at a height of about 80 m above sea level. It is easily reached through a gully in the steep slope down to the water.

"Outcrops 1 and 2 are separated only by a 35 m stretch of vegetation-covered soil, and between 2 and 3 a brook had cut through the dike. Nos. 1, 2 and 3 are undoubtedly one continuous dike.

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[1]) These measurements do not agree exactly with STEENSTRUP's, which may be due to the changes already observed by STEENSTRUP in 1898 (46). Author.

"Between 3 and 4 it was impossible to find the dike along a stretch of 350 m. The ground slopes quite evenly eastwards and is cut by two very deep gullies. In the one to the west (see fig. 3) was a large block of the same rock of which the dike is formed, and higher up the slope was a smaller block of the same kind. Both were slightly mineralized.

"*No. 4.* This outcrop lies 25 m higher up than No. 3 and about 105 m above sea level. Its length in the direction of the strike is 85 m and its width, so far as could be seen, 4 m. The rock is much weathered. No mineralization was observable, although some rust coloured areas are to be found at the north end.

"*No. 5.* This lies 65 m southwest of Outcrop 4. It is much weathered and partly covered by creeping soil. The length is 55 m and the width 2—3 m. The dike contains nickel salts, to be seen at several places over a distance of 30 m, but no ore was observed.

"At a height of about 5 m above sea level near the beach east of No. 3 is an outcrop of basalt. It dips slightly south and rises somewhat to the northwest. It cannot be decided whether the basalt dike or the basalt layer is the older.

"The geological minute survey of the Igdlokunguak area (see figs. 2 and 3) brought out the following facts of practical importance: 1) The mineralization is associated with basaltic dike rocks. 2) Within the area surveyed, outcrops of basaltic dike rock were localized at five different points, presumably belonging to one continuous system and on the south bounded by a basalt layer. No basalt dike was discovered south of that layer. If the dike continues northwest in the direction of its strike, it was impossible to ascertain the fact because of the advancing moraine-covered dead ice right down to the beach. 3) The total length of the basalt dike outcrops is 355 m and across that stretch there is only a single large mass of ore, only 3 m long in the direction of the strike. That ore deposit has the character of a magmatic segregation. It is possible that there are other ore-bodies of similar dimensions, such as the nickel-cuprous pyrrhotite, in those parts of the dike that are not exposed. With occurrences of this type, however, one cannot anticipate large ore-bodies."

The report also contains estimates of what may be obtained by geophysical research and considerations of a technical nature.

As will be seen, the result of the work was not great, from a techno-economic point of view; and it should be noted that no explanation was advanced of the remarkable and rather strong radiophonic interference in the area.

About two years after these investigations some further search was made in the area, including sample-digging at Steenstrup's ore deposit. Nothing new emerged, and since then there has been no occasion for doing anything more.

In 1940 LÖFQUIST and BENEDICKS (22) published a study of the native iron from the basalt at Uivfaq, Disko island. Included in it was a brief reference to the nickeliferous pyrrhotite from Igdlukúnguaq which, working on a mistaken geological interpretation, the authors placed in direct connection with the native iron deposit. They were undoubtedly right in assuming that there must be a connection between the metallic iron on the one hand and the sulphides in the basalt on the other; but it does not seem relevant for them to assume that it actually was ore from Igdlukúnguaq which, by various processes, was reduced in a locality lying about 100 km to the southwest of Igdlukúnguaq, not counting the impressive mountains between the two localities.

LÖFQUIST and BENEDICKS record the following minerals from the Igdlukúnguaq ore: pyrrhotite, pentlandite, bravoite, chalcopyrite, millerite and something which they call nifesite. As appears from what follows, millerite must be a misunderstanding of a rod-shaped or leaf-like mineral occurring at certain places in the ore; it lacks the optical characters of millerite and presumably must be classified as an unknown mineral of the same family as valleriite etc. LÖFQUIST and BENEDICKS employ the term nifesite expressly of a composite metaral of two components, and it is incomprehensible why later in the work they bracket it with valleriite, with which it has no character in common. A mineral name for a composite metaral is also irrelevant, of course. It is quite another matter that this metaral may be of some interest in interpreting the genesis of the deposit.

Finally, I may mention that in 1950, when on my way to the area where the Greenland Geological Survey Expedition was to work that year, I took the opportunity to make a brief inspection of the locality. The time was between 2 and 3 a.m. and we had merely an hour or two to spare, so nothing more could be done except personal orientation. It was possible to verify that STEENSTRUP's and CÖSTER's descriptions of conditions there agreed with the appearance of the place, except that the ore-body itself was no longer "in position". Prospectors subsequent to CÖSTER's visit had blasted and excavated all the ore once present in STEENSTRUP's locality, leaving nothing but a gaping hole in the dike there. On the flat ground just in front the ore is nicely stacked in a heap and one felt that STEENSTRUP's estimate of the quantities cannot

Fig. 4. The locality where the ore was dug out in 1931. The two people in the foreground are standing at the heap of ore. H. P. photo.

have been all wrong. The photo fig. 4 shows how things looked at our visit in 1950.

The walls of the excavation were coated with rusty-red and malachite-green crusts. Part of the green substance is the well-known mineral zaratite.

The presence of ore in the rock cannot be determined directly; at any rate, we failed to do so during our brief stay. In actual fact, the impression received agreed with the description given by STEENSTRUP after he inspected the locality in 1898. On the other hand, the stack of ore consists of very pure material; quite at random one can pick up pieces of ore the size of a head, composed entirely of sulphide mass. On the whole it is curious that no pieces of rock have been seen together with large lumps of sulphide, either in this stack or among the samples at the Mineralogical Museum. This observation by the way is verified by the collections made by Professor ROSENKRANTZ in 1953, when some hundreds of kg of ore were taken from the stack. Among those samples were very few pieces of the dike rock, but none of them contained any large nodules of sulphide; one or two had small nodules, less than 1 cm in diameter. Similar samples are to be found in the material brought home by STEENSTRUP.

General petrography of the area.

Like other basalts of West Greenland and the basalt formations on the East Coast, the basalt rocks on Disko island belong to the North Atlantic basalt region. In West Greenland, Tertiary basalt volcanism actually began in the Danien, an assumption arrived at because tuff beds have been found in Danien sediments on the peninsula of Nûgssuaq (see fig. 1). In the upper part of the Lower Paleocene series argillaceous shale beds alternate with tuff. Overlying that series is pillow lava (with a fossil-free tuff stratum), and uppermost the plateau basalt proper.

Lowest, the plateau basalt is olivine-porphyric, whereupon it changes suddenly to plagioclase-porphyric without olivine phenocrysts but with an olivine content in the ground mass, decreasing upwards to a basalt that is quite free of olivine. Then follows a dense, andesitic basalt which finally may change into anorthoclas-trachyte (for instance the "Tertiary granite" on Ubekendt Ejland, which is an ultimate acid derivative of the basaltic magma). Here and there the plateau basalt has a total thickness of several thousand metres.

The feeder channels of the lava streams have been found at several places (Disko, Svartenhuk). To all appearances the land was submerged under the weight of the basalt while the eruptions were still in process; for example, there are subordinate beds of pillow lava which must have been formed under water.

On Disko there is graphite-bearing basalt and telluric iron associated with some of the rocks of the basalt series.

The beginning of the basalt volcanism has been dated fairly accurately, whereas the upper boundary is not known definitely. It is possible that a closer examination of the intrabasaltic floras on Nûgssuaq and Hareøen, situated high up in the plateau basalt (in the olivine-free section) may help towards a partial solution of the problem of when the basaltic volcanism terminated.

In conjunction with an extensive fault which from Sarqaq on the South of Nûgssuaq peninsula runs approximately SE—NW across Nûgssuaq, quartz-basaltic intrusions have been found at both ends of the fault (S. MUNCK, 23). Ultra-basic rocks have been found on the North coast of Nûgssuaq corresponding to the olivine-porphyric part of the plateau basalt (e. g. sills at Qaersut).

On Svartenhuk there is a similar (Paleocene-Eocene) fault having almost the same direction as the one on Nûgssuaq.

This summary comes from "Oversigt over Grønlands Geologi" (57). More about the geology of this part of Greenland is e. g. to be found in DREVER & GAME (10), NOE-NYGAARD (25), ROSENKRANTZ et al. (30) and (31).

Within the whole region of plateau basalt there are numbers of dike rocks, but they are particularly numerous round about the Vaigat, and it is here, as I have already said, that the Igdlukúnguaq dike with its nickeliferous-pyrrhotite occurs (see fig. 3).

The plateau basalts overlie Cretaceous sediments consisting chiefly of sandstone and shales, bituminous shales. That complex is superimposed upon the pre-Cambrian gneisses etc. which are well known for their limestone content, especially in the region North of Nûgssuaq. Phyllites and quartzites also occur in the pre-Cambrian rocks of that area.

One of the areas in which the Greenland Geological Survey is working these years is the basalt region; the work has not yet progressed so far as to make it possible to account for the relationship between all the rocks in the complex; this is particularly true of the various dike rocks, which thus means the Igdlukúnguaq dike too; but it is hoped that some of the interesting problems bound up in it will be brought nearer elucidation by the work of the next few years.

The ore-bearing rock.

We have two partial analyses of the rock containing the ore. They were made in 1931 by Petrén (58) in conjunction with the research work then in hand. As the deposit was only studied from a technical point of view, the intention was merely to form a rough estimate of the rock type, for which reason the only determinations made were those appearing from the analyses:

	A	B	C
	%	%	%
SiO_2	47.18	49.14	47.16
Al_2O_3	12.86	13.10	11.82
TiO_2			3.62
Fe_2O_3	12.47	12.09	5.96
FeO			7.16
MnO	0.12	0.15	0.09
MgO	10.01	9.59	9.83
CaO	7.08	7.28	7.86
			2.28 Na_2O
Cu	0.42	0.28	1.96 K_2O
Ni	0.19	0.23	0.67 P_2O_5
S	0.91	0.71	trace Cl
Ignition loss	4.77	3.73	trace SO_3
The remainder are chiefly alkalies	3.99	3.70	0.60 H_2O^+
			0.24 H_2O^-
			99.35

Gold, silver and platinum could not be demonstrated.

A and B: Samples of the dike rock from Igdlukúnguaq, anal. Petrén Nos. 4 and 7.

C: Olivine basalt from the coast opposite Penguin Island, collected by Consul Christensen. Anal.: B. Bruun (2).

According to the analyses the composition of the rock corresponds to olivine basalt as given e.g. by BARTH (2) in his work "Lavas of Gough Island". A true calculation of the analyses of the Igdlukúnguaq rock is impossible, the analyses being too summary; nevertheless, the comparison obtainable from the analyses as they are, together with the mineralogical composition of the rock, provides fairly acceptable grounds for placing the material. The felspar, which contains about 65 $^0/_0$ anorthite, represents something less than half of the minerals. Olivine is present in a few untransformed grains. The greater part is serpentinized. Rhombic pyroxene seems to be much more frequent than olivine, but much of that too is transformed into hydrous silicates. Ilmenite is present in the usual rod-like forms and represents about 1 $^0/_0$ of the rock. There is a little magnetite. Carbonates, calcite, and hisingerite, hydrous iron silicate, are all present as cavity infillings. The latter are of interest in that to some extent the plagioclase laths are oriented according to these inclusions—their longitudinal directions follow the circumference of the cavities as seen in the thin sections (Pl. I, 1). Zeolitic material may also be present in the cavities.

The rock may be described as olivine basalt, as I have done in the present work. It occurs in a characteristic basalt-region and belongs to the same era as the surrounding basalts. But with its pronounced character as a dike rock one might bracket it together with gabbro, norite and hyperite. Actually, the analysis has much in common with these rocks and the components of the rock are mainly the same. The secondary products of the silicates widespread in the Igdlukúnguaq dike are really no expression of any marked difference from the appearance sometimes encountered in rocks which, like those mentioned, may bear nickeliferous pyrrhotite. On the other hand, the presence of hisingerite and zeolites should rather be taken as signifying a closer association with basaltic rocks, or better, as an expression of an affiliation with the young rocks which the basalts are. The presence of ultrabasic rocks like pickrite, dolerite etc., as mentioned in the summary of the local geology, so to say intensifies the wish for a parallelization between the basic rocks of Greenland and, for instance, the Karro dolerites.

The ore.

On the evidence of the samples collected the ore may be divided into three types. The main type comprises compact ore, i.e. pieces of up to 20 cm in diameter, consisting of pure sulphide material. This is the predominating type in the collections, and all the ore dug out at the locality is of the same type. From the old reports it does actually seem that there was one compact mass of ore, and therefore it must be warrantable to regard these compact lumps as true samples of how the ore mainly presented itself.

The second type of sulphide material, of which there are only one or two pieces in the Mineralogical Museum, is contained in the rock in the form of small nodules of ore, varying in size from 2 to 8 mm. One piece was found among the material brought back by Steenstrup; and among the samples collected by Professor Rosenkrantz in 1953 were two lumps of the rock which also contained similar small nodules of ore.

Both in these pieces of the rock and in the other samples of the dike there are small sulphide grains of less than 1 mm, and they differ so much from the two former types that it is reasonable to separate them as a third type.

The present work is based chiefly upon the observations made in samples of the compact ore; but although the disseminated ore grains only slightly reflect the relations that are to be read from the compact ore, they are also of significance and therefore have in no way been ignored.

It is regrettable that the digging of the ore in situ in 1931 has prevented an examination of the variation of the ore-body from its outer boundaries and inwards. The differences revealed in some of the polished samples compared with the majority of them, and the differences which appear from the following analyses of the ore made by Petrén (58) in conjunction with the work on the ore in 1931 and the previous period, seem to indicate variations which may have depended upon the position of the particular samples in the ore body.

Analyses of various ore samples.
Anal. Petrén 1931.

	a	b	c	d	e	f
	%	%	%	%	%	%
Ni . . .	1.91	3.22	1.90	3.12	4.72	2.01
Cu . . .	0.80	1.16	0.89	1.18	2.35	0.95
Fe . . .	53.2	54.8	56.9	53.9	54.1	54.5
S	30.22	31.30	32.40	29.65	29.11	32.92

No Au, Pt or Ag was demonstrable in an average of all six samples.

In the report on these analyses, dated May 12th, 1931, Petrén states that the quantities of both nickel and copper are considerably below those found by analysis of the material from the 1928 (and previous) investigations, which are from 2 to 4 times higher.

H. Löfquist and C. Benedicks (22) give the following analyses by R. Treje and E. Hammarberg:

	Igdlukúnguaq %	Vaigat %
Ni	4.13	3.67
Co	0.58	—
As	0.05	—

The samples are in the Riksmuseet in Stockholm and were brought home by NORDENSKIÖLD, which thus proves that he did not throw away all the material on the beach where STEENSTRUP found some pieces.

The earliest analysis of the ore was made by LAWR. SMITH in 1879 (41):

	%
Ni	3.11
Co	0.78
Cu	2.43
Fe	53.01
S	36.85
P	0.42
insol.	3.20
	99.80

The above analyses show some variation, but the most interesting point is PETRÉN's remark that earlier analyses of material from the locality showed a much higher Ni and Cu content. The quantities are not definite, but the figures seem to suggest about 8 % Ni and 4 % Cu. Unfortunately, the composition of the ore cannot be evaluated on that basis. It is presumable that the ore's total composition is rather represented by the lower values in the analyses; but the analysis made in conjunction with the present work, which is known to correspond to a considerable part of the ore samples microscoped and examined, shows about 8 % Ni and over 5 % Cu (see page 25). The nature of the material thus makes it impracticable to advance any positive opinion on the question; but as principal importance is attached to the ore structures and their bearing on the genesis of the ore, it would seem justifiable to renounce a detailed clarification of the deposit's individual character, which may very well involve a variation of the composition of the ore body. On the other hand, we obtain a certain expression of that variation from the description of the mineralogical composition, but the corresponding relations in the field are naturally concealed from us. All we can hope for is that deposits of similar type may be discovered in the area or elsewhere, for it is beyond doubt that it will be of great interest to establish the variation of the ore vis-à-vis its location.

Material for chemical analysis was selected on the basis of the microscopic examination of the ore. This of course does not pretend to be an average sample of the ore, as such a sample could not be expected to provide information of sufficient interest to the present study. The analytical material represents the form of the sulphide mass that has an appearance such as that shown in Pl. II, 1, 2 & III, 1, which in low magnification are reproductions of sections through this form of the ore. The selected sample was as pure and unweathered as it was possible to find. It had a metallic lustre, just as Steenstrup described the ore, and any essay at appraising the amount of "rust" in the sample could not but put it at far below one per cent. Half the sample was taken for preparing a few polished sections, and these corresponded exactly to the freshest and most typical representatives of the chosen type of ore.

The analysis was done in the chemical laboratory of the Kryolitselskabet Øresund A/S by the chief chemist Mr. H. Buchwald. In conjunction with the analysis Mr. A. H. Nielsen, chemist at the same laboratory, made a determination of the nickel, which gave the same value as in the analysis itself:

Analysis of Ni-Pyrrhotite from Igdlukúnguaq Disko, North Greenland (H. Buchwald).

	%		%
Fe	47.07	Pyrrhotite	36.63
Ni	8.70	Pentlandite	26.88
Co	0.50		
Cu	5.62	Chalcopyrite	16.23
Ag	trace		
Pb	0.03	Galena	0.03
Zn	nil		
Cr	trace		
Mn	0.02		(0.02)
Ti	0.02		(0.02)
Ca	0.03	Calcite	0.07
Mg	0.02	Mg-carbonate	0.07
S^{--}	27.96		
SO_4^{--}	3.56	Iron sulphate	4.94
Cl	nil		
P	nil		
CO_3^{--}	0.95	Siderite	1.75
SiO_2	0.05		(0.05)
−110° H_2O	1.50	Water	3.40
+110° H_2O	1.90		
deficit (O etc.)	2.07	(Magnetite)	7.49
	100.00		97.58
		Residual iron	2.51
Total magnetite, calculated from oxygen + residual iron:			10.96

A. N. Nielsen has also determined the content in aqueous extracts of the material.

Extracting with water over a water-bath gives a faintly opalescent fluid with a smell of hydrogen sulphide. The filtrate contains sulphate, iron and nickel. Any copper that may be present apparently evades demonstration owing to the hydrogen sulphide. Extraction with pure methylalcohol gave sulphate, iron and nickel, whereas no copper could be found.

17.9 g material, corresponding to the analytical material, was treated with 200 ml water over a water-bath for two hours. The filtrate had a p_H of 5.5. After washing to a negative sulphate reaction the filtrate + wash-water was found to contain:

0.016 g Ni per 100 g ore
0.19 g Fe per 100 g ore
Co was not demonstrable in the aqueous extract.

After treating the material with HNO_3, filtering and melting with $KHSO_4$ there was a small residue of insoluble material containing a very little quartz and mainly silica, obviously from the decomposition of silicates. The amount of silica appears from the analysis.

A spectral analysis was made in 1946 in Stockholm by B. GUSTAFSSON in the laboratory of S. LANDERGREEN, Swedish Geological Survey, and gave the following result:—

	%
Ni .... ca.	4
Co	0.15
Cu	1
Ag	0.003
Pb	0.02
Sn	0.01 — 0.003
Sb	0.03
Bi	0.01
Cr	0.007
Mn	0.03
Ti	0.03
V	0.003
Be	0.002

The old analyses of the ore give values that agree well with the metal content in the ores of other well-known deposits. The new analysis is rich in Ni and Cu, but they are not abnormally high; ore samples are known from several localities with contents reaching similar values. The components found by analysis are not foreign to this type of ore, but it is a fact that the values of sulphate, carbonate and water are higher than is usual at most places. That these substances also occur elsewhere is to be seen at least from the descriptions of e. g. the Sudbury ore, Australian ore etc. (54, 47, 18).

The demonstration of Be by spectral analysis is presumably to be regarded as an expression of the presence of silicates in the analyzed material (which was drilled out of a sample of the ore corresponding to the one subjected to chemical analysis).

The greater part of the following description of the ore is based upon the type that was analyzed chemically. When discussing the conclusions to be drawn from the description I shall also include the chemical composition, so there is no need to go deeper into it here.

Ore Microscopic Description.

The deposit as it is seen today is shown in fig. 4. In the foreground lies the mass of material dug out in the early 'thirties. In that heap alone is it possible to find lumps of pure ore. No sulphides are visible at all in the niche formed by the excavation, but at several places the walls are coated with rust, greenish here and there with precipitated copper and nickel salts.

The lumps in the excavated ore are exactly the same as the samples which have reposed in the Mineralogical Museum since STEENSTRUP's day. Some of them are completely weathered, but an astonishingly large quantity are quite fresh. It is characteristic that practically all the pieces have one or more flat boundary planes, some of them as large as 10 × 10 cm. They are coated with rust, of course, but this is not always particularly dominant and often the surface has the character of being the surface of the sulphide itself. It is only by very carefully examining this that one discovers other sulphides than pyrrhotite. As a matter of fact, this holds good of the ore as a whole. Macroscopically it is difficult to recognize other sulphides than the pyrrhotite. On the other hand, one very frequently sees rounded nodules of a steely-grey mineral, of sizes from 10 mm downwards. They occur in all samples of the ore and, where they are broken, they can be seen to contain crystals of magnetite in millimetre-sized octahedra as described by O. B. BØGGILD (8, 9). In these magnetite-lined cavities there may also be small, well-developed pyrrhotite crystals (O. B. BØGGILD, 8, 9). Siderite also occurs in the cavities, which are sometimes completely filled with it. Moreover, it happens quite frequently that these inclusions really are hollow, and, where there are many of them, the ore may seem porous.

The surface of these greyish, rounded bodies often displays a fine dendritic pattern on their otherwise smooth exterior.

The natural flat boundary planes mentioned are sometimes the only boundaries on small pieces of ore, as is shown in Pl. I, 2, which almost have the appearance of a rhombohedron. On closer examination, however, this closed form proves to be constituted of basal faces, and the illustrated specimen thus consists of six individuals of pyrrhotite. There seems to be no instance of twinning or other form of regular intergrowth. Natural basal faces in contact may form both acute and obtuse angles, but no regularity in this is observable.

A feature of the ore is its characteristic parting. As STEENSTRUP also observed, breaking of a lump of ore may reveal glossy surfaces of up to 10 cm in diameter, but apparently they do not persist for very long. At any rate, it was not easy to find these cleavage planes in the ore lying at the locality.

Although to the casual eye these partings seem to be continuous, like the aforesaid natural boundary planes or crystal faces, more careful inspection will show that they are composed of scales of pyrrhotite, barely a millimetre in size, surrounded by dull areas. Nevertheless they represent an optical unit of pyrrhotite and therefore really correspond to a single plane. Microscopic examination shows that here again we have the basal plane in the pyrrhotite.

The pyrrhotite.

The presence of these large faces of pyrrhotite in the Igdlukúnguaq ore is actually of fundamental importance, for they prove that this is pyrrhotite ore in the truest sense of the term, i. e. an ore consisting of pyrrhotite. This mineral is not the chief part of the material; it forms a good third of the ore; but each lump of ore consists of one or more individuals of pyrrhotite and the other minerals are present only as inclusions within it; the macro-picture is pyrrhotite, and the two types of plane surfaces show what the structure of the ore is.

The crystal faces of the pyrrhotite, which are easily cleansed of any rust, have the appearance shown in Pl. I, 3, 4 when polished very cautiously. The continuous pyrrhotite surface presents a kind of dendritic pattern spreading over the area, and also a very distinctly drawn triangular network. As the figure shows, the dendrites are composed of small inclusions of a mineral slightly paler and softer than the pyrrhotite, and in addition (see the figure) there may be holes in the central part of these inclusions. The triangular network consists of rectilinear, very narrow lamellae of a mineral imbedded along three different directions, forming angles of 60° with one another. This mineral too is paler and softer than the pyrrhotite.

On polishing the surface a little more vigorously without actually grinding it, i. e. removing merely a very thin layer of the material, the surface assumes the appearance shown in Pl. I, 5. The dendrites are now more distinct rows of inclusions of the lighter coloured mineral, whereas the holes in them have almost disappeared; continuity has been lost to some extent. The pale lamellae forming the reticulation on the surface are still present, but are not so clear in the reproduction. It shows by the way that there may also be large cracks in these surfaces. In their orientation they are distinctly governed by the pyrrhotite.

Further polishing of the crystal face results in the appearance shown in Pl. I, 6. The dendrites have disappeared, have so to say become resolved in the various inclusions of the pale-coloured mineral. These inclusions on their part have assumed a very interesting appearance, many of them being presented in the form of triangles or triangles with truncated corners, seemingly hexagons of a kind with their boundaries at right angles to the still-present narrow lamellae which continue to form the triangular network. At this depth the pyrrhotite surface is still continuous, but largely holed by the other minerals.

Further polishing, with which we must reckon on having got a millimetre down into the pyrrhotite individual from the original crystal face, reveals the pyrrhotite entirely divided up into small, rounded islands as shown in Pl. II, 1, 2. The narrow lamellae forming a triangular network are still to be seen in the pyrrhotite. The material forming the dendrites is now to be seen as currents around the various pyrrhotite islands and also around certain inclusions in the pyrrhotite. On Pl. II, 3 will be seen the pale dendrite substance with its hexagonal boundary against the pyrrhotite, and it can be seen that these inclusions have their central part infilled by a grey mineral: magnetite. As the transition to this appearance took place in the course of a phase when the dendrite structure was lost, it will not do to identify the latter with the structures found in these deeper layers; as far as the dendrites are concerned it is apparently a phenomenon that is closely associated with the crystal faces themselves, whereas the inside of the crystals is characterized in another manner.

On grinding and polishing a fresh parting face we obtain a picture that is a complete replica of the last of the basal sections described above. At any arbitrary depth of the pyrrhotite it thus has the appearance of a surface composed of many small areas. The optical study shows that they are all of the same orientation, which means that they belong to the same individual.

In the same manner a section at right angles to the direction of the base shows that the pyrrhotite is divided into very small areas. If the section is so arranged that one boundary of the specimen is a crystal face, Pl. III, 1, it will be seen that the pyrrhotite is continuous just in the "superficial layer". This means that no material is to be found there constituting "currents" around areas of pyrrhotite, whereas the inclusions to be seen inside the pyrrhotite islands do occur here, as is also shown by the polished natural (0001) face. There seems to be a tendency for the pyrrhotite areas to be elongated at right angles to the direction of the base, at any rate at a short distance out from the basal face. The ratio of pyrrhotite to the materials surrounding it varies somewhat from the natural plane inwards into the sample, the pyrrhotite decreasing slightly in point of area whilst the surrounding material increases.

Accordingly, the Greenland ore consists of pyrrhotite individuals of quite some size, 5 to 10 cm in cross section, and the only other minerals encountered are in the form of inclusions within the various pyrrhotite individuals. The natural basal faces consists of continuous areas of pyrrhotite in which we see very small inclusions along definite crystallographic directions in the pyrrhotite, whereas all other sections in the mineral show it to be divided up into small isolated areas with a common orientation. The individual crystals may therefore be assumed to be "spongy masses" of pyrrhotite with the pores infilled by the other substances. The pyrrhotite and the pore mass are the main components of the ore; but in addition there are the oxidic phases which differ from this picture to some extent, and finally, siderite occurs with such special relations to both main components that, together with its surroundings, it must be regarded as a unit lying within the crystals but still independent.

The pyrrhotite is remarkable in that it has no twin lamellae or other signs of mechanical deformation. In some parts of the samples there are very distinct streaks in the mineral along (0001), a mineral with a low refraction being embedded in that direction. As it seems to be particularly associated with the aforesaid special siderite areas I shall revert to it later in greater detail (pp. 55—56). The same applies to areas in the pyrrhotite, where the latter seems to be converted more or less to what in German is called "Zwischenprodukt". The general impression of the pyrrhotite on the whole is that it differs little or not at all from what is usual in other occurrences. α—β laminations are distinctly seen in the mineral, without it being possible to say that the one type of lamella is more prevalent than the other.

Finally it may be mentioned that here and there in the samples it is possible to observe very small pyrrhotite individuals whose orientation differs from those of the surrounding FeS masses, from which they do not differ in other respects.

In polished samples where the section shows more than one individual, it can be seen that the boundary between the individuals is quite irregular; and it is only by means of the optical characters, the colour of the pyrrhotite and especially its appearance between crossed nicols, that we find there is pyrrhotite from two different individuals.

This isolated occurrence of small pyrrhotite individuals with a different orientation may be an expression of the three-dimensional nature of the sample and therefore may merely indicate that there is another individual below the level of the polished section; but as it is often a matter of only one or two small areas of a size which I have called pyrrhotite islands, it would seem more reasonable to assume that there really are small bodies whose orientation differs from that of their surroundings.

Relations of the pyrrhotite to the other minerals.

As has been mentioned, the pyrrhotite borders upon the minerals forming the pore mass (the filling material between the various pyrrhotite areas in the sections), and it also has what may be called internal boundaries against the inclusions contained in the pyrrhotite islands. Both inclusions and pore mass contain sulphides of copper and of nickel, chiefly chalcopyrite and pentlandite, and here it is the rule that these two minerals alone are in contact with the pyrrhotite where it is fresh and untransformed.

As the various figures show (e. g. Pl. II, 2, 3), the minerals in the pore mass form a distinct caries texture with the pyrrhotite, both where there is contact between the pyrrhotite and the chalcopyrites and between the pyrrhotite and the pentlandite-chalcopyrite; here the nickel sulphide presents itself in an unusual manner together with the copper sulphide, as will be explained later (pages 32, 37—40).

As will appear from what was said above about i. a. the basal faces, the internal boundaries, i. e. the relation between the pyrrhotite in the islands and the inclusions therein, may be divided into two different main types, there being inclusions of both lamella form and of equidimensional bodies.

To these two types of inclusions in the pyrrhotite may be added three others which, on account of their slight individual size or their lower frequency, play a less prominent part in the ore.

Chalcopentlandite, exsolution bodies in the pyrrhotite.

The appearance of the equidimensional inclusions varies a little according to whether they are localized on the crystal faces of the pyrrhotite or in the fortuitous sections cutting into the pyrrhotite, as has already been mentioned. In the ordinary sections the inclusions always appear with a larger or smaller magnetite mass in the centre, and it is often the case that this is the most dominating feature of the inclusion. However, between the magnetite and the pyrrhotite there is always a rim of copper-nickel sulphides. In the crystal faces these sulphides most frequently dominate the inclusion. Either the magnetite mass in the middle is quite small or there may be a hollow at the place out of which it may have been torn in the course of preparation. Finally, these inclusions frequently appear as inclusions of pure sulphide, as is shown by Pl. I, 6. The explanation of the latter seems to be that the magnetite masses in the inclusions in these faces are fairly small and therefore the polishing process may so act on the surface that the central part of the inclusions is removed or is not reached. The three-dimensional nature of the sample must be taken into consideration.

The sulphide material in these inclusions consists of a very fine-meshed reticulation structure of chalcopyrite and pentlandite, which by the way is exactly the same as the marginal zones of the pore material and will be discussed under that heading. The point here is that the two-phase structure, independently of the mutual structures of the phases, can be seen to form distinct rectilinear boundaries against the pyrrhotite, and, as already mentioned, the shape of the inclusion as a whole is often triangular or hexagonal in section. Over the polished surface these triangles are uniformly orientated if only they belong to the same pyrrhotite individual. Regarded as units these inclusions must therefore be considered as exsolution bodies, i. e. the copper-nickel sulphides in them vis-à-vis the pyrrhotite have behaved as crystalline units which could be separated from an original solution in the pyrrhotite and form oriented imbedded crystals in the host mineral. At a later stage these crystals passed from a one-phase system to a two-phase system. In other words, there was again an unmixing in them, which gave rise to the formation of chalcopyrite lamellae in the pentlandite. These relations will be further illustrated in connection with the discussion on the pore material, which embodies the same phenomena; but it should be remarked here that these evidently are the remains — and fairly well-preserved remains at that — of a high-temperature fast mix-crystal (Ni, Fe, Cu) S, whose existence though presumed by various authors has not previously been observed with the certainty permitted by the present material. (But see P. RAMDOHR (29), pp. 128 and 343, observations on material from Igdlukúnguaq.)

The host mineral is pentlandite; the chalcopyrite lamellae form about 10 % of the total aggregate. The original homogeneous phase may suitably be termed chalcopentlandite. As will appear from the following description of the pore material (page 39), a phase has been observed in it which with some probability may be assumed to represent untransformed chalcopentlandite.

Now and then it is possible to observe, as shown on Pl. VIII, 2 magnetite-free exsolution bodies in the central parts of pyrrhotite areas. As it seems to be a regular phenomenon that the magnetite grains in these cases first occur at a certain distance from the central part, but in a form (particularly with regard to size) corresponding to the usual form of magnetite when placed in the central parts of the pyrrhotite, it seems justifiable to regard these exsolution bodies as true, magnetite-free chalcopentlandite bodies and not merely a result of the situation of the section, which now and then will presumably give areas of pentlandite in which the magnetite grain cannot be seen. These bodies contain chalcopyrite lamellae but otherwise might easily be mistaken for pentlandite exsolution bodies — pentlandite discs or regular pentlandite flames; that would be quite understandable, of course, because they are exsolutions in the same medium (FeS) following the same directions (0001).

Chalcopyrite, exsolution bodies in pyrrhotite.

As already said, the lamellar inclusions in the basal faces of the pyrrhotite form a triangular pattern in which the three lamella systems form angles of 60° with one another. The width of the lamellae is usually 10 to 20 μ; they may be narrower but are rarely wider. The lengths of these lamellae as seen in the various samples show that their extent through the pyrrhotite is considerable despite their slight width. The width variations are quite insignificant and we must regard these embedments as very thin, extensive sheets permeating the pyrrhotite in various directions. By its colour and hardness the material in these sheets shows that it must be chalcopyrite, and this seems to be confirmed by thermal etching, which will be more fully described later (page 50). The anisotropy of this chalcopyrite is practically impossible to observe, as the lamellae are so thin and they lie in the highly anisotropic pyrrhotite. Just near the pore material, however, these lamellae may be seen with a greater width than well inside the pyrrhotite and it is sometimes possible there to get a better view of the optical characters of the chalcopyrite, though this does not mean that its crystallographic directions can be determined.

As with the equidimensional inclusions, the placing of these lamellae can be seen to be governed by the host mineral, the pyrrhotite. Within the pyrrhotite individual the lamella systems follow a certain set of directions. On basal faces these directions as already remarked are at right angles to the hexagonal boundaries presented by the equidimensional inclusions. Evidently we have here an exsolution of chalcopyrite in the pyrrhotite not previously described from any other deposit or reported from laboratory tests. Moreover, as it would seem that this exsolution is of special importance to our understanding of the evolution of the Igdlukúnguaq ore, I have endeavoured to clarify the mutual relations of host and guest in this exsolution structure.

In sections parallel to the parting in the pyrrhotite there are always and exclusively lamellae along three systems which form mutual angles of 60°, but in all other sections the relations are more complicated. The slight thickness of the lamellae makes it difficult to orient sections along them; but on the other hand, in every prism section or section at right angles to the basis in the pyrrhotite it should be possible to determine the orientation of the lamellae. It is difficult to say how accurately such measurements can be taken in practice, but the following sources of error and uncertainty may be mentioned:

Sections at right angles to the basis can be cut to an accuracy of a couple of degrees. Measuring the angles between the lamellae and between them and the section plane (on the basis) may perhaps be done to an accuracy of up to 1 degree, but here the absolute length of the lamellae is decisive; and, as it is very small, accuracy is reduced somewhat. Apart from instrumental uncertainty, there is the complication of focussing error, which is all-important.

In order to reduce these margins of uncertainty, areas of the basal section and corresponding prism sections were photographed with only slight magnification, and the photographs were enlarged up to 18 × 24 cm. This provided better conditions for measurement than are obtainable in the microscope itself, for example the possibility of interpolating between the various lamellae of a particular system; comparative measurements with ruler and square also facilitate the work. By this means the total focussing uncertainty should be diminished, but on the other hand it was found that the regularity of detail seen in the microscope at greater magnifications is lost when one tries to extend it to fields of two milimetres or more. There is still an uncertainty of some few degrees.

While bearing these remarks in mind it is quite interesting to see the results found. Pl. II, 1, 2 & III, 1 present sections along the basis and at right angles to it in one pyrrhotite individual.

In the section at right angles to the basis we observe first and foremost that practically all the lamellae at the very margin to the basis are at right angles to it. This can only mean that they represent prism planes in the pyrrhotite. It applies to lamellae lying in the extreme marginal part of the pyrrhotite individual, i. e. a layer of one or two tenths of a millimetre below the crystal face. Deeper in the sample one most often sees the lamellae as non-parallel lines. There are at least two pairs of lamellae systems: there are two systems forming angles of 80° to 84° to the direction of the parting and two forming angles of 25—40°. That it is a matter of pairs of systems is shown by the fact that within each pair the lamellae may be divided into systems that are symmetrical around the normal to the basis. It is possible that there are other directions, but the difficulties of measuring prevented this point from being settled. It is clear, however, that it must be a matter of planes along different pyramids in the pyrrhotite. It is imaginable that the systems which form relatively acute angles to the basal direction may correspond to the familiar twin-plane $(10\bar{1}2)$, whereby the aforesaid prism would become $(10\bar{1}0)$. A pyramid such as $(10\ 0\ \overline{10}\ 3)$ might possibly give lamellae with the observed obtuse angles to the basis. The measurements of course are too uncertain to provide reliable information as to whether this is correct or not. There can be no doubt about the existence of both a relatively flat pyramid and a fairly steep one, along which the chalcopyrite lamellae were unmixed, apart from the prism along which these lamellae lie in the layers of the pyrrhotite near to the crystal face. The frequency of lamellae belonging to the group that was unmixed along the flat pyramid is higher than for the steep pyramid, but it is possible that this changes deeper in the samples, because it seems to happen at least as frequently that we there find lamellae which are almost parallel; in this pair of systems the angle between the lamellae seems to be one of merely about ten degrees.

The main schema in the exsolution lamellae of chalcopyrite in the pyrrhotite looks very attractive as laid out here:

I. Exsolution along prism planes in the "surface" of the pyrrhotite crystal,
II. Exsolution along a flat "simple" pyramid a little way into the crystal, and
III. Exsolution along steep pyramids inside the pyrrhotite—perhaps along several different steep pyramids.

It should be added here, however, that there is no complete regularity in this. In the outermost layer one rarely observes lamellae that are not at right angles to the basis, but both of the other types do occur. In the intermediate zone lamellae at right angles to the basis are fairly frequent and quite a number are observed to be almost at right angles to the basis, not to speak of the type that forms relatively acute angles to it. In the parts farthest from the crystal face it is also possible to see all three types, but as stated there seems to be a high frequency of lamellae almost at right angles to the direction of the basis.

In all three zones one may see lamellae that "begin" with a direction at right angles to the basis, break over and continue mostly along the direction which corresponds to the flat pyramid. As a matter of fact it often happens that lamellae are cut over and displaced laterally as much as their own width, sometimes slightly more, and the connection between the two pieces may have the same direction as the lamellae along the pyramids.

As the various lamella systems seem to have a distinct tendency to be dependent upon their situation in the pyrrhotite in relation to the mineral's crystal faces, it must be a reasonable assumption that exsolution of the chalcopyrite took place under variable conditions. Exsolution to the prism plane became difficult some distance inside the sample and exsolution to the flat pyramid became difficult still further inside the sample. That the primary exsolution laws did not become totally impossible in the inner depths of the mineral seems to appear from the apparant co-existence of different types of lamellae. However, it must be said that at any rate as regards the exsolution to the prism, the criterion for it is the lamellae at right angles to the direction of the basis, and it is not at all impossible that random sections may so cut the crystals that traces of the pyramids in the plane of the section are at right angles to the traces of the basis in the same plane. The same of course applies to the observation of the angles which are regarded as criteria of exsolution along the flat pyramid.

The main purpose of this discussion is, however, to point out that in the ore there are evidently at least three different laws for exsolution of chalcopyrite, and that they exhibit signs of a dependence upon the depth at which the exsolution took place in the pyrrhotite. The regularity referred to is the common rule, but, as Pl. IV, 3 shows, in the margin of pyrrhotite areas one occasionally sees chalcopyrite lamellae with a somewhat winding course and a tendency to a distinct flame-form, in which case they are often wider than the rectilinear lamellae.

Other exsolution bodies in the pyrrhotite.

Besides these two types of exsolution bodies there are the well-known pentlandite flames, imbedded parallel to the basis and, in sections that are at right angles to it, sometimes having the appearance shown in Pl. II, 4. As a rule the material is recognizable as pentlandite. Here and there valleriite in patchy figures can be seen in it, Pl. IV, 2. In areas where the pyrrhotite shows conversion into "zwischenproduct", we see bravoite, or a corresponding product, instead of pentlandite in the flames. It is distinguishable from the pentlandite by its obviously differing hardness and by its colour, which is pale violet. On the whole there is great similarity between this substance and the alteration product of the pyrrhotite, zwischenproduct. These matters will be dealt with in greater detail later.

The relation to the chalcopyrite lamellae is clear in Pl. II, 4. Where the pentlandite flames intersect the chalcopyrite lamellae the latter are often seen to be displaced by as much as their own width or more.

Much less frequently one finds in the ore exsolution bodies of chalcopyrite and pentlandite whose dimensions are considerably smaller than those given above.

The chalcopyrite lamellae (see Pl. IV, 1) are present in two different sizes, which must mean that there are two different generations of exsolutions. The smallest, barely 10 μ in length and less than 2 μ in width, are often seen to form three-pointed stars. They are distinctly flame-shaped, i. e. slightly sinuous in their course and pointed at the ends. The large lamellæ are also flame-shaped and, like the small ones, run in three different directions, though they rarely actually form stellate figures. On the other hand they are often characterized by a serrate border which on close examination is seen to consist of very small pentlandite exsolution bodies along (0001) in the pyrrhotite. It looks as if these chalcopyrite lamellae take the place of the rectilinear chalcopyrite lamellae in some areas of the more compact, pyrrhotitic pieces of the ore. These are not so much intersected by copper-nickel sulphides in the form of pore mass as the ordinary samples; but where the former samples really have these sulphides the rectilinear chalcopyrite lamellae in the pyrrhotite are replaced by the aforesaid flame-shaped lamellae. It is possible that the slightly sinuous, irregular course which the rectilinear lamellae often assume, at the border of the pore mass in the ordinary samples are a transitional phase to these particular exsolution bodies.

On account of their small size the pentlandite bodies mentioned might be designated as pentlandite sparks; they seem to be closely associated with the large flame-shaped chalcopyrite lamellae in the type of ore that is especially rich in pyrrhotite; but they have also been observed in the pyrrhotite itself without direct contact with the chalcopyrite flames; and finally, they are observable in several other places in the ordinary variety of the ore.

The Pore Material.

The bilateral chalcopentlandite of the pore material.

The greater part of the material which in the sections seems to surround the pyrrhotite areas, but in reality must be said to be inclused in it, consists of sulphides of copper and nickel. In all sections where this material is to be seen, it presents a distinct zonal distribution of the components. The middle zone in these "currents" around the pyrrhotite islands is characterized by chalcopyrite, whereas the outer zone, or the area bordering upon the pyrrhotite, consists of an intimate intergrowth of pentlandite and chalcopyrite in exactly the same structure as the equidimensional exsolution bodies in the pyrrhotite, the "pseudomorphoses" after chalcopentlandite. Pl. IV, 3 & VI, 4 show the appearance of these areas.

It is also clear from these pictures that the intergrowth of which the chalcopentlandite now consists must be exceedingly fine-grained. In Pl. IV, 4 there is a very faint suspicion of granularity in the areas of the pore mass adjacent to the pyrrhotite. It is also very difficult when microscoping the ore to see the components forming the outer zone. In a few of the ore samples, however, this intergrowth is more coarse-grained than normally and it is possible to recognize the two sulphide phases. In order to ascertain the general character of this binary structure it was of importance that in the course of the investigation it should be possible to go through some of the samples with a microscope equipped with phase-contrast illumination[1]).

These phase-contrast photographs are reproduced in Pl.V, 2, 3, 4. Very distinctly they reveal the structure in the chalcopentlandite exsolved to pentlandite-chalcopyrite. This field is from the pore mass itself. In Pl.V, 5 is the exsolution structure as it appears in the sulphide rims around the magnetite grains in the pyrrhotite.

It will be obvious, particularly in the picture of the outer zone of the pore mass, that we have here an exsolution structure in the chalcopentlandite where, in a main component, another component is segregated in the form of lamellae running in at least three different directions. The main component — the host — has optical characters that warrant the assumption that this is pentlandite, whereas the other sulphide — the guest — must be chalcopyrite. This assumption is strengthened by the results of the thermal etching later to be described separately (page 50).

Pl.V, 6 & VI, 1 are pictures of the same structure. The former is of the outer zone of the pore mass, the latter is one of the equidimensional exsolution bodies in the pyrrhotite; a hole will be seen, left by a torn-out piece of magnetite. These pictures were taken by Professor P. Ramdohr (with a Leitz Panphot, on which careful stopping down made the exposures possible). It should be added that Professor Ramdohr had previously observed this structure in the Igdlukúnguaq ore and mentioned it in his book on ore minerals (29, p. 128).

On comparing the various forms presented by these two phases in the exsolution structure it seems to be a reasonable assumption that the chalcopyrite appears in the form of lamellae along (111) in the pentlandite. In the form in which it occurs in the Igdlukúnguaq ore, especially in the exsolution bodies in the pyrrhotite, there can be but

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[1]) Thanks to the kindness of Messrs. H. Struers I was able at an exhibition held by the firm to make use of a Reichert MeF-microscope of the latest design, fitted with phase contrast illumination. Dr. A. Findeis of Reichert's was obliging enough to instruct me in its use and assist in taking the photographs reproduced here. For this I tender my sincere thanks to Messrs. Struers and Dr. Findeis.

little doubt that this is an original mass segregated as chalcopentlandite which, in subsequent exsolution, was converted to pentlandite-chalcopyrite. The amount of chalcopyrite in it seems rather small—as already stated about 10 %. In all probability, RAMDOHR's observation (29, p. 375) of pentlandite with exsolution bodies parallel to (111) of chalcopyrrhotine in ore from Mittis and Kaulatunturi will correspond to the mix-crystal from Igdlukúnguaq. It is probable that the copper mineral in these cases became chalcopyrrhotine and not chalcopyrite because the characterizing temperature was too high. In heating tests with the Igdlukúnguaq ore a pentlandite-chalcopyrrhotine structure seemed in fact to be formed at temperatures of about 310°. However, the nature of the ore would not permit of more far-reaching tests of this kind, wherefore the result must be viewed with some reserve.

There is a variation in the coarseness of the disintegration structure (Zerfallstruktur) of the chalcopentlandite, but the variation seems devoid of any regularity. It may be of interest in this connection, however, to mention an intergrowth structure in a sample in which the ore forms a nodule about 1 cm in size in the dike rock; it proved to consist of chalcopyrite and pentlandite etc.; it is very coarse grained, as Pl. XIII, 3 shows. It is described later in connection with the description of this sample (page 63).

In those parts of the ore where zwischenprodukt and bravoite occur, the pentlandite in this structure is also transformed. Here the chalcopyrite lamellae may be somewhat more distinct. On the whole, faint approaches to bravoitization of the pentlandite component are quite frequent.

Pl. VI, 3 shows an area where in a central part of the binary structure there is a field that is not transected by lamellae. The colour of this small region is rather more yellowish than seems to be the normal for pentlandite, but it is not so deep as that of chalcopyrite. The possibility cannot be excluded that this is a non-exsolved chalcopentlandite. The phase is isotropic and its hardness is that of pentlandite. The phenomenon is observed now and then in the samples.

The boundary between the pyrrhotite and the pore mass everywhere forms scallops in the pyrrhotite; the texture is distinctly carious, as mentioned above. As Pl. II, 2 shows, these scallops sometimes cut so far into the pyrrhotite that the chalcopentlandite exsolution bodies there merge with the marginal zone of the pore mass, and at such places it can be seen that the two different ore components are built up of the same minerals, and that these minerals are arranged in the same binary structure. In the same manner as the exsolution bodies may be bordered by quite rectilinear lines on the pyrrhotite, it will be found—though not so frequently—that the binary structure of the pore mass cuts into the pyrrhotite in areas bounded by rectilinear lines and having borders which can be seen to be parts of hexagons of which the sides are at right angles to the chalcopyrite lamellae in the pyrrhotite. Thus on this point too there is conformity with the exsolution bodies in the pyrrhotite. In such cases it can hardly be a part of an exsolution body that has been involved in the corrosion of the pyrrhotite, because there is no sign of magnetite grains also being present in these angular areas; and the observation has been made often enough for it to be beyond doubt that it is not merely due to the three-dimensional nature of the sample that the magnetite grain is not seen in the middle.

In the binary structure, but clearly differing from it, one may see flame-formed lamellae of chalcopyrite which in size many times exceed the true chalcopyrite lamellae of the structure. In point of direction it has not been possible to discern any regularity for these lamellae. On the other hand, their shape must mean that they were formed by an exsolution. Nor do they seem to bear any relation to the pyrrhotite or its lamellae of chalcopyrite, and similarly the chalcopyrite of the pore mass itself seems to be unconnected with these flames. Examples of the chalcopyrite flames in the binary structure will be seen in Pl. IV, 3. Another component in this structure is seen in the form of aggregations of small irregular patches; they consist of the mineral vallerite, Pl.VI, 2.

The copper-sulphidic central part of the pore material.

Conditions on the boundary between the central parts of the pore mass and the binary structure forming its outer zone may be of the appearance shown in Pl.VI, 4. Like a network of amoeba pseudopodia it subdivides the central zone of the binary structure into rounded areas. If the pore mass is wide enough in the section examined there is no such union of the two outer zones, but the relation between their constituents and the central parts is the same.

The roundish areas and large parts of the central zone consist of sulphide material of a colour like chalcopyrite, though possibly the colour may not be quite the same as normal chalcopyrite; it is perhaps a little paler. Anisotropy is observable between crossed nicols, though it is not particularly marked; but of course the anisotropy of chalcopyrite is not generally pronounced either. Considering the fact that the surroundings here often involve the presence of pyrrhotite within the field of vision, there is nothing strange in its being difficult to recognize the anisotropy alongside the pronounced anisotropy of the pyrrhotite. It is most reasonable to assume the mineral to be chalcopyrite; that mineral often shows twin lamellae where it does occur, but it is not to be seen at all in the Igdlukúnguaq ore, which may be a further explanation of its anisotropy being hard to see and seemingly being fainter than normally. With the qualifications implied in the foregoing I would suggest that this perhaps is an abnormal chalcopyrite and that it contains a certain amount — though slight — of pentlandite, which in that case must still be in solution, because in the sulphide mass no form of structure can be seen capable of interpretation as microscopically recognizable exsolution. On the other hand, emanating from the cracks everywhere in this chalcopyrite it is nothing unusual to see bravoite formation — see Pl. VI, 6 — which of course may be of purely secondary origin (in relation to the chalcopyrite), but which here would fit in very well as an explanation of the irregularities which the optics of chalcopyrite may induce one to suppose are present. By its colour, which may unreservedly be accepted as chalcopyrite colour, another type of chalcopyrite present here (to be discussed below) seems to support the above supposition of a difference in the optics of the central zone's dominating copper sulphide. Moreover, it stands out by virtue of the cracks always to be seen in it and, in their most handsome development, having the appearance shown in Pl. VI, 5.

The cracks are always rectilinear and in most instances collectively form a triangular pattern in the chalcopyrite, interrupted by the areas with the binary structure but always running parallel; or, one might say collectively forming a system of three "crack patterns". In association with the cracks, and often in the centre of the "crack stars", there is magnetite whose form is determined by the cracks and thus becomes hexagonal. Quite commonly the magnetite grain is equidimensional, but it may be elongated as in Pl. VI, 5. Sometimes there are branches from the grains, in which case they always follow the cracks. Magnetite and cracks occur exclusively in the chalcopyrite; if there are cracks in the binary structure they are irregular and differ from the surrounding rectilinear cracks in the chalcopyrite. Accordingly, it would seem that the arranging factor of the cracks is to be found in the chalcopyrite; apparently they reflect its structure, which may be hard to understand because they are so distinctly suggestive of a hexagonal form, and chalcopyrite in the normal state is tetragonal. Possibly what is reflected in the crack system is a cubic symmetry; this is not contradicted by the elongated magnetite grains, as they are cut off obliquely at the ends parallel to the cracks, which form mutual angles of 120°; but this does not agree with the crystal form of chalcopyrite either. It is imaginable that these are relict structures of a chalcopyrite with a cubic (scarcely hexagonal) structure, which would mean a chalcopyrrhotine; and then the question arises whether this feature too does not suggest a nickeliferous chalcopyrite. We cannot unreservedly accept chalcopyrrhotine, i. e. the chalcopyrite-pyrrhotite mix-crystal, because it should be possible to recognize a disintegration of it, whilst its continued existence does not harmonize with the optics of the mineral; chalcopyrrhotine is much greyer, with a greenish-brownish tint.

In keeping with several of the detail problems of this ore, the question cannot be further elucidated as the components involved are all of such small dimensions as to make it impossible to remove material for, inter alia, a roentgenological or spectrographical analysis.

In the form of small areas that stand out clearly against their surroundings we find in the central part of the pore mass a chalcopyrite that is intersected by parallel cracks or lamellae. Presumably owing to this lamellation the mineral between crossed nicols displays a shimmer that is foreign to chalcopyrite; otherwise, the mineral is distinctly chalcopyrite. Pl.V,1 shows an area of the pore mass containing this chalcopyrite. Some magnetite may be irregularly imbedded in the mineral, extending along the lamellae; or magnetite may be lying close to it, branching into it along the direction of the cracks. This magnetite by the way is often of rather irregular form. If several of these chalcopyrite areas appear within the same field, they are usually of different orientations, judging from the direction of the lamellae. In that case their extinction directions are also different. Occasionally the mineral cubanite may be seen as part of the sulphide mass, and chalcopyrite of that appearance has been interpreted in the literature as a chalcopyrite transformed from cubanite; therefore it would seem reasonable here too to regard the mineral in that form as a pseudomorph after cubanite.

A chalcopyrite apparently resembling what I have characterized as a cubanite pseudomorph may sometimes be found in a handsome myrmekitic intergrowth with magnetite, as may be seen in Pl. VII, 2.

It seems characteristic of the chalcopyrite in the rounded areas that a grain of magnetite is contained in each; it may be absent here or there, but there is never more than one in the same area. On the other hand, where this type of copper sulphide occurs in larger areas in the pore mass, we sometimes find it quite regularly furnished with small magnetite grains of the same kind and appearance as in the small rounded areas. This is shown in Pl. VI, 6. Veins of the binary structure may be present, but generally only in association with adjoining parts of the outer zone of the pore mass. For that reason it is particularly remarkable to see bravoite formation emanating from the cracks in the chalcopyrite, as will appear from Pl. VI, 6. These areas of copper sulphide with a quite regular pattern of magnetite may contain patterns divided up into what we may call "point clusters", so that a system of magnetite grains "breaks" and takes a new direction.

Associated with large chalcopyrite areas of this particular type with a "magnetite pattern" there may occasionally be areas of a pyrrhotite which so to say replace the chalcopyrite. It is especially remarkable in that it replaces the chalcopyrite so completely that from the chalcopyrite the magnetite pattern continues through the pyrrhotite with exactly the same appearance. In it are both chalcopyrite lamellae and chalcopentlandite exsolution lamellae. Often it is to be seen as an offshoot from the ore-forming pyrrhotite, from which it differs solely by its content of these strikingly uniform, small magnetite grains.

Lying within the internal parts of the pore mass, but observed both in the binary structure, Pl. VII, 1, and in the chalcopyrite in the central parts, we sometimes find a pale grey, very soft isotropic mineral which may be galena. As a rule it appears in vermicular areas which in places have been seen as veritable myrmekites. The lead content shown by the analysis suggests that the interpretation of galena is correct.

Between the outer zone of the pore mass, the binary structure, and the pyrrhotite there may often be a rim of chalcopyrite equalling in thickness the chalcopyrite lamellae in the pyrrhotite, and as a rule it is also possible to demonstrate that this narrow chalcopyrite seam actually is a branch of these lamellae from the pyrrhotite. This will be seen from Pl. IV, 4. To a casual glance it may sometimes seem as if the pore mass had interleaved the pyrrhotite, but examination shows the chalcopyrite squeezed in between the pyrrhotite and the binary phase, whose colour may be hard to distinguish from that of the chalcopyrite. However, it is quite characteristic of these intermediate layers that they do not merge with the chalcopyrite in the decomposed chalcopentlandite. It is more remarkable, I think, that neither do these intercalations reveal any form of relationship with the aforesaid large chalcopyrite flames in the original chalcopentlandite in the pore mass.

When contacted by a chalcopyrite lamella the unmixed chalcopentlandite bodies in the pyrrhotite, which are also split up into pentlandite and chalcopyrite lamellae, may likewise become isolated from the pyrrhotite by a similar border of chalcopyrite. Usually this border is to be found only in one side of the small area; in fact, to some extent this also seems to be the case with the pore mass, which may quite well have a finely developed seam of chalcopyrite against the pyrrhotite on one side, whereas no chalcopyrite is observable on the other, or where it must be exceedingly narrow at any rate.

Magnetite in the Ore.

In the description it was mentioned several times that the mineral magnetite occurs in association with the sulphides of the ore. However, both its optical properties and its occurrence are so special in character as to justify their being singled out for separate attention. On the basis of the quantity of oxygen found as "deficit" in the analysis calculation leaves room for barely $7\frac{1}{2}\%$ magnetite. On calculating the quantity from the residual iron, i. e. the amount of iron not forming part of the other minerals, we get just under 11%; the uncertainty of these findings being relatively great it must therefore suffice to state that there must be something like 10% of magnetite in the ore. This is no overwhelming quantity, but it would seem that this particular mineral is of extraordinary importance to our understanding of the genesis of the ore as a whole; I shall further illustrate this when discussing the collective observations in the description.

The placing of the mineral in the ore makes it reasonable to divide the description into two main sections: the occurrence of the mineral in the pyrrhotite and in the pore mass, and within these again into two and three different types respectively.

Magnetite in the pyrrhotite.

Within the pyrrhotite, that is to say within the various pyrrhotite areas in the polished sections, magnetite appears in the form of small anhedral grains, but, as will have been gathered from what was said above, isolated from the pyrrhotite itself, being always imbedded in the chalcopentlandite exsolution bodies. The ratio of magnetite to sulphide in these inclusions in the pyrrhotite is usually highly in favour of the magnetite, perhaps in the region of 3:1; however, quite close to the crystal faces developed by the pyrrhotite it may be about 1:4. This estimate on the basis of the areas of these materials is very uncertain, of course, but it provides an impression of the trend. As Pl. I, 6 shows, the magnetite may be invisible in the basal faces themselves—which perhaps is connected with the three-dimensional nature of the material. The polished basal faces often have cavities in the central part of the chalcopentlandite crystals. It is impossible to say whether the magnetite had been torn out of these cavities or there never had been any. The magnetite grains measure from some hundredths up to a tenth of a millimetre in length. The smallest are about $10\,\mu$.

Two things are particularly striking. All the grains are clearly rounded in shape, and they are arranged in a distinct pattern. As will be seen from Pl. II, 2, VII, 3, 4, VIII, 1, the shape of the pattern depends upon the situation of the pyrrhotite in the particular section. Generally speaking, however, the magnetite occurs in constellations whose central parts consist of the smallest particles, the individual grains becoming larger and more elongated the farther they lie from these centres. Quite evidently, the relation to the pyrrhotite is that the constellations in the basal section form radial patterns, whereas oblique sections and sections along the c-axis in the pyrrhotite rather give the impression of sheaves. However, their dependence on the structure of the pyrrhotite is also revealed by the fact that each of the constellations or patterns belongs so to say to its own pyrrhotite area. The pattern inside a pyrrhotite island, Pl. VIII, 2, is not joined up across the pore space with the pattern of another island. On examining the pyrrhotite it is often found that the central part of the FeS area may be devoid of these inclusions; then "a short distance out in the pyrrhotite" the very small grains of magnetite begin to occur, and gradually as we move from the central area we find the larger, elongated grains, or "drops" as they may also be called. Where two pyrrhotite areas adjoin the magnetite grains may appear as if affected by that fact, for they may be bent away or flattened up against the boundary, as Pl. VIII, 4 shows; such grains in the margin of a pyrrhotite area are often distinctly claviform, Pl. VIII, 3. Larger magnetite grains lying in the pore space can always be shown to belong to the magnetite pattern in an adjoining pyrrhotite area, because in shape, size and position they correspond to the magnetite grains in the vicinity, whereas the patterns of more remote pyrrhotite islands have no room for them.

In sections that are not parallel to the basis the elongated magnetite grains here and there may partly be arranged along (0001), the grain in question bending away and following the basal direction in the form e.g. of a crack in the pyrrhotite. This is not particularly prominent, however, and the usual shape of the magnetite is by no means governed by being thus forced into this direction of the pyrrhotite.

In addition to this type of magnetite, Pl. IX, 4, 5 show the mineral in the form of rather large inclusions in the pyrrhotite. These large grains correspond to the macroscopically recognizable inclusions referred to earlier (page 27). One of the grains in Pl. IX, 5 represents the inclusion consisting wholly of magnetite. In the figure, half of the grain is missing, which may be due to the preparation of the section; but there often is a cavity in association with these inclusions, and in fact it is in these that we find the magnetite crystals described from the deposit. The other grain consists of a thin shell of magnetite with the interior completely infilled with siderite, which generally proves to consist of several individuals. These infillings differ considerably by their size from the aforesaid type, but otherwise their relation to the pyrrhotite is quite the same; and, as the figure shows, they may be "fused" together with the small grains of magnetite.

Optically, the magnetite in the above forms is neither homogeneous nor normal. In practically all grains of these types a zonal division is observable, and often in the central part of the grains there is a cavity which — in the small grains too — is sometimes infilled with siderite. As a rule the zonal division is such that the grain has an external, relatively narrow zone distinctly delimited from an inner zone differing in colour from the outer one. No definite rule can be laid down for the variation; often the inner zone is seen to be darker than the outer one, but the reverse is not at all rare. Pl. IX, 1, 2 & II, 3 give a few examples. The sharp boundary between the two zones may be almost rectilinear, giving the impression of a crystallographic boundary; but apparently it is not certain that this is the case, having regard to the observations on the material in its entirety. On the other hand, as will appear from Pl. IX, 2 the outer zone may be seen to intersect the grain in the form of lamellae; and even though these lamellae must be called flame-shaped, it seems —a certain systematization being observable—presumable that they represent crystallographically oriented bodies. Sometimes in the inner part of the magnetite grain there may be an irregular, mottled, dark phase instead of the inner zone. In this particular type of grain the material of the inner zone may often present a bluish-grey tone, which must mean that that material is maghemitized. There is no question of oxidation of the magnetite by polishing, because it is to be seen in samples prepared at different places (Copenhagen or Heidelberg) and also in samples prepared by different methods of polishing (cloth and lead laps); finally, maghemitized grains and untransformed grains are often so close together that it is hard to imagine how maghemite could be formed in one and not in another by the polishing process.

In colour, this magnetite approaches the normal for the mineral, but with the above variations whose quality is partly to be seen from the photographs of the ore. As far as can be judged, the hardness also corresponds to that of the mineral magnetite. Between crossed nicols the outer zone is not demonstrably anisotropic—or, more precisely, the paler areas of the grains seem to be isotropic, but in the inner zone, especially where it is even and darker than the outer, it is quite usual to observe a distinct, but not pronounced, anisotropy. The latter may in fact show that there are differences between the various parts of the zone, their anisotropy is different, and here sometimes there is the remarkable fact that the anisotropy may increase somewhat towards the inner margins in the zone. Undoubtedly this must signify abnormalities in the material here; I should add, however, that magnetite from quite different deposits and from other types of deposits sometimes has a clearly observable anisotropy, but without the uneven distribution of the effect between crossed nicols. No question of error in the optics of the microscope is involved; not all the fields of a magnetite grain show anisotropy, or, in other words, one can see what seem to be variously oriented grains within the field examined. Incidentally, in the same manner sphalerite can be seen to show anisotropy, and twin lamellae in it are often beautifully distinct. With modern microscopes and the improvements made to lenses etc. (coated lenses and prisms, better designs etc. as in the Leitz AMOP 1951), it seems that we must revise some of our views regarding the optics of cubic minerals; on the other hand it is perhaps also imaginable that the dependence of the anisotropy phenomenon upon submicroscopic pores, inclusions etc., on closer study may turn out to correspond to just this form of faint anisotropy which I have mentioned. It is not incredible that the inner zone of the magnetite grains of the Igdlukúnguaq ore is built up of porous magnetite. It seems to be little resistant; in several samples, especially in association with areas in which zwischenproduct and bravoite have formed, the zone may be seen to be more or less cavitated, and often there is nothing left of it at all. Submicroscopic porosity of this kind might just be the cause of a darker tint in the mineral than it should normally display. Heating tests with this ore seem to bear these ideas out, because several magnetite areas in a sample which had been heated to about 625° had the appearance of normal magnetite after treatment, but were split up into many small polygonal grains, were crackled, which might suggest a certain diminution of volume.

Enclosed in the outer zone of the magnetite there may be sulphide grains of quite small size, as shown in Pl. IX, 2. Some samples contained inclusions in the internal parts of the magnetite grains, consisting of a very pale, whitish mineral that must be softer than the magnetite. The size of these inclusions would not permit of more definite identification.

Magnetite in the pore material.

As has already been said, the central part of the pore material, which is characterized by copper sulphides, contains magnetite in very small, regularly imbedded grains. Their slight size makes it impossible to give the character of the mineral in detail, but on rare occasions a cavity was observed in the central part, which might lead to the assumption that its structure is the same as that of the magnetite grains found in the pyrrhotite.

Both shape and situation in the sulphide mass are, as I said above, closely associated with the cracks in the sulphides; but it seems worth while underlining the fact that the groups of magnetite grains present the regular feature that the distance between the individual grains is surprisingly constant; the grains are distributed evenly over the areas in which they are observable (Pl. VI, 4, 5, 6).

In association with the laminated chalcopyrite, the cubanite pseudomorphoses, there are patchy areas of magnetite grown together with the sulphide, partly along the direction of the lamellae. Chalcopyrite may be seen imbedded in this magnetite in the form of very small grains, but, as stated, there may also be regular myrmekites between the chalcopyrite and the magnetite.

Optically this magnetite seems to be more homogeneous than the other types mentioned. On the other hand it is not unusual to find magnetite in association with this kind of chalcopyrite grown together with magnetite from the pyrrhotite, or it may pass straight into the magnetite which is found so often in the samples in the form of crack-infilling in the pore material. For its own part this type may have grown together with the grains in the pyrrhotite where, through the corrosion of the pyrrhotite by the pore material, they ended by lying sufficiently far out in the pore space. Pl. IX, 6 & X, 1 show an extreme case in which the pore space is so to say replaced by magnetite.

Accordingly, these various types of magnetite may be characterized as structural types, because, as far as their substance is concerned, they cannot be very different when they often merge into one another.

Pl. X, 1 is quite interesting, in that it very instructively illustrates the relations between magnetite vein and the pyrrhotite with its inclusions. Very obviously there must have been a massive replacement by the magnetite of the pore material and parts of the pyrrhotite. Even here the latter mineral does not border directly upon the oxide. Almost everywhere we can recognize chalcopyrite as the border sulphide to the magnetite. In the field illustrated it will be seen that the chalcopyrite may have formed with an appearance conforming mostly to the cubanite pseudomorphoses, and it is very interesting to see that the chalcopyrite lamellae of the pyrrhotite can still be identified in this other kind of chalcopyrite. In the corrosion of the pyrrhotite, exsolution bodies of the chalcopentlandite were "cut through", and it is seen here how the magnetite grains may merge with the magnetite of the vein. At such places it is impossible through the microscope to see any difference between the magnetite from the drop in the pyrrhotite and that from the vein.

Spinel in the ore.

In addition to the magnetite, in two of the polished sections I found another oxidic phase that is highly reminiscent of the magnetite in both appearance and position. Pl. IX, 3 shows one of these mineral grains. It is characteristic of the mineral that it always presents a very distinct crystal form, its colour is grey and it may be mistaken for magnetite when it is not in the immediate vicinity of that mineral, it is isotropic and, though very rarely, may show internal reflections. There is no doubt that this is spinel. The most interesting of the spinel grains was found like the others in the pyrrhotite, likewise with a margin of disintegrated chalcopentlandite against the FeS itself. This grain, however, was itself surrounded by magnetite of the usual zonal structure; there was also a little maghemite in this magnetite. In the spinel was a beautiful subdivision into an inner, darker zone and a narrow, outer one, mutually separated by a rectilinear border parallel to the outer boundary to the magnetite. The latter mineral was paler than the outer zone of the spinel and its grey tint contrasts with the delicate rose of the spinel. In shape and structure this spinel crystal recalls a description of a chromian spinel by Ödman in his work on the rocks of Mount Elgon (56). The colour of the internal reflections in the spinel in the Igdlukúnguaq ore does not detract from the supposition that it may be a Cr-spinel, and the analysis quantity of Cr is at any rate adequate for the amounts that would be involved.

Ilmenite.

This mineral was found solely in samples containing rock, and its association with the sulphides is such that rods of the mineral are to be seen lying partly in sulphide and partly in silicate; it is rarely seen wholly in sulphide, and in such cases always in the very margin of the sulphide grain. The relation otherwise is as that of rods of feldspar to sulphide. As the analysis shows, the content of titanium in the compact ore is slight.

In the silicate mass, however, there is abundant ilmenite and its appearance there is quite normal. Sulphides may be found apparently imbedded in the ilmenite, but the bizarre forms of that mineral and the three-dimensional nature of the samples compared with observations of the relation between sulphide and ilmenite in the silicates make the question of a spatial inclusion in the ilmenite improbable.

Unknown mineral A.

In association with a large area of magnetite in the pore material I observed a grain of a white to pale greyish mineral which could not be identified. In its anisotropic effects it bore some resemblance to arsenopyrite. The grain consisted of several polygonal individuals. Its hardness was clearly greater than that of pyrite but less than the hardness of magnetite.

Unknown mineral B.

In a similar position, i.e. between magnetite and chalcopyrite, I twice observed an almost chocolate-brown mineral with a hardness that seemed closely to approach that of chalcopyrite. Apparently it was not anisotropic. Closer identification was impracticable.

Identification by Thermal Etching.

The special nature of the Igdlukúnguaq ore, as a result of which a large quantity of the components occur in extremely fine-grained structures, has the effect that it is generally impossible to identify the components by the usual methods. The optical characters such as colour and reaction between crossed nicols are difficult to discern, material cannot be drilled out for chemical or roentgenological analysis, and other ordinary methods are also useless.

It was therefore with some interest that the thermal etching method of identification known to metallurgy was applied to this Greenlandic ore and, for comparison, to some samples of ore from Sudbury.

The polished ore sample was heated to about 185° for about four hours (in an ordinary thermostat). The samples measured about $2 \times 2 \times 1$ cm. This treatment causes the ore to tarnish, and it proved that there are wide differences in the oxidizing colours of the various minerals. Of course, there is no question of absolute identification by this method, but it provides a clue which, together with the other observations, permits of an evaluation of the possibilities of what substances may be present.

No doubt it would be unreasonable to assume that the method is applicable to every kind of ore; but there is a possibility that it will be useful in respect of quite a lot of ores if only deep changes do not occur at the temperature employed. Moreover, the temperature may be varied, of course; and finally, all that happens to the various minerals is an expression of their own particular character and as such must be diagnostically useful. The idea of employing the method being just that, the quantitative relations are of no significance. However, it would undoubtedly be interesting to study the variations that are expressed by the different colours appearing, because they must be closely associated with the oxidation possibilities of the substances treated. This for instance applies to the various colours of pyrrhotite's two components, the α and β lamellae. The following, however, is only a record of the results of applying the method to the two ores named.

Pyrrhotite.

The treatment caused this mineral to be coloured rather vividly, making it most nearly comparable with bornite. The colouring was distributed somewhat irregularly, some areas being less tarnished than others; the various areas merged into one another. There was a distinct difference in the tarnishing of α and β lamellae. The subdivision of pyrrhotite into these two lamella systems became very distinct through this etching.

The same treatment of the Sudbury sample resulted in a rather weaker coloration of the pyrrhotite; its α and β lamellae stood out less clearly, but the difference seemed to be the result merely of the intensity of the discoloration.

Chalcopyrite.

The colour of this mineral did not seem to change under the treatment, a circumstance which contrasts it very pronouncedly with the other minerals, especially the pyrrhotite, in the Greenlandic ore. The chalcopyrite lamellae in the pyrrhotite stood out sharply against the darker FeS. The chalcopyrite of the pore material in its various structural forms all had the same colour, or absence of colour change. The only thing observable was that dark bluish spots appeared here and there in the lamellae, and more rarely in the larger areas of chalcopyrite. In places in the ore it almost seemed that narrow chalcopyrite lamellae had been replaced by the blue material formed. The reasonable explanation no doubt is that at these spots the chalcopyrite was not quite pure, but beyond that the phenomenon could not be elucidated.

In the heated sample from Sudbury too the chalcopyrite seemed to retain its colour. There were no bluish tarnish tints like those observed in the Greenlandic ore.

Pentlandite.

The decomposed chalcopentlandite, consisting mainly of pentlandite, on being heated assumed a brownish, golden colour like ripe oats. In the larger areas of this sulphide material, the outer zones of the pore material, some variation of the coloration was distinctly visible. The large chalcopyrite flames in this material stood out well, the small ones in the decomposition structure less so.

Heating the Sudbury sample gave the pentlandite in it the same coloration as that of the pentlandite material of the Igdlukúnguaq ore, though perhaps with scarcely the same intensity.

The main result of this thermal etching is to establish the fact that within the same sample it is possible to say that the same material in different structural elements gives the same reactions; this, combined with the other observations, makes it reasonable to assume that the mineral is the same. This holds good of the various forms of chalcopyrite in the Greenlandic ore, but it is true particularly of the forms in which pentlandite occurs. In the sample it is seen that the etching coloration is the same for the outer zone of the pore material, the exsolution bodies in the pyrrhotite—both those which have been interpreted as chalcopentlandite in which chalcopyrite is visible, and those which correspond to the well-known pentlandite flames. In association with the special forms of siderite in the Greenlandic ore (to be discussed below) there is a complicated mixture of sulphides. In these areas thermal etching gives colours corresponding to pyrrhotite, pentlandite and chalcopyrite in small irregular patches.

It is also interesting of course that there is agreement with the colouring of the corresponding minerals in quite another ore, and it is of importance that the relations between the minerals are also in agreement.

Siderite in the Ore.

The mineral siderite occupies such a special position in this ore that I have found it necessary not only to describe it as a mineral occurring in the ore, but also simultaneously to examine the ore as it appears in those regions where the siderite is to be found; the point is that there, and there only, the ore presents itself in a form which differs considerably from what has been described hitherto. For the sake of completeness the aforesaid inclusions of magnetite with siderite cores in pyrrhotite will also be referred to.

Siderite in the Pyrrhotite.

As has already been said, siderite surrounded by magnetite is to be found imbedded in the pyrrhotite, corresponding to the other magnetite inclusions in the pyrrhotite and differing merely by the fact that their size may be up to 100 times the diameter of the latter inclusions (see Pl. IX, 5). At times the magnetite forms a serrated border against the siderite, which may represent a tendency towards idiomorphism vis-à-vis the carbonate. The siderite itself is usually built up of polygonal grains, but it may be observed with a concentric structure, as shown in Pl. XI, 1. The concentric structure has the convex side turned towards the centre of the siderite region. In the largest siderite masses, visible macroscopically in the ore, a radial structure was also observed.

The index of refraction of the siderite as far as the extraordinary ray is concerned was determined at

$$e = 1.602$$

which according to WINCHELL (55) is most closely comparable with iron carbonate having a mixture of 5 % $CaCO_3$ and 5 % $MgCO_3$. A calculation of the analysis quantities of Mg and Ca gives 0.07 % of each expressed as carbonate, and the amount of CO_2 found gives additionally 1.75 % siderite. The agreement is good, but the uncertainty of the analysis on these determinations does not permit definite conclusions.

Chalcopyrite may occur sporadically within these inclusions, whereas pyrrhotite in large masses is to be found in some of them. The mineral takes the place of the siderite, and if there is also siderite inside the magnetite shell, the pyrrhotite is pronouncedly idiomorphic vis-à-vis the carbonate. The magnetite in turn is idiomorphic to the pyrrhotite. This mineral differs from the ore-forming pyrrhotite in that it is free of inclusions. It is pure FeS, whose sole characteristic is its well developed (0001) parting. Placing and appearance will be seen in Pl. X, 2.

The crystals described by O. B. Bøggild (see page 14) must have been crystals of pyrrhotite of this kind.

Siderite in the Pore Material.

When present in the pyrrhotite the siderite is always in the form of infillings in the magnetite bodies and therefore cannot be said to occupy an independent position; but matters are practically reversed when the mineral is present in the pore material. There it is not enclosed by magnetite and it most certainly displays independent forms in its contact with the surrounding sulphides. In Pl. X, 3, 4 examples are given of how it may appear. Apart from the fact that the boundary line is distinctly curved, it is scarcely to be doubted that crystallographic directions must form the foundation of a figure such as the three-pointed star with all its lateral branches, to be seen in Pl. X, 3. The other forms displayed by some of these siderite areas must also have been shaped under the influence of a regulating factor of crystallographic nature; but there is nothing obvious about what caused that regulation. The siderite itself is now built up of polygonal grains, so that we can distinguish no direct connection between this mineral and the forming of the area. And finally, it is also a question whether the figures formed are to be regarded as having been regulated hexagonally or they should rather be viewed as a cubic configuration. If the latter is the correct version, it is imaginable that the shape was determined by the surrounding sulphides.

However, as the latter are not now recognized as being a continuous crystallographic whole, it is difficult to see how they can have exerted the regulating influence which must have been present when the siderite was developed.

As will appear from the following description of the sulphide material around these siderite areas, the eutectoid forms of the siderite seem to have a particular tendency to appear in surroundings which correspond to the outer zone of the pore material — the chalcopentlandite. True, the sulphide mass round about is now a heterogeneous material of many components, but it is dominated by nickeliferous sulphides, wherefore it is possible that at the time when the siderite was formed this sulphide mass was possessed of a cubic crystal structure which was the governing factor in the forming of the carbonate.

Naturally, the siderite does not appear everywhere in such regular configurations. Rather more than half is presumably to be found in more simple figures which may be regarded as fragments or parts of the more complicated kind, or the mineral is present as crack infillings through the ore. These siderite-filled fissures may usually be localized as forming a kind of connection between larger areas of siderite.

The position of these siderite areas seems to be regular, for apparently they occur at places in the pore material where more than two pyrrhotite islands form the boundary: where the pore material in the sections (the polished surfaces) ramifies, areas of siderite may generally be expected. They have not been observed as present in the natural crystal faces, and to all appearances it may be asserted that they are to be found predilectively inside the pyrrhotite individuals. In the sections through a sample containing several such individuals, siderite areas may be seen on the border between them.

In a few hand specimens of the ore I have found areas where the ore is of a form differing slightly from the rest, chiefly in the way that the pore material is less prominent. In this manner the pyrrhotite areas become larger and more continuous. In such areas I have observed siderite regions differing both from the aforesaid eutectoidally formed areas and from the round siderite inclusions which, surrounded by a coat of magnetite, have been observed in the normal pyrrhotite. As will be seen from Pl. XII, 5 & XIII, 1, they are rounded in form, and it is characteristic of them that their immediately surrounding sulphides are chalcopyrite and pentlandite which, quite evidently, represent original chalcopentlandite, the mineral which thus enclosed these inclusions in the same manner as the round siderite inclusions with shells of magnetite found in the usual the pyrrhotite. There is often a magnetite shell, but it is situated a little way into the carbonate. Bravoitization is observable in association with the surrounding pentlandite and to some extent the pyrrhotite is transformed into zwischenprodukt. However, these phenomena are not so pronounced as in the eutectoid siderite areas. On the other hand, the pyrrhotite as a whole has an appearance that indicates differences from the normal pyrrhotite in the ore; in particular, basal cracks infilled with limonite are very prominent. In areas containing this siderite, which so to say is an intermediate type between the two described above, there is no small-grained magnetite in the pyrrhotite.

Minerals surrounding the siderite.

To the uncritical eye and using a low power, say about ×80, it may look as if the siderite areas were imbedded within a homogeneous sulphide mass differing from the other ore components in both colour and hardness. This is illustrated fairly well by Pl. X, 4. It is intersected by many cracks and fissures and, taken as a whole, might well be assumed to be bravoite. Examination with a power of ×600 or higher is more necessary here than otherwise in this ore, of which it is almost a characteristic that it has to be viewed with high magnification. Close examination of the sulphide mass surrounding the siderite reveals that it is not a homogeneous mass of bravoite but a variegated complexity of small patchy areas of pentlandite, bravoite, chalcopyrite, pyrrhotite, zwischenprodukt, chalcopyrrhotine, cubanite and valleriite. Intersecting everything are cracks and fissures, some so fine as to be almost submicroscopic, the coarser ones containing material of oxidic nature, perhaps limonite—its true identity cannot be determined with reasonable certainty and may equally well be carbonate, sulphate or other substance with a refraction lower than that of sphalerite (judged according to the reflection colour). The question of structures hardly arises in connection with these materials as a whole; but one may see bravoitized remnants after the pentlandite-chalcopyrite exsolution of original chalcopentlandite, which may be regarded as a kind of continuation of the materials of the pore space in these specially built-up areas. The area occupied by this double-sulphide structure is irregularly bounded by the surrounding minerals. Notwithstanding the difficulty of identifying the components around the siderite, the structure may be considered as the most widespread component in the area. Pyrrhotite, most easily recognized because of its anisotropy, occurs in small areas and is not nearly so frequent. Chalcopyrite is only sporadic in discernible areas adjacent to the siderite, except that it is present in the disintegrated chalcopentlandite. Nevertheless the mineral is also apt to dominate areas in association with the siderite areas, and in these cases it is a so to say optically pure chalcopyrite. This seems to depend upon the nature of the materials surrounding the siderite area. Where material of the central part of the pore space forms the adjacent parts of the ore the converted chalcopentlandite may become secondary in volume to the chalcopyrite. Siderite areas of more irregular or rounded forms are sometimes entirely surrounded by chalcopyrite. In these cases, however, there is a marked difference in the appearance of the siderite as a whole, and inter alia it looks as if there often were a magnetite zone a little distance into the siderite; this will be further discussed when dealing with the minerals lying in the siderite.

The places where the bravoitized, decomposed chalcopentlandite runs into chalcopyrite areas belonging to the pore space are usually the site of occurrence of chalcopyrrhotine, cubanite and valleriite, all of which are present in the form of small, irregular areas. In this transitional zone the small magnetite drops, which are characteristic of areas in the pore space, may also be seen to extend their patterns some distance into the characteristic sulphide mass of the siderite, which must mean there has been a corrosion of the pore material caused by the placing of the materials of the siderite surroundings. In the immediately adjacent part of the pore-space chalcopyrite with magnetite drops one may see bravoite material emanating from the cracks, and a little farther away the pore material seems to be normal. This all takes place within tenths of a millimetre or less, which may be taken as a characteristic of the dimensions of the components described. The regular fields of siderite themselves may be of millimetre size. See Pl. X, 4.

At the places where the siderite areas are bordered by the ore-forming pyrrhotite, the sulphide mass lying directly up to the siderite is characterized almost wholly by bravoitized pentlandite; here, however, is a complicating factor in the form of the material that has been called "zwischenprodukt".

The sulphide masses may be subdivided into three zones. Commencing at the siderite there are first the sulphides surrounding the siderite itself; then there is what may be called a transitional zone, and finally the third zone, the pyrrhotite.

The first zone, directly adjoining the siderite, may have an appearance such as that shown in Pl. XI,1. The mineral content conforms to the above description, which in the main means that it consists chiefly of bravoitized pentlandite and only small amounts of the other sulphides. It is interesting that one can see the traces of the chalcopyrite lamellae from the pyrrhotite continuing in these special sulphides (as Pl. XI,1 shows). Sometimes the chalcopyrite is still present some distance into the special sulphides in the form of a strand of pure chalcopyrite; but most frequently the copper sulphide is replaced a little way in by a dark strand of transparent material, whose nature defies determination. Out here there may also be magnetite grains whose size and position make it obvious that they belong to the magnetite pattern in one of the adjoining pyrrhotite areas. As with the pore material bordering upon these areas, we thus see here that they replace the pyrrhotite with its components.

The term transitional zone was used above for that part of the pyrrhotite which lies in direct contact with the sulphides that are characterized by bravoite and zwischenprodukt. Pl. XI, 2, 3, 4 & XII,1 present some examples of the occasional appearance of the pyrrhotite with its components in this zone. The dark areas with light patches can be seen directly to be replaced pyrrhotite areas. The dark material cannot be identified, but there is a possibility of sulphates, for instance; at any rate, this is not contradicted by the refractive index as expressed in the reflection colour. These transparent materials do not emerge when powdered materials are examined by ordinary microscopy, because they are so small in extent and, as the figures show, they are strongly pigmented. The light material in these dark areas consists of sulphides which in colour and general appearance are indistinguishable from the sulphide materials directly adjacent to the siderite, characterized above as bravoitized pentlandite. The basic material of the transitional zone otherwise consists of pyrrhotite of the kind forming the ore and its special character there will be seen from Pl. XI, 3, 4 & XII, 1, which show that the other minerals imbedded in the sulphide have undergone considerable changes; changes in the pyrrhotite itself can also be seen in patches. If in these areas one finds the chalcopentlandite exsolution bodies containing magnetite grains, it can be seen that the sulphide mass there has also been subjected to considerable changes. In their converted form these areas and pentlandite flames of the ordinary type have the same appearance as the bravoitized sulphide mass in the zone adjacent to the siderite and it is natural to characterize the present substance of these inclusions as bravoite. The transformed areas in the pyrrhotite, which are particularly distinct in Pl. XII, 1, may most reasonably be characterized as zwischenprodukt, a term which would also seem to be the proper one for the decomposition products observed in Pl. XI, 4 as borders on the chalcopyrite lamellae in the pyrrhotite.

These very marked transformations in the pyrrhotite which has been called the transitional zone or the second zone in relation to the siderite, pass gradually into unaffected pyrrhotite where the inclusions that are characteristic of it are present in the form previously described. This part I have called the third zone.

It is interesting, by the way, that there may be pentlandite flames in the second zone that have not been transformed. As a rule they are slightly smaller than the transformed flames and are quite distinct. It may be that they represent lamellae of a later exsolution and thus were not affected by the transformation processes.

On considering the above picture in reverse order an interpretation of the various phases may be somewhat difficult on account of the fact that the bravoitization of pentlandite and the forming of zwischenproduct by pyrrhotite give rise to products that are not easy to distinguish from one another. The colour and hardness are pretty much the same for both and—which is at least as important—both products are of a somewhat indefinite character; in both cases there is a question of the formation of di-sulphides—$(Ni, Fe)S_2$ and FeS_2 with a certain content of water, sulphate etc. For the position between these two compounds is that several nickeliferous pyrites may be set up between the bravoite and the pyrite; we have a mix-crystal series. Therefore it is not incomprehensible that the formation of disulphide in the Greenlandic ore could give rise to products that may be difficult to distinguish from one another. In any case, they are undoubtedly products of the formula $(Ni, Fe)S_2$, but the proportions of Ni and Fe will certainly vary with the transformed product. Where there is a conversion of pentlandite flames it is reasonable to assume that the product approximates the bravoite link, whereas the greyish substance formed in the pyrrhotite (Pl. XII, 1) corresponds better with a pyritization. Obviously, the latter need not be free of Ni; we need merely bear in mind that the ore everywhere presents the so-called pentlandite sparks which through the formation of disulphide may have passed into the new product.

In a microscoped area the first sign of the propinquity of a field of siderite is the bravoitization of the chalcopentlandite exsolution bodies. The pentlandite flames also begin to show signs of the transformation. Cracks begin to appear in the pyrrhotite along (0001), and incipient zwischenproduct formation appears around the chalcopyrite lamellae. The pyrrhotite itself becomes mottled, and we are quite close when the pyrrhotite presents the transformations shown in Pl. XII, 1. The nickeliferous exsolution bodies begin to become prolonged along (0001), several may fuse together and form longer, continuous veins, and finally, as Pl. XI, 2 shows, there are patches of disulphide in a transparent mass. The pyrrhotite is gone, but its structures are still recognizable because the shape of the pentlandite flames still mark the (0001) direction. I may add that in the transitional zone the chalcopyrite lamellae often become rather wider and assume as it were a more flame-shaped outline.

In these areas the magnetite grains from the pyrrhotite will usually be unchanged, but here and there the inner zone will appear to be riddled, or it may have disappeared as if dissolved.

Minerals in the siderite.

Lying in the siderite we find the sulphides: chalcopyrite, valleriite, pentlandite, covellite and "graphite-like sulphide". In addition, there are magnetite and a grey mineral resembling magnetite as well as a mineral observed in a few cases, greyish-greenish in colour, which may also recall magnetite. Pyrrhotite is present in a special form in association with the oxidic phases within the siderite. Chalcopyrite is the sulphide most often found in large areas in the siderite itself. It is optically pure with the characters corresponding to chalcopyrite. Twin lamellae were not observed in it. It is often intersected by cracks which split the sulphide up into polygonal grains. The cracks are very narrow, so that one presumes them to be infilled with carbonate only because they run direct into the siderite.

Pl. XIII, 1, 2 is one such area of chalcopyrite. These areas may join up with chalcopyrite areas outside the siderite. No direct association has been observed, but the character of chalcopyrite bordering directly upon the siderite is the same, and, with intergrowths of siderite which may partly be regarded as wider cracks in the sulphide, the sulphide may be seen on both sides of the border as if there were two areas of the same material.

On rare occasions the mineral valleriite may be seen lying in the chalcopyrite in the siderite, but the most interesting observation is that the chalcopyrite rather often has a border of a leaf-like mineral, as shown in Pl. XIII, 2. Between that mineral and the chalcopyrite there is frequently an intermediate layer of valleriite.

The leaf-like mineral is interesting, but I must say at once that presumably it cannot be a single phase. It appears in two different colours: It may be greyish, almost like graphite, and it may have a yellowish tint which must be described as something in the direction of dull chalcopyrite colour. In both forms the mineral is strongly anisotropic. The colour difference between the two forms is not due to reflection-pleochroism. For the graphite-like grains the latter is clearly less pronounced than for true graphite, though it definitely is very marked. The colour change with one nicol is from pale greyish to brownish grey. The yellowish variety of the leaf-shaped mineral is distinctly reflection-pleochroitic but the phenomenon is not particularly pronounced. Between crossed nicols the graphite-like grains are anisotropic to almost the same degree as valleriite, whereas the yellowish grains are more comparable with cubanite, for example.

In the grains which resemble graphite there is sometimes observable a central strand, rectilinearly bordered by the surrounding mineral, consisting of a yellowish sulphide which can scarcely be other than chalcopyrite. In one or two samples the mineral covellite is seen instead of chalcopyrite, and occasionally the covellite can be seen to have replaced the leaf-shaped mineral completely.

In some samples or parts of samples the graphite-like variant seems to dominate, and in others it is chiefly the yellowish one. There is no strict regularity about this, however, and both may be observed together.

In magnetite in the siderite there are sometimes rosette-like areas of chalcopyrite. The radial structure of these areas may give the impression of transformations of the leaf-like mineral into chalcopyrite.

Pl. XII, 2, 3 show areas in which the leaf-like mineral is presented in its most characteristic and most frequent form.

It is improbable that these are two essentially different minerals, the graphite-like being one and the yellowish, leaf-shaped the other, having regard to the manner in which they "replace each other" and sometimes can be seen to be contiguous. The probable presence of copper and some iron seems to emerge from the frequency of the presence of chalcopyrite in it. It is perhaps rather doubtful as regards the presence of the iron as there is the possibility of access of that element from the surroundings. However, the yellowish variety may perhaps be cited in support of the theory because, at least as regards the optics, it may be said to agree with the various FeS-rich forms of "chalcopyrite". Seeing that both chalcopyrite and covellite may take the place of the mineral, it is a reasonable assumption that this is an S-bearing compound. Indeed, the yellowish variety is rather to be considered a sulphide. With these different assumptions, and bearing in mind the close similarity of the grey variety to graphite, it may be of importance to note the fact that both graphite and covellite as well as valleriite, which occurs in association with the leaf-like mineral, all crystallize hexagonally or are of the layer lattice type. The form of the unknown mineral or minerals and the optics actually correspond to the assumption that the fundamental structure of the leaf-shaped grains is a layer lattice structure, and therefore it may be that these are relicts of a particular phase which was stable when the siderite was being formed.

As will be seen from the figures, the size of the leaf-shaped grains is so small that it is impossible to isolate them and therefore also impossible to make a close examination of their nature. But it is imaginable that the formation of the siderite caused the formation of a mix-crystal of graphite and copper-iron sulphide. The formation of graphite in such a milieu is not impossible and various cupro-iron sulphides have their natural habitat there. Chemical demonstration of this postulated quantity of graphite will be impossible, partly on account of the very small values and partly because according to the assumption they must be present as an extremely fine grained pigmentation together with the appurtenant cupro-iron sulphides. Were it merely a matter of contamination of the sulphides with graphite as a kind of pigment, one would expect to find a marked variation in the colour of the grains, with all shades from the lightest to the darkest. But as in fact there are pale yellowish sulphide-like grains and greyish graphite-like grains, but no intermediate shades, it must be permissible to assume that these are rather well delimited forms of two phases.

It is not wholly impossible that the graphite-like mineral may be delafossite. It would be most interesting if $CuFeO_2$ were present in it.

However, Professor Ramdohr, who has seen this material, considers that it lacks the normal appearance of delafossite.

Pentlandite was occasionally found in pure, crystal-like forms such as that shown in Pl. XII, 4. It was also seen in the margin of the siderite areas, but its occurrence was rare and the crystals were small.

Magnetite drops which in shape, size and position can be recognized as belonging to the magnetite pattern of an adjoining pyrrhotite area, are sometimes encountered in the siderite. Otherwise in this type of siderite there is magnetite in the form of quite irregular areas (Pl. XII, 4) and a type which in the sections has the appearance of strands situated a little way into the siderite, following the boundary for shorter or longer distances. It may possibly be open to doubt whether everything which I have called irregular areas of magnetite really are of that mineral. In point of colour they conform, as far as can be judged; the hardness, and the fact that the mineral is optically isotropic, also answer to magnetite, but it may be difficult to decide whether it may not be a variant within the spinels; nor is it wholly impossible that some sphalerite may occur here. The latter is not very probable, however, as one would certainly expect a closer association with the chalcopyrite; so presumably it is magnetite or a corresponding oxidic substance. Another thing is that no Zn was demonstrable spectrographically in the samples. The greyish green magnetite-like mineral was observed in just such surroundings. It was isotropic and no internal reflections were observed with certainty.

Pl. XII, 6 & XI, 1 illustrate the other form of magnetite in these siderite areas. Here and there it looks as if there were a magnetite rim, similar to that observed around siderite imbedded in pyrrhotite; but in most cases this rim is only partially developed and now, as stated, it is to be found some way into the carbonate. One special form of this type of magnetite is shown in Pl. XII, 5, 6, where the oxide is scarcely visible otherwise than as the bearer of a pigmentation which is presumed to consist of a finely distributed FeS. This pigmentation may be observed as a zonally placed, quite regular coloration of the oxide, recognizable in some grains because the pigment is not wholly dense. The pigment may possibly be zwischenprodukt or even bravoite, but it is impossible to decide. This form of oxide-carbonate is frequent, especially where we find the intermediate type of siderite that has developed in ore samples having only little pore material; but imperfect examples of "magnetite rims within the carbonate" may also occur in the eutectoid siderite areas.

As I have already said, the foregoing very variegated picture of the ore, its components and structures, sketched from the microscopical observations, refers to the compact pieces of ore and, in so far as it is permissible to say from the sparse information available about the deposit, may be regarded as an expression of how the ore described by Steenstrup was built up.

In a few of the samples which Steenstrup brought home I have found lumps of sulphide of up to 10 mm in diameter. In addition, the material collected on the spot by Professor Rosenkrantz in 1953 was found to include some rock material from the dike where there are similar small lumps of sulphide.

Generally of course the dike rock has been found to contain very small sparks of sulphide which in both appearance and occurrence have proved to conform to what is usual in these rocks.

On the other hand, the larger grains of sulphide in the rock are so special in character that they must be of value to an interpretation of the genesis of this ore, for which reason they are described at greater length in the following.

Ore Associated with Rock.

Large sulphide nodule in rock.

Prior to the preparation of this rock sample I observed, in addition to a sulphide mass of over 10 mm in diameter, quite a quantity of hisingerite; some of it was found together with the sulphide but only on one side of it, and some in the form of veins and crack-infillings through the sulphide. Quite preponderantly it consists of pyrrhotite lying in a kind of polygonal structure, in which the polygons—in contrast to the pyrrhotite islands in the compact ore—are not of the same orientation. The diameters of the polygons range from about two-tenths to half a millimetre.

The magnetite drops in the compact ore which, imbedded in the disintegration structure of the chalcopentlandite, were observed as inclusions in the pyrrhotite, were not seen in this sample. But in a few of the pyrrhotite polygons there are drops of hisingerite approximating them in shape and size; on the other hand, I have observed nothing but sporadically occurring chalcopyrite between this hisingerite and the pyrrhotite.

The cracks bounding the individual polygons are filled with hisingerite, and chalcopyrite is to be seen regularly between that mineral and pyrrhotite. There is also a small amount of pentlandite. Inside the pyrrhotite the sulphides of Cu and Ni are present merely in the form of small exsolution bodies. The chalcopyrite appears in the form of lamellae which take three different directions in the pyrrhotite. They are somewhat more irregular than the usual chalcopyrite lamellae in the compact ore and seem almost comparable with the small flame-shaped lamellae observed in the compact ore as forming three-rayed stars.

Along the basal direction there is frequently a bravoite-like (or zwischenprodukt-like) mineral, but it agrees with the transformed pentlandite lamellae in the compact ore. It is scarcely to be doubted that these are transformed pentlandite flames.

In addition to these exsolution bodies there are quite small sparks of pentlandite. Similar small flames of chalcopyrite are to be seen, but possibly they are merely small exsolution bodies of the same origin as the chalcopyrite flames mentioned above.

Wholly imbedded in the hisingerite drops are occasional subangular grains of magnetite. But they have this peculiarity that they are intersected so much by cracks that the originally rounded grains are now seen in the form of a group of fragments of polygonal small grains, but altogether presenting the original picture.

In the outer margin of the sulphide mass are a few grains of ilmenite, sometimes lying half in the silicates and half in the sulphide mass. The shape of the ilmenite is exactly as in the silicates: long, narrow laths. There seems to be no predilective position in relation to the various sulphides. The mutual relations of these minerals seem to correspond to those between sulphides and felspar, which may also be observed occupying a position like that of the ilmenite.

In the form of two areas of the same dimensions as the pyrrhotite polygons the margin of the sulphide nodule contained chalcopyrite and pentlandite as well as small quantities of other minerals. The pentlandite-rich chalcopyrite seams bounding the cracks in the pyrrhotite merge with these two larger areas of chalcopyrite and pentlandite, which perhaps may be regarded as "violent expansions" of the border material of the cracks.

The transition from the pyrrhotite to these areas consists of pentlandite or bravoitized pentlandite which, together with the chalcopyrite, forms a handsome fingerprint structure, as Pl. XIII, 3 shows. It will be seen that this is an intergrowth structure that is much coarser than that formed in the compact ore through the disintegration of the chalcopentlandite. In some parts of this myrmekite, as it may also be called, are holes, or hiseringerite-infilled holes, which it must be permissible to regard as corresponding to the regularly distributed small magnetite grains in the pore material of the compact ore.

It must be stated that the chalcopyrite in this sample is clearly recognizable as such; there are no differences in the optics of the minerals here or in the compact ore.

As a sporadic component of the myrmekite one may see areas containing a grey substance instead of the chalcopyrite. I have been unable to decide whether sphalerite is present in these areas or not, but there is the possibility in so far as it is an optically isotropic mineral whose hardness may be likened to that of sphalerite. No internal reflections were seen, but this fact cannot be taken as direct evidence of the absence of ZnS, as in these surroundings such large amounts of FeS may be dissolved in the mineral as to make the observation of internal reflections very difficult.

Here and there the mineral valleriite is present replacing chalcopyrite; in these cases it may occupy up to half of the particular area. Moreover, valleriite occurs disseminated in the chalcopyrite, where the mineral cubanite was also observed.

Hisingerite pellets with sulphide in rock.

The most remarkable feature connected with this occurrence of sulphides is, as will be seen in Pl. XIII, 4, the manner in which they are imbedded in the rock, enclosed in a spherical cavity together with hisingerite, the sulphide mass lying like a melt in a small crucible full of hisingerite. That this simile is not wholly unreasonable will be seen from the circumstance that both cavity-fillings seen in the picture have the sulphide mass lying at the same side. The material secured in 1953 presents the same phenomenon — in fact several of these identically oriented inclusions. Instead of hisingerite the cavity may be full of a zeolite-like mass.

The greater part of the sulphide mass, consists of pyrrhotite which here, apart from a small corner, is formed of one individual. The sulphide is full of cracks, running chiefly from the hisingerite out towards the surrounding rock; they are partly radiate in relation to the sphere.

Chalcopyrite and pentlandite are present along the cracks through the pyrrhotite like a bilateral seam, and also in the periphery of the sulphide mass as well as in the form of exsolution bodies in the pyrrhotite. In the marginal region it is often found that the chalcopyrite is separated from the pyrrhotite by the pentlandite, which here may sometimes have a rectilinear boundary against the pyrrhotite. The dimensions of such pentlandite areas make it reasonable to regard them as exsolution bodies — but of a more regular kind than the familiar pentlandite flames whose chief characteristic is that they are oriented parallel to (0001) in the pyrrhotite. Moreover, the pentlandite flames which also occur in this sample appear to be quite unusually serrated and irregular. Close examination with highest magnification shows that they are actually pentlandite sparks appearing in the form of a border on chalcopyrite lamellae (see Pl. XIV, 1).

As regards both the sulphide nodules in basalt and the numerous, very small ones scattered about in the rock, the rule is that the pyrrhotite forms the nuclear part of the sulphide mass, with chalcopyrite and pentlandite in the outer margin. This of course can be observed only in grains down to a certain minimum size.

Relation of sulphides to silicates and ilmenite.

The relations of the rock components to the three principal sulphides are identical in the three cases.

As already stated, vis-à-vis ilmenite they form sharp boundaries. In many cases very small grains of sulphide may be seen "enclosed" in the ilmenite; but the position may equally well be explained by regarding it as a special instance of "impacted" sulphide grain; they often appear wedged in between lamellae of ilmenite and, as that mineral may be rather bizarre in shape, it is easy to imagine it as having enclosed the sulphide. Like the ilmenite, the felspar may be seen bordering upon the sulphide with sharp boundaries. Small grains of sulphide may be found wedged in between the felspar laths (Pl. XIV, 2). Both felspar and ilmenite may be said to be passive in their relation to the sulphides, whereas in relation to the pyroxenes, olivine etc. it is very clearly a matter of "reactions between silicate and sulphide". The two are never seen in direct contact with each other; there is always a narrow or wider border of fine-grained transformation material in the border area of the silicate which, as far as can be discerned, must have become antigorite.

List of Minerals in Igdlukúnguaq Nickeliferous Pyrrhotite.

Pyrrhotite
Pentlandite
Chalcopyrite
Chalcopentlandite
Chalcopyrrhotine
Cubanite
Valleriite
Graphite-like mineral
Galenite
Unknown mineral A
,, ,, B

Bravoite
Zwischenprodukt
Covelline
Magnetite
Siderite
Spinel (Cr.-spinel?)
Maghemite
Ilmenite
Hisingerite
Limonite

FORMATION OF THE ORE

DISCUSSION OF THE ORE-MICROSCOPIC OBSERVATIONS

> The particular development of the sulphide melt may be observed today in the strange projection that is formed by the ore components and their mutual structures. In the two-dimensional sections we shall, by knowing their three-dimensional character, endeavour to create for ourselves the picture of the original or actual "four-dimensional" nature of the ore.

Introduction.

A wealth of detail such as that presented by the ore from Igdlukúnguaq suggests, or perhaps we had rather say demands, a minute discussion of the phenomena observed. The purpose of such a discussion of course is to gather the various observations into a correlated picture. Only by that means will they acquire their true value as an aid to our understanding of the origin of the ore, which then will be available for comparison with developments as described for other ores.

In a case like the present, where a whole series of observations has been added to the picture of the ore which, as a type, has hitherto been known, it seems additionally imperative to essay a synthesis on the background of these observations. However, it is essential to realize that a synthesis of this kind can hardly be other than largely subjective. That is also true of the description, where the conditions do not permit of parallelization with phenomena known from other places, or where it has been impracticable to illustrate the observations with photographic reproductions. One highly important factor of the description, the succession, is not unlikely to be bound up with a certain subjectivity. Nevertheless, the description stands as something fundamentally objective. A synthesis of objective elements, but linked together upon what actually is a non-objective basis, will perhaps be apt to be regarded by "quantitative" science as of little interest, at any rate from a scientific point of view. But it is the sole possibility for one who works with the products of nature, and for that matter also for one who is occupied in the technical utilization of these products. The tests and experiments on which to base one's assumptions must all be conducted under conditions that are entirely foreign to conditions in nature, quite apart from the simplifications which must necessarily be made.

The ore, *qua* ore, does not lend itself to rational tests. As it lies it represents an indefinite system, the number of its components being at least five or six.

A rational synthesis is impossible; all the same, it is surely reasonable to make an attempt, embracing every detail, at achieving a synthetization, or discussion if one will, for one reason because by that means the observation material can be elucidated from various aspects and placed in relation to phenomena known elsewhere.

Sulphides and other Late-Magmatic Components of the Dike Rock.

The dike rock in which Igdlukúnguaq nickeliferous pyrrhotite is found may be parallelized with olivine basalt, as indeed has been done; and, as will appear from what was said in the foregoing, there is good agreement between the ore-bearing rock and the analysis of olivine basalt given by Barth (2) in his work on the lavas of Gough Island. Contrasting with the analytical agreement, we have the extensively transformed picture of the various components of the Igdlukúnguaq dike and the fresh mineral ensemble of the Gough Island olivine basalt. Aqueous silicates must have been formed at the expense of the olivine and the pyroxenes, and in cavities we find zeolites, for instance. The cavities also contain both carbonates and hisingerite, which is another aqueous silicate. Accordingly, there is no doubt that carbon dioxide and water played important rôles in the forming of the rock.

Now as the felspar laths in the rock present a very clear arrangement in association with these cavity infillings, the latter must have existed at a time in the formation history of the rock when there was a possibility of influencing the position of these felspar laths; as "vacuoli" they must have been present before the rock consolidated. This means that both water and carbon dioxide were components that must have been present at a very early stage of the rock's formation. These volatile components are actually to be regarded as belonging to the primary components of the magma.

The rock samples last referred to in the description, in which were cavity infillings containing sulphides, are of particular interest. As the sulphide mass in the various cavities within a hand-specimen seems actually to suggest a gravitational placing, the assumption is that these cavity materials existed as "infillings in liquid form" in the rock while the sulphides were still in the liquid state, presumably at or over about 1000°.

The presence of the carbonates in the rock shows that very high pressure must have ruled during and for a time subsequent to the placing of the rock.

It is interesting that $CaCO_3$ as well as hydrous iron silicate formed in the rock, whereas in the sulphide mass we find $FeCO_3$ besides the iron oxides, hydrous sulphates etc. This means that there was no possibility of a connection between the volatile phases of the rock and the sulphide mass. Quantitative exploitation of the conditions of which the presence of these phases is an expression seems impossible today; but just by means of a greater understanding of the relations between these phases at the high temperatures in question it should be possible some day to give valuable information as to what the conditions may be during the formation of a sulphide occurrence of the type dealt with above.

It was remarked above that there seemed to have been no possibility of a connection between the gaseous phases of the sulphides and the rock. Nevertheless there must have been a "connection" between the gases of the sulphides and the components of the rock, but at fairly late stages. This at any rate seems to be the explanation of the transformation of the pyroxenes and olivine observed wherever the sulphides border directly on these silicates. The phenomenon is a familiar one and indeed has been mentioned by several authors. If the gases were already present before the consolidation of the magma, as seems to have been the case from the materials examined here, it is natural to suppose that they distributed themselves among the phases then present. Taking due regard of the pressures, the sulphide drops for instance must have been excellent reservoirs for these gases; and as the sulphides were still fluid after the consolidation of the silicates, after the pyroxenes and olivine had been formed there were reservoirs (the fluid sulphides) with the gases, water and carbon dioxide, lying in contact with these minerals besides others. With the consolidation of the sulphides the gases (or their reaction products—see later in the discussion on the inclosed oxidic phases of the sulphides) were liberated, and reactions between them and the silicates resulted in the formation of the products on the border between the two phases—principally antigorite. The connection between the gases and the sulphides seems to be so obvious in the materials of the Greenland deposit that I consider it reasonable to emphasize the point here. As a matter of fact, the problems involved in the presence of late-magmatic gases and the silicate/sulphide phases were discussed by SCHOLTZ (35) in connection with his work on nickeliferous pyrrhotite from South Africa, a work which will later be reverted to in the discussion on other deposits.

As stated, water and carbon dioxide must be regarded as being among the primary components of the magma. This means merely that these gases must have existed within the melt when it pressed forward in the shape of the intrusion observable today. Naturally it is a question whether the gases were present as orthomagmatic components, or it is not more likely that they were absorbed by the magma while in a magmatic chamber, or again whether they are to be considered as substances absorbed in the course of the intrusion itself.

The sediments at the locality itself are chiefly sandstone, and it seems hardly reasonable to connect them with the presence of the gases in the rock materials. The quantity of limestone in the sediments is not great, and, if the carbon dioxide of the rock is to be attributed to such an origin, it will apparently be necessary to establish a connection with the well-known occurrences of marble in the surrounding Precambrian. However, carbon dioxide might just as well have originated in other sediments, because there are fairly widespread deposits, large and small, of coal in the Cretaceous. A third possibility is that the basalt absorbed hydrocarbons from bituminous shales which are also known in relatively large occurrences in the region. Absorption of water would certainly be possible in connection with several of these sedimentary deposits, and I would merely point out that as regards the presence of water in connection with the absorption of hydrocarbons, there may be several interesting possibilities of reactions not directly involving water absorption, but simply the formation i. a. of water by the reaction of the hydrocarbons with the other compounds in the magma.

One might indicate several ways along which to approach an understanding of these problems, but with the material at present available it would not be realistic to single out one particular possibility as being the most probable. It is an interesting fact that along the coast where Igdlukúnguaq itself is situated there are dike rocks that are markedly characterized by the presence of carbonates. For example, at Qutdligssat there are several dikes with a fairly high carbonate content. In all probability a study of these dike rocks and their relations will provide information as to the likely explanation of the presence of the gases.

The relation between the sulphides and the gases will be gone into later, but that between sulphide and hisingerite or zeolite-like material may be examined here. In several hand-specimens it was observed that sulphide nodules of 2 mm or more were always accompanied by a certain quantity of these silicates, sometimes of the handsome "crucible-like" form shown in Pl. XIII, 4. This concurrence is so regular a phenomenon that the large body of ore found by Steenstrup may also be assumed to have been surrounded by similar silicates. But as hisingerite is very readily transformed and weathered, this may explain why the large pieces of sulphide were not found adhering to dike rock; the silicate material had probably weathered away. The analysis shows that the ore contains some small quantities of silicates, and it is noteworthy that a little quartz was also observed in this material. That mineral was also seen in connection with a cavity infilling in the form of a few small crystals and thus seems to be one of the formations that are characterized by the occurrence of hydrous silicates. The picture of the very considerably weathered walls of the excavation where the ore was removed from the dike would seem to be further evidence of the perishable nature of the material there in contrast to the rest of the dike material.

Evolution of the Ore.

The Sulphides.

The conclusions arrived at regarding the evolution of the sulphides are supported inter alia by the researches of various workers who have made laboratory tests with melts of known compositions (5, 15, 17, 24 and 33). Without attempting any quantitative comparisons with these excellent tests I may mention that I have made heating tests with the Greenlandic ore; its peculiar nature seemed to call for some such experiments; and even if they could be no more than rather primitive in plan, I think they provide interesting points for consideration.

As was stated e. g. in conjunction with the reference to the relation of the ore to the rock in which it occurs, we find it in intimate connection with some other late-magmatic products, among which water and carbon dioxide especially are of importance. While the sulphide mass was in the liquid state a certain part of the gases, water and carbon dioxide, must under the particular P/T conditions (and especially considering the high pressures prevailing) have been "dissolved" in the melt.

The evolution of the ore is thus the product of the evolution of the sulphides, the evolution of the gases "dissolved" therein and the interaction of these two phases one upon the other.

In the form in which the ore appears to us, pyrrhotite crystals enclosing and surrounding all other components, we may also regard the presentation of the process of its formation as a clarification of pyrrhotite crystallization and, as a supplement, an account of the relation of the other components to it.

On crystallization the FeS phase incorporated extraneous elements in two entirely different ways. In the first place, in its structure it embodied a number of elements which by subsequent unmixing in solid solution were segregated as independent phases; in the second place, it "mechanically" enclosed extraneous substances which, at the crystallization of the FeS phase but in conformity with their own natures, became placed in it:

I.
- 1. Crystallization of the pyrrhotite.
- 2. Unmixing of the Ni—Cu sulphides dissolved in the pyrrhotite.
- 3. Formation of the pore mass by the insoluble sulphides (or the one mechanical phase).
- 4. Development of the pore mass by processes in solid solution.

II.
- 1. The phases formed by the gases in the pyrrhotite, and
- 2. The phases formed by the gases in the pore mass.

} or the second type of mechanical inclusions.

Pyrrhotite Crystallization.

As is observable both from the macroscopic appearance of the hand-specimens and from their microscopic features, crystallization of this pyrrhotite is not merely a primary stage in the consolidation of the sulphide melt, but the predominating process almost right forward to the stage where the reactions in solid solution begin. As the conclusion must be drawn from the structures formed by these processes that the cooling of the ore proceeded in fact very rapidly, the explanation of the unusually coarse grain of the pyrrhotite must be sought either in a far-fetched assumption that cooling was slow in the initial stages, which means that the ore remained at temperature just under the sulphide melting point, about 1000°, for quite a long period and then was subjected to sudden quenching; or it must be assumed that the presence of the mineralizers, water and carbon dioxide in the melt reduced the viscosity so effectively as to make the coarse-pegmatitic development possible. The circumstance that chalcopyrite and pentlandite were not found in any of the fragments of ore outside the FeS structure must be regarded as a sign that there can have been no mechanical deformation during the crystallization of the pyrrhotite; that mineral's total absence of crushing with possible re-crystallization, twin-lamellae formation or other signs of mechanical influence, shows that no movement can have taken place after the pyrrhotite had crystallized. It must therefore be considered probable that the sulphide mass was taken to its present place in liquid form and there passed through the whole of its evolution. The assumption of an initial, very slow cooling succeeded by a later, very sudden quenching, is accordingly most difficult to harmonize with the general opinion of the geological development of such an environment.

It would therefore seem that we must regard the presence of the aforesaid mineralizers as a both necessary and adequate condition of the pegmatitic development of the pyrrhotite.

The pyrrhotite occurs as an aggregate of tabular individuals whose sole crystal face is (0001). That plane may attain to sizes of about 100 sq.cm., the usual size being about 10 sq.cm.

The character of the crystal faces as continuous pyrrhotite planes, compared with sections through the individuals, shows that they must have been formed first. In other words, we must imagine that the melt when crystallization began was intersected by planes which quickly brought about a subdivision into cell-like cavities having an appearance something like that shown in Pl. I, 2. Within these cells were the liquid sulphides which in them had the other components of the residual magma, whilst between the cells apparently there was not so much sulphide melt as to leave a record by the forming of other sulphides outside the pyrrhotite individuals. At any rate, no such thing was observed in the ore. On the other hand, in all likelihood there may have been some of the other components of the residual magma, that is to say water, carbon dioxide and perhaps silicates. Actually, however, only very small quantities of these were observed in the form of a little undissolved material in the piece of ore analyzed; it was mostly chemically precipitated silica, which must mean that soluble silicates were present which, in the course of the analysis, became converted into silica. It should be added that a slight amount of quartz was observed in this undissolved material.

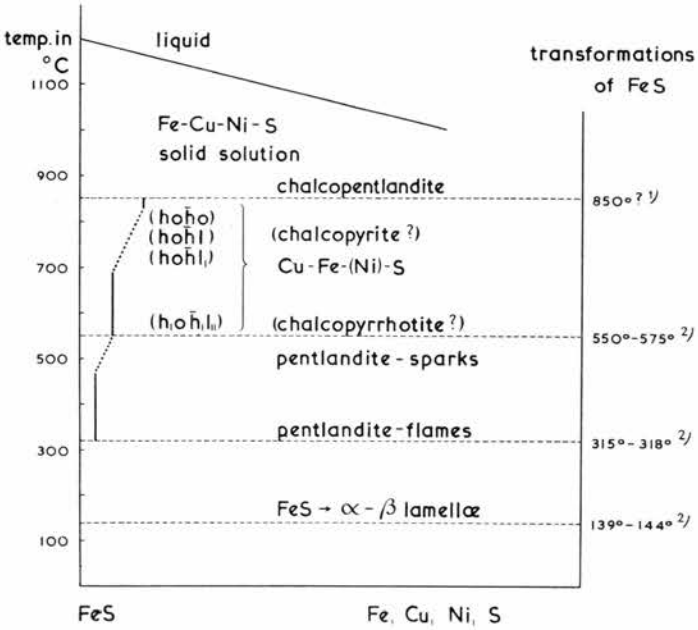
The formation of the crystal faces could evidently proceed unhindered until the entire mass was intersected by them. However, Pl. I, 3, 4 shows that these faces contain regular arrangements of cavities or inclusions which together form a dendritic pattern on the face. This is probably an expression of an embedment of extraneous substances during growth. Pl. III, 1 shows that after the formation of the (0001) face the growth of the pyrrhotite proceeded as a continuous front only a short distance inwards in the "cell". The presence of substances unable to find room in the crystal lattice brought about the formation of lacunae in the pyrrhotite structure. In the immediate vicinity of the crystal face it looks as if growth took place as a kind of columnar structure from the face inwards to the enclosed cavity. This form of growth, which appears partly from the structure of the pyrrhotite in the polished sections and partly from the appearance of the other sulphides, which seem to increase in frequency the deeper into the "cell" we get from the continuous crystal face, has the effect that the inner border line between the individuals forming the cell must be quite irregular, which in fact is the case.

This sketch of the formation of the pyrrhotite involves a unilateral growth inwards from the original crystal face into the space formed of several individuals. This of course cannot be applied as a universal formula. As a general rule the crystal face when formed may be supposed to grow to both sides if situated free in an environment consisting of liquid sulphide, of which the ore here consists. Indeed, in some sections through ore bodies I have observed rectilinear borders between "pyrrhotite individuals" with the same orientation. This is rare, however, and it is particularly remarkable that in several of these instances I have seen a strand of non-opaque material through "the border between the individuals", which, however, has the appearance of a continuous, elongated area of pyrrhotite. This must signify that non-sulphidic residual-magmatic material must have accumulated unilaterally on the face, so that the growth of the pyrrhotite could proceed only in one direction, i. e. the opposite to that of this accumulation. The large individuals of pyrrhotite, the rare occurrence of bilaterally developed crystal faces and the presence of the aforesaid non-sulphidic partition between uniformly oriented pyrrhotite individuals, suggest after all that the above theory of the formation of the pyrrhotite applies to the greater part of the ore. The fact that the ore, as is observable in several specimens, may be of somewhat varied development: for instance there may be pieces containing relatively compact pyrrhotite which thus does not have such large amounts of pore material, must be ascribed to the variable composition of the original melt. An example of this is to be seen in Pl. IX, 4, where it will be observed that the basal direction in the pyrrhotite is strongly outlined by non-sulphidic material. Such variations from the suggested picture of the genesis of the pyrrhotite are rare in the samples; there are perhaps 50 polished sections exhibiting what has been suggested as the rule, whereas only a few show deviation from it. Accordingly, it must be warrantable to base the theory of the pyrrhotite's formation upon the majority of the samples and, as far as is practicable, to try to place the variants within the suggested norm.

This will also apply to the following presentation as a whole. I would especially add that the small sporadic grains of ore in the rock, of millimetre size or less, would also seem to be adaptable to the proposed picture based upon the general samples of the compact ore. And it needs no saying that they can never reflect the details of the process of development; for instance it is presumable that the cooling processes of the small particles may have differed considerably from those of the compact ore.

At the time when the pyrrhotite was finally crystallized there must have been a "spongeous" FeS structure containing a certain part of the other sulphides, the Ni- and Cu-sulphides, and in the pores of the sponge a mass of those substances that were incapable of being built into the FeS structure. To a certain extent the pore mass must have corroded the existing pyrrhotite, and the same is true of some other products in the ore; but otherwise the pyrrhotite must have been altered by repeated un-mixing of such dissolved substances as in cooling could no longer be kept in solution in the FeS lattice. Finally, the pyrrhotite must have collapsed into a binary structure characterized by the so-called α–β lamellae which are considered to be a low-temperature product in the FeS structure.

Exsolutions in Ni—Cu-pyrrhotite.



1) See page 11 in (33).
2) See page 345 in (15).

Fig. 5. The above graphic diagram represents an attempt to visualize the succession of the exsolutions in the pyrrhotite, and also to express the placing of these processes. Here the relative age of the products is taken as the basis together with the information contained in the literature on exsolution and transformations concerning pyrrhotite.

Exsolutions within the FeS Structure.

Chalcopentlandite.

The first exsolution to take place in the Greenlandic pyrrhotite was that of the chalcopentlandite, which is now to be seen as a binary structure of pentlandite embodying chalcopyrite lamellae. That it was the first is evident from the chalcopyrite lamellae which, along the prism and pyramid planes in the pyrrhotite, "hug" the sides of the exsolution bodies and also form a zone between the sides of the pore material, which also consists of original chalcopentlandite. This intermediate rim of chalcopyrite can only have been formed after the coming of the nickel-copper sulphide. The chalcopyrite lamellae in the disintegrated chalcopentlandite seem to have no relation to these intrusive rims of chalcopyrite, a fact that places these two exsolutions of chalcopyrite quite independently of each other. The exsolution of the flame-shaped pentlandite is seen to traverse the chalcopyrite lamellae in the pyrrhotite, and these lamellae are often seen to be staggered at these intersections, showing that the pentlandite flames are later than the chalcopyrite lamellae. The pentlandite sparks and the flame-shaped lamellae of chalcopyrite in the pyrrhotite cannot be placed in direct relation to the other exsolutions. Their placing will be discussed later when dealing with these exsolutions.

Of the circa 27 % of pentlandite contained in the ore according to a calculation from the analysis, much the greater proportion is present in the form of chalcopentlandite unmixed from FeS. The amount cannot be stated with much accuracy, of course, but approximately it is two thirds, perhaps more. The remainder is in the form of pentlandite flames and sparks, pentlandite and bravoitized pentlandite associated with the siderite areas. The quantity of chalcopyrite in the exsolution bodies is estimated at about 10 % of their material, which means barely 2 % chalcopyrite. Thus the first exsolution was the one of the greatest magnitude in the pyrrhotite, about 20 % of the ore material having been unmixed from an original solution in the pyrrhotite.

According to the researches made by several workers in the system Fe–Ni–S, exsolutions are not to be expected at temperatures in excess of 870°. This temperature is indicated by HAWLEY, COLGROVE and ZURBRIGG (15) as that of a peritectic reaction which, as HAWLEY and HEWITT (16) say, may be regarded as resulting in true exsolution structures. SCHLEGEL and SCHÜLLER (33) state that they and other workers have found a pyrrhotite transformation point at about 850°. These circumstances, viewed together with the necessity of placing the large-scale unmixing at a high temperature, make it a reasonable assumption that it proceeded in the region of between 800° and 900°.

Parallelization with syntheses based upon pure ternary systems suffers of course from the defect that the products of nature themselves are not so well defined. In even this very simple paragenesis there are upwards of four components. Nevertheless, some useful purpose may be served by utilizing the laboratory results. Part systems in the ore may sometimes be regarded as closed systems and as simple systems, and finally, it is not always certain that the presence of other substances need exert any great influence on the main course of the process. This indeed seems to be the case with regard to the large-scale exsolution in the Igdlukúnguaq ore, where chalcopentlandite was segregated. The fact that a phase is segregated which is mainly a nickel-iron-sulphide phase, in which copper occurs in solution, must mean that copper came in on equal terms with nickel. Possibly this may have a bearing on the quantitative proportions of Ni which was in solution in the pyrrhotite; but it seems unreasonable to suppose that the unmixing process itself was affected by it so much that we may expect it to be observable in the analysis that can be made mineralogically.

The main thing must be that the large-scale exsolution of chalcopentlandite can be put into its relative position as the first exsolution; and, taking the fact also into consideration that the pyrrhotite has transformation points at: 135°—144°, 315°—318°, 550°—570° and about 850°, and that there must also be room for other exsolutions after the chalcopentlandite, it seems impossible to choose any other temperature than 800°—900° for the exsolution (in the following referred to as 850°).

I consider that the difference between chalcopentlandite exsolution bodies in polished crystal faces of the pyrrhotite and polished internal sections in the mineral is a sign that cooling in the first crystal faces was more rapid than in the internal parts of the pyrrhotite crystals, the consequence being an earlier freezing of the structures then formed. In the internal parts the slower cooling provided the possibility of a certain interchange of substances, whereby the shape of the bodies there was affected. The governing influence of the pyrrhotite, however, is also clearly observable here on many of the inclusions.

Chalcopyrite lamellae, rectilinear.

After the first "large" exsolution of the chalcopentlandite and prior to the exsolution of the familiar pentlandite flames, there was an exsolution of chalcopyrite in the Greenlandic ore, one that seems to have followed several different crystallographic planes, as the description shows. Thus in itself it is not easy to understand; and, what is more, exsolution of chalcopyrite in pyrrhotite cannot be said to be a common phenomenon. RAMDOHR (29, p. 130), makes the remark that it does occur but does not amplify his statement. As far as I am aware he is referring to Igdlukúnguaq.

HEWITT (17) studied the relation between pyrrhotite and chalcopyrite in samples heated to high temperatures and cooled suddenly, and arrived at the conclusion that an exsolution of chalcopyrite presumably occurs along the basal direction in the pyrrhotite, within the temperature range of 800—900°.

We may say with certainty that the chalcopyrite exsolution in Igdlukúnguaq must have proceeded within a temperature range above that which corresponds to the exsolution of the pentlandite flames, judging from the relation between these two exsolutions in the Greenlandic ore. This must mean that the exsolution of the chalcopyrite may be ascribed to temperatures above 300—400°.

To judge from their mineral composition, many deposits containing Cu-Fe sulphides etc. may be assumed to have been formed at temperatures up to around 400°; by means of his analyses of sphalerite from such deposits KULLERUD (20) has shown that they were presumably formed or acquired their character at 500—600°. Although many of these occurrences have been unusually well described (i. a. ore-microscopically), there is no mention anywhere of exsolution structures between pyrrhotite and chalcopyrite corresponding to the rectilinear lamellae in the Igdlukúnguaq ore. This makes it reasonable to believe that the temperature interval of this exsolution must lie above the highest temperature indication of these other deposits, i. e. above 500—600°.

In other words, we must try to find the exsolution temperature for the chalcopyrite in the pyrrhotite somewhere between 500—600° and 850°. For exsolutions of this kind, involving a regulation so strict as that presented in the shape of the rectilinear lamellae, it would be desirable to be able to indicate important changes in the lattice either of the host or of the guest, or perhaps of both. As regards the pyrrhotite, we know the transformations already referred to, of which the following two lie within the range indicated: 550—570° and about 850°. About the chalcopyrite we know that from the direct crystallization we may get a part of the mix-crystal series $CuFeS_2$—$Cu_3Fe_4S_6$ determined by the composition of the melt, and this mix-crystal transforms into a binary structure at just about 700° (SCHLEGEL & SCHÜLLER, 33). Together with pyrrhotite we know that at lower temperatures chalcopyrite forms a whole series of mix-crystals: valleriite at 225—235°, cubanite about 250° and chalcopyrrhotine, which is considered to be stable from about 300° to 550°. Both in the descriptions and in the samples from the writer's heat tests the exsolution structures between pyrrhotite and chalcopyrrhotine are composed of flame-like lamellae which form a network of three (or perhaps four?) lamella systems, wherefore they seem hardly comparable with the rectilinear chalcopyrite lamellae in the Greenlandic ore (see page 79).

Viewed against that background it seems presumable that this exsolution took place in the temperature interval 600—850°. As it is obviously later than the "large" chalcopentlandite exsolution, it rather seems possible to regard it as belonging to about 700°. The transformation point at 550° is probably of no significance to the formation of these chalcopyrite lamellae, inasmuch as that particular temperature stage corresponds to the upper stability limit of the chalcopyrrhotine; and if the exsolution were to be placed there, one would expect it to bear the impress of the forms that are considered to be characteristic of the pyrrhotite-chalcopyrrhotine relation.

If the lamellae which we now see as chalcopyrite were chalcopyrrhotine earlier, it would mean that FeS had been removed from the neighbourhood of the lamellae, which then could scarcely be so clearly rectilinear as they actually are.

The different lamella systems followed by this exsolution seem to argue that the controlling factor in the un-mixing was altered during the exsolution process. Whereas the chalcopyrite exsolution in "the surface of the pyrrhotite crystals"—i. e. in and close by the natural crystal faces (0001)—mainly follows $(10\bar{1}0)$, pyramid planes become more frequent inside the crystal, firstly what we may suppose is $(10\bar{1}2)$ and then several fairly steep ones $((10\ 0\ \overline{10}\ 3)$ perhaps). If this is to be taken as a regular change inwards in the crystals, it may signify that the exsolution along the prism plane corresponds to the first stages of the process, that is to say represents the structure as formed at the highest temperatures; and as the crystal faces correspond to the parts of the ore that were first established, i. e. to those parts where cooling began, we must suppose of the inner parts of the cells thus formed that the temperature fell more slowly there and provided the possibility for some adjustment of the exsolutions gradually as the temperature fell.

There can be no doubt that with this exsolution series we have a very unusual feature within this ore type, unusual because conditions must have been present for the preservation of this product which obviously were absent in other deposits. Actually, of course, this is an exsolution that is very difficult to fathom. The heat tests with the Igdlukúnguaq ore show that the chalcopyrite in contact with the pyrrhotite is converted to chalcopyrrhotine, which by the way agrees completely with the tests by Borchert (5) and others. This applies to heating to a temperature of about 300° for some hours. One sample, heated to about 625° for about 20 minutes, then cooled in cold water, showed very widespread formation of chalcopyrrhotine, and the chalcopyrite lamellae in the pyrrhotite seemed to have merged with the pyrrhotite except the broadest ones, which stood out as chalcopyrrhotine. The relation between chalcopyrite and pyrrhotite in the formation of the special mix-crystals, and also the chalcopyrrhotine, has the effect that in such a heating test it is impossible to ascertain the relation of the $(ho\bar{h}l)$ lamellae to the temperature. That the heating brings about a homogenization is merely an expression of the relation between pyrrhotite and chalcopyrrhotine which, as Borchert (5) says, are unconditionally miscible at over 550°. However, the formation of this mix-crystal is evidently possible only by heating. The experiments of Schlegel & Schlüller (33) in attempting to fuse the pure copper and iron sulphides did not confirm Borchert's (5) unconditional miscibility. In one of the tests in their experiments chalcopyrite became unmixed in pyrrhotite in the form of small exsolution bodies, and Hewitt's (17) experiments at heating a chalcopyrite-pyrrhotite ore to the melting point followed by rapid cooling also resulted in the formation of chalcopyrite exsolution bodies in the pyrrhotite. This suggests that on cooling it is possible for chalcopyrite exsolution bodies to form at temperatures of over about 600°, and that the results depend exclusively on the manner of establishing the exsolutions.

In the Hewitt test (17) the chalcopyrite lamellae were found to be exsolved parallel to the basal direction of the pyrrhotite. It is possible that this corresponds solely to the combination of pyrrhotite—chalcopyrite and that the presence of the pentlandite means that the chalcopyrite must be unmixed along other directions; but it is also possible that the exsolution produced by Hewitt represents another stage than that observed in the Igdlukúnguaq ore. The unmixing of chalcopyrite observed by Schlegel & Schüller (33) in pyrrhotite was in the form of fine sparks of chalcopyrite in the pyrrhotite, and no details are given of the exsolution structure.

According to these syntheses and laboratory tests it may be taken for granted that chalcopyrite may be separated from pyrrhotite when the latter is cooled from high temperatures. It may be said with equal certainty that on heating ore with chalcopyrite and pyrrhotite in the border zone of these minerals the special compounds cubanite and chalcopyrrhotine are formed. However, what happens between the melting temperature and 500—600° is not well elucidated and further study is desirable.

Chalcopyrite lamellae, flame-like.

The above circumstances, and perhaps especially the conditions round about 550°, will presumably also play a large part in the formation of the flame-like chalcopyrite lamellae observed in the pyrrhotitic variety of the Igdlukúnguaq ore. As was stated in the description of the ore, two types of these lamellae were found, which must signify two generations of exsolutions. The mutual relations cannot be clarified entirely, but it would seem as if the large flames, which tend to follow the rectilinear chalcopyrite lamellae in the surrounding pyrrhotite, were the earlier.

Such chalcopyrite lamellae have not been described in the literature as exsolution lamellae. On the other hand, some authors mention lamellae that may correspond to them, and while examining ore from the Norwegian deposit at Beiernfjord I have found flame-like chalcopyrite lamellae which may be an exsolution corresponding to one (the large one?) of the types in the Igdlukúnguaq ore. I shall have more to say later about my observations in the other deposits. However, it is evident at once that flame-like exsolution lamellae of chalcopyrite in pyrrhotite are not among the more common phenomena in nickeliferous pyrrhotite ore, and therefore it is justifiable to assume that they represent temperatures which have not ordinarily left relicts in ore of this type, or on the whole in ores containing pyrrhotite and chalcopyrite.

As already stated, the relicts or products which are evidence of rather high temperatures in the usual ores are the various copper-iron sulphides, of which the chalcopyrrhotine corresponds to temperatures of over 250°. The exsolution bodies of pentlandite, the so-called exsolution flames, are assumed to correspond to temperatures of over 310° and under 425° (HAWLEY, COLGROVE & ZURBRIGG, 15). It is perhaps possible that they are associable with the transformation point of the pyrrhotite at 315° (see below). Accordingly, from their presence in practically all nickeliferous pyrrhotite ore we may say that temperature indications of 300° or more are usual. In intervals from there up to 850° no structural relicts are described in the literature. On the other hand, KULLERUD (20) in his studies of ZnS-FeS shows that some ore occurrences can be traced back to about 600° on the basis of the iron content in the sphalerite.

Against this background it is natural to assume that the flame-like chalcopyrite lamellae must belong to the temperature interval above at least 310°. On the other hand, as in the Igdlukúnguaq ore they take the place of the rectilinear chalcopyrite lamellae within certain areas of the ore, one would suppose them to belong to a temperature interval below that at which the rectilinear lamellae were formed. This was assumed to be in the vicinity of 700°. In that case they may belong to just below the 700° if they were simply formed in continuation of the exsolution of the earlier chalcopyrite lamellae in the pyrrhotite. Should this be incorrect, it may be that they were exsolved as chalcopyrite at a temperature near the pyrrhotite transformation point at about 550°; in that case, however, we have another possibility: According to BORCHERT (5), the stability range of chalcopyrrhotine is up to about 550°, and therefore it is imaginable that the formation of the "flame-like" chalcopyrite lamellae proceeded through the formation of chalcopyrrhotine lamellae. As BORCHERT's studies show, the latter are precisely of the flame-like form presented by the chalcopyrite lamellae here. In my own heat test, too, a zone was formed on the border between pyrrhotite and chalcopyrite containing such flame-like lamellae in a fine-meshed network.

It would accordingly appear that the chalcopyrite lamellae were formed thus: that at some stage within the temperature interval where the chalcopyrrhotine is stable, chalcopyrrhotine became exsolved in the pyrrhotite, and later that phase passed over to the chalcopyrite which we now find in the lamellae, the excess of FeS being transferred to the surrounding pyrrhotite.

Just what the circumstances were can only be accounted for by means of the further studies already suggested; but I am inclined to ascribe the chalcopyrite lamellae which are flame-like to formations belonging to a temperature region in the neighbourhood of 550°.

Pentlandite sparks and pentlandite flames.

As the description showed, in association with the large flame-like chalcopyrite lamellae there were very small pentlandite exsolution bodies observable in the form of a serrated border on these lamellae, and some out in the surrounding pyrrhotite. It is possible that involved in the forming of these pentlandite sparks, as I have preferred to call them, there is a kind of induced activity, in which case it is perhaps a difficulty that they also occur free in the pyrrhotite. Here it should be interposed that these sparks in association with the chalcopyrite lamellae have been observed in the Norwegian deposit. There they are also to be seen extending into the chalcopyrite. This opens up the possibility they may have been exsolved from the pyrrhotite through the aforesaid chalcopyrrhotine, which may have received a small amount of nickel in solution. On the transformation to chalcopyrite the pentlandite may thus have been liberated. But, as I have said, the presence of the free pentlandite sparks argues that this may be an independent exsolution, in which case it must suffice to establish the fact that it is difficult to place exactly.

It is otherwise with the large pentlandite flames. There can scarcely be any doubt that they actually correspond to the ordinary exsolution bodies observable in most other nickeliferous pyrrhotite ores. As already said, I assume it to correspond to processes somewhere between 310° and 425°. In my own tests it was found that a sample heated to about 325° for about ten hours and then cooled quickly showed that the pentlandite flames became homogenized with the pyrrhotite. According to HAWLEY, COLGROVE & ZURBRIGG (15), homogenization was obtained by 60 hours' heating at 310°. Therefore it is perhaps feasible to associate the formation of these exsolution bodies to the pyrrhotite transformation point round about 315°.

The Pore Material.

The very fact that inside the pyrrhotite, like pores in a sponge, there is a mass with different properties, copper sulphides in contrast to the FeS mass round about, shows that during the crystallization process in the melt two different systems of material must have been present. At the moment the pyrrhotite became a solid phase it was permeated by a melt which as a whole corresponded to chalcopyrite. From the work on the Cu-Fe-S system (SCHLEGEL & SCHÜLLER, 33) it appears that among melts of about that composition there are compounds whose lowest melting point is about 930°, which presumably would be the lowest temperature of the pore mass as a melt. As we must suppose that this residual melt of the sulphides contained a little nickel, it is not of course directly comparable with Cu-Fe-S melts, so that the indication of the lowest temperature for that part of the ore in liquid condition must naturally be regarded as approximate.

As will appear from the description, the materials in the pore mass are, as far as the sulphides are concerned, divisible into three different kinds. In the central part there are always chalcopyrite-like sulphides, whereas the border zones against the surrounding pyrrhotite are occupied by the binary structure of chalcopyrite and pentlandite formed by the disintegration of chalcopentlandite. Like the chalcopentlandite inside the pyrrhotite, the nickel sulphide of the pore mass is seen to be formed by exsolution from the pyrrhotite, because here and there it is observable with a "crystal margin" against the pyrrhotite and the structure otherwise is identical with the bodies in the pyrrhotite. As already stated, this exsolution is assumed to have been formed at about 850°. Naturally, the marginal zone between the pyrrhotite and the pore mass is completely dominated by this structure and the texture here must be ascribed to the processes in the exsolution of that material. The original margins against the pyrrhotite are no longer to be found in the ore at any rate; we can merely note that the original pore mass cannot have occupied more than about a third of the space it does now.

The copper sulphides in the central parts of the pore mass are formed of a chalcopyrite-like mineral, here named chalcopyrite, which seems to be characterized by the presence of small inclusions of magnetite grains and of chalcopyrite with a lamellae structure which seems to bear witness of a transformation from cubanite, or perhaps more correctly, through that mineral.

The position of the first type of chalcopyrite in relation to the chalcopentlandite in the pore mass, and the aforesaid small grains of magnetite, suggest a sulphide mass traceable to at least 850°, and it seems most reasonable to suppose that in reality this material represents the cupriferous sulphide originally in the pore mass. On the other hand, the chalcopyrite with its reminiscence of cubanite seems to present such relations to magnetite in large, irregular areas that it is more likely to be a product of secondary character in relation to the sulphide material of the pore mass.

The chalcopyrite in the central region forms the main part of the chalcopyrite in the pore mass. The chief characteristic of this sulphide is that patterns of magnetite drops are usually found in it, as shown in Pl. VI, 5. As was stated in the description, the shape of these individual grains may be taken as a sign that the substance in which they are imbedded must once have had a cubic crystal lattice. Running from these magnetite grains there are always cracks cutting into the sulphide and forming angles of 120°, and their direction is always parallel to the directions of the grain borders. Having regard to what is said in the following as to the magnetite grains in the pyrrhotite, it is understandable that the oxide here in the pore mass must have received its shape from the surrounding sulphides. The completely equal distribution of the magnetite grains in the copper sulphide is striking. As was stated in the description, they may even form "point constellations", e. g. two systems of point assemblies forming well-defined angles to each other. In contrast to the magnetite grains in the pyrrhotite (see pp. 86—87), this would seem to indicate that crystallization in the copper sulphide proceeded spontaneously; there was no advancing crystallization front in which the "foreign bodies", the oxide, could assemble. This picture of the oxide placing in the sulphide mass harmonizes well with the idea that there must have been oxidic material evenly distributed throughout the sulphide mass.

An equally prominent structure between this chalcopyrite and the disintegration material of the chalcopentlandite will be seen in Pl. VI, 4.

As the description shows, there is every reason for regarding the chalcopentlandite as an exsolution product from the pyrrhotite, and this is not contradicted by the position of this material in the outer parts of the pore mass. But it is difficult to understand why this reticulation structure formed between the chalcopentlandite and the chalcopyrite under discussion. So much may be said, however, that all the various areas of this chalcopyrite with the magnetite grains imbedded in it, must form a single individual. The rectilinear border of the magnetite is the same for all the grains in the field of vision, and the cracks radiating from these grains are also parallel. The cause of this must lie in a structural fellowship for all the individual sulphide areas. It looks as if the appellation of "spongeous structure" is also applicable to this mass. Here the chalcopyrite corresponds to the pyrrhotite, and thus the chalcopentlandite to the pore mass in the main structure in the ore itself. It is noteworthy that no magnetite grains are found lying wholly within the chalcopentlandite. The exsolution of the nickel sulphide took place relatively soon after the consolidation of the copper sulphide, and at that high temperature it was possible for the exsolved masses to permeate the pore mass with the aforesaid structure picture as the result. That this picture formed must then mean that there was no possibility of a mix-crystal containing so much copper sulphide as the pore mass could give here.

The position occupied by the chalcopyrite here, framed in and permeated by the chalcopentlandite, shows that the material holds a position that was filled before the large exsolution of nickel from the pyrrhotite at 850°. Thus the chalcopyrite material here may quite well be pore material of primary origin. Its optical characters are not clearly identifiable with those of normal chalcopyrite, and bravoite formation is often seen emanating from the cracks in this chalcopyrite. Of course, bravoite may have been formed by a supply of nickel from elsewhere, but the possibility cannot be excluded that nickel was supplied direct from the adjacent material to the cracks, i. e. from "the chalcopyrite". On heating the Igdlukúnguaq ore to about 310° for about ten hours it was found—inter alia—that scattered new small pyrrhotite-like areas formed in this type of chalcopyrite. This seems to show that the chalcopyrite contains material that is extraneous to it.

All in all, then, the conditions seem to argue that our chalcopyrite differs slightly from normal chalcopyrite, and that this difference may be due to a certain, though small, content of nickel. The formation of pyrrhotite in the heated specimen also demonstrated an excess of iron, so it would doubtless be most reasonable to compare this chalcopyrite with a kind of chalcopyrrhotine. The presence of nickel thus explains why the optical characters of the material do not agree with those of chalcopyrrhotine. It is remarked in the literature that there is a possibility of the presence of nickel in chalcopyrrhotine. Accordingly, the present material seems to indicate the possibility of the forming of two different mix-crystals, one of them of nickel character, the other characterized by copper. The former is here termed chalcopentlandite and would seem to contain about 10 % chalcopyrite in solution. The other must then be the phase described here as chalcopyrite; perhaps it should rather be called nickel-chalcopyrite. I have maintained the term chalcopyrite because after all the phase is difficult to distinguish with certainty from chalcopyrite. The structure of the pore mass shows the impossibility of the formation of mix-crystals between the two members.

Assuming the above to be correct, it should be possible between the two minerals pentlandite and chalcopyrite to form a chalcopyritiferous pentlandite and a pentlanditiferous chalcopyrite, but not an arbitrary mixture of the two minerals from the conditions in the ore described here. Mention is made in the literature of small bodies of pentlandite in chalcopyrite; this may be an expression for an exsolution of the pentlandite originally in solution in the chalcopyrite.

The division of the chalcopentlandite into two phases, pentlandite with lamellae parallel to the (111) of chalcopyrite, is the expression of the exsolution in this mix-crystal. As stated, however, there was also an exsolution of large chalcopyrite flames within the chalcopentlandite. It is not clear how this coarser exsolution is to be placed, but it is observable from the studies of the ore that it is not directly concerned with either the (111) lamellae in the chalcopentlandite, the formation of chalcopyrite lamellae in the pyrrhotite, or the chalcopyrite in the pore mass. Perhaps the explanation is an exsolution prior to the exsolution to the (111) lamellae.

As was mentioned in the description of the Igdlukúnguaq ore, in the central parts of the chalcopentlandite areas in the pore mass we occasionally find yellowy-creamy coloured areas where it is impossible to discern the (111) lamellae of the chalcopyrite. The assumption is that this is a non-exsolved chalcopentlandite.

In the development of the pore mass, the course of the process was evidently that when the pyrrhotite finally consolidated there remained a still fluid copper-rich sulphide mass containing a little nickel as well as the inclusions of oxidic material that are characteristic of the ore as a whole. The melt solidified in its entirety as the presumably nickeliferous chalcopyrite, which seems to have crystallized in the cubic system. By the subsequent exsolution of the chalcopentlandite from the pyrrhotite the area of the pore mass was extended considerably, thus providing the picture of marked corrosion presented by the ore, the caries structure between the pyrrhotite and the pore mass. That first reaction in solid solution was later followed by more exsolution processes in the extended pore mass.

In the form of small areas in the pore mass we find the aforesaid fields of chalcopyrite with lamellar structure which are interpreted as cubanite pseudomorphoses, as well as the oxidic materials. This chalcopyrite seems to show a special relationship to the occurrence of magnetite in more irregular parts of the pore mass; and, as will be discussed later, there are larger areas of corresponding chalcopyrite which seem to owe their origin to various secondary processes, from which the oxide in its ultimate form must have emanated. This chalcopyrite thus becomes secondary in relation to the other sulphides in the pore mass. As will be seen later (page 92), one might perhaps rather assume a formation of hydrothermal nature — a formation, be it noted, that was conditioned by the original composition of the ore melt.

The presence of an oxide phase that was formable during the development of the sulphides, signifies that we cannot wholly ignore the fact that it was more or less affected by the oxide phase. In the pyrrhotite too we find oxide phases whose formation must largely have been determined by the surrounding sulphides; and here again it is not impossible that they exerted a certain influence on the formation of the sulphides. Moreover, as will appear from the foregoing the ore on the whole was associated with mineralizers whose oxidizing character cannot be ignored; in the following I shall therefore discuss what influence these substance had on the whole evolution of the ore.

The Non-Sulphidic Mechanical Inclusions.

Pyrrhotite's Mechanical Inclusions.

Although the analytical figures provide no unequivocal basis for evaluating the quantity of magnetite in the ore, it is undoubtedly in the region of about 10 $^0/_0$. The quantity of Ti found by the analysis (0.02 $^0/_0$) therefore contrasts sharply with the dominating mineral of the mother rock, ilmenite. In other words, on this basis the oxide phase in the sulphides cannot simply be regarded as being of the same origin as the oxide mineral of the silicate mass.

The special character of the magnetite is also underlined by the textural relations. Firstly, scarcely any parts of the ore reveal an absence of magnetite. Secondly, it is fairly fine-grained everywhere in the ore. Thirdly — and this perhaps is the more interesting — the mineral occurs in definite patterns within the pyrrhotite areas. The individual magnetite grains are seen to be rounded and sometimes elongated, and it is evident that their shape is regulated by the pyrrhotite, as for instance when an elongated grain bends away and follows the basal direction of the pyrrhotite. What is more, the entire "magnetite pattern" in a pyrrhotite area is distinctly dependent on the sulphide. This is shown very instructively in Pl. VIII, 1, 2. The central part of the pyrrhotite contains no magnetite. At some distance from the centre small magnetite grains begin to appear, and these grains become the larger the farther they lie from that centre. In addition to their size, the shape of the grains is also affected by their distance from the centre, becoming more elongated and they are distinctly radial in their arrangement. Again, the elongated grains often present a characteristic claviform outline with the broad end pointing away from the pyrrhotite centre.

Evenly distributed in the molten sulphide mass there was apparently a substance which now can be recognized only in the magnetite. During the FeS crystallization the sulphide was first able to push this substance right outside of the solid phase. Gradually as crystallization advanced large quantities of the substance collected in the "crystallization front" and assumed the form of drops; then came a moment when the FeS structure was no longer able to keep them out, they became inclused in the solid phase as "vacuoles" in the sulphide. The longer the advance of the crystallization front, the larger became the drops of this repelled substance. When these large drops became imbedded they became moulded into shape by the crystallizing mass, chiefly by being pressed out in the direction of the crystallization; hence the familiar elongated shape and the claviform grains. Pl. VIII, 4 shows a case where two crystallization fronts met, with the result that the broad end of the "clubs" was somewhat deformed.

The assumed even distribution of the aforesaid substance in the melt means that the material was also present where the pore mass was formed; furthermore, that part of the substance originally on the site of the pyrrhotite areas was forced right away from the area of the FeS structure and was thus added to the pore mass. The material transferred in one way or another to the pore mass will be dealt with later.

This substance which, as a foreign body in the sulphide melt, was segregated by the crystallization and is now to be seen as magnetite, cannot have been magnetite when the sulphides crystallized, because that mineral has a melting point at 1538°. To judge from conditions in the pore mass, it seems presumable that this particular material must have been formable right down to the temperatures that prevail at the crystallization of the copper sulphides, i. e. around 950°.

As will appear from the description, the magnetite is not wholly normal, optically. It has a zonal structure, and parts of the mineral are distinctly anisotropic. As to the darker areas in the mineral one might imagine a mixture of spinel which had not found expression in a regular exsolution, but the very low content of the substances required for this, as shown by the analysis, makes it evident that this is scarcely the explanation of the differences.

When the ore was heated to about 625° for about twenty minutes, followed by rapid cooling, one of the observations made was that the magnetite grains, especially those which had been slightly on the large side, had undergone a radical change in their appearance. After this treatment their optics seemed to conform to what is normally seen in this mineral, and at the same time the large individual grains had shattered into a quantity of small ones so that they now appeared as rounded areas composed of a lot of small grains, separated by distinct intervals. They were crackled. From these observations one might suppose about the magnetite that it represents a partially porous mass, in which its darker areas are more porous than the lighter zones. It is possible that this porosity — of submicroscopic kind — may be the full explanation of the optically diverging picture; but it is also possible that, by the very reason of the porosity, there may be small amounts of extraneous matter imbedded in the mineral in submicroscopic particles.

Before turning to a discussion of what possibilities may be imagined for the composition of the substance that caused the formation of the magnetite, it should be interposed that by the crystallization of the sulphide mass — as the description shows — another kind of oxidic material was also imbedded, that is, spinel. This is the only mineral imbedded in crystal form in the sulphides, so it is presumable that it was already crystallized in the sulphide melt. The quantity of spinel crystals observed corresponds well to the small quantities of the corresponding elements found by the analysis.

The presence of siderite encased in a thin rim of magnetite imbedded in the pyrrhotite like the magnetite grains (see Pl. IX, 5) shows clearly that $FeCO_3$ must be regarded as a primary constituent. This means that the carbonate must be a product of processes between substances present in the original ore melt in the same manner as the magnetite grains must be assumed to have been.

That there is an intimate relation between the iron carbonate and the iron oxide can be seen, not only from the fact that the large grain of siderite shown in Pl. IX, 5 are surrounded by magnetite in a rim, but also that a lot of magnetite grains of the patterns in the pyrrhotite have a cavity in their centre which may be full of siderite.

Carbonate as a primary product in the ore is also evidence that the melt originally must have contained carbon compounds. Of course it is imaginable that the magnetite was also a product of reactions between these compounds and the ore melt, but it is not very probable, for then we should expect the presence of other carbonaceous compounds or larger quantities of carbonate than we actually do find. The analysis shows a content of 1.89 $^0/_0$ carbonate and 7 to 10 $^0/_0$ oxide.

On this background it seems a reasonable assumption that besides the carbon compounds there must have been oxygen in the ore melt. Presumably there was water from the magma, absorbed in the molten sulphides where, however, the compound H_2O itself can no longer have been present. (All the same, it may be convenient to operate with that compound).

The occurrence of pyrrhotite together with carbonate within a rim of magnetite shown in Pl. X, 2, an inclusion in the pyrrhotite of the same kind as that in Pl. IX, 5, must express that together with the formation of the reaction product iron carbonate there was a possibility for the formation of FeS. In other words, S^{--} was present. Iron sulphide of this kind is present in the ore in quantities that are much smaller than the quantities of iron carbonate, even if the pyrrhotite crystals described by O. B. Bøggild (8, 9) must of course be included. The ratio of iron sulphide to carbonate is presumably lower than 1:10.

Vis-à-vis the siderite this form of pyrrhotite is idiomorphic, the meaning of which may be that the sulphide consolidated before the carbonate. The magnetite within the rim seems to be rectilinearly delimited against both carbonate and the sulphide in the interior, and that may likewise signify an earlier consolidation.

The forming of the magnetite inclusions permitted, as will be seen in Pl. IX, 2, the incorporation of very small sulphide masses in the outermost layers of magnetite grains, a phenomenon that is in no way counter to the assumption as to the formation of the magnetite grains. It is quite a different matter with the small, pale inclusions observed in the magnetite grains. These are certainly not sulphides such as those found in the other part of the ore, and it is a question whether they are not actually metallic grains; at any rate it is a possibility that must by no means be ignored.

That all these inclusions are to be found in the pyrrhotite, but within a border of original chalcopentlandite, which at times is even seen to have a distinct crystallographically limited shape, is evidence that the inclusions existed at any rate at the temperature when this exsolution was formed, i. e. at about 850°. What form the materials then had in the inclusions is another matter. It is obvious that they too must have existed in the pyrrhotite before the exsolution and it must mean that they were present there at still higher temperatures. It will hardly be wrong to reckon with degrees of over 900, or even over 1000.

As far as can be seen, the condition of the substances at such high temperatures has not been studied, so it is impossible to determine what compounds were present in these inclusions. As stated, magnetite cannot have been there as a separated phase within the pyrrhotite, as Fe_3O_4 already crystallizes at 1538°. Haematite, Fe_2O_3, and wüstite, FeO, may also be precluded as their melting points lie at 1565 and 1420° respectively. Nor can the siderite as such have existed at these temperatures. Although the dissociation pressure cannot be calculated from the available data, it is obvious that there must have been a pressure of thousands of atmospheres to keep the components within the system at all.

The presence of these phases which completely infilled the cavities of the inclusions in the pyrrhotite — as isolated bodies, be it noted — proves that the components must have been present in stoichiometrical proportions. The radial fissures that are visible on several pictures of these inclusions (Pl. IX, 2) suggest rather more contraction in the pyrrhotite round about the inclusions than their own contraction, or at any rate a certain pressure effect outwards from the inclusions. These effects, however, must be designated as minimal. When the pyrrhotite crystallized these inclusions as a kind of vacuoles became placed in the sulphide mass, containing all components required for forming the substances which we see today.

The vacuole material was doubtless formed at the crystallization of the pyrrhotite, but it must be assumed to have been formed at a much earlier stage, namely at the moment when the molten sulphides were supplied with the gaseous substances of which the products must have been formed.

The processes may be suggested schematically as follows:

$$\begin{array}{llll} \text{sulphide} + (\mathrm{O}) & \rightarrow & \text{oxide} & + (\mathrm{S}) \\ \text{sulphide} + (\mathrm{C}) & \rightarrow & \text{carbonate} & + (\mathrm{S}) \end{array}$$

Formally, we may consider the following equations:

$$\begin{array}{ll} FeS + 2\,H_2O \rightarrow Fe(OH)_2 + H_2S & \mathrm{I} \\ FeS + H_2O \rightarrow FeO + H_2S & \mathrm{IIa} \\ FeO + CO_2 \rightarrow FeCO_3 & \mathrm{IIb} \\ FeS + H_2O + CO_2 \rightarrow FeCO_3 + H_2S & \mathrm{III} \end{array}$$

The molten sulphides presumably contained the reaction products evenly distributed throughout the mass, and perhaps we should rather say that here and there in the melt the sulphur was replaced by the oxygen and carbon compounds. This "solution", however, had no chance of continuing in the crystallized FeS phase, wherefore the material was expelled. The most interesting point here, however, seems to be that these processes were obviously accompanied by the formation of a certain excess of sulphur, whether it happened to be as hydrogen sulphide or as some other compound. The excess was not great, but from the equations we can reckon that it must have corresponded to somewhere between 50 and 100 $^0/_0$ of the amount of "water" (I and III). As will be discussed later, these relations seem to apply to all deposits of nickeliferous pyrrhotite, and we may think that the absence of stoichiometrical agreement in the pyrrhotite formula is caused by the excess of sulphur produced by the presence of the other gases in the ore melt.

The presence of sulphur in excess must also mean that Hawley, Colgrove & Zurbrigg's (15) conditions for the processes in the evolution of the sulphides were in fact met, which indeed also seems to emerge from the agreement between the above interpretation of the sulphide evolution and the conditions found by these authors in their laboratory melts.

The signification of these reaction products as they lie imbedded in the pyrrhotite itself is, partly, that they give the ore as a whole a special textural character, and it is obvious that by their very position they acquire a specific theoretical interest. It cannot be said that they had any influence on the formation of the surrounding sulphides, in the sense that after their imbedment in the pyrrhotite there were no reactions in which these products were involved. In particular, they caused no transformation of the surrounding sulphides. That the mix-crystal chalcopentlandite was unmixed around the inclusion is regarded merely as expressing that the pyrrhotite there had an "outer boundary" to which it could exsolve the material. By the formation of the iron oxide the material of the inclusions became so to say shut in, encapsuled, whereby further reactions were prevented. This also holds good of the siderite inclusions in the pyrrhotite, they being enclosed in a magnetite rim.

As I have already stated, in the pore mass there must have been similar gases and their reaction products with the sulphide melt at the places concerned. It must also be supposed that the crystallization of the pyrrhotite transferred to the pore mass a certain amount of these substances. The description of the ore shows that the oxidic phases in connection with the pore mass appear in three different forms and that these differ markedly from the form in which they occur in the pyrrhotite.

Mechanical Inclusions in the Pore Material.

Large areas of magnetite.

One of the forms of mechanical inclusion or oxidic material in the pore mass is the elongated veins of magnetite, which may have the appearance shown in Pl. X, 1. The magnetite grains in the pyrrhotite are often observed to "merge" with the material of these veins; they have grown together with it and now form part of the magnetite in the vein. This also applies where there are no actual veins of magnetite but merely irregular, large areas of this oxide in the pore mass. This shows that there must be an intimate developmental relationship between the two groups of magnetite material. Whether the formation substance of the magnetite was conveyed to the pore mass solely by expulsion from the pyrrhotite during the latter's crystallization, or this material was present in the pore mass in such a quantity as to suffice for the formation of the large veins, can scarcely be decided; the truth may be something of both. The main point is, however, that there is such a close association between the two types of magnetite that we can ascribe the same origin to them, materially speaking, no matter from what part of the ore melt the material came.

One observation that is particularly clear in connection with these large areas of magnetite, but which also has been made now and then in relation to the smaller magnetite grains mentioned above, is that chalcopyrite, which in structure seems to betray original cubanitic features, is fairly frequent in these surroundings. Its occurrence, partly along the margins of such magnetite areas and partly imbedded in the outer areas of the magnetite, reveals that there is a close connection between these two minerals. It looks as if this chalcopyrite in its genesis is dependent upon the magnetite. The relict structure, which suggests that the original copper sulphide was cubanite, or at least that it passed through that phase in its formation, shows that the copper sulphide when formed was rich in FeS. This copper sulphide differs e. g. from the copper sulphide otherwise occurring in the ore by displaying no form of intergrowth with Ni-sulphide. Where the latter borders on the copper sulphide there is always a sharp boundary formed by a crack between the two. It is a characteristic feature that cracks are often present in this chalcopyrite, not only those which are assumed to reflect the lamellae of the cubanite, and all are full of a non-opaque material. The cracks are too fine for determining what kind of material they contain, but there is the possibility of its being carbonate or sulphate.

Pl. X,1 shows that the formation of chalcopyrite of this type along a magnetite vein proceeded with the simultaneous corrosion of the pyrrhotite, but the curious point is that neither chalcopyrite lamellae nor chalcopentlandite bodies in the pyrrhotite were affected. FeS alone was replaced. The picture otherwise shows that this chalcopyrite formation took place after the formation of the chalcopentlandite bodies and the chalcopyrite lamellae in the pyrrhotite. This may perhaps signify that the formation of magnetite — Fe_3O_4 — instead of the original oxidic phase took place at this stage. The outstanding feature is the corrosion of the pyrrhotite, which is wholly replaced by the special type of chalcopyrite, whereas the chalcopyrite lamellae and the chalcopentlandite were not visibly affected by the processes.

If the oxidic material contained copper in a form that was for instance analogous with the mineral delafossite ($CuFeO_2$), and that compound was not stable in combination with FeS, that may perhaps explain this curious circumstance. As the formation must be placed subsequent to the exsolution of the chalcopyrite lamellae, it is possible that it proceeded within the stability range of chalcopyrrhotine, whereby the copper sulphide acquired the possibility of containing a certain excess of FeS which, through the cubanite phase with its lower-temperature stability, gave the final phase in the form of chalcopyrite its particular structure. All this of course is highly speculative and it may be proper here to state that I at any rate cannot suggest any explanation founded upon a more definite basis. The main point is, perhaps, that we seem to have here a formation which has provided the origin of a copper-iron sulphide and simultaneously there was formed what we today see as magnetite; the circumstances seem to indicate that this was what might almost be called a kind of hydrothermal process.

Small magnetite grains in regular patterns.

The other type of oxidic material occurring in the pore mass is present in the form of the small magnetite grains so often mentioned in the foregoing, appearing in the copper sulphide surrounded by, or rather divided up into rounded fields, by chalcopentlandite. The grains are so small as to make it difficult to decide the nature of the material itself. The shape of the grains, however, is interesting for it seems to have been governed exclusively by the crystallographic directions in the surrounding sulphide whose cracks, most of which actually start from these magnetite grains, can distinctly be seen to run parallel with the boundaries of the magnetite.

As was said above, the very regular distribution of the magnetite grains in these particular parts of the pore mass may indicate that the crystallization of the sulphide here was spontaneous. The magnetite grains cannot have been placed there afterwards, so that their position can only have been determined by the crystallizing sulphide mass. From a consideration of the texture one might be inclined to assume it to be a kind of exsolution structure; but having regard to the nature of the materials this is not very probable; nor does it harmonize with the often observed offshoots from the grains along the frequent cracks in the sulphide, starting at the magnetite drops. During crystallization the oxide was of such a composition that it was plastic, which is the reason why today it reflects the original crystallographic structure in the copper sulphide. Here the magnetite grains must be viewed in the same light as those in the pyrrhotite, and their regular distribution in these areas of the pore mass must be assumed to be an expression of the originally regular distribution of the reaction products between the sulphide melt and the gases present in the molten sulphides. The first type of magnetite in the pore mass represents areas in the sulphides where during their development there was a possibility for the formation of large oxide masses, perhaps also as a consequence of the extrusion of materials from the crystallizing pyrrhotite, whereas the second type seems to have been formed solely on the basis of the gases in the molten pore mass.

Siderite in eutectoid-like structures.

The third type of oxidic material in the pore mass is represented by the areas of eutectoid-like siderite with the various oxides and other minerals occurring therein. As siderite is known to be a primary component of this ore, there is no *à priori* reason for assuming that this type is not of primary origin too. On considering how it occurs in the various ore samples it would also appear to be most reasonable to regard these siderite masses as closed forms, i.e. no supply channels to them can be discerned. One situation of these areas, illustrated in Pl. X, 3, is actually quite typical. No matter whether they lie bordered upon by several areas of pyrrhotite belonging to the same individual, or the surroundings consist of pyrrhotite belonging to several separate individuals, this position would seem to be explained as meaning that the carbonate material was originally supplied from these surrounding areas of pyrrhotite when they crystallized. Naturally, it is not impossible that part of the material was within the pore mass originally.

This placing of the siderite areas applies to the areas which are distinctly formed as eutectoid structures. In addition to these, as was mentioned in the description there are those siderite areas which, rounded in shape, lie completely inclused in areas of pyrrhotite, as Pl. XIII, 1 shows. The structure of the ore in which these areas of siderite appear differs from the usual appearance of the Igdlukúnguaq ore, in that the pore mass is present in much smaller quantities. The siderite areas here are in fact comparable with the previously mentioned and discussed rounded siderite masses which, surrounded by a rim of magnetite, were found imbedded in the pyrrhotite and where, between the pyrrhotite and the magnetite, there was unmixed original chalcopentlandite. Here again we find the original chalcopentlandite as well as the magnetite rim, but in this case the rim is some distance inside the carbonate, and the surrounding sulphides, both those close by and those some distance away, display changes of the same kind as those observed around the areas of eutectoid siderite. After being enclosed in the pyrrhotite the carbonate did not remain passive; the position seems to be that the magnetite rim was formed more or less in parts, and at a later juncture the material accomplished the corrosion of its surroundings. The products of the corrosion are of the same kind as those around the areas of eutectoid siderite, except that the copper-nickel sulphides of course are less frequent. It is presumable that the conditions concerning the areas of eutectoid siderite apply here too, with the exceptions natural to the somewhat different surroundings.

In its most handsome form the main type of siderite structures is that shown in Pl. X, 4. Not only has there been a transformation of the adjacent minerals round about this siderite, but the siderite replaces a large proportion of these minerals. This is observable from the fact that within the siderite there are grains of magnetite which obviously fit into patterns belonging to surrounding pyrrhotite areas. This means that the siderite must have replaced the pyrrhotite and the other sulphides without affecting the magnetite otherwise. Pl. XI, 1 shows how the pyrrhotite around these siderite areas may undergo changes without erasing the traces of the chalcopyrite lamella, and in Pl. XI, 2 it is seen how the pentlandite flames are still faintly discernible in the transformed mass. These observations show that the siderite can only have occupied its present position after the formation of the aforesaid minerals and structures. It is later than the exsolution of the chalcopyrite lamellae; and, as the magnetite may be regarded as having consolidated later than these lamellae, and the siderite embodies these magnetite grains within it, it must also be later than the latter's formation, at which no doubt we get down to temperatures of about 700°. The pentlandite flames emphasizing the basal direction of the pyrrhotite seem to determine when the transformations and replacements in conjunction with the siderite took place, as far as the temperature alone is concerned. Some of the flames are of characteristic shape and doubtless form part of the exsolution series that is presumed to lie within the range of 300—400°. They are to be seen untransformed in areas quite close to the siderite. Other flames are more regular and should properly be called spindle-shaped. These are transformed in the vicinity of the siderite and are of the type to be seen showing the relict structure in Pl. XI, 2, 3. However, this type of pentlandite exsolution lamellae corresponds to those occurring in some central parts of the pyrrhotite area where there are no magnetite grains, and where the chalcopentlandite has passed through a development that makes it highly reminiscent of normal pentlandite flames or discs. In other words, it is presumable from this that the temperature must have been at a level somewhere between 300—400°, as indicated by the ordinary pentlandite flames, and about 700° where the chalcopyrite lamellae are presumed to belong.

It is difficult to see if the temperature interval of these formations can be arrived at more precisely, apart from the fact that the presence of valleriite in the siderite together with the chalcopyrite occurring there shows that at about 225° there was time to establish the copper-iron sulphide which is stable at that temperature. The nearest one can say seems to be that these products may justly be described as hydrothermal: in the first place, mineralizers like water and carbon dioxide are evidently present, and in the second place, they belong to the said temperature region which on the whole just corresponds to that of the familiar hydrothermal formations.

Before these transformations took place we must suppose, having regard to the picture of corrosion now presented by these areas, that the siderite and the accompanying other minerals—or rather the substances which occasioned the formation of all these minerals—occupied a smaller space; in the nature of things we must assume it was the carbonate that was present in smaller compass, because the sulphides can scarcely have been less in volume than they are now. As the description of these areas showed, it is extremely difficult to decide what sulphides are present and especially what structures they occupy; but it seems that a large part of them correspond to the form of chalcopentlandite which we find in the marginal zone of the pore mass; in addition there is some chalcopyrite which doubtless corresponds to the chalcopyrite in the pore mass but which, under the influence of the gases contained in this particular area, acquired a different form in analogy to the type of copper-sulphide which occurs together with the large areas of magnetite.

Of course it would make things a good deal easier to assume that these areas were formed while being supplied with material from the outside. For example, there would be no spatial problem in that sense; but in the first place we could only assume that water and carbon dioxide were brought in, and in the second place, with such a form of supply we should expect a gradual increase of these substances, either outwards in the ore samples or — which would perhaps be the more probable — along certain cracks and fissures in the samples. But no such increases of the quantity of these areas or of their extent are to be found. Moreover, in all the samples examined there is reason for regarding these finely developed "figures" of siderite as closed forms without supply channels. It is another matter that cracks and fissures have appeared in the surrounding ore as a link in these formations. When these are cracks which from these areas and outwards become smaller and as a rule can be traced to a nearby area of similar kind, whereas none can be followed to the surface zones of the ore with signs of more general weathering, there is no reason for ascribing this to extraneous secondary processes.

The circumstance that among its primary components the ore must presumably have contained the aforesaid gases, makes it probable that they exerted their influence here too. It is of particular significance that this influence came from a number of small, delimited areas in the ore. *The natures of the primary components being what they were, small local hydrothermal centres were established, whence the ore was subjected to a certain measure of transformation as part of its total genetical history.*

The principal process in these transformations was the conversion of the iron sulphide into iron carbonate, whereas the copper sulphides would either endure or simply undergo recrystallization. Nickel would remain in sulphidic compounds but altered from pentlandite to bravoitized varieties of that mineral. Simultaneously there would be a transformation, lessening as the distances from these areas increased, of the surrounding pyrrhotite which would be transformed into the so-called zwischenproduct.

What happened chemically in these areas was that sulphides were replaced by siderite, iron carbonate, and some iron oxide was also formed at the expense of the sulphides. All in all this means a liberation of sulphur, which thereby became available for the formation of other compounds. Therefore, when we observe a transformation of the pentlandite to bravoite starting from these areas, and the degree of transformation decreases distinctly in proportion to the distance from the areas, the assumption will probably be that at least part of the liberated sulphur helped in the forming of that bravoite, which of course is a nickel compound corresponding to pyrite with a certain content of H_2O etc.

The pyrrhotite adjacent to these areas was transformed more or less to the so-called zwischenprodukt, an intermediate stage in the transformation of pyrrhotite to pyrite; and as this formation too decreases in intensity away from the areas, the assumption is that it was also subject to the amount of sulphur liberated by the forming of siderite and oxide.

The ore analysis revealed the presence of 1.75 $^0/_0$ siderite. The greater part of this siderite is to be found in the areas referred to above, which are dominated by the mineral. However, we must also assume that the quantities of water and sulphate shown by the analysis to be present, about $3^1/_2{}^0/_0$ water and about 5 $^0/_0$ sulphate, calculated as iron sulphate, must be within these areas, for the simple reason that they could be nowhere else. As far as the areas are concerned, however, it is not only possible but also necessary to have certain amounts of these substances present, because both bravoite and zwischenprodukt are minerals known to contain water and sulphate in one form or another.

This means that the local hydrothermal centres must be assumed to have contained compounds of both carbon dioxide and water. The particular point to be observed here is that it was possible for these compounds to appear imbedded in the sulphide mass, which, as will be seen from the corrosion by the siderite and its concomitant minerals, was first able to follow the line of development described as applying to the greater part of the sulphide mass. Quite evidently the corrosion affected a mass that originally was continuous with the surrounding sulphides.

From the picture presented by these areas it would seem to be a reasonable assumption that the "motive power" in these processes is to be found in the reaction possibilities of carbon dioxide, and that the other processes taking place were secondary to the formation of the siderite.

These other processes in the area, i. e. the formation of the disulphides, that is to say the absorption of sulphur in the surrounding sulphides and the formation of sulphates which evidently contained water, are best elucidated by a consideration of the two sulphidic compounds.

Concerning zwischenprodukt RAMDOHR (29, p. 412) writes that its relations to pyrrhotite seem to suggest "ein chemischen Abbau (zeolithartigen) des Magnetkiesgitter, ewtl. mit Einbau von H_2O oder O. Das Zwischenprodukt ist weder auf bestimmten Lagerstättentypen noch klimatische Bedingungen beschränkt, es fand sich z. B. besonders schön in einem Sommaauswürfling, von Baldoivi bei Sulitelma, vom Bärenbad bei Hollerbach im Pinzgau und der Ping Riesenglück bei Harzburg."

The quantity of sulphate found by the analysis of the Igdlukúnguaq ore does not harmonize with the fresh character of the particular sample; indeed, it was impossible to find sulphates in any of the samples by either ore-microscopy or ordinary microscopy. It should be added that not even in samples ground and polished in oil could I recognize phases capable of being interpreted unequivocally as sulphates.

In connection with these areas one observes (see Pl. XII, 1) cracks that are very fine and seem to be filled with a material whose refractive index is lower than that of limonite. This, together with the special characters of these cracks, may perhaps be advanced in support of the argument that the material in the cracks must be sulphates, as these places seem to be the only ones to which sulphates can reasonably be localized. However, the frequency of these cracks definitely forbids the exclusive placing of all quantities of sulphate to them.

In analogy with RAMDOHR's (29) above-quoted opinion of the position of the water in relation to the pyrrhotite lattice it might therefore be imagined that the sulphates as such would occur there. The mottled appearance assumed by the pyrrhotite in the vicinity of these areas, and the great variation displayed by the zwischenprodukt as to colour, do actually suggest irregularities of a submicroscopic kind. The presence of the foreign bodies is expressed by a change of the mineral's colour; and I would add that as we often find the basal direction of the pyrrhotite very markedly accentuated by cracks and colour variations, it might be interpreted as meaning that the mineral is so to say permeated with extraneous material. When the pulverized ore is treated with hot water both iron and nickel-sulphates are extracted. As the appearance of the bravoite is very like that of the zwischenprodukt, it seems probable that both contain foreign elements in the form of both water and sulphate. From what is to be judged from the Greenlandic ore, these products in their origin were wholly governed by the components primarily in the ore.

With the sulphates placed "inside" the two components, the zwischenprodukt and bravoite, we may arrive at an explanation of the problem raised e. g. by RAMDOHR of the curious weathering of certain types of pyrrhotite, depending neither on ore type nor on climatic conditions. He makes the particularly interesting remark that secondary bravoite may also "disintegrate" suddenly. As he points out, this plays an important rôle in the ore-treating processes where the sudden appearance of *sulphates* in the flotation might exert considerable influence.

The presence of both sulphate and the ubiquitous magnetite in the ore signifies the action of processes that caused oxidations, which must have been coupled with reductions. In conformity with the opinion advanced as to the genesis of the ore, these processes must evidently have taken place in the closing stages of the development that proceeded within the ore body among the latter's original components.

The compounds among which the reactions took place must have been the simple sulphides of the composition FeS, $(Fe,Ni)S$, $CuFeS_2$ and the like on the one hand, and CO_2 or CO & H_2O on the other. Redox processes, which occasioned the formation of ferrioxide and sulphates, must therefore be assumed to have taken place simultaneously with the formation of free carbon and/or free hydrogen. No doubt there are other possibilities, but these are doubtless the more probable having regard to the fact that in the ore we are unable to register any phase corresponding to the oxidation products. If hydrogen was liberated it was possible for it to disappear — or at any rate its presence would be hard to demonstrate. As to carbon, matters are somewhat different because one would expect to register it in the form of graphite or graphite-like material.

Consequently it is of some interest that in these areas together with the siderite we find the curious leaf-like grains of one or two minerals, of which one phase not only in form but also in colour and other optical features largely resembles graphite. It is not graphite, as will be seen from the discussion in the course of the description of the material concerned. But that it may very well be a phase in which graphite, or rather carbon, forms a part seems to appear from the processes which presumably took place in these areas. For example, a collective process such as the following might be imagined in this connection:

$$2\,FeS + 3\,CO_2 \rightarrow 2\,SO_2 + 2\,FeO + 3\,C$$

or:

$$2\,FeS + 5\,CO_2 \rightarrow 2\,FeCO_3 + 2\,SO_2 + 3\,C$$

The ratio between the sulphur dioxide converted to $FeSO_4$ and $FeCO_3$ in this process is only partially in harmony with the quantities of iron sulphate and siderite ($304 : 232 = 1.3$; $4.94 : 1.75 = 2.8$) found by the analysis. Perhaps the excess of sulphate is the result of the effect of the water on the sulphides.

The magnetite may have been formed by the transformation of iron carbonate with the simultaneous formation of free carbon. This, however, betokens a close interdependence between the magnetite and the carbon which has not been demonstrated in the ore, whereas the second of the two equations above associates carbonates and carbon more closely.

Nor does the formation of sulphate seem to belong together with the formation of magnetite, so evidently we can only conclude that the redox process with magnetite as one of its end products had hydrogen as the other. It is hard to imagine that ferric iron could form in the molten sulphides themselves, and therefore the substance formed prior to the magnetite was probably a ferrocompound. Formally, on transformation from ferro-oxide to Fe_3O_4 there must either be a supply of oxygen or the formation of free iron. The former is scarcely credible and the latter has not been observed. Attention might perhaps be called to the observation of small "sparks" of a very white substance seen here and there in the magnetite within the pyrrhotite; this, however, is a phenomenon which has not been observed at least with a distribution that would justify the assumption of a process with such a course. But if the substance originally preceding the magnetite contained a suitable quantity of water, it would theoretically be possible for the required quantity of ferric iron to be formed with the simultaneous formation of free hydrogen. If we imagine the compound $Fe_3O_2(OH)_2$, we can at least set up the equation:

$$Fe_3O_2(OH)_2 \rightarrow Fe_3O_4 + H_2$$

In all likelihood we cannot ignore the fact that conditions are a good deal more complicated and that sulphur for instance formed part of the original compound; but it has not been possible to demonstrate the presence of sulphur in association with the magnetite, and as we cannot directly indicate possible compounds, I shall refrain from advancing further suppositions.

It should be remarked that the observation of the maghemitization of the magnetite, recognizable from the bluish, irregular areas in the internal parts of the magnetite, indicates the formation of pure ferri compounds and underlines the activities of the oxidizing processes.

Regarding the processes in the ore which have been suggested above, their products are highly comparable with the industrial processes employed in extracting the metals i. a. from this very type of ore. This fact has also been mentioned earlier by other writers. There is this vital difference, however, that the industrial processes work at ordinary pressures and in practically open systems, whereas for the ore we must take it that there was a closed system where the prevailing pressures undoubtedly were extremely high. In the attempts at clarifying the processes in industrial plants it is possible of course to work under well-defined conditions; but even then it proves impossible definitively to describe all the processes leading to the end products. Certain main equations can be set up, certain reactions may be supposed to be the initial phases in the total processes, but it is often hard to establish definitely that they actually take place. With this as a background it is obvious that the processes of nature in the formation of ore must be extremely difficult to clarify, even despite the fact that, as with the Greenlandic ore, we can indicate a wealth of detail products from these processes. The temperatures of the various stages can be established only for some of the steps, and even then only very approximately. The pressures seem to be beyond our range of computation, today at any rate.

These difficulties must of course be borne in mind; but as the mere establishment of the succession of the facts often calls for consideration of the occurrence of the particular products in various processes, the above discussion has been considered advisable.

COMPARISON WITH OTHER DEPOSITS

Introduction.

The description given in the foregoing, embodying many more details than has hitherto been observable in a deposit of nickeliferous pyrrhotite, owes that wealth of detail to the evidently unique conditions prevailing when the ore body at Igdlukúnguaq was formed.

An examination of the available literature has discovered no other deposit which, with a similar chemical composition, has so many and such a variety of structures; the fine grain of the structures is also exceptional.

My examination of a quantity of samples from some of the "classic" occurrences and from some Scandinavian has verified the paucity of the literature in detailed structures of the kind found in the Greenlandic ore, though it should be noted that in this material, including that from the Scandinavian deposits, I found samples in which were some structures comparable with those in the Greenlandic ore.

The general monotony of the ore type, and the remarkable divergences of the Igdlukúnguaq ore, might make it tempting to judge the Greenlandic ore to be a variety so special that it could be of little or no significance to the type as a whole. However, as I have endeavoured to show in the description and its interpretation, the particular feature of the Igdlukúnguaq ore is its preservation of a number of phenomena associated with high-temperature formations, and, be it noted, the assumed temperature interval lies within the range to which this ore is usually placed. Thus in applying the knowledge gained in the study of the Greenlandic ore, we do not introduce any element foreign to the ore type. The extreme element lies in the cooling history, or rather in the cooling rate.

It might be pointed out that the content of gases has very greatly influenced the picture of the Greenlandic ore — but without changing the initial development of the sulphides and exsolution processes — and that in this lies a fundamental difference from the usual representatives of this type of ore. However, my examinations of the occurrences elsewhere seem to show that they present several signs of formations arising from a primary content of gases. As will appear from the following discussions of other deposits, it should be possible on this point too to establish the connection between Igdlukúnguaq and the known occurrences of nickeliferous pyrrhotite. As regards the gases in the Igdlukúnguaq ore, by the way, it is clear from the description that the processes originating from them have rather contributed towards effacing the special structures than emphasizing them.

I am therefore of the opinion that the Igdlukúnguaq ore, instead of being an unusual—freakish—form of nickeliferous pyrrhotite must be regarded as a representative, though rare, of this type of ore in its early stages; in other words, that the study of this occurrence reveals such ample features of the high-temperature development of the type, as well as of the ore's primary reactions to the inclused magmatic gases, that this Greenlandic ore can be utilized in an attempt to describe the genesis of nickeliferous pyrrhotite ore.

The Igdlukúnguaq ore has its main significance in the unusual development of the structures and phases in the ore minerals themselves, whereas its petrographic and tectonic placing does little to increase our knowledge. Its obviously unilateral position on the foot wall of the dike may of course be said to harmonize quite well with what we know about the position of other occurrences of the ore. In the same manner, the composition of the dike rock may be said to conform fairly well with those of other known occurrences. It would be of interest, however, to know more about its placing in relation to the surrounding basic rocks. The work of the next few years in the basalt region of Greenland—work which by the way has already been going on for some time—will it is hoped throw some more light on these matters.

In turning from Igdlukúnguaq to a comparison with other deposits it is natural to attach importance to the microdetails there. Unfortunately this is somewhat difficult. Many of the occurrences were described at a time when the technique of ore-microscopy was not so far advanced as it is today; then again, the authors, who often are mining geologists at the particular mine, have to direct so much attention to the tectonic and positional aspects of the deposits that their descriptions of these dominate the work, the ore itself dropping somewhat into the background, inasmuch as it is characterized first and foremost by means of a brief mineralogical description, the essential characterization being based upon chemical analyses. Obviously, it is the aspects of most importance to the mining geologist that are elucidated; but as far as I can see, this is also one of the main reasons why the setting up of the ore type and its description often receive such a highly local character that parallelization from one occurrence to another is difficult. This is very clear for instance in the Sudbury/Petsamo occurrences. There is more or less agreement that they are very closely related, but the differences between their appearances are so marked that one is easily tempted to describe "the type" quite variously when working on only one of them.

The petrographic affinity of the type is agreed almost everywhere, and nature will simply not permit of nickeliferous pyrrhotite ore being torn off from its basic rocks. From there, however, there is a tendency towards making the main evaluation dependent on the tectonic factors, thus opening a loophole by which to "get round" nature's linkage between the ore and the basic rocks. The ore may be regarded—as in fact has been done at Sudbury—as being distinctly younger than the principal rocks which accompany it, whereby it has been possible to introduce hydrothermal modes of formation of various kinds from, as BATEMAN (4) says, rather peculiar hydrothermal solutions.

Sudbury, Canada.

The following survey is based chiefly on the following publications: WANDTKE & HOFFMAN (54), BURROWS & RICKABY (7), FREEMANN (14), and others.

The outstanding feature of the Sudbury region is the Sudbury Basin, a formation composed of the so-called Whitewater Series. Lying unconformably on granites and gneisses, which perhaps are Algomian and which in their turn overlie the Sudbury Series containing greenstone sediments of from basic to acid lavas, basic intrusives, arkose, greywacke, conglomerates and quartzites, we find this series containing tuffs and agglomerates, schists and sandstone. Then in intrusive contact, and appearing in the form of a sill or sheet-like masses, follows the intrusion of the nickel magma, the norite-micropegmatite. There is a series of other intrusive rocks, occurring especially in the southern nickel region and consisting of gabbro, granite, basalt and olivine diabases. They are all considered to be of Keweenawan age, with the gabbro rocks older than the nickel-norite, whereas the granites and dike rocks are younger. All this intrusive series forms a shallow oval bowl-shaped figure with the Huronian sediments filling the bowl up. The dimensions are 37 × 17 miles and the thickness of the intrusive mass is estimated at from one to four miles.

The rocks have been described in several different publications, but it is impossible to set them up into one uniform series; in my opinion a study of the subject from modern aspects, with the entire complex correlated with e. g. the massifs of Greenland—the Skærgaard massif—and the West Greenland plateau basalt complex, as well as the occurrences of the same type in Africa, would help to throw light upon several problems which today are rather complicated. Many of the relative age determinations made between the various rocks are undoubtedly correct, but the length of the periods to be placed between the various formations is not clear. If matters are the same as for instance in the West Greenland basalts, the relationship between the different rocks becomes much more intimate, and the ore acquires an association with the rocks which does not appear directly from the rock descriptions today.

In Sudbury the ore is present partly as a marginal ore, partly as an offset ore. COLEMAN (according to WANDTKE & HOFFMAN 54) applies the term offset to the dike-like intrusive bodies extending from the norite mass itself. These occurrences may be of both dike and stock character. The rock found there is quartz diorite, but these quartz diorites are not confined to the offset occurrences as for instance the descriptions of the typical marginal deposit Creighton indeed show. The quartz diorite is a dark grey, medium to fine-grained rock which generally contains drops of pyrrhotite disseminated evenly over the whole. The rock contains andesine, hornblende, biotite and quartz with apatite, magnetite and ilmenite as lesser components.

Whereas in marginal ores it is usual for nickel to outweigh the copper in the sulphides, the opposite is the case in the offset ores. In addition, the arseno-minerals have a tendency to occur especially in the offset ores. Pyrite, sphalerite and galena increase in the ore outwards from the southern margin of the nickel irruptive. The gangue minerals vary somewhat too, siderite, quartz, chlorite and serpentine becoming distinctly more frequent away from the contact. Whether the ore minerals occur in the marginal or the offset ore, their succession has been read as: pyrite, magnetite, pyrrhotite, pentlandite, chalcopyrite, sphalerite, galena. It is usually stated that their proportional quantities vary.

There are several interesting descriptions of ore-microscopic observations of the Sudbury ores, but there is an unfortunate lack of a general survey of how conditions vary from one mine to another, the variation through the ore bodies, the variations with the depth, etc. A thorough ore-microscopic work of that kind would be capable of providing information of undoubted value to our understanding of the entire evolution within the mineralized region.

Ore-microscopic description.

Pyrrhotite is the most prevalent ore mineral. It is stated that its macroscopic form may be hexagonal or show some approach to it. Before the mineral crystallized magnetite formed, of rounded appearance in the sulphide mass and also as more or less euhedral crystals. Pyrite is considered to have crystallized prior to the pyrrhotite and also to the magnetite. It is found in crystals i. a. in the pyrrhotite. When pyrite appears in pentlandite its shape is described as quite irregular. The pyrrhotite often displays twin lamellae due to pressure and the mineral may be broken up into small polygonal grains. The familiar α–β lamellae (dark and pale flames) are to be seen in the pyrrhotite.

Inclused in the pyrrhotite are the familiar exsolution bodies of pentlandite, pentlandite flames. As stated, magnetite grains are also present, and some chalcopyrite and pentlandite are often seen in association with these grains. Inclused between the pyrrhotite areas — not the small polygonal grains but the large, original areas, there are pentlandite veins. This is handsomely illustrated, for instance, by VAN DER VEEN ((49), fig. 15). There the pentlandite appears as a kind of intergranular mass. This was also observed by HAWLEY, COLGROVE & ZURBRIGG (15), who give a corresponding illustration in their fig. 11. They also have a description of the pentlandite relations in the ore samples that show variations as regards this mineral. The lamellar ore from the Murray mine, Sudbury, is quoted as an example of one differing from the aforesaid type. There the pentlandite is in the form of lamellae parallel with (0001) in the pyrrhotite, and, in addition to the familiar flames of small size, there are also some up to half a millimetre in width. In ore with about equal proportions of pentlandite and pyrrhotite the former mineral is present in grains that are almost equidimensional, in contrast to the aforesaid intergranular pentlandite. The pentlandite may be over a quarter inch in diameter. The two minerals contain inclusions of each other. Pentlandite is thought to be the younger but the mutual ages are not clear. Finally, the pentlandite may occur as large, ovoid masses with interstitial pyrrhotite, which seems to be later than the pentlandite. The authors consider this pyrrhotite to be homogeneous whereas the pentlandite contains very fine inclusions of pyrrhotite.

This information is interesting in connection with the study of the relations between the pyrrhotite and the pentlandite. For an understanding of the ore as a whole it might have been of interest to know something of the appearance of the chalcopyrite in this association, but it is not given, unfortunately. In WANDTKE & HOFFMAN (54) it is mentioned that this mineral is present in the form of veins through the pyrrhotite and as grains in the same mineral closely following the pentlandite. In many cases, they say, the chalcopyrite is to be seen fingering into the pentlandite and replacing it. Chalcopyrite is also to be seen as well-delimited crystals in the pyrrhotite. It would have been interesting to see pictures of these crystals.

Cubanite occurs in Sudbury, and sphalerite is found in the chalcopyrite. Arsenopyrite is present in small grains in the pyrrhotite and seems to be earlier than that mineral. A number of other minerals are to be found in several of the deposits. Galena occurs in several. Sperrylite, braggite, platinum, gersdorffite as well as the secondary minerals marcasite, bravoite and others have also been observed in the ores.

Of particular interest as regards the bravoite, or whatever this secondary mineral after pentlandite may be called in the various descriptions, is what is mentioned by several and emphasized by WANDTKE & HOFFMAN (54). The transformation of the pentlandite can be seen to have taken place even in quite fresh ore samples, i. e. samples in which the other sulphides show no sign of transformation. Here and there the transformation had even gone so far that the mineral had been replaced or veined by limonite. These authors think it very probable that this was due to the pentlandite's outstanding cleavability and they consider that the formation was due to supergene solutions. BUDDINGTON's (6) discussion of the transformation of pentlandite into polydymite or violarite, etc., is very interesting in this connection. His original view was that there must have been some form of hypogene transformation, it being obvious that the original shape and even the mineral's external relations are quite preserved; thus he says it has rather the appearance of transformation subsequent to the primary deposition of the sulphides.

Discussion of the microscopic features.

The essential features of the Sudbury ore are fairly clear and reveal the main outlines of its development which, as presented by the various authors, forms an excellent parallel to Igdlukúnguaq. It is difficult, however, to discuss the more detailed structure of the Greenlandic ore and to correlate them with the "known" phenomena in the Sudbury ore. Nevertheless, some points deserve to be singled out and it may be of interest to mention some observations which I have been able to make in the material from the Canadian deposit. These will therefore be submitted in the following, which is an attempt to elucidate certain stages of the genesis of the Sudbury ore in the light of what we now know of the Greenlandic ore.

Sperrylite, which is not contained in the Greenlandic ore, is undoubtedly an early mineral in Sudbury. As another early mineral there we have the magnetite. Here, however, it should be remarked that this mineral seems most often to be present in rounded grains in the pyrrhotite; the size of these grains, idiomorphous or rounded, is comparable only with the larger or largest grains in Igdlukúnguaq. Here we find a very distinct difference in the evolution of the two ores. It is practically certain that Igdlukúnguaq was formed in very quiet conditions, whereas in Sudbury there was at least a good deal of mechanical deformation in the later stages. It is imaginable that in the earlier stages too the

Canadian ore was under mechanical influence, so that the gases and their reaction products in the ore — in the Greenlandic ore placed preponderantly to the crystallization of the sulphides — were so to say kneaded out of the sulphides and thus provided with the opportunity of collecting in larger drops. The idiomorphy observed in the magnetite in Sudbury is not necessarily the expression of early crystallization; it may also have vied with the sulphides in their crystallizing properties.

The difference in the development of the magnetite in the two ores may also have been due to differences in the pressures prevailing when the ores were forming. A suitable decrease of the pressure would presumably favour the formation of larger drops of the gases and their reaction products. If so, we must doubtless assume that consolidation of the sulphides was sufficiently slow to permit these drops to accumulate in the still fluid sulphide mass. Slow development at that stage may also mean a possibility for the formation of crystals of magnetite or some related phase. On the other hand, if the crystallization of the sulphides was rapid the assumption must be that a lessening of the pressure would lead to the picture presented by Igdlukúnguaq; decreased pressure may cause many small air bubbles to form in the mass, but the latter's rapid crystallization would hinder them from collecting into larger drops.

The presence of ilmenite in the Sudbury magnetite indicates another difference between that ore and Igdlukúnguaq. No doubt the significance of this can be determined only by means of a comprehensive study of the ore, but it should be added that the quantity of ilmenite in the samples which I have seen was not great. Titanium formed no dominating component of the oxides in these samples, for which reason the presence of that substance need not make it difficult to view the oxide phase of the Sudbury ore in the same manner as that of the Greenlandic ore. A striking feature seemingly in support of that opinion was observed while examining some polished samples from Sudbury with a handglass. The magnetite grains were seen quite distinctly lying in a pattern of closed "rings". No markedly intergranular position in relation to the pentlandite could be observed with certainty, but it will undoubtedly be worth while studying the ore from that point of view. It will be seen from the account of the observations made in samples of a Norwegian nickeliferous pyrrhotite, Beiernfjord, that the magnetite may in fact by placed together with the intergranular pentlandite.

In this intergranular form the pentlandite is considered by several authors as an indication of early exsolution from the pyrrhotite. In Igdlukúnguaq the parallel is the binary aggregate lying round the pyrrhotite islands, consisting of chalcopyrite in the form of lamellae in the pentlandite. In the central part of the "currents" around the islands I found chalcopyrite. If this picture is a universal one, applicable to the Canadian ore too, more or less chalcopyrite may be expected to be found as a regular component in the pentlandite. The binary aggregate, whose origin is presumed to be a stable high-temperature form, chalcopentlandite, containing both Cu and Ni and Fe, was observed in Igdlukúnguaq as a very regular exsolution structure between chalcopyrite and pentlandite. There is no mention of any corresponding phenomenon in Sudbury, at any rate not in the regular form. On the other hand I find that the literature on this deposit points out that chalcopyrite and pentlandite often appear in company, a relation which I have also observed in several of the samples. An interesting point is the mention of chalcopyrite (by WANDTKE & HOFFMAN, 54) as fingering into the pentlandite, which is interpreted as a replacing of the latter mineral. Possibly it is actually a relict of the disintegration structure of the chalcopentlandite. It seems likely that the conditions observed in the Greenlandic ore have their replica in the Sudbury ore. As yet we have no definite knowledge of phenomena by which to correlate the two ores, but the above features are interesting and it would be desirable for the ore to be examined from these angles.

The pentlandite flames in the Sudbury ore need no comment. As HEWITT (17) and others believe, they correspond to an exsolution at 300—400°. In this respect there is agreement with Igdlukúnguaq. But apparently there is no exsolution of pentlandite (chalcopentlandite) inside the pyrrhotite corresponding to the first large exsolution in the Greenlandic ore. (Otherwise the intergranular pentlandite does conform.) Possibly this has some relation to the difference in the development of the two ores, which also caused the difference in the placing of the magnetite in the ores.

The occurrence of the chalcopyrite is generally regarded as an indication that this mineral is later than the other sulphides named, and this harmonizes with the chalcopyrite of the Igdlukúnguaq ore. The detailed relations between the chalcopyrite and the pyrrhotite are not sufficiently elucidated in the literature to permit of further parallels to be drawn with the Greenland deposit. The crystals of chalcopyrite mentioned by WANDTKE & HOFFMAN (54) as being in the pyrrhotite are interesting and more clarification might be valuable. Veins of chalcopyrite through pyrrhotite are often mentioned and I have been able to see these long, narrow veins in the samples, their position suggesting special relations with the surrounding pyrrhotite. Lamellae of a similar kind have been observed in large numbers in the Norwegian ore from Beiernfjord, to which I shall revert presently. This must undoubtedly be a kind of exsolution. It does not correspond to the rectilinear lamellae in Igdlukúnguaq, but presumably to the flame-like lamellae there.

The special placing of bravoite and zwischenprodukt formation in the Igdlukúnguaq ore is of interest in consideration of what BUDDINGTON (6) has to say about the transformation of the pentlandite and the observations of bravoite in the Sudbury ore communicated by other authors. It seems scarcely possible to doubt that these formations are of hypogene origin and as such have their equivalent in the special development of the Igdlukúnguaq ore around the eutectoid areas of siderite.

East Griqualand and Pondoland, Africa.

The following pages are compiled from SCHOLTZ's work on these deposits (SCHOLTZ, 35).

The sulphide occurrences are associated with gabbro intrusions of Permian age. They have a wide distribution and a rather varying composition. The entire intrusive is divisible into three petrographic units: the roof, central and basal zones. The ore content in the roof zone is much higher than in the main mass of which the central zone is formed. At the same time there is a distinct increase of the ore content towards the upper parts of the roof zone. In the upper acid part of the intrusion the sulphides are present in millimetre-size aggregates or grains. There is about 1 $^0/_0$ (by volume) of ore and the ratio of sulphide to oxide is about 1: 5. Pyrrhotite, secondary pentlandite, chalcopyrite and melnikovite-pyrite have been found in it.

In the central zone there is ore in smaller volume all through, but as a rule not in grains visible to the naked eye. Magnetite and ilmenite are always the dominating ores, the latter being particular prominent in certain horizons. Small quantities of pyrrhotite and chalcopyrite have been seen and pentlandite is presumed to be present in view of the analyses. SCHOLTZ says it looks as if the ore sustains its percentage throughout the zone. The oxides remain as the dominating part.

In the basal zone there is a very gradual increase of the sulphide content in the rock. In the olivine-hyperite there is a sudden, but irregular increase due to the presence of the sulphides in scattered lumps. The ore may impregnate the transformed sedimentary rock along the contact or transect the hornstone for some feet downwards; the rock on the other side is often irregularly patchy with rounded or pear-shaped lumps of sulphide.

SCHOLTZ differentiates between scattered ore, massive ore and chalcopyrite-cubanite ore. There seems to be a tendency for Cu to be rather concentrated in the scattered ore at the expense of Ni. In the third type of ore Cu is unusually concentrated, and the precious metals also seem to be present in strikingly large quantities.

The isolated nodules of ore in the olivine-hyperite are regarded as expressions of the ore coming directly from the magma, as there seems to have been no noteworthy migration there. The quantity of chalcopyrite, and possibly of the pentlandite, seems to have been reduced somewhat by the formation of the massive ore. Where cubanite begins to appear in the ore it looks as if the quantity of pyrrhotite is reduced and the quantity of chalcopyrite increased. This variety of the ore may perhaps be regarded as a transitional type to the so-called chalcopyrite-cubanite ore. This view harmonizes well with the interpretation of the latter ore as a later copper-rich differentiate — a kind of pegmatite of the massive ore corresponding to the pegmatites of a pluton. It is mentioned that the high content of precious metal in copper-rich sulphides in Norway and Sudbury caused VOGT to conclude that they represented consolidated residual magmas of ore squeezed out in the closing stages of the crystallization of large pyrrhotite-rich ore bodies.

The study of the silicates in connection with the ores in Insizwa make it presumable that the quartz-hypersthene-monzonite represents a transitional stage between olivine-rich hyperite and the acid dikes and sheets which transect the lower contact of the basal zone.

The quartz-hypersthene-monzonite phases seem to have been formed by a reaction between late magmatic residues and early, anhydrous, basic differentiates at a stage when the latter were in an advanced stage of crystallization. The transition from the mineralized olivine-rich hyperite to the more heavily mineralized quartz-hypersthene-monzonite, the constant later crystallization of the sulphides in relation to the silicates — in all the rocks — and the constant association of acid silicates with the more massive ore masses, and vice versa, are a strong indication that the residual "ore magma" contained appreciable quantities of mineralizers and late-magmatic residues which were in a state of instability and therefore reacted with the magmatic minerals formed earlier. The products of these reactions made an important contribution to the acid differentiates which are known to transect the basal zone in the region of its lower contact.

SCHOLTZ also considers that assimilation cannot have played any particular rôle, because the magmatic rocks have a marked cooling-contact against the sedimentary rocks.

On examining the mineralized olivine-hyperite the sulphides are seen to envelop the silicates, having crystallized later than the olivine, plagioclase and pyroxene, which they corroded and replaced, but never to such an extent as to lead one to suppose that there had been a hydrothermal formation of the sulphides. On the other hand, the spongy nature of the sulphides shows that they existed in a highly mobile state in a mush of silicate crystals at relatively high temperatures. Biotite is found in association with the sulphides and often in such a manner that it might probably be regarded as a reaction product, formed at a time when the sulphides were not yet crystallized.

Polished samples of mineralized rock show that some minerals such as olivine have a distinct rim of serpentine when imbedded in the sulphides. The rock as such may be perfectly fresh and sound. This indicates that the sulphides are the cause of these alterations. SCHOLTZ considers there is no other explanation of these phenomena than that the sulphides were associated with hydrous late-magmatic components; they were liberated by the crystallization of the sulphides and thereby had an opportunity of exerting their transforming effect on those of the silicates that were susceptible.

On this background the presence of the quartz-hypersthene-monozite in association with the ore is significant, as it appears to represent a transitional stage between the olivine hyperite and the more acid silicates associated with the ore veins.

It is SCHOLTZ's opinion that where concentrations of ore occurred in the magma, not insignificant quantities of late magmatic differentiates may also be expected. Owing to reactions with the earlier magmatic products, minerals were formed belonging to late stages in the reaction series. This would account for the constant association of acid silicates with sheets and veins of pyrrhotite-rich ore.

The presence of water, as indicated by various minerals, the characteristic texture, the chilling contacts, the deduction regarding the temperature of the magma as well as the trend of the differentiation, make it difficult to acknowledge any other origin than igneous for the acid rocks of the basal zone. Their relation to the massive sulphides is indicated by the analogous mode of occurrence and the transition from ore including acid silicates to silicates including sulphides. It has already been shown that such relations in differentiated intrusives are generally regarded as providing evidence of genetic relationship and magmatic origin.

Summarizing, SCHOLTZ says that all available evidence seems to show that the ore behaved in a manner essentially analogous to a residual granitic magma. It existed in liquid state after the greater part of the silicates had crystallized. The ore magma must be regarded as the ultimate source and carrier of the agents which caused the hydrothermal alterations observed in the basal zone, not vice versa, as in the case of deposits of hydrothermal origin.

Ore-microscopic description.

Magnetite and ilmenite are present in all zones. SCHOLTZ remarks that in the massive sulphides of Insizwa these oxides seem less abundant, richer in titanium and more irregular in habit than some of the Sudbury nickel ores which he examined. Idiomorphic magnetite is most frequent in the olivine-hyperite, and titaniferous varieties are especially associated with the more acid rocks appearing late in the reaction series. He points out that rounded or irregular forms are prevalent in "the intrusion", which means the mineralized parts. This anhedral character cannot be wholly due to corrosion by sulphides, since the oxides in the surrounding silicates are also extremely irregular. He adds that all the magnetite may belong to one generation, as all gradations exist from idiomorphic to quite irregular grains.

In the pegmatitic and pyrrhotite-rich varieties of sulphidic ore the magnetite exhibits three different habits:

1) Euhedral or rounded equidimensional grains.
2) Irregular rosette-like concentrations.
3) Tabular crystals imbedded parallel to the basal parting of the pyrrhotite.

Sperrylite is present in handsome idiomorphic crystals in the ore and quite evidently was crystallized earlier than the sulphides.

The pyrrhotite varies in individual sizes from less than a millimetre to several centimetres. The mineral exhibits a well-developed (0001) parting. The grains always have irregular boundaries. Division of the pyrrhotite into a darker and a paler component, α and β, intersecting each other along (0001), is handsomely developed in the ore and Scholtz discusses the phenomenon in detail. He remarks that the β-phase seems to be gathered especially around or in the margins of the pyrrhotite grains, about certain inclusions and along fractures which may be infilled by material of apparently secondary nature. Twin lamellae due to mechanical deformation were observed.

Primary massive pentlandite exhibits idomorphic boundaries to pyrrhotite and the other sulphides, but it occurs much more frequently as rounded or angular masses. In the pyrrhotite-rich ores pentlandite occurs in the form of discontinuous envelopes about the pyrrhotite or as vein-like masses between the pyrrhotite areas. The more massive vein-like aggregates of chalcopyrite in the pyrrhotite-bearing sulphides are usually lined by more or less continuous rims of pentlandite.

Secondary pentlandite appears as the familiar exsolution bodies in the pyrrhotite, pentlandite flames. They may have "grown fast on" the primary pentlandite where it borders upon pyrrhotite. In chalcopyrite too, pentlandite may appear in the form of flame-like bodies. In pyrrhotite-free ore they may be present in the form of arborescent collars of remarkably constant width about grains of primary pentlandite.

Scholtz's conclusions as to the probable paragenetic sequence of the pyrrhotite and the pentlandite are summarized as follows:

1) The fact that pentlandite is present in the genetically related pyrrhotite-bearing and pyrrhotite-free varieties of ore shows that the former was still separating after the crystallization of the pyrrhotite. That the copper-enriched residues remaining after the separation of all the pyrrhotite still contained much nickel is indicated by the abundance of pentlandite in the sheets of chalcopyrite-cubanite ore.

2) The marginal and intergranular distribution of the largest aggregates of pentlandite with reference to the pyrrhotite, as well as the characteristic pentlandite fringes about intrusive veins of chalcopyrite, suggests that much of the pentlandite in the ore under consideration crystallized after the pyrrhotite and before the chalcopyrite.

3) That the narrow vein-like masses of pentlandite inclined or parallel to the (0001) parting in crystals of pyrrhotite cannot be regarded as providing adequate evidence of the invasion of the latter by the former, since much, if not all, of its substance may be of secondary origin.

4) Secondary pentlandite contributed to the substance of the massive primary pentlandite by merging insensibly with the latter. Marginal inclusions of pyrrhotite are, therefore, regarded as remnants and not as advance islands which replace the pentlandite. Secondary pentlandite may assume definite crystalline boundaries in pyrrhotite.

5) The fact that veinlets of pyrrhotite appear to penetrate the margins of aggregates of primary pentlandite along directions approximately parallel to the trace of the octahedral cleavage cannot be considered as a criterion of the later crystallization of the former, since the more massive clusters of pentlandite often grade marginally into secondary pentlandite which has been shown to be definitely orientated in the pyrrhotite.

SCHOLTZ believes that a condition of limited miscibility set in at the freezing point of pyrrhotite which induced the separation of the major portion of the nickel in the form of pentlandite more or less contemporaneously with the crystallization of the pyrrhotite which held a certain amount of the pentlandite molecule in solid solution. Shortly after consolidation, a nickel-bearing phase segregated from the pyrrhotite and concentrated principally about grain boundaries, inclusions and cracks of early origin. Probable overlapping in part with this exsolution phenomenon was a further change marked by the separation of secondary pentlandite, which contributed not inconsiderable amounts of (Ni, Fe)S to certain parts of the larger pre-existing vein-like masses of primary pentlandite, as well as the entire, or at least major portion of the substance of the minor veins, lenticular bodies and flame-like growths in the pyrrhotite away from the primary pentlandite. A consideration of the distribution of the pyrrhotite and pentlandite in the different varieties of ore leads one to the conclusion that, although both minerals appear to have separated more or less simultaneously, the latter continued to crystallize after the former had been completely precipitated. Apart from the nickel sulphide present in the primary pentlandite and that held in solid solution during the early stages by the pyrrhotite, minor quantities of it — no doubt augmented by the resorption of primary pentlandite — were retained by the residual ore liquid, from which it separated, at different stages later in the paragenetic succession, in the form of unstable solid solutions with chalcopyrite and irregular cubanite, and nickel-bearing minerals stable at lower temperatures.

Chalcopyrite occurs everywhere in the ores, in varying quantities. It is always in the form of veins, which may be large or small. The habit of this mineral clearly shows that it must be later than both pyrrhotite and pentlandite. Veinlets can be seen traversing the pyrrhotite in any direction, but not from one pyrrhotite grain to another. Some veins appear to thin out, whereas others reappear following the same direction in the pyrrhotite. Veins following the cleavage of pyrrhotite often break away from that direction and follow the direction of parting for a short distance before reassuming their former course. In basal sections of pyrrhotite, chalcopyrite may be seen following the $(11\bar{2}0)$ cleavages. The best examples of invasion and replacement are encountered within and about the borders of segregations, and the larger veins of chalcopyrite. Isolated and dissected residual masses of pyrrhotite in optical continuity occur well within the substance of the chalcopyrite. Pyrrhotite crystals along the margins of such veins may possess scalloped borders, whilst protruding grains may be partially replaced by chalcopyrite, which cuts abruptly across both components of the pyrrhotite.

In some instances the chalcopyrite may penetrate the pentlandite as irregular veins; in others, the mineral is present in the form of irregular triangular or rectangular networks; the character of the pattern is determined by the cleavage and orientation of the pentlandite.

Cubanite or valleriite may replace the chalcopyrite in the pentlandite. Both minerals occur in an exceptionally fine development in the type of ore within the range of what SCHOLTZ calls chalcopyrite-cubanite ore. This whole type of ore is most interesting and exhibits a differentiation within the concept of nickeliferous pyrrhotite ore which must be of importance to our understanding of the type. No similar manifestations have been found in conjunction with the Igdlukúnguaq ore, whose evolution doubtless would not permit of this series. Therefore, apart from the fact that the Greenlandic ore also shows that the chalcopyrite is reactive in late stages of its formation, and that the late consolidation of the chalcopyrite makes differentiation from the rest of the ore magma possible, there is no basis for a comparison of the two deposits on this point. I have therefore thought it unnecessary here to go into details on this otherwise interesting subject of the chalcopyrite-cubanite ore.

One point may be of interest, however. SCHOLTZ refers to the venation of the pentlandite by valleriite as a replacement of the former. It is remarkable, as SCHOLTZ says, that the most widespread development of valleriite in pentlandite in pyrrhotite-rich varieties of the ore has been found only in the scattered sulphide grains in the olivine-hyperite at Ingeli. Small flakes of valleriite are diffused throughout the pentlandite mass, both primary and secondary. Here and there are acicular grains of valleriite which seem to follow the octahedral cleavage of the pentlandite. Intersecting systems of lamellae may form trigonal, square or rhomboidal patterns. Under crossed nicols only parts of such lamellae aggregates extinguish simultaneously. A single crystal of pentlandite may exhibit groups of differently extinguishing aggregates of valleriite lamellae. Each simultaneously extinguishing valleriite aggregate is evidently characterized by consisting of valleriite of one particular orientation; this seems to imply that there is no definite leptological relation between guest and host. Networks of valleriite in the pentlandite are often seen to continue out into concentrations of the mineral along the margin of the pentlandite. There seems to be a close association between the chalcopyrite and the valleriite and also the valleriite within the network in the pentlandite. Both chalcopyrite and valleriite may be seen to traverse the pentlandite, and the valleriite can be seen to follow the chalcopyrite. SCHOLTZ concludes from this that the valleriite owes its existence first and foremost to the chalcopyrite, which primarily invaded the pentlandite. This refers to pentlandite from chalcopyrite-rich ore. He remarks that he has never observed chalcopyrite veins partly replaced by valleriite in pentlandite in the pyrrhotite-rich varieties of the ore; so that the possibility that valleriite may have replaced the pentlandite should not be ignored. He states that the microscopic study of Insizwa and other ores clearly indicates that there is nothing to suggest that valleriite should be regarded as an exsolution product of pentlandite.

Some chalcopyrite-rich ores are unique in that they are accompanied by a number of rare minerals and that they tarnish very soon after polishing. This refers particularly to ores from the marginal zone or extremes of chalcopyrite-cubanite ore sheets.

The bravoite belongs to a much later epoch of mineralization, and, SCHOLTZ says, there can scarcely be any doubt that this mineral is of supergene origin. The transformation of the pentlandite can be seen to proceed along cracks and cleavages in the mineral. It would seem that the transformation proceeded inwards from the margins, since bravoite-lined cracks and cleavages often terminate, leaving an unaltered core of fresh pentlandite. All stages of transformation can be seen, right on to completely altered pentlandite grains. Pentlandite crystals partly transformed into bravoite are sometimes studded with minute rounded grains of pyrite. The last stages of hypergene alteration appear to be the replacement of pentlandite (and bravoite) by limonite and the removal of the more soluble nickel salts in solution.

Pyrite in the massive ores is seen to replace pyrrhotite along its partings and cracks; where veins of pyrite intersect they become somewhat thicker. The traces of the parting and the cracks in the pyrrhotite are also recognizable in the pyrite pseudomorphs; thus in this mineral one can see the orientation of the original pyrrhotite. Occasionally in the pyrite bravoite pseudomorphs are to be seen after flames of pentlandite. Another interesting occurrence of pyrite within pyrrhotite is in the form of small more or less equidimensional anhedral grains, or crystals of square or rectangular cross sections, in which the traces of the crystal edges trend parallel to the dominant crystallographic structure of the pyrrhotite. The secondary character of the mineral is clear from its localization in the pyrrhotite, where it is concentrated particularly around partings and cracks. Scholtz draws attention to the instructive point that the presence of idiomorphic crystals is not always a reliable foundation on which to base conclusions regarding the paragenetic sequence. (Compare the reference to the Finnish ore from Nivala, page 122).

In addition to the main components mentioned above, these ores contain other minerals of considerable interest, but they need scarcely be discussed here in conjunction with the question of the general process of development of a nickeliferous pyrrhotite.

Discussion of the microscopic features.

It will be seen that the main outlines of the Igdlukúnguaq, Sudbury and the African ores are the same. The magnetite is early, the crystallization of the pyrrhotite is followed by the consolidation of the chalcopyrite, and pentlandite is exsolved. No further direct parallization with Igdlukúnguaq is possible. However, Scholtz's work is outstanding by reason of its extraordinarily exact description of a wealth of details regarding the mutual relations of the various minerals, and I consider it possible to compare many of these details with those observed in the Greenlandic ore; I shall therefore endeavour in the following to correlate the observations in the two deposits and draw what conclusions may be possible from them.

Morphologically, the magnetite grains in the African ore seem to approximate those of the magnetite in the Greenland deposit more closely than those from Sudbury. It may perhaps be possible to procure a transition from Igdlukúnguaq through the ore from the Norwegian deposit Beiernfjord, which will be described later (page 131). Whether or not there may be a possibility of demonstrating positional relations in the ore, corresponding to what seems to appear from the Sudbury samples examined, cannot be decided from SCHOLTZ's work in spite of its otherwise excellent illustrations. SCHOLTZ points out that the optics of the mineral exhibit considerable variation, and he states that there is a variation from pure magnetite to ilmenite, indicating a titanium content in the iron oxides of the sulphides which cannot be elucidated from the Greenland deposit. No doubt this is a problem worth investigating on the back-ground for instance of such a highly detailed occurrence as the African deposits evidently are.

The pyrrhotite in the African samples is very clear evidence that mechanical deformation played an important rôle during and perhaps subsequent to the formation of the ore, a factor which no doubt would be of greater significance to the local formation of the ore than to the general type as such. On the pyrrhotite as a whole, it would seemingly suffice to say that its true significance to the ore lies in its relations to the other minerals occurring in it. This of course applies to all minerals in a paragenesis, but of the pyrrhotite in this paragenesis it is also true that it is so to say the bearer of all other minerals.

It is very evident from SCHOLTZ's description — and indeed from the descriptions of other deposits — that owing to the special position of the pyrrhotite the nickeliferous pyrrhotite ore possesses the possibility of a specific differentiation, the result being a special variety of ore rich in chalcopyrite. The details of how that differentiation takes place should be examined on a broad basis, and it would be particularly interesting to have it clarified what elements are concentrated in the differentiates by that means. Suggestions of these matters have already appeared in several works, and in the work by VOGT quoted by SCHOLTZ it is pointed out that in particular the precious metals are present in the copper-rich parts of the ore. A study of these questions may possibly help to throw more light upon the formational mechanism of sulphide deposits of true hydrothermal nature, as processes of a hydrothermal kind seem to be highly prominent also in the late stages of the magmatic ore, as the nickeliferous pyrrhotite must be called.

SCHOLTZ distinguishes between primary and secondary pentlandite. The latter is quite evidently the form existing in the familiar pentlandite flames in the pyrrhotite. It is important that SCHOLTZ also records this form of pentlandite in the chalcopyrite, but how he regards the primary pentlandite is less clear. Here it seems to be a question partly of pentlandite in the form of intergranular strings or veins between pyrrhotite grains, and partly of pentlandite present in accumulations or larger grains which, according to SCHOLTZ, may exhibit idiomorphic margins to the pyrrhotite. One will scarcely agree with SCHOLTZ in his views regarding the intergranular pentlandite. Several authors consider it to be an indication of an early (first) exsolution of pentlandite from the pyrrhotite (see e. g. VAN DER VEEN (49), HAWLEY, COLGROVE & ZURBRIGG (15) and others); and the observations made in the Greenlandic ore seem clearly to show that there was an exsolution of nickel from the pyrrhotite in the very first stages after the consolidation of that mineral. This exsolution, however, was not of purely pentlandite material such as one might assume from the descriptions of the observations e.g. in Sudbury. It was accompanied by a certain quantity of copper, the result being the formation of what I have called chalcopentlandite. On the background of this observation in the Greenlandic ore it is, I think, justifiable to attach very great weight to SCHOLTZ's reference to chalcopyrite lamellae or copper-sulphide lamellae in the pentlandite. He regards these as an indication of the replacement of the pentlandite and categorically rejects the theory that the copper sulphide valleriite was exsolved from the pentlandite. With the introduction of the concept chalcopentlandite, however, it should be possible to adopt quite other opinions concerning both the relations to the pyrrhotite and the relations between pentlandite and copper sulphides. Actually, on this background the African ores become one of the most important links between the Igdlukúnguaq ore and the Sudbury ore, to use that classic deposit as an expression of the usually visualized picture of nickeliferous pyrrhotite ores. There is also close agreement with the Greenland deposit in the circumstance pointed out by SCHOLTZ that the chalcopyrite veins often have a zone of pentlandite along the pyrrhotite contact.

In the Greenlandic ore there are also exsolution bodies of chalcopentlandite within the pyrrhotite areas around the magnetite grains. No corresponding phenomena is recorded in SCHOLTZ's description. The explanation may possibly lie in the difference between the developments of the two ores as shown by the magnetite. Evidently the African ores had no "outer surfaces" "within" the pyrrhotite to which the exsolution could go.

The large massive areas of pentlandite to which SCHOLTZ refers in connection with the primary pentlandite have their counterparts e.g. in the Sudbury ore and other nickeliferous pyrrhotites, but apparently not in the Greenlandic ore. SCHOLTZ's assumption of a true primary pentlandite cannot be rejected; according to the experiments of HAWLEY, COLGROVE and ZURBRIGG (15) it is possible for pentlandite to separate in a melt, but on the other hand there is every possibility that all nickel will turn into pentlandite through solution in and exsolution from pyrrhotite (see HAWLEY & HEWITT, 16). However, such an assumption does not directly explain the large massive areas of pentlandite. In the Greenlandic ore around the eutectoid-like siderite areas there is a sulphide mass that is particularly rich in nickel sulphide, in this case in the form of the heavily bravoitized pentlandite. With this observation in mind it might perhaps be thought that the massive pentlandite in the African ores and elsewhere actually was not a primary pentlandite but a pentlandite formed by recrystallization of the nickel sulphides in parts of the ore that were attacked and altered by the late-magmatic, hydrothermal processes whose origin was the primary gaseous components inclused in the ore. In Igdlukúnguaq too it is possible to find such areas, presenting rectilinear margins to the surrounding sulphides, even if the crystals so formed are of but small dimensions. The discussion and description of the nickeliferous pyrrhotite from Nivala in a following chapter (page 122) will show that there really are grounds for such an opinion.

The chalcopyrite in the ores described by SCHOLTZ has already been touched upon, but there are also interesting details concerning that mineral's relations to the pyrrhotite. Having regard to the finding of what quite clearly are chalcopyrite exsolution lamellae in the pyrrhotite in Igdlukúnguaq, it seems most natural to regard the veins of chalcopyrite described by SCHOLTZ in the pyrrhotite as expressing an exsolution, and not as the result of a replacement as SCHOLTZ suggests. The direction of these lamellae is stated to be $(11\bar{2}0)$. It is difficult to say whether there is actually a question of prisms, or whether a pyramid would not explain the structure better; but there can hardly be any doubt that this is not an exsolution corresponding to the rectilinear lamellae in the Igdlukúnguaq ore. On the other hand, there seems to be a possibility that it answers to the later exsolution which in the Greenlandic ore was the cause of the flame-like chalcopyrite lamellae. At any rate the drawings (fig. 11) in SCHOLTZ (35) seem capable of that interpretation. This form of exsolution is not very prevalent in Igdlukúnguaq, but in the description of the Norwegian ore from Beiernfjord (page 131) it will be seen how very beautifully developed it can be, wherefore there is a valid reason for regarding it as an essential element in the formation of nickeliferous pyrrhotite ore.

In advancing these opinions there is no thought of exempting the chalcopyrite wholly from having corroded the other sulphides. In the Greenlandic ore it is quite evident that there was a certain amount of corrosion, i. a. of the pyrrhotite, by the copper-sulphidic pore mass, and it is beyond question that the picture of the African ore reveals intensive corrosion, i. a. by the chalcopyrite. But it may perhaps be remarked how improbable it seems that corrosion of the pentlandite by the chalcopyrite, even if it follows the pentlandite cleavage, should be the cause of the widespread reticulation structures in the mineral. It seems much more reasonable to say that if instead there was a possibility of ex-solutions, there was a greater likelihood of such processes in these particular cases.

The fact that the valleriite occurs in the lamella system of the pentlandite must doubtless be taken as an indication of the temperature interval that characterized the African ores. This of course is not saying that I assume that mineral to have been exsolved direct from the pentlandite. It is understandable that the valleriite seems to have been formed as a product advancing into the pentlandite from outside, but it is also imaginable that the supplement of FeS that distinguishes valleriite in relation to chalcopyrite, came from the pentlandite itself; this, however, is perhaps less likely, as SCHOLTZ's description seems to indicate that chalcopyrite is to be found farther into the pentlandite, and this had no supplement of FeS.

The bravoite in the Greenlandic ore is undoubtedly of hypogene origin, and presumably the Sudbury bravoite too. In the African ores SCHOLTZ apparently has no doubt of the mineral's supergene origin and his description of the ores provides no possibility of deciding upon that opinion.

The pyrite in the ore is also supergene in origin, in SCHOLTZ's opinion, which may perhaps be difficult to challenge. But it should be remarked that the position of pyrite in the pyrrhotite is of interest compared with the formation of zwischenprodukt as observed in Igdlukúnguaq. That formation proceeds along the (0001) planes of the pyrrhotite and there is a possibility that slightly different conditions might have given rise to the formation of FeS_2, which then would have been very similar to the pyrite in the African ores. In this connection I would refer to the following description of the nickeliferous pyrrhotite from Nivala (page 122), in which the pyrite in fact is present in a form that seems to recall SCHOLTZ's description and would seem capable of being interpreted as another type of what appears as zwischenprodukt in the Igdlukúnguaq ore. SCHOLTZ's remark that the idiomorphic nature of the pyrite need not have a bearing on its placing at the beginning of the paragenetic sequence, is worth noting.

As to the magnetite, if we cannot find parallels between the two ore deposits, in Africa and in Greenland, there is so much the more reason for attaching importance to SCHOLTZ's discussion of the magmatic gases and the part played by the late residual masses in the development of the ore and its immediate environment. Here SCHOLTZ's work throws light upon the peculiar petrographic conditions connected with nickeliferous pyrrhotite ores, and I am of the opinion that in the same manner

Igdlukúnguaq widens our understanding of the action of the same substances on the ore itself, as mentioned in the discussion on the Greenlandic ore. It would have been interesting if SCHOLTZ had been able to go into these questions in relation to the African ores. His description does not indicate any direct basis for such a discussion; on the other hand I am inclined to believe that the very assumption of the presence of gases within the sulphide melt could not but lead to speculation as to the reactions of the sulphides to these gases. Inter alia, SCHOLTZ presents the opinion that the presence of these gases in the sulphide globules must have influenced their specific gravity and thereby their behaviour in relation to the gravitative differentiation. Once such speculation had started, it would probably have led to a further investigation of the relations of the iron oxides within both the ore and the marginal silicates; for it is quite likely that there were variations within the oxides, which are in fact governed by these relations. SCHOLTZ draws attention to a variation of ilmenite and magnetite in the silicates, but their dependence on the gases in the magma is not directly perceptible in his observations. In other words, all this involves a problem which will certainly be worth while solving where the nickeliferous pyrrhotite ore, as in the African deposits, exhibits a sufficiently differentiated picture.

Nivala, Finland.

Ore-microscopic description.

The following description is based upon polished sections from a hand specimen kindly supplied to me by Professor M. SAKSELA while in Helsingfors in 1954. The specimen is from Sample No. 5466, University of Helsingfors.

Pyrrhotite is the chief mineral in the ore sample, which is characterized by the fact that the sulphides form a kind of network inclusing small rounded areas of silicates etc. These areas measure a few millimetres in diameter.

The outstanding feature of the sample is its clear signs of dynamic metamorphism. The basal parting of the pyrrhotite is very prominent and the cracks are infilled i. a. with limonitic material. This makes them very distinct and it is easy to see that the ore has been subjected to pressure. The results of this dynamic influence are most clearly evident when the ore is viewed between crossed nicols, where the pyrrhotite exhibits a particularly fine fan-shaped extinction. On closer examination these large areas of pyrrhotite are seen to consist of very small polygonal grains whose orientation varies but little. It is this variation that causes the fan-shaped extinction. Cuneiform lamellae are also seen here and there in the pyrrhotite, where it has been under such heavy stress that the orientation is greatly altered. The phenomenon may possibly be connected with the formation of twin lamellae. If these pyrrhotite areas with their undulating extinction are examined as separate units it can be seen that the total orientation from area to area is arbitrarily variable.

Optically the pyrrhotite is quite handsome and pure. The α and β lamellation is not particularly prominent. It seems to be present but is much harder to discern than is usual in this type of ore.

The pyrrhotite is the chief component in the ore, not solely on account of its quantity but also in virtue of its relations to the other minerals present. They are all placed regularly in relation to the pyrrhotite, either along the mineral's crystallographic directions or placed intergranularly in the pyrrhotite in such a manner that it has determined the external shape of these particular minerals. The ore also exhibits large pentlandite (or bravoite) areas, in diameter approaching those of the pyrrhotite, but these too occupy an "assigned" position. There is a separate group of minerals in association with the silicates inclused in the ore.

Pentlandite, or, to be more correct, bravoitized pentlandite, is the next dominating mineral in the ore. Fresh pentlandite is visible as the familiar flame-like lamellae in the pyrrhotite along its basal direction, but they are rare. The most frequent form of pentlandite, and perhaps the one most characteristic of the ore, is that found intergranularly between the large areas of pyrrhotite. The width of the area it occupies here may be up to one-tenth of the diameter of the pyrrhotite area. As a rule it is a large patch of—bravoitized—pentlandite, prolonged as it were along the margins of the pyrrhotite areas between which it lies. Often there are two or three "arms" in the pentlandite area, but there may be more. The pentlandite may be lying for instance between three areas. The strand or vein from such a pentlandite area may exhibit extensions here and there, and sometimes it is seen to be constricted, making rather a chain of pentlandite grains in the intergranular space. Together with this bravoitized pentlandite there is always more or less chalcopyrite. Magnetite too is often frequent in this association.

In almost every case the large areas of bravoitized pentlandite are found in the margin of the sulphide mass out towards the inclused silicates. It is also characteristic that these areas are always veined with magnetite, and also with limonite and silicate-like material. Finally, siderite, or at any rate carbonate, is present as a vein material (Pl. XIX, 1).

Here the bravoitization is very evident, but remnants of the unaltered pentlandite still remain, though they occupy very small areas between the bravoite emanating from the cracks.

It is a very interesting feature of the structure of these areas that chalcopyrite is present here, as also in association with the aforesaid pentlandite; but the chalcopyrite in this case occurs in long, rectilinear lamellae. These lamellae are not parallel with the cleavages of the original pentlandite and exhibit no relation to the crystallographic directions in the pentlandite as a whole. This is otherwise the usual for several of the other minerals imbedded in the mass; for example both the magnetite and the limonite are present as crack infillings along the (111) direction of the bravoitized pentlandite. Chalcopyrite is also present here as small, irregular areas, but this is rather the exception. The chalcopyrite lamellae are so much the more remarkable as it appears that where several are present within the same area, it can be seen that there is parallelity between them and also that there are several systems of lamellae. Three groups of lamellae were seen once or twice, and two were fairly frequent.

Chalcopyrite was occasionally found in the pyrrhotite in the form of long flame-like lamellae. A lamella may reach half way through the pyrrhotite grain, and the width is about a tenth of the length. If they do have any relation to the crystallographic directions of the pyrrhotite, the fact could not be determined. In the silicates there are small areas of pure chalcopyrite.

At one or two places where the chalcopyrite was found together with intergranular pentlandite I observed a very fine-grained intergrowth between pentlandite (and bravoitized pentlandite) and chalcopyrite. To a very small extent the latter mineral seemed to have been replaced by chalcopyrrhotine. There was some variation in the phases, but the presence of different minerals could not definitely be established, as the fine grain of the structure made it necessary to work with the highest magnification. It is certain, however, that both chalcopyrite and pentlandite were present.

A highly anisotropic mineral was observed in a few small grains in association with the chalcopyrite in the bravoitized pentlandite areas. With a dry objective its colour is a faint bluish-green, something like the colour assumed by chalcopyrite in high magnification in oil immersion under crossed nicols. Its hardness seems to be more or less the same as that of chalcopyrite, perhaps between that and the hardness of pyrrhotite. The pleochroism varies from greenish in the one position to yellowy-brown in the other. The anisotropy colours under crossed nicols is greyish bluish-green to a very striking purple, observed through a dry objective, whereas with oil immersion the colours change somewhat; the last-named colour, purple, in particular undergoes a marked change and now appears as a pretty, delicate rose. The mineral cannot be cubanite, because optically the difference from chalcopyrite and pyrrhotite is much too great. Valleriite is also out of the question.

Cubanite was observed in one small area of chalcopyrite.

Magnetite is present mostly in the cracks and fissures through the bravoitized pentlandite areas, but the mineral also occurs in the form of veins through the large areas of pyrite to be mentioned later. It is difficult to say whether magnetite or spinel is present in small isolated, more or less idiomorphic to rounded grains lying right inside the pyrrhotite. Grains of similar appearance, observed in the inclused areas of silicate, often have internal reflections of yellowish-brown, and I suppose that spinel is present there at least. This spinel may sometimes exhibit a handsome bizonal structure, the outer zone showing rectilinear boundaries against the interior.

Wherever the magnetite was observed it was quite distinctly but faintly anisotropic. The mineral is thereby seen to be built up of small irregular patches.

As already stated, the pyrrhotite is considerably fissured basally and the cracks are generally infilled with limonitic material. Pyrite is also found in this environment, but matters are complicated: apparently there are two types of the mineral and one of them in fact is a multiphase product. One type of pyrite can be seen as fairly large areas (perhaps a quarter of the size of the pyrrhotite areas) lying within the pyrrhotite, and the other is found in the form of small areas, and rather frequently, in conjunction with the cracks along (0001).

The large areas cannot be other than pyrite, for both optical characters and hardness correspond to that mineral. It is clearly associated with the pyrrhotite, because it lies completely surrounded by the latter—inside the large areas of pyrrhotite with fan-shaped extinction. In shape these pyrite areas follow the crystallographic directions of the pyrrhotite. The border across the basal direction of the pyrrhotite is serrated, and when the teeth are produced into the pyrrhotite there is parallelity with (0001). It is beside the point that the individual teeth have a handsome idiomorphic margin. In also appears that the pyrite has a "cleavage" parallel to that of the pyrrhotite, or actually that the parting directions of the latter continue into the pyrite—not continuously but in rows of tapered fissures. Otherwise they are of the same appearance as the basal cracks in the pyrrhotite. There are few inclusions in this pyrite and as a whole they consist of pyrrhotite in small areas. There is limonite in the cracks. The total shape of these areas is often triangular or square, so that on the whole it is possible to say that there is one large crystal (Pl. XVIII, 1, 2).

The other type of pyrite consists of small, often idiomorphic, inclusions of the same size as the pentlandite flames, for instance, about one-hundredth of the diameter of the pyrite areas. The small grains are often lying several in a row and clearly are confined to what space is offered by the pyrrhotite cracks and what can be occupied at a breadth extending a little way into the pyrrhotite. The grains are often rectangular with their longitudinal direction parallel with (0001) in the pyrrhotite.

The reason why this cannot be said directly to be pyrite lies in the fact that for instance the rectangular grains exhibit a zonal division into a pale pyrite-yellow outer zone and an inner zone whose colour is midway between pyrite and pyrrhotite. The border between the two zones is rectilinear and the outer zone is rather narrow. The zonal border is often parallel with the outer margin of the grain. Lamellae transecting the inner parts of the grain, and consisting of the same material as the outer zone, are often observed. Both phases are judged to be isotropic.

In addition there is what might be called a white phase, which is vividly anisotropic. It may be seen as part of the outer zone, and also in the form of inclusions in the grain. However, this phase may also occur independently, in which case it lies like an edging along limonite-infilled cracks in the immediate vicinity of the small "pyrite" grains. The shape of these separate white grains is oblong, tapering at both ends, so that there is no question of idiomorphy. But if they are a part of the margin of the "pyrite grains" they share in its form. The white mineral has the same hardness as the pyrite.

Perhaps these are compounds with Co and possibly also with As or the like; it is difficult to decide owing to the smallness of the grains. Nevertheless, there are so many of them that the particular elements contained in them would presumably be recognizable in a chemical analysis of the ore if due consideration were given to the determination of the accessory components.

A few strictly idiomorphic grains, triangles or rhombs, were seen consisting of a white, hard material that is isotropic. Presumably this is sperrylite.

The mineral graphite belongs to the picture of the ore. It occurs mainly outside of the sulphides in the silicate masses, where it lies in the form of rounded, often oval nodules or nests. One or two of these nests were also found in the sulphide mass in the pyrrhotite. The very presence of free C in association with this ore seems to be of some interest, and of much importance when it occurs as nests inclused in the pyrrhotite. The mass preponderantly consists of graphite scales of varying orientation, chiefly radiating from the central part of the inclusion. Small areas of pyrrhotite can be found in the graphite, which seems to indicate that the latter displaced the former or was formed at the expense of a mineral which here replaced the pyrrhotite. The graphite nest contains but little other material; it seems to be silicate-like but evades a better description on account of its small quantity and extent.

The ore was polished on an automatic machine with lead discs, which gives the minimum of relief. As a result the boundary between the pyrrhotite and the silicates surrounded by the sulphides is clearly delineated. When this boundary was examined under high power (700—1200 ×) there was observed a curious, possibly unknown mineral forming a kind of border or an edging of fringes on the pyrrhotite (Pl. XVIII, 3). The individuals are rectilinear, with a length of some μ and a width of about a fifth of that. They lie strictly parallel to the basal direction of the pyrrhotite. If the latter is at right angles to the margine against the silicates the "leaves" of this unknown mineral extend straight out in the silicates. If the basal direction of the pyrrhotite is oblique to the silicate margin, all the "leaves" are "combed" as it were in that direction. It would be tempting to regard this is a "frayed" pyrrhotite, but it can be seen at once that the colour differs from that of pyrrhotite and the pleochroism is much greater. The mineral also lacks the rosy tint of pyrrhotite, being more yellowy-grey, to brownish in the darker position. Under crossed nicols it is vividly anisotropic, comparably with covellite for instance. It cannot be valleriite or cubanite; nor can graphite come into consideration; the optics of these minerals do not correspond to those observed in this unknown substance. On the other hand it is imaginable that it belongs to the same group. The graphite-like mineral observed in the siderite of the Igdlukúnguaq ore is somewhat reminiscent of it, but there the mineral exhibited some variation, whereas in the Finnish ore the mineral is constant in its optical features. Unfortunately the small size is inimical to a closer examination.

Carbonate was seen here and there in the ore, especially as veins through the areas of bravoitized pentlandite but also in association with the large pyrite areas. It seems to be siderite.

Development of the ore, discussion of the ore-microscopic features.

First the pyrrhotite crystallized and formed the large areas which now are shattered by the mechanical deformation.

On crystallizing the pyrrhotite incorporated all Ni and most of the Cu in its first lattice. This is presumed because all pentlandite lies intergranularly or as exsolution bodies. The large pentlandite areas lie so close up to the intergranular that it must be reasonable to assume that there was merely an accumulation of pentlandite because the region received supplements of pentlandite from several areas of pyrrhotite at once. As regards Cu, I have seen no large areas of chalcopyrite whose origin could be attributed to the presence of a copper-rich residual melt, even if the possibility of the existence of such a melt cannot be disregarded; it is reasonable to suppose that such areas of chalcopyrite would be found on examining more samples. Our ore type probably contained very little copper. The first exsolution to take place, furnishing the origin of intergranular pentlandite, must also have caused the extrusion of chalcopyrite because there are always small quantities of chalcopyrite together with this pentlandite. The assumption therefore is that there was an exsolution of chalcopentlandite. It may be of this that traces are found in the ore in the form of the aforesaid fine-grained intergrowth of copper and nickel sulphides.

The few lamellae of chalcopyrite observed in the pyrrhotite may be evidence of an exsolution of chalcopyrite in that mineral. The absence of sufficient data makes it impracticable to characterize that exsolution in greater detail.

In a later stage the pentlandite was again separated from the pyrrhotite in the form of the familiar pentlandite flames.

The chalcopyrite lamellae in the large areas of bravoitized pentlandite might seem to indicate relations between cupriferous and nickeliferous sulphides; but as these lamellae seemed to exhibit no relation whatever to the crystallographic directions of the pentlandite, that is scarcely credible. A closer examination of the position of these areas makes it presumable that after the formation of the pentlandite they spread some distance over the pyrrhotite: there are signs of their having corroded that mineral. It is therefore conceivable that during subsequent processes in the ore there was a replacement of pyrrhotite by bravoite-pentlandite, in accordance with the conditions observed in Igdlukúnguaq in the nickel-rich sulphides around the areas of eutectoid siderite. If this assumption is correct, the chalcopyrite lamellae may represent lamellae that were originally situated in pyrrhotite and now preserved in the Ni sulphide. A similar phenomenon was also observed in the Greenlandic ore.

As already stated, there is a possibility that the bravoitization in the large pentlandite areas proceeded simultaneously with corrosion of the adjoining areas of pyrrhotite. The magnetite that is present in the bravoitized areas, in the form of veins through the material, in that case would probably originate from the same processes.

In the Greenlandic ore the pyrrhotite was here and there transformed into zwischenprodukt. This has not been observed in the Finnish ore, but the pyrite areas and small, pyrite-like crystals in them are so imbedded in the ore that it is reasonable to regard them as being products of the transformation of the pyrrhotite to disulphide, in analogy to what has been found in the Greenlandic ore. Presumably the chief difference between the two ores is thus that the Finnish ore underwent a process whereby the zwischenprodukt material could be transformed into pyrite proper. Whether this must be connected up with mechanical transformations to which the ore was subjected, or there was simultaneous action by moderate temperatures, is a question that is difficult to decide. In this ore there is no question of the ore having been weathered,

i. e. transformed by supergene agency. In this ore there is no sign, such as in the Greenlandic ore, that the pyrrhotite contains portions that have been attacked by hypogene transformation. The only indication of transformation is to be seen in the bravoitized pentlandite areas. As both bravoitization and formation of zwischenprodukt are transformations from mono-sulphide to disulphide, it seems probable that both processes took place in this ore. What happened, however, was that the intermediate disulphide products by metamorphism were altered into end products. We may assume that the bravoite was actually stabilized as a nickeliferous disulphide, just as zwischenprodukt was transformed into pyrite.

The analogies need not stop there. The silicate masses inclused in the ore seem to be associated with the products emanating from the late-magmatic processes. Bravoitized areas of pentlandite often lie in the neighbourhood of these silicate areas. In the latter we find chalcopyrite in a handsome pure form; there are also iron oxides, as well as the mineral graphite. The presence of the latter may be an indication that redox processes took place in the late-magmatic processes, exactly as is thought to have occurred in the Greenlandic ore. These ideas about the ore can only be advanced as suppositions, of course, and it will require very thorough studies of the deposit in all its variations to put matters on a more concrete basis.

In 1938 M. SAKSELA and E. HACKZELL (32) gave a preliminary description of the ore in Finnish. Professor SAKSELA was kind enough to furnish me with the following more detailed account of their paper:

General character of the ore.

The ore occurs in ultrabasic rocks, peridotites, which form concordant intrusives in migmatitized paragneiss. The ore body extends almost to a depth of 200 metres and its thickness here and there is over 20 metres. The ore mass is not homogeneous, inasmuch as it contains ore-free portions of peridotite and paragneiss. The contacts between the ore, which might be called pyritiferous peridotite, and the ore-free peridotite, are sharp.

The ore formations are very highly tectonized. Wall-rock alteration is widespread and the ore contains numerous fault fissures which are infilled with mica and chlorite minerals. The structure of the ore is brecciated. The non-metallic minerals (rounded olivine-serpentine-grains or amphibolite rods) are present as fragments. The matrix consists of ore minerals, chiefly of pyrrhotite, chalcopyrite and pentlandite. A considerable part of the sulphide material is concentrated in large nodules, from which narrow veins of sulphide radiate in all directions. These veins force their way in between the mineral particles or into cracks in them.

Microscopical description of the ore.

On the basis of the non-metallic components the ore is divisible into two types: the serpentine type and the amphibolite type. There is no really sharp boundary between them, however; they merge more or less insensibly into each other.

The chief minerals are pyrrhotite, pentlandite and chalcopyrite. Others present are pyrite, magnetite, cubanite and very little sphalerite. The pyrrhotite is the principal mineral. It is present both in large nodules and as infilling in the narrowest cracks.

The pentlandite seems to be trying to form large equidimensional grains (about 0.8—0.9 mm in diameter). This mineral is much less common in the narrow sulphide veins than in the large sulphide nodules. Most frequently the pentlandite occurs inside the pyrrhotite in the central parts of the sulphide nodules. Sometimes the pentlandite is bordering upon the non-metallic minerals, and then it is possible to see that the pentlandite does not continue as narrow veins into the adjacent narrow cracks. Numerous fissures are often observed in pentlandite grains and the grains may be entirely brecciated. The fissures are infilled with magnetite. The magnetite veins do not continue into the surrounding pyrrhotite.

The chalcopyrite is generally of finer grain than the pentlandite. It should be added that the chalcopyrite together with the magnetite may surround the large sulphide concentrations but also the narrow sulphide veins. In these zones the chalcopyrite and the magnetite have sometimes intergrown to form an implication structure.

Pyrite is present mostly in the form of idiomorphic grains. Now and then the grains are fissured and the fissures are often infilled with magnetite. It can be observed here and there that the magnetite from these fissures has made its way into the pyrite and replaced it.

The sulphides were the last minerals to crystallize. Regarding the genesis of the ore on the whole, the ore and the peridotite are very closely related genetically. It is equally clear that the advance of the peridotite and the formation of the ore took place under violent tectonic movements. It seems probable that the sulphide material, already in the deeper stages as a melt, was differentiated from the peridotite mass. Afterwards the latter advanced and consolidated. It was only thereafter that the sulphide magma advanced and forced its way into the peridotite.

Beiernfjord, Norway.

The deposit was described in 1892 by J. H. L. Vogt (50) in NGU No. 7 under the title: "Jernnikkelkis fra Beiern i Nordland". The following account of the deposit is from that work (in translation):

> The Beiern deposit is a typical "gabbro"-contact occurrence. Exactly along the boundary surface between gabbro rock (uralite-norite) and adjacent schists (garnetiferous micaceous schist, gneiss etc., probably of Cambrian age) runs an almost completely compact "dike" of nickeliferous ore. The "dike" is sharply delimited from the schist and more or less sharply delimited from the gabbro itself—which over towards the boundary is rather richly impregnated with pyrrhotite. In the accessible parts the thickness is from $^1/_4$th to 1 metre. The ore dike consists of nickeliferous pyrrhotite mottled with small individuals of iron-nickel-pyrite (pentlandite. H.P. note); there is also some chalcopyrite which is concentrated especially along the schist boundary; and finally there is some ilmenite. The ore has a small admixture of gabbro components and sometimes some quartz and mica. Random ore samples analyzed for Ni+Co reveal a content varying from about 5 to about 20 per cent. The Co content in the ore is one or two tenths per cent. and there is also about 2 per cent. Cu.

Unfortunately, no more thorough microscopical examination of the ore is available. On material from the mineral collection of Kryolitselskabet Øresund A/S I have studied the sulphides, and Mr. H. Granli, of the Geological Museum in Oslo, was kind enough to provide me with further material from the deposit. The following description of the ore was written on the basis of that material. Having regard to the special structures exhibited by this ore, it would be of interest if it could be subjected to further studies.

The samples contain pyrrhotite, pentlandite, chalcopyrite, magnetite, spinel, sphalerite, sperrylite, valleriite, cubanite and chalcopyrrhotine, ilmenite, an unknown brownish mineral (cooperite?), bornite, a graphite-like mineral, an undetermined mineral in the sperrylite (braggite?), siderite and limonite.

Ore-microscopic description.

Sperrylite always occurs in handsomely developed crystals or small accumulations of crystals. One small crystal supposedly of sperrylite was observed in the chalcopyrite, otherwise they were found solely in pyrrhotite. Lying in the sperrylite were small areas of a slightly different colour, very slightly darker greyish-bluish (viewed in oil immersion).

The hardness is exactly the same as that of sperrylite. It is clearly anisotropic. This mineral is perhaps braggite. Pl. XV, 2 shows a group of sperrylite crystals in which this mineral was observed.

Spinel and magnetite occur in all sulphides. They may be of crystal form, but most frequently the magnetite is present as rounded inclusions in the sulphides. These oxidic components will be discussed in greater detail later, because they are associated with a number of special phenomena which rightly belong to a later stage.

The chief minerals in the ore samples are pyrrhotite, chalcopyrite and pentlandite in that order. The chalcopyrite occurs as inclusions, mainly in the pyrrhotite, and also as large veins irregularly cutting through the pyrrhotite and sometimes assuming the appearance of more independent parts of the ore. The pentlandite is also present as inclusions in the pyrrhotite, more rarely in the chalcopyrite, and it likewise occurs partly as veins of more or less continuous character round about areas of pyrrhotite and partly as a kind of intermediate mass between pyrrhotite and chalcopyrite, a "transitional zone" between these two minerals. With some justification the pyrrhotite may be called the bearer of the other minerals present in the ore.

Optically, the pyrrhotite does not differ from what we know elsewhere. There are nicely developed α and β lamellae which, as will be seen later, exhibit some dependence upon inclusions there. Cuneiform twin lamellae are observed here and there in the pyrrhotite and, in conjunction with some of the inclusions of magnetite, the optical features indicate recrystallizations in the mineral. The pentlandite is optically normal, as is the chalcopyrite. The latter mineral exhibits the normal twin lamination along several different systems.

The most characteristic feature of this ore, however, lies in the mutual relations of the three sulphides.

As stated, the pentlandite forms more or less continuous veins around areas of pyrrhotite. In two of the samples there are unusually finely developed intergranular structures between pentlandite and pyrrhotite (Pl. XV, 1), corresponding to what various authors have illustrated for instance from the Sudbury ore (49, 15). A considerable portion of the pentlandite is present in these areas. The mineral is also to be seen in the form of the familiar flames, lying imbedded in the pyrrhotite along its basal direction. Another form of pentlandite inclusion may be called pentlandite sparks; they are small "flames" some μ in length and about $^1/_2\,\mu$ in width and are probably of another exsolution generation than the flames. They exhibit a close relationship to lamellae of chalcopyrite in the pyrrhotite, and possibly we have here an exsolution determined by the formation of the chalcopyrite lamellae. It was stated above that the pentlandite in the intergranular represents a fairly large quantity of that mineral in the ore. But it is a question whether the pentlandite vein between chalcopyrite and pyrrhotite should be included as part of the intergranular or reckoned as a separate unit. It lies around the pyrrhotite in so far as it covers that mineral's border against the chalcopyrite (at any rate partly). In its mode of occurrence, however, it is more like the chalcopyrite and, like that mineral, the pentlandite just there sometimes occupies large independent areas. No connection with the aforesaid intergranular was observed, and therefore nothing can be said of their direct relations.

The chalcopyrite in this ore is present in a new and rather interesting position, viz. in the form of the lamellae already mentioned. Pl. XV, 3 gives an impression of their appearance. The individual lamellae are flame-like with pointed ends. In their slightly winding form, however, they follow three different directions, so that we may speak of three lamellae groups. None of these systems are seen parallel with the basal direction of the pyrrhotite and presumably they represent an exsolution series in which the material was separated along prism or pyramid planes in the pyrrhotite. It is in association with these chalcopyrite lamellae that we have the pentlandite sparks. They are frequent in the margin of the chalcopyrite lamellae but they occur both within and without the latter. On the other hand, they do not seem to be present in other parts of the ore where there are no chalcopyrite lamellae.

In their form the chalcopyrite lamellae exhibit no relationship to the chalcopyrite outside of the pyrrhotite. Out towards the margins of the host mineral they taper off, and nowhere do we observe a junction between the two forms of chalcopyrite.

Wherever the chalcopyrite in the large veins through the ore borders upon the pyrrhotite the chalcopyrite has convex boundaries against that mineral. At one place a pentlandite flame in the pyrrhotite was observed near the border against the chalcopyrite. The pentlandite continued into the chalcopyrite as if it were part of the flame, but there its various parts were orientated otherwise than in the pyrrhotite. The pentlandite almost seemed to contain chalcopyrite in the form of lamellae along (111) in the pentlandite.

The chalcopyrite in the pyrrhotite seems to exhibit a special relationship to the dark component in the pyrrhotite, for these lamellae are always surrounded by it.

Sphalerite was seen in small quantities in large chalcopyrite veins.

The hard, pale grey grains contained in the ore, which one would be inclined at first to call magnetite, exhibit such a variation in optics and exterior form that it would doubtless be wiser to assume them to represent both magnetite proper and spinel. Internal reflections were not observed, however, so this determination is uncertain.

The grains as a rule are barely $^1/_{10}$th mm in diameter. As Pl. XVI, 1, 4 show, the shapes vary a good deal. The most frequent forms are rounded, often slightly elongated, but in some samples about 10 $^0/_0$ of the grains have a sharp rectilinear margin. Some of the rounded grains present a marked similarity to the angular grains. Both types, or one should rather say all variations, may be present side by side.

The hardness corresponds to magnetite. The colour actually resembles that of magnetite too, but a number of grains occur with abnormal colours. Magnetite should be optically isotropic, but among these grains there are variations. A large proportion of the grains present colour variations, as shown in Pl. XVI, 1 where there are several differently tinted zones in the mineral. As a rule the variation is one of reflectivity, but the darker greyish parts may also exhibit a faintly yellowish tone. Moreover, there is a tendency towards a continuous colour variation within the various zones; one zone may at the last stretch towards the boundary to the next zone assume a fairly light tint, whereas the next zone is rather dark at the beginning. There is a clearly discontinuous colour change between the two zones. These observations were best with the most powerful immersion lens. Examination of these matters gives an impression that there is a submicroscopic zonally arranged pigmentation of the ground mass. Two of the three zones shown in Pl. XVI, 1 are faintly anisotropic. The third answers best to "normal" magnetite.

These oxide grains can be found in all three main sulphides, though most frequently in connection with the pyrrhotite. It is a very interesting feature that the grains are often seen together with the intergranular pentlandite in the veins around the pyrrhotite areas. In corners where several pyrrhotite grains cluster one can actually observe crowds of oxide grains. Magnetite in this arrangement is shown in Pl. XV, 1 and XVII, 1.

Occasional ilmenite lamellae have been observed imbedded in these magnetite grains.

A mustard-brown mineral (Pl. XVII, 2) was observed in two samples, seemingly replacing part of the magnetite grains. The hardness is a little less than that of the magnetite. The mineral is isotropic. The descriptions of cooperite may correspond to this mineral, but a comparison with daubreelite should not be overlooked. The quantity of the material is so small as to make closer study impossible.

In all the samples of this ore it has proved that the oxide grains to a greater or lesser extent may be replaced by a sulphide which, judging from the optical characters, can only be pyrrhotite, Pl. XVI, 2, 3, 5. This replacement of the oxide phase is to be seen both in entirely rounded grains and in the angular ones, which suggests the presence of a substance in both types which at least have this property of replaceability in common. (This may perhaps imply that spinel is not present anywhere in them?)

The quantity of replacing sulphide that may be present varies a good deal. Some grains are quite free of it and the neighbouring grains may be transformed as far as the complete replacement of the oxide by sulphide. Pl. XVI, 4 shows an instance of that neighbourship.

Magnetite in all three main sulphides occurs in more or less advanced stages of this transformation to pyrrhotite, and there is no difference in the transformation picture as regards the mineral grain itself. If chalcopyrite borders on the grain, or the grain lies completely inside chalcopyrite, we see bordering on the outside of the grain a formation of the mineral valleriite. It may ramify a little way into the original oxide phase, but the rule is that it lies along the latter's margin. The iron sulphide in the interior is often seen to ramify along certain directions in the oxide phase. There may be long, very thin laths parallel with several different systems; this probably signifies a replacement along the octahedral planes in the magnetite. This is to be seen i. a. in Pl. XVI, 3. In cases where the sulphide has replaced the entire grain, the latter is clearly recognizable nevertheless, for the boundary towards the surrounding sulphides stands out quite sharp as a narrow, limonite-infilled crack. The grain itself is also distinguishable from its surroundings, the material often being transected by fine cracks which form a reticulation pattern across the entire surface.

The valleriite referred to is to be seen in handsome, graphic intergrowth with the surrounding chalcopyrite. Sometimes long offshoots run into cracks in the chalcopyrite from these areas of valleriite. As a rule this mineral and pyrrhotite form an irregular border around the transformed oxide grain when it lies in chalcopyrite. At one place bornite was seen in graphic intergrowth with the chalcopyrite, forming part of the border around a magnetite grain.

When the oxide grain is present in pyrrhotite with veins of chalcopyrite bordering against the magnetite, valleriite may be seen; but cubanite, and chalcopyrrhotine too on one occasion also were observed in such a position.

The margin against surrounding pyrrhotite may be of two different types. One is represented by an apparently quite sharp limit, as will be seen in Pl. XVI, 2. The shape in the pyrrhotite seems more to reproduce the shape of the original oxide grain than that of the present sulphide material, which is more rounded. A closer examination of the boundary of the pyrrhotite here reveals a distinct cleavage of the mineral along the base. It looks almost as if the marginal zone were built up of pyrrhotite lamellae in optical conformity with the surrounding pyrrhotite. One might also say that there has been a kind of foliation of the surrounding pyrrhotite along (0001), and this foliation reaches a certain distance into the pyrrhotite (Pl. XVI, 2).

The other form assumed by the boundary is illustrated in Pl. XVI, 3, where it will be seen that the oxide grain is irregularly bordered by the displacing FeS, which more or less irregularly passes into the pyrrhotite of the surroundings. In this case the latter is apparently quite regular in the border zone, but a closer examination, especially between crossed nicols, shows the presence of a zone, of different optical orientation, corresponding to the aforesaid laminated pyrrhotite zone in width; here the marginal pyrrhotite has a mottled appearance, which suggests that it is built up of optically differently oriented small individuals. The differences are small, however. A similar change in the orientation of the pyrrhotite was observed in the outer edge of large pyrrhotite areas where they border upon grains of magnetite in the pentlandite intergranular (Pl. XVII, 1).

Silicates imbedded in the sulphide mass may be found as solitary, discrete grains resembling the rounded grains of magnetite. Individual flakes of mica may be seen now and then near large clusters of magnetite.

Siderite may also appear in forms resembling the magnetite grains. This mineral is not especially frequent. In some cases there seems to be a question of a lining in cavities, but it is not impossible that a cavity in siderite may have been caused by the preparation process. A little siderite may be seen in association with the large magnetite clusters.

Limonitic material intersects the ore as thin veins, but there is nothing dominating about them. It is an interesting feature that where these veins cut through pyrrhotite with pentlandite flames the latter are quite unaffected, lying partly in pyrrhotite and partly in the limonitic material (Pl. XVI, 6). In association with the limonite veins are small rounded inclusions consisting of similar material. In two inclusions of this kind I found graphite flakes, or at any rate mineral grains resembling graphite.

Development of the ore, discussion of the ore-microscopic features.

To all appearances the first mineral to be formed in this ore was the sperrylite, which occurs idiomorphic in the earliest of the main sulphides, the pyrrhotite.

In the sulphide melt the material now present as magnetite, the oxide phase, was evolved in the form in which we now see it, and only thereafter it was imbedded in the crystallizing sulphides. This conclusion is drawn partly from the fact that inclused in the pyrrhotite are what may be designated as idiomorphic grains of that material, and partly from what I consider to be very important—the prominent placing of a large part of the magnetite grains in the intergranular mass.

Apparently this will imply that magnetite grains originally placed where the pyrrhotite began to crystallize, were pushed before the crystallization front and ended in the space between two or more fronts. In this respect there is a very distinct difference between the Greenlandic and the Norwegian ores. An explanation of this difference can scarcely be other than guesswork. The fact that the oxide phase forms relatively large aggregate masses in the Norwegian ore may possibly mean that it had time to collect; crystallization of the sulphide mass began late and doubtless proceeded slowly. In the Greenlandic ore all the small drops were caught in the rapidly crystallizing sulphides and only a small portion of the oxidic components had a chance of forming large masses corresponding to the Beiernfjord magnetite. Characteristically enough, these large masses are also found in the Igdlukúnguaq ore in close association with the intergranular mass.

Crystallization of the pyrrhotite was the next phase in the genesis of the ore. We must imagine that there was crystallization simultaneously from numerous centres in the sulphide melt, hence the formation of the various individuals. Even today they can be seen marked by the intergranular mass. On crystallization the pyrrhotite inclused both nickel and copper in its lattice. All pentlandite may be placed in relation to the intergranular mass or exsolution bodies in the pyrrhotite, and some of the chalcopyrite may likewise be interpreted as exsolution bodies in the pyrrhotite. The intergranular pentlandite of course might also be regarded as a kind of residual mass, remaining after the crystallization of the pyrrhotite in the same manner as the chalcopyrite remained liquid after the crystallization of the iron sulphide. This, however, harmonizes neither with the view of the position of the nickel sulphide in the ore judged from the Greenland deposit, nor with the opinions of the relations between FeS and NiS based upon laboratory tests or those advanced by various workers after studying other deposits. Nor does the chalcopyrite, which certainly crystallized last, exhibit the same development in a true intergranular mass. Even in the Igdlukúnguaq ore the chalcopyrite, which forms the central parts of what I have called the pore mass, is more irregular in its appearance and displays a tendency to assemble in large veins wherever it can. Similar features would also be expected of the pentlandite if in the intergranular it was to be regarded as a residual melt and not a later exsolved phase.

This first exsolution of pentlandite is the next step in the evolution of the pyrrhotite, but before it came into existence the chalcopyrite as a residual mass was placed in the ore in the form of large veins which were largely coactive in corroding the pyrrhotite first formed. It is difficult to say whether or not this corrosion proceeded side by side with the exsolution of the nickel phase; but on considering the border relations between the pentlandite and the pyrrhotite as well as the chalcopyrite it seems presumable that there is also a connection between the corrosion and the exsolution.

As far as can be judged from reports on other deposits and laboratory tests, these phenomena in the ore belong to the interval between about 1000° (the ore's lower temperature in the molten state) and about 850°. At the latter temperature the chalcopyrite presumably was crystallized, and the large pentlandite exsolution is assumed to have taken place in that interval.

Before turning to the next traceable stages in the ore it will be necessary to point out certain deviations from the picture formed by the Greenlandic ore. Firstly, in it we see that the large exsolution of nickel was a simultaneous exsolution of a certain quantity of copper, as I believe it reasonable to suppose that there was an exsolution of a nickeliferous-cupriferous phase called chalcopentlandite. There is no directly observable indication in the Beiernfjord ore that the same took place there; but on the other hand it is quite common for pentlandite to be accompanied by small quantities of chalcopyrite, and the position of the pentlandite as a sheet between chalcopyrite and pyrrhotite may perhaps after all be interpreted as a sign that here too there was an exsolution of chalcopentlandite in the first stages. Another point is the exsolution material of the Igdlukúnguaq ore around the magnetite grains inclused in the pyrrhotite. Nothing similar was observed in the Norwegian ore, or in fact distinctly in the ore of other deposits. One may perhaps refer to the fact that a little pentlandite and chalcopyrite occurs now and then with such grains, but it is remarkable that such a large number of these grains lie quite clearly in the pyrrhotite alone. No doubt there is a connection between this and the development of the oxide phase in the Greenlandic ore, in contrast to other ores of this type, but it seems that the relations cannot further be clarified.

The next evidence in the genetic history of the ore was produced in an interval below 850°. The familiar pentlandite flames are generally supposed to belong to the 300—400° interval. Placing the chalcopyrite exsolution is more difficult, however. There can scarcely be any doubt that this exsolution does not correspond to the rectilinear exsolution lamellae of chalcopyrite in the pyrrhotite from Igdlukúnguaq. On the other hand, it is possible that the flame-like chalcopyrite exsolution lamellae of the latter represent the same exsolution. Consequently, as was mentioned during the discussion of Igdlukúnguaq, there is reason for assuming that the temperature of the exsolution must lie somewhere between 310° and 550°. Possibly the chalcopyrite flames are associated with the transformation point for pyrrhotite at about 550°.

The pentlandite sparks are perhaps induced products in connection with this chalcopyrite exsolution, and if so may be placed to the aforesaid temperature interval. If this is not the case, I must admit that they are difficult to place. The fact that they are also to be seen in chalcopyrite material in the exsolution lamellae suggests that they are closely associated with that sulphide. The position here may be that the exsolution material contained the nickel sulphide as a component in solution, as was described in connection with the Greenlandic ore, page 81.

In its development the sphalerite in the large veins of chalcopyrite is linked with that mineral. Curiously enough there is no question here of the so-called sphalerite stars, which otherwise seem to occur in ores of a certain high-temperature origin.

The minerals chalcopyrrhotine, cubanite and valleriite represent copper-iron sulphides with a certain content of FeS, depending on the formation temperature. The first two may be regarded as present in this ore as relicts, their sole significance being that they indicate processes in the stability interval of the two minerals, without telling us anything about the phenomena in the ore at those particular junctures.

The mineral valleriite in the first place is present in rather large quantities in the ore, and in the second place it exhibits marked relations to important processes in the ore, i. e. those which caused the transformation of the oxide phase to the sulphide phase. According to BORCHERT (5), valleriite's stability interval, which is fairly narrow, lies at about 225°. The close association between these transformations and the presence of the mineral makes it presumable that the processes took place, or at any rate were active, precisely at that temperature interval. The fact that cubanite may occur in conjunction with these transformed oxide grains indicates that the processes also took place in the stability interval of that mineral. According to BORCHERT (5), this lies in the interval above valleriite and is supposed to reach up to 250°. If this is so, the sulphidization of the oxide phase took place between 225° and perhaps 300°.

If these relations are compared with Igdlukúnguaq ore, it will be seen that they can be correlated with the phenomena that are associated with the eutectoid siderite areas. There too the characteristic feature was that valleriite was present, apart from the unknown graphite-like mineral, and it was also presumable that the processes in the Greenlandic ore took place over a temperature interval which extended at least up to just above 300°. In the Greenlandic ore it was scarcely open to doubt that there had been processes due to certain gases etc. originally belonging to the ore, a kind of autometasomatosis. Actually, this parallel between the two ores extends further, because the Igdlukúnguaq ore also exhibits oxidic material permeated with newly-formed fine-grain sulphide.

The transformation picture in the Norwegian ore would seem to be capable of an interpretation similar to that of the Greenlandic ore, when the two are compared. Considered by itself it must be admitted difficult to imagine that the transformation "came from the outside", because in that case the ore as a whole would be expected to display some sign of it. The limonite-infilled veins are too few and small to be seriously considered as channels of supply for the transformation substances. On the other hand, the theory of the activity of primary components is rather bold in an environment such as that presented by the Norwegian ore. We lack the retrospective connection, so to speak, the connection which seems to be more clear in the Greenlandic ore.

Even the observed transformation of the magnetite is very difficult to understand. In the first place, it seems to be independent of the environment in which the grains occur, pyrrhotite, chalcopyrite or pentlandite. The difference in placing gives rise merely to special products round about the magnetite grains when these lie in chalcopyrite or together with that mineral. As the magnetite is seen to have been replaced by the sulphide, along what seem to be octahedral directions, we must assume the presence of a well-defined mineral prior to the transformation. In all the grains the transformation is seen to have advanced inwards from the outside. It consisted of an introduction of sulphur which subsequently replaced the oxygen in the iron compound, whereby the latter turned into FeS and the oxygen was liberated. Whence that excess of sulphur came is not easy to see. It may have been the sulphur that was left over from the original formation of the magnetite substance in the molten sulphides; but the question at any rate must be asked where that sulphur was after the crystallization of the sulphides and before those processes began? In the Greenlandic ore it seemed that the material of the pore mass had served as a reservoir, but there is no counterpart of this in the samples from Beiernfjord. It is also difficult to account for the liberated oxygen. In the Igdlukúnguaq ore the analysis found a certain amount of water and it was reasonable to suppose that it belonged to the product of the pyrrhotite transformation, zwischenprodukt and the newly-formed bravoite. The latter mineral was not observed in the Norwegian ore, but as regards hydrous pyrrhotite there is actually nothing but the newly-formed sulphide phase in the oxide grains to consider. It cannot be precluded that the new pyrrhotite may be the seat of a certain quantity of water; its finely crackled appearance and its faint divergence of colour from the surrounding pyrrhotite may be evidence of it; but it is not wholly clear, to say the least. The limonite in the ore may of course absorb some water, but its quantity is insufficient to hold all the water that would be involved.

Whereas the gases with which these processes are connected are credited with the property at high temperatures of forming oxides from the sulphides (which also occurs in the smelting of the matte), in the latter processes at lower temperatures (the valleriite indicates temperatures down to about 225°), they should cause sulphidization of earlier-formed oxides and perhaps oxidation to sulphates. The first reaction would doubtless liberate a quantity of sulphur, but it is questionable whether that sulphur could be kept within the ore body so that it could become active again later. At Igdlukúnguaq it does seem to be so, but there are also indications which may reasonably be taken as a sign that everything proceeded within a static environment.

Regarding the development of the mineral valleriite together with the new-formation of FeS, it is imaginable that this mineral emanated from the hydrothermal processes which supposedly took place—so much the more as everywhere in the ore there are contacts between pyrrhotite and chalcopyrite without the FeS-bearing chalcopyrite mineral having formed there. However, I would rather regard this as an indication that owing to the height of the temperature it was possible for valleriite to form, but that this process could not always take place wherever the components were present. But at those places where there was activity at that particular juncture, an inertia was overcome and as a consequence the development of the valleriite was "catalyzed". Thus the mineral need not be regarded as having been formed hydrothermally, owing its origin to later solutions; it is merely a mineral whose existence is due to the "catalyzing" effects of later processes.

The presence of bornite in myrmekite with chalcopyrite together with the valleriite border around a transformed oxide grain may be explained only by assuming that there were local conditions favourable to its development. In itself bornite in this environment is a quite unstable or unnatural phase.

Zeehan, Tasmania.

Description of the Ore.

Thanks to Mr. Thomas Dodds of North Mine, Broken Hill, New South Wales, I have been enabled to examine a sample of material from Tasmania, from a mine belonging to the same region as the above ore.

Mr. DODDS was also kind enough to send me a copy of FRANK L. STILLWELL's work (47) on the Zeehan deposit. As it contains observations of great interest in connection with the present investigation, I have considered it best to reproduce STILLWELL's work as it stands. As the sample I examined agrees well with STILLWELL's description I have not thought it necessary to add my own description.

"*Copper-nickel ore from the Zeehan District, Tasmania.*

A sample of nickel ore from Munro's Shaft, Melbourne Copper Nickel mine, near the Five Mile Siding, Zeehan, has been submitted for mineragraphic examination by the Melbourne Ore Dressing Laboratory. The ore is reported to assay:

Copper	3.95 °/₀
Nickel	9.75 °/₀
Iron	42.85 °/₀
Insoluble	0.55 °/₀

The ore consists of massive, medium to fine grained sulphides, in which the individual crystals are mostly under 0.5 mm in diameter. Some specimens show a crude banding, and the ore has undergone incipient oxidation, indicated by slight green staining along some of the closely spaced parallel joints which trend parallel to the banding.

Polished sections reveal that the ore consists essentially of a medium to fine grained granular association of magnetite, pyrite, pyrrhotite, pentlandite, chalcopyrite. A little(?) chalcopyrrhotine is minutely intergrown with pentlandite, and there is an occasional trace of sphalerite and gold. Assays of the ore from this locality reveal the presence of about 1 to 2 dwt. of platinoid metals per ton, and spectroscopic examination of a prill of the platinoid metals, carried out by Mr. A. J. GASKIN, indicated that it consisted of platinum and palladium in about equal proportions. In addition, nonsulphide gangue, amounting to several per cent of the total ore, occurs disseminated throughout the sections.

The sequence of mineralization appears to have been magnetite, pyrite, pyrrhotite-pentlandite solid solution, and chalcopyrite. The pentlandite and pyrrhotite subsequently unmixed and segregated, but fine intergrowths of blades of one in the other are common along grain boundaries. The magnetite occurs in grains up to 0.1 mm across. Some preserve crystal outlines, but the majority have undergone more or less corrosion by the sulphides and the gangue minerals. In some sections, the grains of magnetite are uniformly imbedded in carbonate or surrounded by narrow rims of carbonate.

The pyrite occurs as occasional coarse crystals from 1 mm to 2 mm across, and as lens-like clusters of smaller crystals with the long axes of the lenses parallel to the banding in the ore. The crystals are more or less shattered and have been invaded along the fractures by the other sulphide minerals. In addition, it is present as more or less minute residual particles distributed as inclusions in the other minerals excepting magnetite, and in their grain boundaries. These inclusions range down to .005 mm × .002 mm.

The chalcopyrite, pyrrhotite and pentlandite occur in about equal proportions, the relative amounts varying patchily through the section. The chalcopyrite is perhaps the youngest, since it tends to occur in interstitial positions. The pyrrhotite occasionally forms clusters of grains up to 0.5 mm across, but generally smaller (0.1 to 0.5 mm). It is brownish to pinkish-brown, pleochroic and strongly anisotropic, and is stained by KOH. In places, it encloses minute parallel blades of pentlandite.

The pentlandite is readily recognized by its pale violet colour, its isotropism, and its susceptibility to fracture. The bulk of it occurs as discrete grains or clusters of grains with similar dimensions to the pyrrhotite areas. Individual grains range from 0.10 mm to 0.05 mm across, but clusters of grains are up to 1.0 mm across. In places, it encloses lamellae of pyrrhotite, or occurs as blades in the pyrrhotite. These intergrowths are presumably exsolution intergrowths, and are too fine to permit mechanical separation of the minerals, the individual blades being about 0.005 × 0.002 mm.

A portion of the pentlandite has a faintly mottled appearance under high power. Under an oil immersion lens (1200 mag.), these mottled areas are seen to consist of an intimate, more or less graphic, intergrowth of pentlandite with a creamy-coloured mineral of almost identical hardness. It appears weakly anisotropic, slightly creamier than pyrite, and distinctly softer than it, and is inert to etching reagents. It has not been identified with certainty, but corresponds in many respects with chalcopyrrhotine, CuS, Fe_4S_5, by Borchert (Über Entmischungen in System Cu-Fe-S. Chemie der Erde, 1934, p. 147). The grains are too minute and too closely associated with chalcopyrite, pyrrhotite and pentlandite to carry out microchemical tests.

A particle of gold, measuring 0.06 mm × 0.03 mm was observed in an area of gangue enclosed by pyrite, and a trace of sphalerite occurred associated with chalcopyrite in a vein filling a fracture in pyrite.

The non-sulphide gangue, apart from magnetite, is mainly soft, and consists chiefly of aggregates of fine-grained carbonate and sometimes of rhombs of carbonate. The solubility of the carbonate accounts for the low percentage of "insoluble" in the reported assay."

First of all it is interesting to be presented with an ore whose components conform very well with the Greenlandic ore. A point of particular interest is that the ore contains carbonate. The remark that the magnetite is seen to lie inclused in carbonate seems to open up possibilities for comparing with the siderite phase in Igdlukúnguaq. But what seems most remarkable is STILLWELL's reference to a fine-grained intergrowth between pentlandite and a mineral which he assumes to be chalcopyrrhotine. It is not incredible that this is an exsolution structure corresponding to what the Greenlandic ore contains.

SUMMARY, GENERAL AND SPECIFIC REMARKS

The foregoing contains a description of the Greenland deposit of nickeliferous pyrrhotite from the Tertiary basalts at Igdlukúnguaq, on the island of Disko, West Greenland. As the examination of that ore revealed a great wealth of detail which permitted the recognition of an almost unbroken series of stages in the developmental history of the ore, the account of the ore-microscopic relations has been made as comprehensive as possible; likewise, in the discussion on the observations importance has been attached to placing them in harmony one with the other and also with observations from elsewhere, i. e. laboratory tests and the descriptions of other deposits. However, the study of the ore having been based upon the ore-microscopic relations makes it difficult in many instances to refer to descriptions of other occurrences, either because the microscopic examination of them did not go into such detail as to provide a suitable material for comparison, or the authors were more concerned with other aspects than those which I considered should be emphasized about the Greenlandic deposit. Consequently it has been necessary to some extent to cite or compress the descriptions from elsewhere and, where possible, to include observations which I have made on materials from outside deposits. In the comparative material I have above all included the known large occurrences of nickeliferous pyrrhotite; but on account of particular observations in material from smaller deposits I have thought it necessary to give them a relatively large place among the other comparative materials. When going through these other deposits I have endeavoured to correlate them with or refer them to the Greenlandic deposit as clearly as possible, and I hope that at the same time the account can be regarded as a fair treatment of the outside material.

Correlation with Igdlukúnguaq has been attempted in each case as regards the deposits at Sudbury, Insizwa, Nivala, Beiernfjord and Five Mile. The choice of these deposits was intended to cover those which could be said to represent the ordinary forms in which this type of ore occurs, and it was also the idea to provide room for variations not directly reflected in the Greenlandic deposit.

As to age, the distribution is as follows: Sudbury, Nivala and Beiernfjord are presumably Late Pre-Cambrian; the Norwegian deposit is probably the youngest. The occurrences in the Five Mile region are supposed to be Carboniferous, and Insizwa is believed to be Permian.

The Norwegian and Finnish ores occur among rocks which undoubtedly were involved in orogenic disturbances; apparently this does not apply to Sudbury, and Insizwa may be regarded as occurring in a still environment.

On this background it is really astonishing that it is possible to establish such far-reaching parallels with the Tertiary ore of Greenland, whose environment would seem to have been in a state of complete tranquillity both during and after its formation.

The study of the sulphide masses in these deposits, the ore-microscopical observation material, seems to give a fairly unequivocal general picture of the development through which the ore minerals passed. It seems to be of some importance, and therefore will be emphasized here, that only large lumps, or at any rate fair-sized nodules of compact ore, can display the various features of that picture. Small grains of ore a millimetre or two in size exhibit insufficiently detailed indications of the same development as that observable on the large sulphide nodules. The description of the Greenlandic ore, and the examinations I have made of other ores, show that there is also a difference when the sample comes from a centimetre-sized nodule or it represents part of a much larger piece. This difference also becomes evident in the various authors' studies of "disseminated ore" and "compact ore" respectively.

Moreover, it is obvious that there must be a difference in the cooling history of a small sulphide grain and of a large sulphide mass. Furthermore, considering that as an essential factor in developments there are reactions in which gases of various kinds are involved, it goes without saying that when comparing the various deposits we must, as far as possible, try to base our speculations on the compact ore.

The study of the compact ore from Igdlukúnguaq showed that the ore formation had an initial stage, from which the primary oxides came, followed by a main stage when consolidation of the sulphides took place, and finally a third stage in which the predominant processes were hydrothermal in character, and the formation of both sulphidic and oxidic material took place at this juncture in the development of the ore.

Almost immediately after the consolidation of the sulphides there began a series of processes in solid phase, exsolutions and inversion of the sulphide material; we may call them recrystallization in the widest sense, adaptation recrystallization. These processes ran parallel with the principal line in the development of the ore. They are especially remarkable because they often gave rise to the formation of phases and structures that were governed by the prevailing temperatures.

Spinel and magnetite are characteristic minerals of the first stage. The spinel was clearly crystallized so early that it appeared as crystals here and there in the sulphide melt before the latter even began to crystallize. But it is quite another matter to conclude from this that the mineral crystallized at a temperature corresponding to its melting point as determinable in the laboratory. Such a conclusion would hardly be reasonable; all we can say is that the mineral must have crystallized over the 1000° more or less at which the sulphides crystallized. The magnetite in the sulphides may have crystallized before the latter, but the greater part of that mineral occurs in such forms that it is justifiable to regard it as having consolidated some time after the sulphides did so. Particularly noteworthy is the difference between this oxide phase and the iron oxide of the silicate mass, which is characterized by titanium. The oxide phase which was the origin of the magnetite is a phase characteristic of the sulphides, one which must have formed as a consequence of the various gases contained in the sulphide mass. Both water and carbon dioxide must have been present in one form or another, but in what form cannot be determined, and evidently it is impossible to say definitely what oxidic iron compound was formed as the first stage of the magnetite. It must have been a compound with a melting point lower than the temperature of sulphide consolidation. That phase is placed in the ore in conformity with the crystallization of the pyrrhotite and likewise had its form characterized by it. In the Greenlandic ore the copper sulphides likewise governed the placing and forming of the oxide phase.

Sperrylite and related minerals belong to this stage of the development of the ore.

The next stage comprises the crystallization of the sulphides, and here it is worth noting that it proceeded in an environment where sulphur was present in excess, thanks to the oxide formations that took place in the first stage. Crystallization of the pyrrhotite dominated the picture. All nickel was merged into the first FeS lattice to be formed, and some copper too. The remaining copper sulphide was distributed in the sulphide body as a pore mass. As a result of the distribution between phases we must assume that a certain amount of nickel was present in this copper-sulphide melt, but we cannot decide whether the quantities were large or not; judging from the Greenlandic ore one would be inclined to say it had not been more than a trace. After consolidation of the pore material the ore as such was solid. Only the products of the gases would be likely to be in any other state. The further development now consisted of recrystallizations within the solid phases, above all in the pyrrhotite, but also in the chalcopyrite. In addition, there were secondary reactions in the newly formed solid phases. Preserved relicts of the various adaptation recrystallizations provide interesting evidence of the passage of the ore through various temperature stages; but only in so far as they give information about the ore's formation temperature and characterizing temperature can they be said to be of importance in the formation of the ore as a whole. If we can establish a series of exsolutions and temperature-determined phases within an ore, ranging from the highest to the lowest temperatures, this must furnish reliable evidence of the ore's formation temperature, whilst a dominant occurrence of certain exsolution structures and phases must make it possible to establish the characterizing temperature.

The following exsolutions were found in the pyrrhotite from the Igdlukúnguaq ore:

1) Chalcopentlandite.
2) Chalcopyrite in rectilinear lamellae.
2a) " " "
2b) " " "
3) Chalcopyrite in flame-like lamellae
3a) " " "
4) Pentlandite sparks.
5) Pentlandite flames.
6) Pyrrhotite α–β lamellae.

The chalcopentlandite of itself broke down to pentlandite and chalcopyrite, and within the chalcopyrite we observe remnants or traces of chalcopyrrhotine, cubanite and valleriite. The latter mineral also occurs independently, so to say, associated with the phases of the third stage.

The first exsolution in Igdlukúnguaq produced both internal exsolution bodies and intergranular mass or, better, corona around all pyrrhotite. This phase I have called chalcopentlandite because the internal exsolution bodies show that there must first have been a homogeneous phase, but it is now seen as a binary structure of mainly pentlandite, with chalcopyrite in the form of thin lamellae. In other words, nickel sulphide was first exsolved with some copper sulphide. This exsolution is presumed to correspond to the familiar intergranular pentlandite, the great exsolution which Hawley, Colgrove and Zurbrigg (15) place at about 850°. In Igdlukúnguaq between this exsolution and the pentlandite flames, which presumably originated at temperatures between 300 and 400°, we find first of all exsolutions of rectilinear lamellae of chalcopyrite, presumably with modifications at falling temperatures, for which reason they are shown above in three stages. Here they are assumed to have been formed at about 700°. Next follow the lamellae observed as chalcopyrite flames: there may have been an exsolution through a phase of chalcopyrrhotine. They are shown in two stages, because the Greenlandic ore exhibits the presence of two generations of lamellae. They may possibly correspond to the pyrrhotite transformation point at 550—570°. The pentlandite sparks may be a companion phenomenon to this copper sulphide exsolution, but there is a possibility that the sparks correspond to a separate exsolution prior to these lamellae. It seems less probable that they should correspond to a latter time than the chalcopyrite flames.

In the literature no mention has been made earlier of such exsolutions from these ores. The last three were observed in the Beiernfjord ore, and it looks like being possible to find remains of the chalcopyrite flames in other nickeliferous pyrrhotite ores (Nivala and Insizwa). The conclusion drawn from this is that they correspond to temperatures slightly above the usual characterizing temperatures, which simply means something over 310°, though anything more exact is unobtainable. This of course agrees with the general ideas as to the temperature at the formation of the familiar pentlandite flames. These being of very frequent occurrence in most deposits, it may be permissible on that basis to place the three exsolutions well above the 310°, whereby the suggested 550—570° perhaps becomes more probable.

The pentlandite flames were succeeded by the exsolution in the pyrrhotite itself, when the light and dark flames of the iron sulphide were formed. This exsolution is referred to 139—144° by some workers.

I consider that with these series of exsolutions we now have an established continuity right from temperatures round about the melting temperatures of the sulphides down to the aforesaid 140° or thereabouts. The simultaneous exsolutions in the copper sulphide mass and in the newly formed exsolution phases are difficult to place in this picture, apart from chalcopyrite's "substitutes": valleriite, cubanite and chalcopyrrhotine.

Before this series of exsolutions was established, perhaps before the pentlandite flames made their appearance, the third stage in the development of the ore began. We may assume that these processes, originating chiefly in various gases in the ore, were active all the time, but then (at some indeterminate stage) they acquired such importance that their products as permanent components of the ore characterize its appearance. Siderite, and to some extent iron oxide, belong to this stage. One marked feature, however, is the changes proceeding in the sulphide mass surrounding these areas. There the reactions seem particularly to reflect an addition of sulphur to the monosulphides, resulting in the formation of FeS_2 and $(Ni, Fe)S_2$, both of which in the Greenlandic ore are hydrous and possibly also contain sulphates. There the two phases are zwischenprodukt, the result of a transformation of pyrrhotite and bravoite, which owes its formation to pentlandite. In association with these formations we see chalcopyrite, which in its behaviour and to some extent also in its appearance differs somewhat from the chalcopyrite elsewhere in the ore. There are larger and more pure areas of this mineral, which in its localization exhibits relations to these areas rather than to the other components of the ore. It seems characteristic of these regions, and thus of this stage, that the mineral valleriite occurs somewhat frequently, which perhaps may be understood as meaning that the reactions at least were characterized by temperatures around the stability region of that mineral, i. e. about 225°. A graphite-like mineral is to be observed in the Greenlandic ore, and it seems not incompatible with these very processes that free carbon is to be found in these areas. Sulphide pigmentation of some of the related oxide phases form part of the picture.

This brief survey is based upon the Igdlukúnguaq ore; but, as an examination of the deposits elsewhere shows, it is also applicable to them, even if they are very different as to age and environment. The similarities extend further than to the three main stages, for several of the more detailed structures are recognizable in the ores of the other deposits.

These points of similarity are worth noting, but the differences between the various deposits actually call for a correspondingly detailed examination if we would ascertain the factors that caused the variations. It is not the intention here to make any such profound studies, nor would that be possible having regard to the voluminous material it would require. It would not be out of place, however, to discuss some main factors which might contribute towards turning in other directions the development of which Igdlukúnguaq is the picture.

It is not a question of whence the ore or its elements came. That problem will be touched upon briefly later on. The three main stages in the development of the ore are referable to developments within the "ore body". We may put a limit to the discussion by saying that it covers the period starting with the intrusion.

Factors Affecting the Ultimate Appearance of the Intrusive Ore.

The nickeliferous pyrrhotite ore as we find it in the various deposits always occupies an "assigned place". As a rule it is localized at the "bottom" of the mother rock, or in its margin. Often it is possible clearly to observe a position that is conditioned structurally. The position may be within or without the mother rock. Where the wall-rock has been opened, for example in connection with the intrusion, the ore may be in the openings so formed, and it may also be found where openings have formed in the mother rock. All this is quite compatible with the belief that the sulphide mass is a true melt.

The appearance of the ore from the moment when it arrives at its permanent location must now depend upon the environment into which it has been placed. Changes in the pressure from that to which it was originally subjected, the temperature of the new environment, and the movements taking place in these fresh surroundings, must be the main factors determining the final appearance; according to what has been shown in the foregoing we may take it that the bulk composition of the ore underwent merely insignificant changes.

The intrusion places the ore under certain pressures and conditions of temperature, with a certain form and content of gases. If now its further development proceeds on the spot, if there is no longer any movement, the local pressure and especially the temperature will govern the ultimate appearance. The Greenlandic ore is assumed to have evolved in high pressure and low temperature; the formation of siderite as the primary component must indicate a pressure of several thousand atmospheres in the initial stages. The absence of total recrystallization of the sulphides, as appears from the extremely fine-grained structures, indicates a rapid fall of temperature, with little opportunity for readjustment to the phases and structures of lower temperatures.

If low pressures prevail on the spot there may be a liberation of large or small portions of the gases in the sulphides. Large quantities of sulphur may be given off in the form of hydrogen sulphide and the ore must be capable of considerable change. It is not incredible that under such conditions there may be far-reaching redox processes, and presumably the ore may be radically changed. No example of this has been described; at any rate I have been unable to discover descriptions of deposits that could be regarded as evidence of it. Actually this is rather strange, because it is surely imaginable that a deposit could have originated under such conditions—unless the deposits of native iron in the island of Disko in Greenland may be taken to be an expression of these extreme conditions. This question will be reverted to later (page 158).

Moderate to high temperatures at the site of the intrusion will result in the special development of certain phases, i. e. those phases which are stable at these particular temperatures. Several of the known deposits betray signs of such conditions. The minerals valleriite and cubanite characterize—if not entire deposits at any rate large parts of individual deposits. (By the way, it is remarkable how often we read in descriptions of deposits that their lower parts are characterized by cubanite, for instance, whereas the upper parts contain no noteworthy quantities of that mineral. It would be interesting to go thoroughly into a material of that kind in order to see if this circumstance is connected with the original geothermal gradient at that location.)

If the temperature of the locality lies at a higher level than 300—500° the ore will receive its character from the phases that are stable there; but as activity at this level is also much more marked, we must suppose that the separation between the various sulphides, especially copper from iron sulphide, will be much more effective and the original structures may become blurred. Thus there is reason for assuming that copper, originally in chalcopentlandite and emerging as chalcopyrite intergrown with pentlandite, will have an opportunity of migrating to parts of the ore that are richer in copper. This temperature interval covers the stability range of chalcopyrrhotine, and as there seems to be a possibility of some absorption of nickel in that mineral, a protracted interval at that temperature may mean a transformation of nickel in the ore, which would doubtless be indicated in the form of an occurrence of pentlandite in the chalcopyrite.

If the intrusion does not proceed to a quiet environment, several possibilities are open. There may be an environment in motion during and after the intrusion; the movements may begin later than the intrusion, in the second or third stage of the evolution of the ore body. On the background of the main course followed in that evolution in the various stages there are thus possibilities of various formations of the ore, depending on the stage at which the influences are brought to bear.

Supposing this combination of movements in the initial stage at very high temperatures, for example only slightly below the sulphide melting point, there must be an opportunity for some separation between the sulphides and the embodied gaseous components. At the incipient crystallization of the pyrrhotite with the copper and nickel sulphides in solution inside it, the movements may cause some separation of these sulphides from the other, more copper-rich, sulphide melt. A regular squeezing of the later crystallizing copper sulphide melt is imaginable if the movements can exert their forces especially after the greater part of the pyrrhotite has crystallized. As to the retention or escape of the gases, this of course also depends upon the prevailing pressures. The gasses having a certain affinity for the late-crystallizing copper-rich sulphides, a separation of them may provide an occasion for the formation of copper sulphides in an environment likely to exhibit pronounced indications of hydrothermal activity—which accordingly would be due to the activity of the enclosed gases.

One may be inclined to think that some of the deposits in the Sudbury region passed through a course of development such as this. However, the intergranular pentlandite is represented extensively in the descriptions of the Sudbury ore, and thus must be taken as meaning that crystallization in so far was undisturbed. Perhaps the conclusion to be drawn from this is that the differentiation of sulphide in masses richer and poorer in copper was an early process in the history of the intrusion.

Occasionally we see ore pictures in which the intergranular pentlandite is extensively displaced. This is true of samples of the Petsamo ore, which through the kindness of Professor M. Saksela were placed at my disposal from Helsingfors University collections. They comprise samples from Kaulatunturi and the "breccia ore" of Petsamo. Pl. XIX, 2 gives some impression of the appearance of the "intergranular pentlandite" in these samples. The examination showed what might be called the main texture of the material, a kind of fluidal structure comprising both the sulphides, especially the pentlandite, and the silicates imbedded in the ore. There is not much chalcopyrite in these samples, but the placing of that mineral reveals a distinct connection with the silicate-rich areas and there seems to be some arrangement along the directions indicated by the fluidal structure, so that for instance the chalcopyrite is not found squeezed in between pyrrhotite and pentlandite but so to say pushed away from that environment.

One is tempted to regard this ore as a product of a normal mineralization of nickeliferous pyrrhotite which, in the stage of exsolution of the pentlandite from the pyrrhotite and in the immediately succeeding phases of the ore's normal development, became involved in more violent movements. At this stage the gases in the ore were very much on their way out of the pyrrhotite and collecting in the copper sulphides, which then had great possibilities of acting very independently in this ore. From Väyrynen's description of these ores (53) it appears that copper-rich types of ore are present at several places, and in the wider sense it would also seem possible to give an explanation along the lines suggested above.

If the ore is subjected to mechanical forces later than the above stages, i. e. in the third stage and afterwards, we must suppose that the resulting picture will be characterized above all by what is actually a dismemberment of the normal picture. It is difficult to say how greatly it may differ from the normal. My examination of the ores from various deposits shows that in this association the pyrrhotite is the mineral most readily reflecting what may be called weaker mechanical influences. For one thing, in this mineral we often see twin lamellae that are the result of pressure, and we also see the mineral broken up into small polygons. Within the net structure of the intergranular pentlandite we no longer find continuous areas of pyrrhotite. They are replaced by a "pavement" of small pyrrhotite polygons of various orientations. In some deposits it can be seen that the orientation of the various small areas varies considerably, whereas in others a difference is just perceptible. The Finnish deposit at Nivala described in the foregoing is a fine example of shattering, in which the consequent change of orientation in the small areas is not particularly striking. It may almost be compared with the undulating extinction observable in quartz that has been subjected to mechanical forces. A weaker force of this kind may actually have been exerted at any stage late in the formation of the ore, or for that matter after its formation. This pronouncedly polygonal structure with the small polygons all different in their orientation must presumably belong to stages where more widespread recrystallization could proceed.

Another result of the forces acting on the ore in its third stage may be imagined in connection with products of the gases such as bravoite and zwischenprodukt. There is a possibility of an escape of water and sulphate as a result of exterior influences; for instance, zwischenprodukt might become pyrite as an outcome of late influences. The Nivala ore is perhaps an example of this.

These thoughts on the possibilities of deviations from what may be called the normal ore picture, and on the causes of these deviations, all refer to changes that might be imagined as subsequent effects during the actual formation of the ore. Naturally, we cannot ignore the possibility of influences on the ore at much later stages, even those which may be entirely unconnected with the phenomena of the formation epoch itself. Forces that are likely to accompany orogenesis, block dislocations, re-mineralizations etc. will of course be capable of causing profound changes in the original picture.

It goes without saying that one cannot embark upon speculations concerning the consequences of such influences; but the fact may be pointed out that at temperatures of 200°—300° the relation between pyrrhotite and chalcopyrite may be altered. Moreover, judging from the experiments on heating the Igdlukúnguaq ore it would seem that the relation between chalcopyrite and pentlandite can be affected at somewhat higher temperatures. What seems to happen is that the formation of the chalcopyrrhotine in the presence of nickel sulphide causes the absorption of some nickel into the lattice of the newly formed mineral. Between pyrrhotite and pentlandine what happens is merely that on heating to something above 300° the pentlandite flames may disappear. No critical reaction between the two minerals has been observed under temperatures of over 600°. This perhaps is one explanation of the really surprisingly good condition in which the primary main structures are most often observed in this type of ore, notwithstanding the greatly different ages of the deposits.

Pentlandite itself seems to be a very stable mineral in these deposits and at the same time one that is specific for the type of ore. True, it has occasionally been found in deposits which seem to have nothing to do with nickeliferous pyrrhotite; but considering that it is found in hundreds of deposits of this type, it seems to occupy a somewhat unique position among ore minerals. It is not incredible that with the presence of the mineral in a deposit we have proof of the latter's originally magmatic formation, wholly or partially.

Regarding the Finnish deposit Outokumpu, the immediate impression one receives in view of the foregoing is that this is an ore in which the pentlandite is out of harmony with the type as such. If anything, Outokumpu is an iron-copper-zinc ore. But from Vähätalo's description of it (52), it appears that in one particular part of the ore there is a small mass of true nickeliferous pyrrhotite. It would seem that this deposit consists of a copper mineralization associated with schists, which has struck a complex with an earlier mineralization of nickeliferous pyrrhotite. In the new paragenesis pentlandite, i. a. is not stable and it looks as if the mineral linnaeite assumed the rôle played by the nickel mineral in the ore's pyrrhotite.

If this view is correct, the deposit at Outokumpu is interesting evidence of the meeting of vastly different mineralizations.

Development Prior to the Formation of the Ore Body.

The course of developments in the formation of the ore as discussed in the foregoing covers conditions from the stage at which we may speak of the existence of the ore body. The connections back to what lies prior to that stage must be sought in a study of the structure of the deposit and in the petrographic and structural relations of the surrounding rocks.

However, there is a possibility that in the ore body there are characters that may be traced back to the preceding conditions. The composition of the ore as such must have been governed by the previous processes, and among the ore components particular attention must be given to the curious position of the dissolved gases in the sulphide melt. Scholtz (35) has discussed this foregoing section of the history of the ore, with weight attached particularly to the presence of gases in the sulphides, emphasizing the comparison with the well-known phenomena that the liquid matte is capable of dissolving very considerable quantities of gases. He considers it not unreasonable to suppose that under magmatic conditions the sulphide melt can hold even greater quantities of gases than the matte.

In globules of small dimensions the presence of such dissolved material will have the effect of increasing their buoyancy and thus counteract the influence of gravity, but when they are sufficiently numerous the globules will tend to coalesce to form larger drops, until finally the critical size is reached. When this happens, SCHOLTZ says, gravitation will become the governing factor, and the larger the liquid pellets become, the more rapidly will they settle. At the same time they will tend to become larger still by uniting with smaller, more slowly-settling pellets and by coalescing with very small ascending globules.

From a study of the ore in the ore body one can scarcely take a definite attitude to this theory of SCHOLTZ's. All the same, it must be warrantable to evaluate "harmony-non-harmony" between the development which can be read more or less directly in the ore itself and the development such as has been assumed by various writers for the stages prior to the ore body stage. To my mind, the opinion of the ore advocated in the present work is more in harmony with the ideas presented by SCHOLTZ regarding the stages prior to the formation of the ore body than those which other authors, for instance those who have worked on the Sudbury ores, are disposed to submit, in which they favour a purely hydrothermal formation.

The intimate relationship of the sulphides and the magma gases to late magmatic components of various kinds, to which SCHOLTZ also refers, shows clearly that together with the ore there must be products capable of being interpreted as hydrothermal in their origin; but it is equally obvious that there is no reason for believing that the hydrothermal picture thus formed is to be read as signifying that the entire formation was hydrothermal in nature. Structural placings of the ore are possible, of course, whether it is of magmatic or hydrothermal origin. If, as BATEMAN (4) puts it, we must assume hydrothermal solutions of *a very special kind*, it seems quite unreasonable to attempt to maintain the idea of a hydrothermal origin for these ores.

In his speculations on the ore genesis SHAND (39) goes a step farther back in his desire to know the conditions so to say in the initial state. In his petrology he says in the chapter on ores and rocks—a very inspiring chapter—that it would not be wise to suppose that all ore of the kind (sulphide ores on the whole) had their origin in magmatic rocks. He is certainly quite right in that, but it transpires that SHAND is anxious to evolve a common principle for sulphide ores of all kinds; that undoubtedly would not be prudent either. The principle of convergence should not be overlooked. Even if for instance we may have copper sulphide ores in wholly different parageneses and yet see far-reaching mutual traits in them, there is nevertheless a possibility that some may be purely magmatic and others decidedly hydrothermal. The points of similarity may be a result of the compounds having been the same and of their having the common trait of having passed through the same range of temperature in the same manner. One may originate from temperatures lying just a trifle above the particular range, whereas the other perhaps emerged from a medium whose temperature originally was several hundred degrees higher than the supposed interval. In this manner it is easy — and should be easy — to find many mutual traits between copper-rich sulphides from a nickeliferous pyrrhotite ore and similar sulphides from hydrothermal copper-iron sulphide ores proper.

It will certainly be wise to reckon with two radically different principles for the formation of sulphide ore: one applying to a magmatic ore of the kind to which nickeliferous pyrrhotite is here considered to belong, and one applying to hydrothermal ores proper. Genetically, nickeliferous pyrrhotite belongs to its basic magma and has always existed as a sulphide material in it, whereas the other sulphide ores cannot claim a similar relationship to any particular form of rock, even if of course they occur in certain predilective environments. In their occurrence the latter are governed by certain mineralizers and are placed in accordance with the nature of these, whereas the former are natural to the place they occupy.

Shand points out that one of the principal difficulties with nickeliferous pyrrhotite ores is that the amount of thiophil elements in ordinary gabbroes is so small as to make it difficult to imagine how an ore can be so effectively separated by gravitation alone from the dominating silicatic matrix as in these ores; at the same time he raises the question of why they are separated as sulphides and not as oxides or silicates. As has been said, it is my opinion that the metals are present with a corresponding quantity of sulphur as a natural component of the rocks concerned, just as naturally as in meteorites we find a similar complement of sulphides besides metallic elements. Whether the sulphides were actually dissolved in the silicate melt, or they were present as mechanically in-mixed components in the magma, is difficult to decide, and opinions will depend upon the estimation of the quantities observed. As Vogt's researches (51) show, it is quite possible that very small quantities are present as dissolved sulphides in the silicate melt.

Shand also raises the question of how the small quantities of sulphide material can become effectively concentrated into the large ore bodies we now see. The explanation perhaps lies in Scholtz's hypothesis of the processes leading to the formation of the ore body, in other words: in the very presence of the gases dissolved in the sulphide phase we may perhaps have the medium for facilitating concentration or even for assisting it.

If this is so, however, a very interesting question becomes involved: Do the gases belong to the wholly original components of the magma, and was it merely the change in the external conditions—the occasion for the intrusion—that actuated the differentiation with the aid of the gases, or were these gases first absorbed after the initiation of the intrusion processes—from the wall-rock—and is it thus the direct supply of the gases that started the unmixing of the sulphide material in the form of large, concentrated masses? (It should perhaps be remarked that the ore can by no means be called hydrothermal, or pneumotolytic, just because it may be necessary to credit the gases with a rôle so important as that suggested. Here the gases may be regarded as a kind of lubricant, not as the bearer of the total material precipitated as sulphide.)

In this connection it would certainly be useful to have an analysis from the intrusion environment at various deposits of nickeliferous pyrrhotite. Certain special conditions seem to be in evidence. For example, mention is usually made of the presence of shales, or various metamorphic derivatives of these rocks, either as bordering directly on the ore deposit or at least in close association with it. If there are bituminous shales, as seems to emerge from some descriptions, there is a possibility that the magma absorbed not only water and carbon dioxide, but hydrocarbons too. This brings an entirely new factor into the picture and it is possible that the pressure-temperature conditions at the site of the intrusion will be of particular importance as regards these substances. As was mentioned at the beginning of the section on the main factors in the composition of the ore picture, the long-familiar deposits of native iron in basalts in Disko island may be a result of certain special processes, in which low pressure at the spot was a main factor in the determination of the final form of the ore. In order to throw more light upon this I shall very briefly describe the conditions connected with the metallic iron from Disko as we know them today.

Drops of Native Iron in Basalt — Original Mineralization of Nickeliferous Pyrrhotite.

It was stated earlier in this work that LÖFQUIST and BENEDICKS (22) had studied the nickeliferous pyrrhotite from Igdlukúnguaq from the viewpoint that the native iron in the Disko basalt may be the product of a natural reduction process, in which the sulphide ores were the initial material. It was in fact assumed that material from Igdlukúnguaq had contributed to the formation of the large blocks of metallic iron in the locality known as Uivfaq. It will not be out of place to remark here that the two localities, Uivfaq and Igdlukúnguaq, are both situated in the island of Disko but at opposite corners, SW and NE, and between the two lies a rather mountainous region.

The large blocks of almost pure iron are most conspicuous, of course, but an explanation of the formation of the metallic iron must be based on more than that; the explanation must also be applicable to the extensive basalt deposits which contain droplets of metallic iron diffused throughout the rock. These rocks are to be found along the more or less 100 km of West coast and on the North coast of the island (Steenstrup, 44, and O. B. Bøggild, 8, 9). The blocks of iron must be regarded as a special concentration of these droplets.

It is not the intention here to reject the idea of the genesis of the metallic iron through a natural process of reduction; moreover, from the composition of the iron, containing inter alia about 2 per cent. nickel, it seems to be a reasonable assumption that the initial material was nickeliferous pyrrhotite. Within the region are coal-bearing Tertiary deposits intersected by the basalts, and Löfquist & Benedicks believe that coal from these deposits was active in the supposed processes. It seems difficult to imagine, however, that the small, scattered drops of metal in the rocks were formed by reduction with the assistance of coal from these deposits, having regard to the area covered by the rocks and the even distribution of the drops in them.

In order to illustrate the relations of this metallic iron I have reproduced two microphotographs of iron droplets in the basalt, Pl. XX, 1, 2, but they need not be described here. Besides cohenite, the cementite of metallurgy, there are rather frequent occurrences of graphite in the basalts as evidence of the co-operative action of carbon in the processes which led to the formation of the iron. The metal drops themselves may measure one or two millimetres across, though some almost a centimetre in size are seen now and then, but the size may also diminish to tenths of a millimetre, and sometimes the iron is observable merely as a fine pigmentation in the rock. It should also be mentioned that grains of sulphides are found here and there. The main component is iron sulphide. In it both chalcopyrite and pentlandite are observed. Concerning the chalcopyrite it is of interest to note that this mineral rather often is seen as lamellae of the flame type known from Igdlukúnguaq (see f. i. page 148 no. 3 in the table). This feature seems to indicate a close connection between the material in question and the Igdlukúnguaq ore.

One is naturally at liberty to assume that the drops of metal were part of the rock's primary components which had been borne up from the deeper parts of the earth; but that assumption would hardly be reasonable. It would place the Greenlandic plateau basalts in a most unique position as regards the origin of the magma, as long as metallic iron is not known as a "normal" component of plateau basalts. Petrographically the Greenlandic rocks do not differ remarkably from other known plateau basalts. And as iron in the free state is not of very frequent occurrence, there must after all have been conditions here which did not behave in the usual manner.

In a discussion on the subject with Professor ARNE NOE-NYGAARD he referred to the frequency of bituminous shales in the region and pointed out that they might have played an important part in the reduction processes. Here and there the shales contain such large quantities of organic material that they are liable to ignite through the slipping of steep cliffs (see i. a. ROSENKRANTZ, 31).

In these shales, which are widespread in the region, we thus have a very interesting possibility of elaborating the idea of a natural reduction process which, it seems to me, is more acceptable as a solution of the problem set by the small scattered droplets of metal.

If before the ultimate intrusion the magma was contained within a chamber where it was in contact with the shale rocks, the latter may have been deprived of their hydrocarbons by a distillation, from which the gases would spread evenly through the magma. This would give the sulphide drops an opportunity to absorb hydrocarbons, but this cannot be synonymous with the starting of a transformation from sulphide to free metals. We must assume that the pressure in the magma was considerable, at any rate while in the chamber. The redox processes, which we must presume were active in conjunction with the conversion of sulphides to metals, involve inter alia the formation of gases, liberation of hydrogen sulphide etc., and that is not compatible with the supposed pressures. It must mean that the conditions governing the intrusion directly determined the further development of the phases involved. The balance between the various gases present is of course of great importance too.

The thickness of the basalt deposits is usually estimated at several kilometres — sometimes right up to ten. This would mean that the magma chamber was at such a depth that the pressure may have been several thousand atmospheres. The intrusion carried the magma up to levels near the surface, providing an occasion for a drastic release of the pressure, the result of which, I consider, was the formation of the metallic drops in the rock.

The circumstances mentioned in the previous section that in association with deposits of nickeliferous pyrrhotite there often are shales which may even be classified as bituminous shales, indicate that the Greenlandic deposits of basic rock together with bituminous shales are not necessarily unique. The particular factor which gave rise to the formation of free iron in the rocks must thus be the conditions accompanying the intrusion, where in the Greenland deposits it is fairly safe to reckon with a considerable release of pressure. On considering the deposits of nickeliferous pyrrhotite in other parts of the world it is obvious that they intruded at deeper levels. They occur in the form of laccoliths, large sills etc. Under such circumstances there need not have been such great releases of pressure as those reckoned with in connection with an intrusion of the Greenlandic kind.

The basic nickeliferous-pyrrhotite-bearing dike, to whose ore this work as a whole is devoted, lies in practically the same environment as the metal-bearing basalts, and it would be unsafe to preclude the possibility that this rock was also in a position to absorb similar gases during its existence as magma. The presence of siderite in the ore, however, shows that the pressures there did not develop at all in the manner suggested as regards the metallic iron. In the dike it was possible to store rather high pressures, and therefore the sulphide mass there was not converted into a mass of metallic iron. If there had been a pressure release here too, the assumption is that Igdlukúnguaq would have borne iron in masses corresponding to the blocks at Uivfaq. Curiously enough STEENSTRUP (45) long ago compared these two deposits, pointing out that as at Uivfaq, dense masses were carried up with the basalt in the Igdlukúnguaq rock. The fact that the two different masses appear under forms permitting of the drawing of certain parallels is due, among other things, to their melting points being fairly close together.

ACKNOWLEDGEMENTS

In the course of an examination of the Greenlandic collections at the Mineralogical Museum in Copenhagen during and just after the Second World War, I was invited by Professor ARNE NOE-NYGAARD to scrutinize the ore minerals among them. It was while microscoping these samples that my attention was drawn for the first time to the interesting ore from Igdlukúnguaq. I realized at once that it called for a closer study, and Professor NOE-NYGAARD for his part then urged me to tackle this special subject. However, in the years immediately following my time was fully occupied with several other tasks and the year 1951 arrived before I was in a position to devote myself in earnest to studying the Igdlukúnguaq ore.

Early in 1952 Professor NOE-NYGAARD was approached by Professor P. RAMDOHR of Heidelberg, who had had occasion to see samples of the Igdlukúnguaq material in Stockholm. Professor RAMDOHR wished to draw attention to the interesting problems that were obviously contained in the ore, which of course in itself was highly encouraging for me to hear. Professor RAMDOHR moreover was kind enough to invite me to Heidelberg, where I could continue working on the ore and utilize the opportunities for making comparisons with other ores reposing in Heidelberg in the form of comprehensive collections of polished samples. I was delighted to accept the offer and it is self-evident that it had a highly important bearing on the compilation of the present work, not to speak of the fact that my sojourn at Heidelberg on the whole was a source of inspiration to me. It is therefore a privilege here to extend my warmest thanks to Professor RAMDOHR. I am also grateful to Dr. E. SEELIGER, who worked with Professor RAMDOHR, for animated and interesting discussions and pleasant conversations about the problems.

As will appear from the foregoing, Professor RAMDOHR took a number of the microphotographs reproduced here. Through him I also received several from Dr. H. REHWALD, for which I now record my thanks.

To Professor E. KNUTH-WINTERFELDT and Mr. E. LANGER, M.Sc., of the Laboratory of Metallurgy, Denmark's Technical University, my heartfelt thanks for the interest and readiness with which they acceded to my wishes to perform experiments with the heating of ore samples.

While on a study visit to Stockholm in 1946 I had an opportunity of submitting a sample of the ore to Dr. S. LANDERGREN, head of the Geochemical Department of S.G.U., who very kindly undertook to make a spectrographic analysis of the material.

In conjunction with the expeditions of the Greenland Geological Survey to the Umanak district, Professor A. ROSENKRANTZ on several occasions made collections of material from Igdlukúnguaq which he kindly presented to me. I must add that in many ways Professor ROSENKRANTZ has signalized his great interest in the work which I have been enabled to do.

Civil Engineer TH. DODDS, of Broken Hill, New South Wales; keeper H. GRANLLI, Oslo; Dr. G. KULLERUD, Chicago, and Professor M. SAKSELA, Helsingfors, have all been kind enough to present me with nickeliferous pyrrhotite material from various other deposits in the world and of great use to me in this work.

May I express my warmest thanks to all.

It is a pleasure to me to utilize this opportunity to voice the gratitude which I feel for the possibilities with which I have been favoured at the Kryolitselskabet Øresund A/S for much research work essential to my purpose. This applies for example to the preparing of the polished samples, employing an automatic plane-polishing machine (of German make), and the photographic work.

To Mr. H. BUCHWALD, chief chemist of the company, I tender my best thanks for his analysis of the ore, and also to Mr. A. H. NIELSEN for the individual chemical determinations made for me.

Mrs. SOLE MUNCK, M.Sc., curator at the Mineralogical Museum Copenhagen University, has helped with materials of various dike rocks from Disko and I have had many interesting discussions with her on matters relating to the position of these rocks. For this I am glad to make use of the present occasion to express my thanks, and also to Mr. CHR. HALKIER, leader of the photographic laboratory at the same institution for much valuable advice and guidance on the photographic work, and especially for the photographs which he kindly prepared for me.

I must also take this opportunity to extend all due thanks to the Ministry of Greenland for permission to make use of the reports on divers investigations concerned with the deposit at Igdlukúnguaq, with special thanks to Mr. ESKE BRUN, permanent undersecretary for Greenland, for permission to publish extracts and maps from them.

The manuscript for this work was fair-copied by Mrs. I. ROSENBERG. The translation has been made by Mr. W. E. CALVERT. I want to express my best thanks to both for the good collaboration.

The study journeys which I have made in connection with the work could only have been undertaken with the aid of various grants. I need hardly say that they have been of fundamental importance to my ore studies, and for this support I wish to express my sincere thanks to the Copenhagen University.

In closing, I feel it but natural to thank Professor ARNE NOE-NYGAARD, not only for his interest and support in the work on this present study, but on the whole as my teacher. By his liberal outlook on the problems he has succeeded in inspiring and encouraging those who studied under him; he has not only tried to instil in us a knowledge of the intrinsic nature of science, but also to demonstrate geology as an active science of practical life.

I hope that by means of this work I have gone some way towards fulfilling his justified expectations of his pupils.

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Færdig fra trykkeriet den 4. juni 1958.

PLATES

Plate I.

1. Thin section, × 285 + nicol.
   Detail of the boundary of the zeolite-infilled cavity, showing that the feldspar laths in the rock are arranged in conformity with the cavity boundaries. See page 22. H.P. photo.

2. × 2.
   Rhombohedron-like piece of pyrrhotite. Actually it consists of six pyrrhotite individuals, and all planes are basal planes in the pyrrhotite. (STEENSTRUP's material from 1873). See pages 27, 72. H.P. photo.

3. Polished section, × 35. 1 nicol.
   Slightly polished natural basal plane in the pyrrhotite, clearly showing the dendritic pattern of pale sulphide inclusions, many with small cavities. The picture also shows pale, rectilinear lamellae of another sulphide intersecting the pyrrhotite along three systems forming mutual angles of 60°. See pp. 28, 72. H.P. photo.

4. Polished section. × 73. 1 nicol.
   Slightly polished natural basal plane, showing a single dendrite. See pp. 28, 72. H.P. photo.

5. Polished section, × 88, 1 nicol.
   Natural basal plane in the pyrrhotite, polished somewhat more than the plane shown in fig. 4. The dendrites are hardly perceptible, though the pale sulphide inclusions in the pyrrhotite seem more numerous. The rectilinear lamellae along three directions are still present. See page 25. H.P. photo.

6. Polished section, × 95, 1 nicol.
   Natural basal plane in the pyrrhotite, vigorously polished. The pale sulphide inclusions, exsolution bodies, originally of chalcopentlandite, in large numbers evenly distributed in the pyrrhotite. Note the often triangular shape of the inclusions. The pale, rectilinear lamellae, exsolution lamellae of chalcopyrite in the pyrrhotite, are still present but difficult to see in the reproduction. When visible, it is seen that their direction is at right angles to the boundary of the equidimensional inclusions. See pp. 29, 32, 44. H.P. photo.

Fig. 1 (285×)

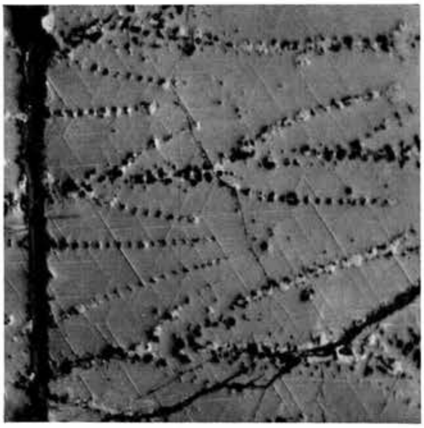

Fig. 3 (35×)

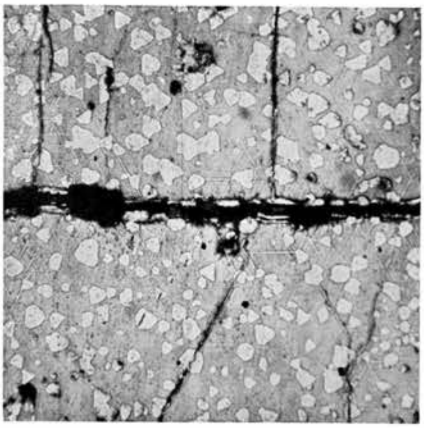

Fig. 6 (95×)

Fig. 2 (2×)

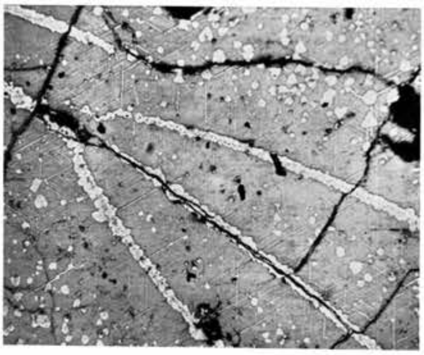

Fig. 4 (73×)

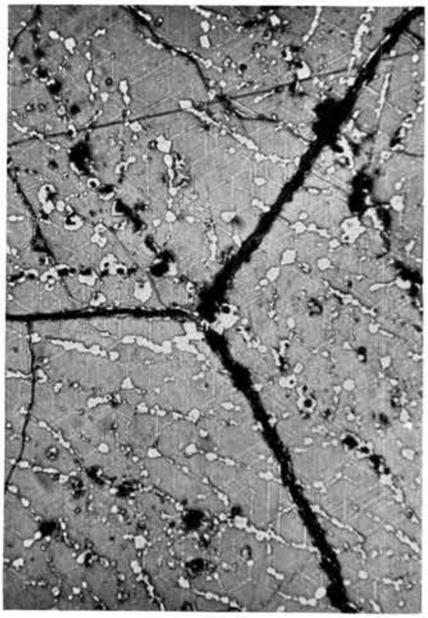

Fig. 5 (88×)

Plate II.

1. Polished section, × 20, 1 nicol.
   Ground and polished natural basal plane of pyrrhotite. The pyrrhotite visible as islands in the area, surrounded by paler sulphides. In the pyrrhotite are darker inclusions of magnetite. All pyrrhotite areas are oriented in the same manner, i. e. (0001). The pyrrhotite still contains chalcopyrite in a triangular system. The material of the chalcopentlandite exsolution bodies are also still present in the pyrrhotite, surrounding the magnetite grains but barely visible in the reproduction. See pp. 25, 29, 34. H.P. photo.

2. Polished section, × 125, 1 nicol.
   Section in the direction of the base in the pyrrhotite. Magnetite with rims of chalcopentlandite material, now pentlandite and chalcopyrite, and rectilinear lamellae of chalcopyrite visible in the pyrrhotite, which is surrounded by pale sulphides consisting of chalcopyrite and chalcopentlandite material, now pentlandite and chalcopyrite, bordering directly on the pyrrhotite. See pp. 25, 29, 31, 34, 39, 44. P.H. photo.

3. Polished section, × 280, 1 nicol.
   Magnetite surrounded by chalcopentlandite inclused in pyrrhotite. Note the rectilinear boundaries of these pale inclusions in the pyrrhotite in the right bottom corner. The zonality in the magnetite is distinct and two magnetite grains are visible with central cavities. In the pyrrhotite are the rectilinear chalcopyrite lamellae, and "pore mass", consisting of chalcopyrite and pentlandite, can be seen intersecting the pyrrhotite like a vein which exhibits distinct corrosion of the pyrrhotite; a crack partly infilled with limonitic material appears in the pale sulphides. See pp. 29, 31, 46. HALKIER, photo.

4. Polished section, × 585, 1 nicol.
   Pentlandite flames and chalcopyrite lamellae in the pyrrhotite. The latter are sheared and staggered by the pentlandite flames. The pyrrhotite α and β lamellae are faintly visible. See p. 36. H.P. photo.

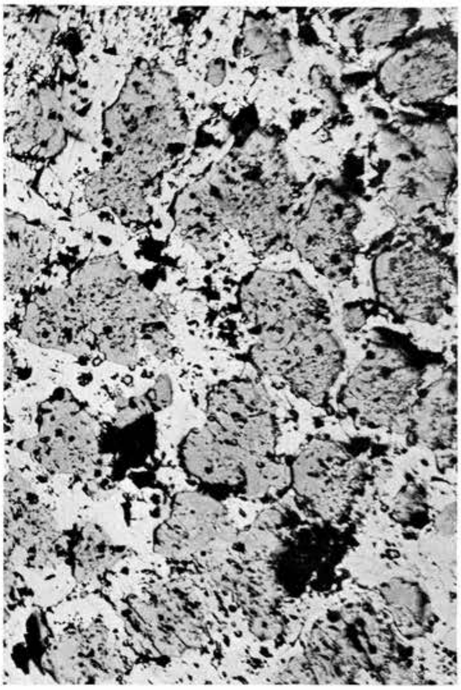

Fig. 1 (20×)

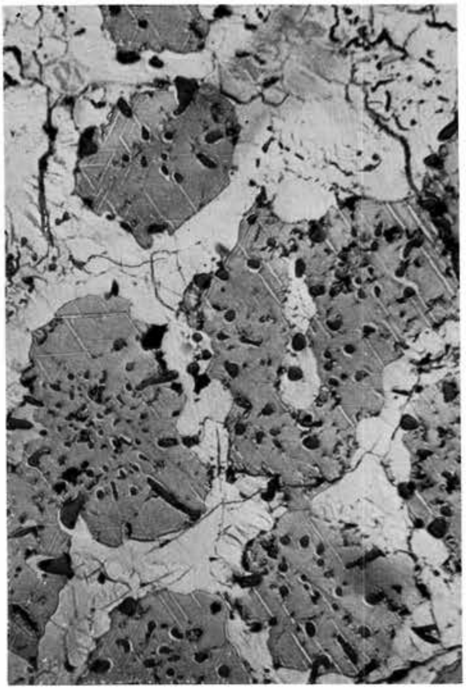

Fig. 2 (125×)

Fig. 3 (280×)

Fig. 4 (585×)

Plate III.

1. Polished section, × 73, 1 nicol.
   Section at right angles to the natural basal plane ((0001) at right angles to the picture plane along the left edge). Several systems of chalcopyrite lamellae, pale, rectilinear are visible. See pp. 25, 29, 34, 72. H.P. photo.

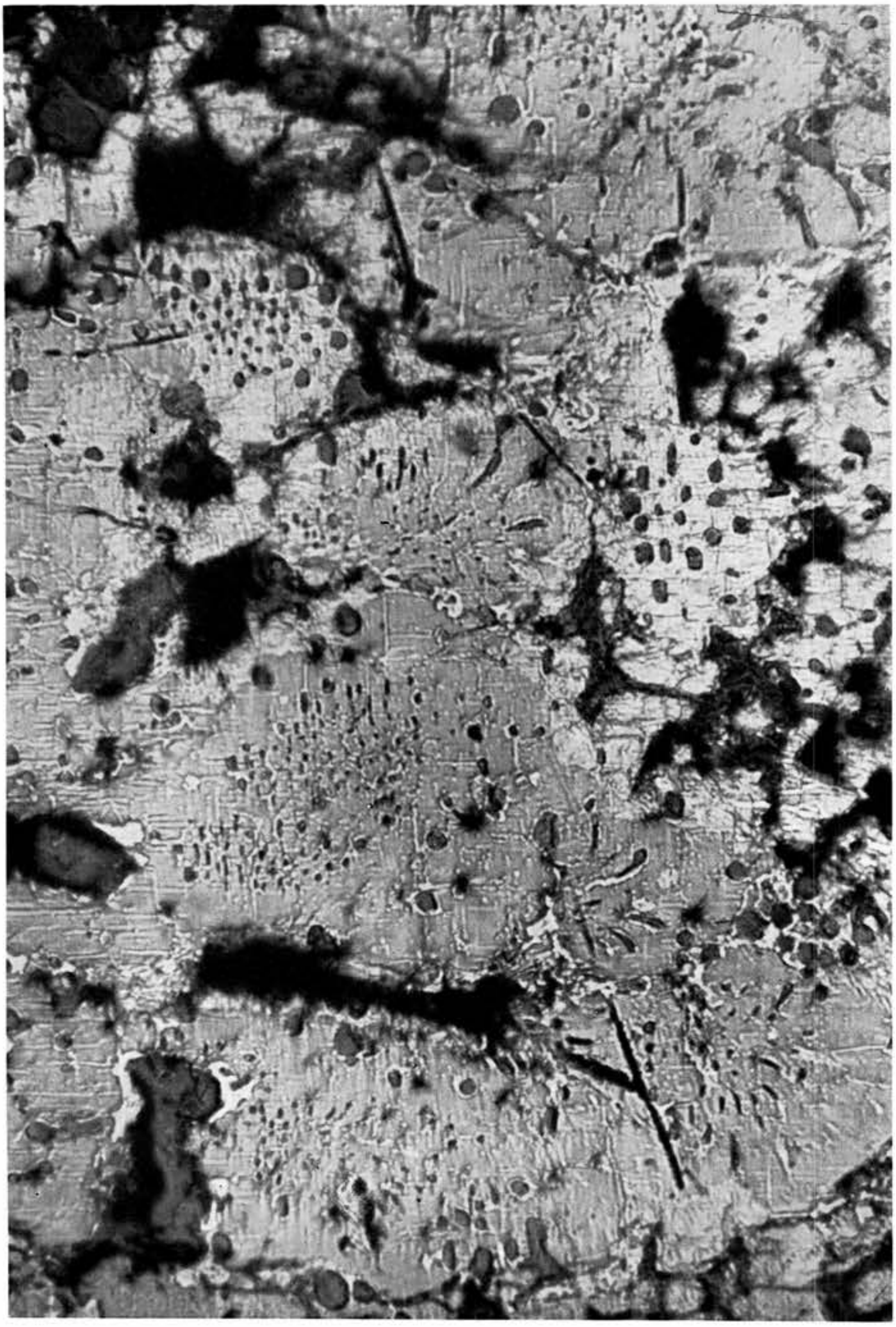

Fig. 1 (73×)

Plate IV.

1. Polished section, × 293, 1 nicol.
   Chalcopyrite lamellae which are flame-like. Two generations visible. The small ones are pure chalcopyrite lamellae, whereas the large ones have pentlandite sparks (along (0001) in the pyrrhotite) along the sides, with the appearance of serrated edges. See page 37. RAMDOHR, photo.
2. Polished section, × 583, 1 nicol.
   Pentlandite flames with valleriite inclusions. There are also chalcopyrite lamellae in the pyrrhotite. See page 36. H.P. photo.
3. Polished section, × 560, 1 nicol.
   Pore mass surrounded by pyrrhotite, and showing a cracked area of chalcopyrite. On the left below is a flame-like lamella of chalcopyrite in the original chalcopentlandite of the pore mass. See pp. 36, 37, 40. H.P. photo.
4. Polished section, × 560, 1 nicol.
   Chalcopentlandite material as pore mass between areas of pyrrhotite. A little chalcopyrite (paler) visible in the border of the pore mass against the pyrrhotite. The division of the chalcopentlandite into two phases, pentlandite and chalcopyrite lamella, is faintly perceptible. See pp. 38, 43. H.P. photo.

Fig. 1 (293×)

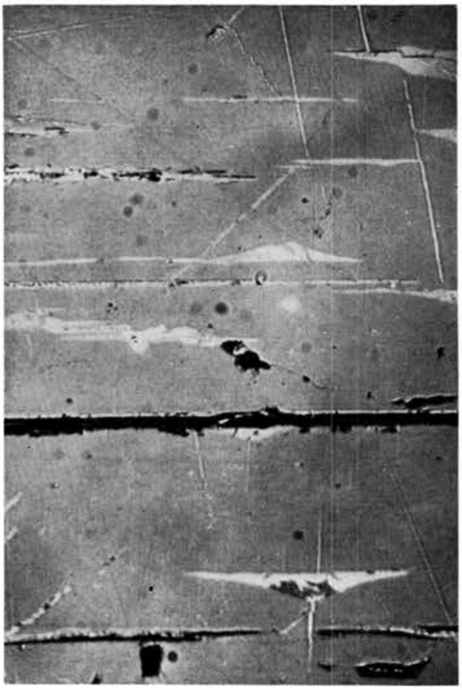

Fig. 2 (583×)

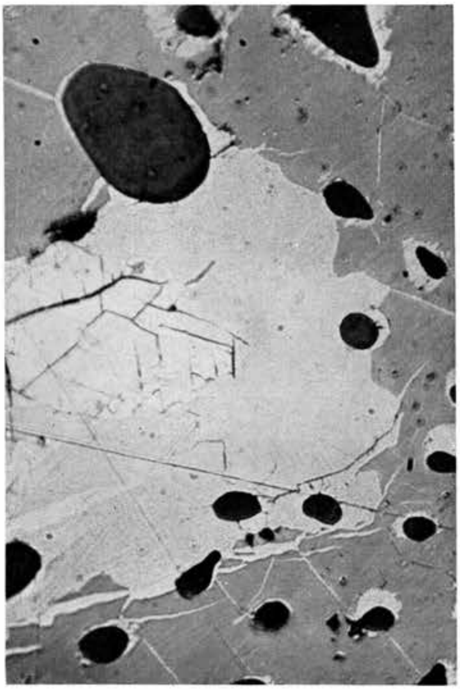

Fig. 3 (560×)

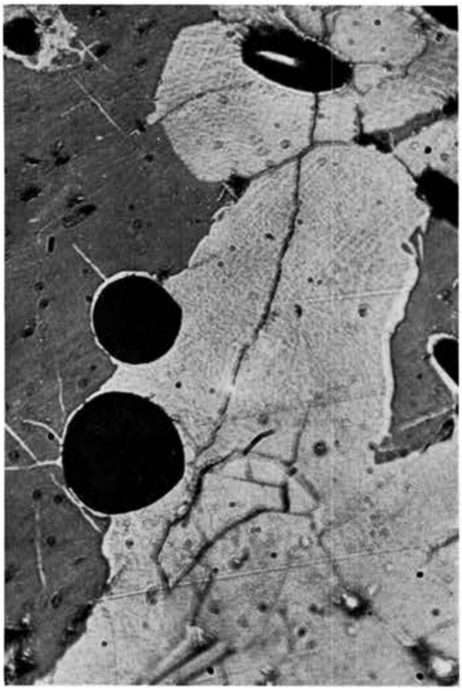

Fig. 4 (560×)

Plate V.

1. Polished section, × 327, 1 nicol.
   Chalcopyrite, intersected by cracks, in the pore mass. Pyrrhotite on the right of the picture. Below in the centre is chalcopyrite with lamella-shaped cracks. This chalcopyrite is presumably pseudomorphic after cubanite. See page 42. H.P. photo.

2. Polished section, × 1150, 1 nicol.
   Slightly bravoitized area with pentlandite in the pore mass. See page 38. FINDEIS, photo.

3. The same area with negative phase contrast. The binary structure in the original chalcopentlandite is distinctly visible. The slightly bravoitized pentlandite includes chalcopyrite lamellae in the direction (111). See page 38. FINDEIS, photo.

4. The same area with positive phase contrast. See page 38. FINDEIS, photo.

5. Polished section, × 1230, 1 nicol.
   Magnetite grains surrounded by the binary structure after chalcopentlandite; negative phase contrast. See page 38. FINDEIS, photo.

6. Polished section, × 440, 1 nicol.
   Pentlandite-chalcopyrite after chalcopentlandite in the pore pass. A small stop made the picture possible with usual micro-technique. See page 38. RAMDOHR, photo.

Fig. 1 (327×)

Fig. 2 (1150×)

Fig. 3 (1150×)

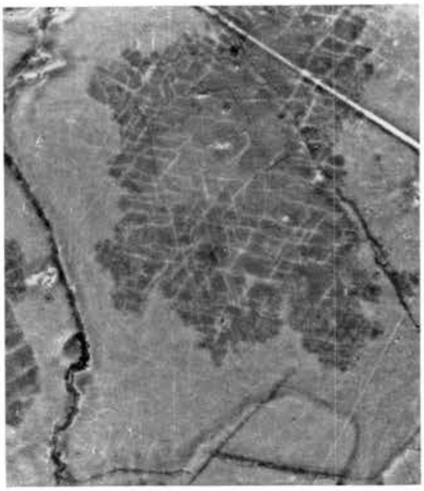

Fig. 4 (1150×)

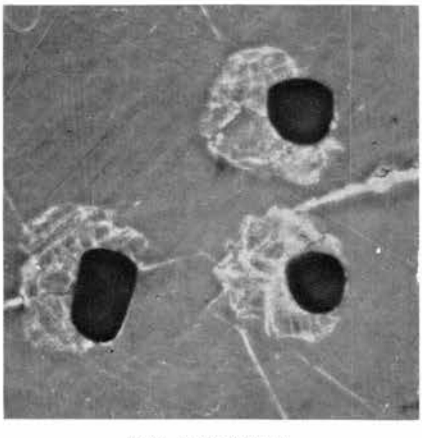

Fig. 5 (1230×)

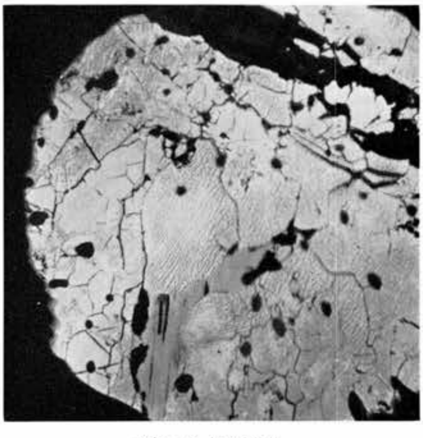

Fig. 6 (440×)

Plate VI.

1. Polished section, × 625, 1 nicol.
   Original chalcopentlandite exsolved to pentlandite with chalcopyrite. Small stop. Inclusion in pyrrhotite. The black areas are apparently holes left by torn-out grains of magnetite. See page 38. RAMDOHR, photo.
2. Polished section, × 470, 1 nicol.
   Valleriite in original chalcopentlandite in the pore mass. See page 40. H.P., photo.
3. Polished section, × 460, 1 nicol.
   Part of the pore mass between areas of pyrrhotite. Between irregular magnetite in the pore mass and the two large magnetite grains in the pyrrhotite is a pale area of sulphide surrounded by a greyish sulphide mass with the characteristic exsolution structure of chalcopentlandite. The greyish tint is due to bravoitization of the pentlandite. The pale sulphide mass inside this grey border exhibits no exsolution structure and presumably is untransformed chalcopentlandite. See page 39. H.P. photo.
4. Polished section, × 325, 1 nicol.
   Pore mass bordering upon pyrrhotite. The chalcopentlandite, exsolved to pentlandite and chalcopyrite lamellae, forms a network containing areas of chalcopyrite. In the latter are almost black magnetite grains. Note the three rectilinear systems of cracks associated with the areas of chalcopyrite. See pp. 37, 40, 47, 83. H.P. photo.
5. Polished section, × 440, 1 nicol.
   Pattern of elongated magnetite grains in the chalcopyrite of the pore mass, which is also intersected by three systems of cracks. The chalcopyrite areas lie like windows in the chalcopentlandite material, whose division into pentlandite with lamellae of chalcopyrite here is very fine-grained. See pp. 41, 47, 83. H.P. photo.
6. Polished section, × 382, 1 nicol.
   Pattern of magnetite grains in pore mass. The area consists mainly of chalcopyrite of the type that is characteristic of the central part of the pore mass. Note the three crack systems and an incipient bravoitization from them. See pp. 41, 42, 47. H.P. photo.

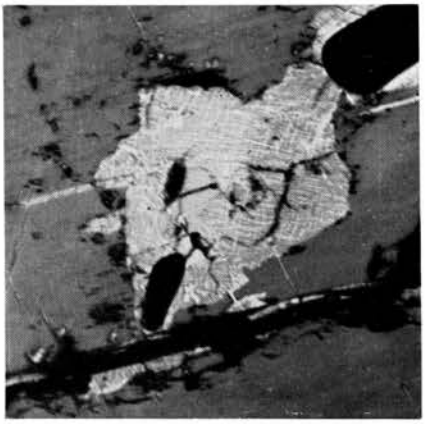

Fig. 1 (625×)

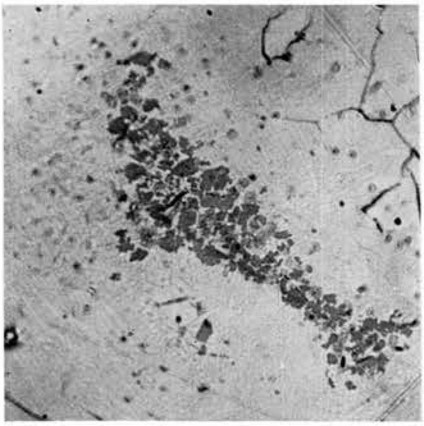

Fig. 2 (470×)

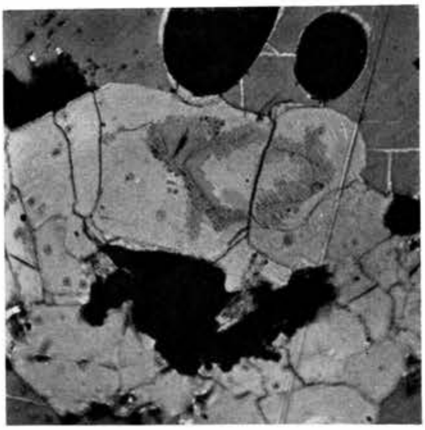

Fig. 3 (460×)

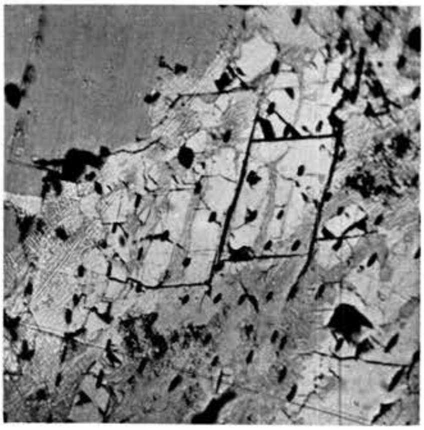

Fig. 4 (325×)

Fig. 5 (440×)

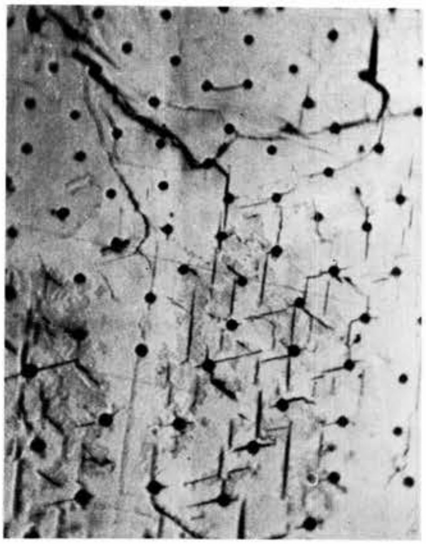

Fig. 6 (382×)

Plate VII.

1. Polished section, × 560, 1 nicol.
   Pore mass, surrounded by pyrrhotite. In the pale sulphides of the pore mass in the middle picture are greyish areas of a mineral supposed to be galena (badly polished). See page 43. H.P., photo.
2. Polished section, × 580, 1 nicol.
   Myrmekite between magnetite and chalcopyrite of the type usually characterized by a lamination of cracks, interpreted as original cubanite. See page 42. H.P. photo
3. Polished section, × 255, 1 nicol.
   Pattern of magnetite in pyrrhotite, the section parallel with the C-axis. Siderite with a magnetite border on the left in the picture. See page 44. H.P. photo.
4. Polished section, × 295, 1 nicol.
   Pattern of magnetite in pyrrhotite, the section in the direction of (0001). See page 44. H.P. photo.

Fig. 1 (560×)

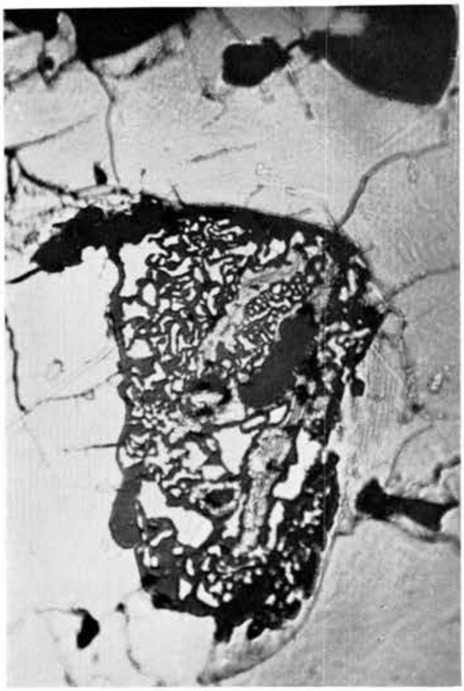

Fig. 2 (580×)

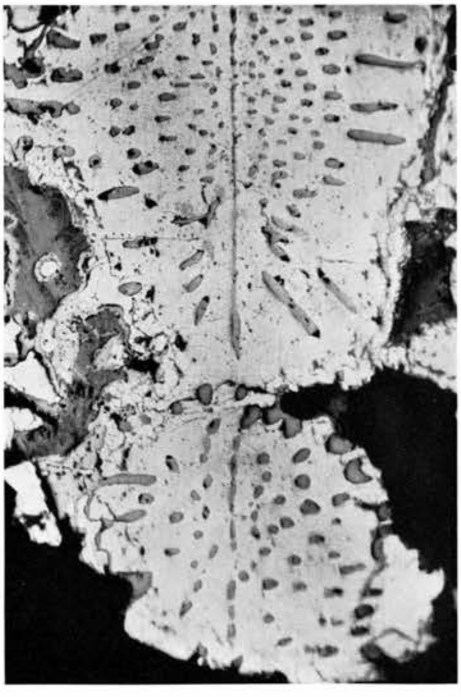

Fig. 3 (255×)

Fig. 4 (295×)

Plate VIII.

1. Polished sample, × 53, + nicols.
   Magnetite in pyrrhotite of fortuitous orientation. All the pyrrhotite, pale, is of the same orientation, the same individual. See pp. 44, 86. H.P. photo.

2. Polished section, × 63, + nicols.
   Pattern of magnetite in pyrrhotite (pale). The central part of the pyrrhotite—emphasized by the basal parting—is free of magnetite grains. See pp. 32, 45, 86. H.P. photo.

3. Polished section, × 250, 1 nicol.
   Characteristic appearance of elongated claviform magnetite grains in pyrrhotite. See p. 45. Rehwald photo.

4. Polished section, × 550, 1 nicol.
   Magnetite grains, the claviform with a unilateral bend owing to the growth conditions in the pyrrhotite. See pp. 45, 87. H.P. photo.

Fig. 1 (53×)

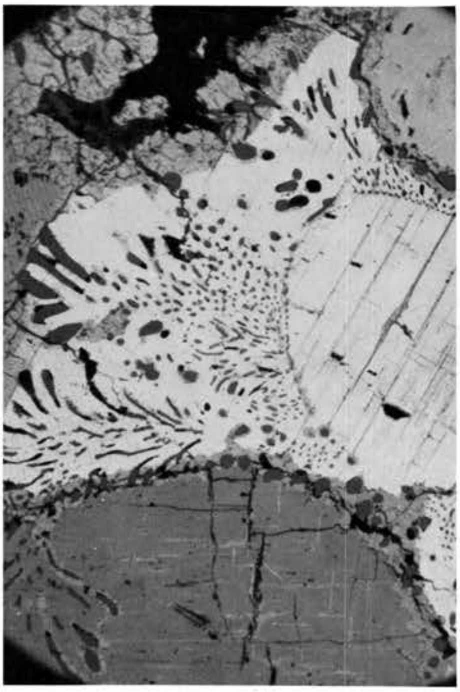

Fig. 2 (63×)

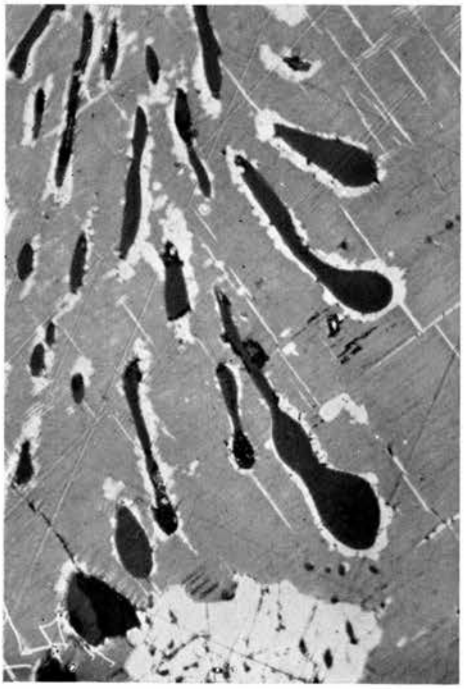

Fig. 3 (250×)

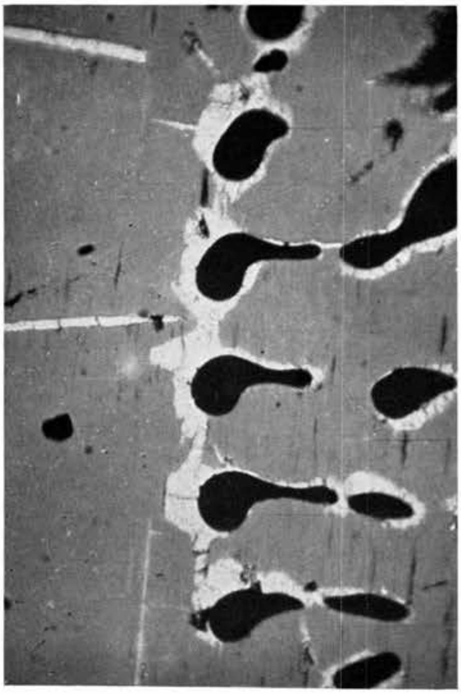

Fig. 4 (550×)

Plate IX.

1. Polished section, × 520, 1 nicol.
   Magnetite grain with zonal structure, surrounded by the binary structure that is formed by the breakdown of the chalcopentlandite. All surrounded by pyrrhotite. See page 46. H.P. photo.

2. Polished section, × 485, 1 nicol.
   Magnetite grains in pyrrhotite. The interior of the grain is intersected by lamellae of a slightly paler tone. In addition, small sulphide inclusions in the peripheral part of the grain. See pp. 46, 47, 89. H.P. photo.

3. Polished section, × 490, 1 nicol.
   Grain of idiomorphic spinel with zonal structure, imbedded in pyrrhotite with the same rim of chalcopentlandite material as exhibited by magnetite grains in pyrrhotite. See page 48. H.P. photo.

4. Polished section, × 100, 1 nicol.
   Magnetite in an irregular area together with magnetite grains of the usual type in the pyrrhotite. The two form-types may sometimes be "fused" together. Basal cracks in the pyrrhotite are very distinct. The material in them is magnetite, and also carbonate. See pp. 45, 73. H.P. photo.

5. Polished section, × 68, 1 nicol.
   Pyrrhotite with inclusions of the usual small magnetite grains and a large magnetite grain as well as one of siderite bordered by magnetite; the siderite consists of two individuals. All three types of inclusion have the same relation to the pyrrhotite, all being surrounded by chalcopentlandite material. See pp. 45, 52, 88. H.P. photo.

6. Polished section, × 480, 1 nicol.
   Broad vein of magnetite through pyrrhotite. Pentlandite flames in the pyrrhotite now partly in magnetite. See page 48. H.P. photo.

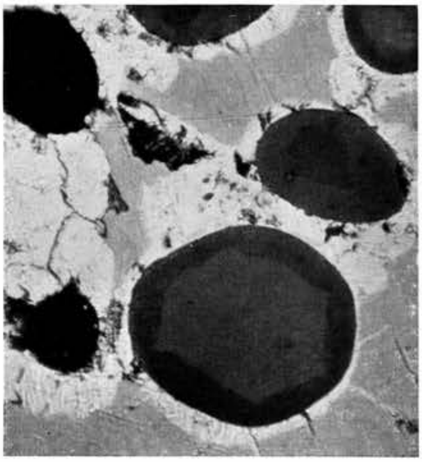

Fig. 1 (520×)

Fig. 2 (485×)

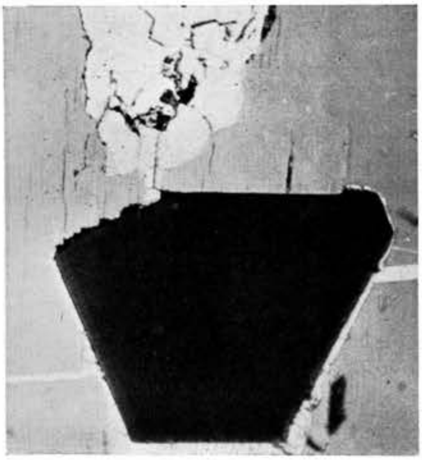

Fig. 3 (490×)

Fig. 4 (100×)

Fig. 5 (68×)

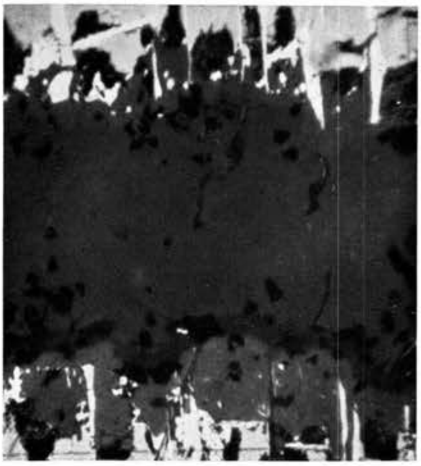

Fig. 6 (480×)

Plate X.

1. Polished section, × 405, 1 nicol.
   Magnetite vein through pyrrhotite. Note that the magnetite grain in the pyrrhotite "fuses" with the vein material and that the chalcopentlandite at such magnetite grains may border upon the vein. The mottled, greyish sulphide mass in the picture middle, adjoining the magnetite vein, is chalcopyrite with a cubanite character, seen displacing the pyrrhotite so that the latter's chalcopyrite lamellae are still recognizable in the new copper sulphide mass. See pp. 48, 91, 92. H.P. photo.
2. Polished section, ×125, 1 nicol.
   Siderite surrounded by magnetite in pyrrhotite. Together with the siderite inside the magnetite rim is an area of pyrrhotite, where the basal parting is emphasized by holes due to faulty polishing. Note the clear crystal boundary of this pyrrhotite against the siderite. See pp. 53, 88. H.P. photo.
3. Polished section, × 97, 1 nicol.
   Siderite in stellate pattern in the ore. See pp. 53, 94. H.P. photo.
4. Polished section, ×120, 1 nicol.
   Siderite of another form of eutectoid texture. See pp. 53, 55, 56, 94. REHWALD, photo.

Fig. 1 (405×)

Fig. 2 (125×)

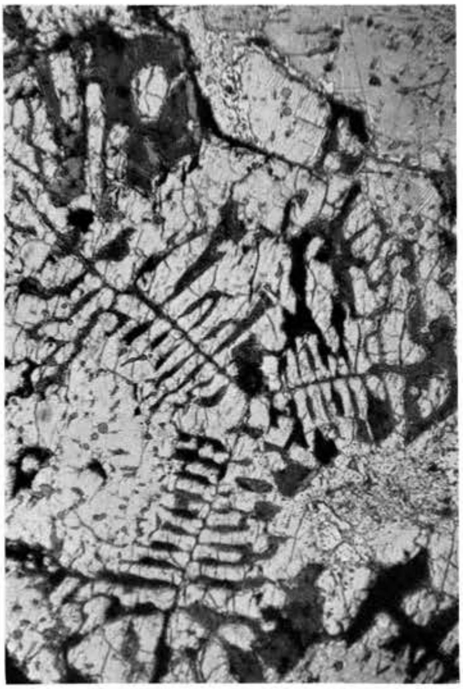

Fig. 3 (97×)

Fig. 4 (120×)

Plate XI.

1. Polished section, × 470, 1 nicol.
   Sulphides bordering immediately on eutectoid siderite; the chalcopyrite lamellae in the pyrrhotite on the extreme right run unchanged through the pale sulphides. The picture is mainly of bravoitized pentlandite and/or zwischenprodukt, but under high power both chalcopyrite and pyrrhotite can be seen in very small patches. The pale sulphides have replaced a normally developed pyrrhotite originally on the spot. See pp. 52, 56, 61, 94. H.P. photo.

2. Polished section, × 590, 1 nicol.
   Pyrrhotite in the immediate vicinity of an area with siderite in eutectoid texture. The pyrrhotite has dissolved and passed into a mixture of zwischenprodukt and non-opaque material. Sulphates may be involved here, but cannot be demonstrated in the microscope. The pentlandite lamellae remain as bravoite lamellae. See pp. 56, 58, 95. H.P. photo.

3. Polished section, × 580, 1 nicol.
   Pyrrhotite with a slightly mottled appearance. In it are pentlandite discs that have been bravoitized, chalcopyrite lamellae and a completely dissolved area now seen to contain bravoite and non-opaque material. See pp. 56, 57, 95.
   H.P. photo.

4. Polished section, × 550, 1 nicol.
   Bravoitization around broad chalcopyrite lamellae in pyrrhotite, near an area of siderite. See pp. 56, 57. H.P. photo.

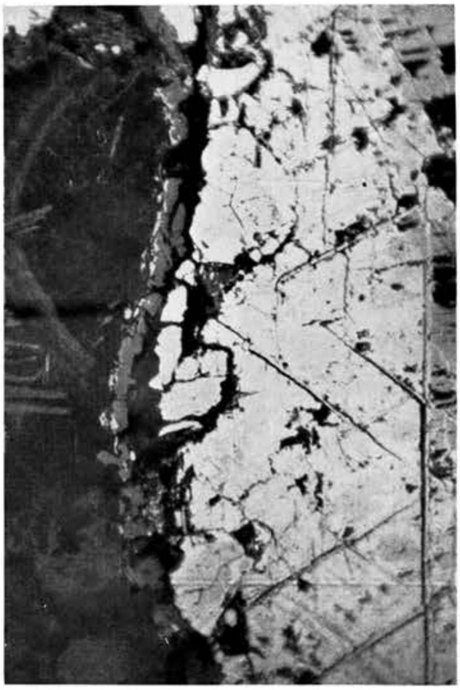

Fig. 1 (470×)

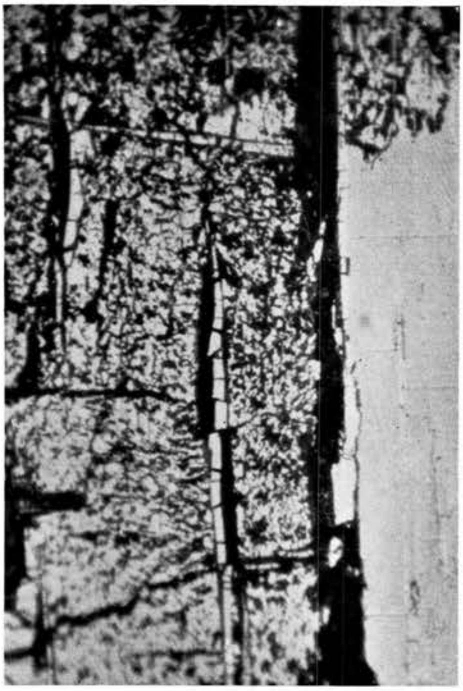

Fig. 2 (590×)

Fig. 3 (580×)

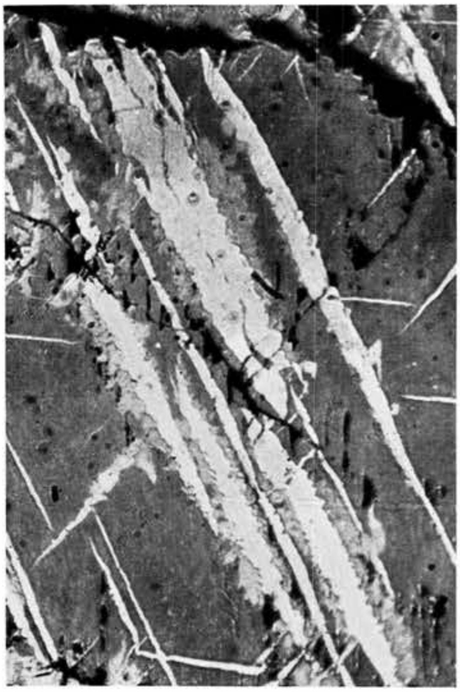

Fig. 4 (550×)

Plate XII.

1. Polished section, × 520, 1 nicol.
   Pyrrhotite with zwischenprodukt with cracks, bravoitized pentlandite discs (in the basal direction across the longitudinal axis of the picture) and a chalcopyrite lamella, also affected by the transformations. See pp. 56, 57, 58, 98. H.P. photo.
2. Polished section, × 475, 1 nicol.
   Graphite-like mineral in siderite. Part of a eutectoid pattern of siderite. See page 60. REHWALD photo.
3. Polished section, × 520, 1 nicol.
   Graphite-like mineral in siderite. The greyish inclusions in the completely black siderite consist of oxide in which are very small grains of sulphide, FeS. See page 60. H.P. photo.
4. Polished section, × 110, 1 nicol.
   Pentlandite crystals in siderite surrounded by oxidic material, placed in an irregular area of siderite of the same character as the eutectoid carbonate areas. See page 61. H.P. photo.
5. Polished section, about × 475, 1 nicol.
   Irregularly rounded area of siderite in pyrrhotite. The siderite has an oxidic border, within which is zonal sulphide pigmentation. Presumably the sulphide is pyrrhotite or zwischenprodukt. See pp. 54, 61. H.P. photo.
6. Polished section, × 400, 1 nicol.
   Zonal, and rhythmically developed sulphide (FeS) in oxide phase in picture centre, contained in siderite in eutectoid pattern. See page 61. H.P. photo.

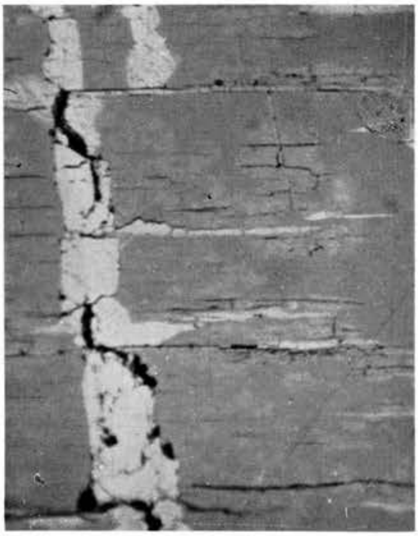

Fig. 1 (520×)

Fig. 2 (475×)

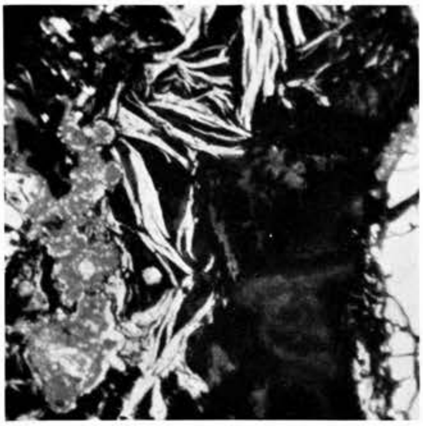

Fig. 3 (520×)

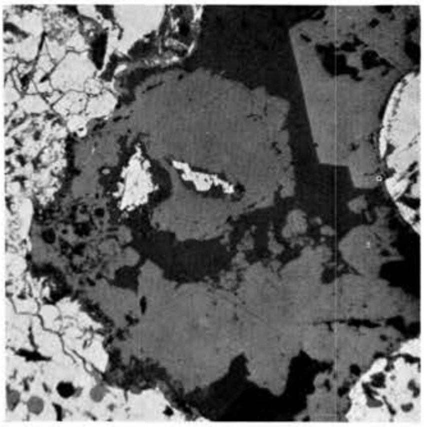

Fig. 4 (110×)

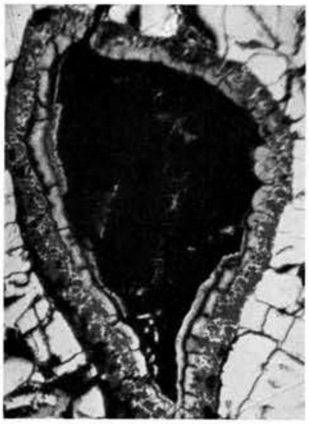

Fig. 5 (475×)

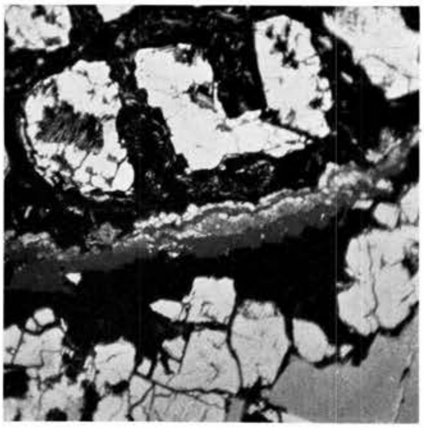

Fig. 6 (400×)

Plate XIII.

1. Polished section, about × 115, 1 nicol.
   Irregular, rounded siderite area in pyrrhotite. In the siderite is pure chalcopyrite. Just below the middle is chalcopyrite wreathed in a border of graphite-like mineral, wherein valleriite between it and chalcopyrite. See pp. 54, 59, 94. H.P. photo.

2. Polished section, × 495, 1 nicol.
   Chalcopyrite wreathed in graphite-like mineral, lying in siderite. See page 59. H.P. photo.

3. Polished section, × 150, 1 nicol.
   Coarse fingerprint structure between chalcopyrite and pentlandite. From cm.-sized ore inclusion in the dike rock. See page 39, 63. H.P. photo.

4. Polished section, × 2.3, 1 nicol.
   General picture of the two small sulphide inclusions in the dike rock. Both lie on the same side in a hisingerite-filled cavity. See page 64, 69. H.P. photo.

Fig. 1 (115×)

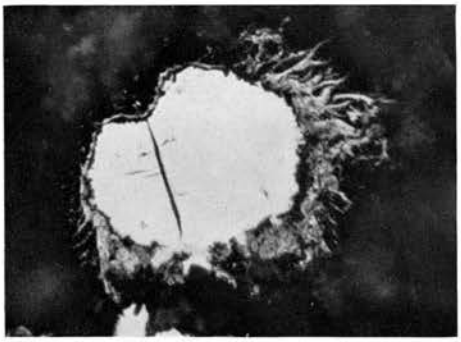

Fig. 2 (495×)

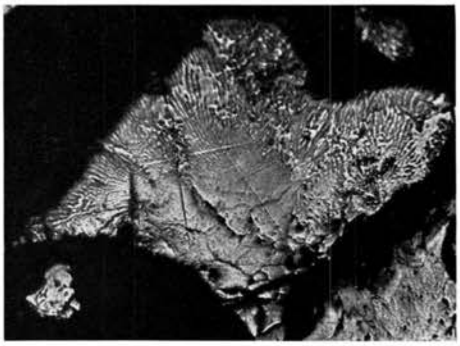

Fig. 3 (150×)

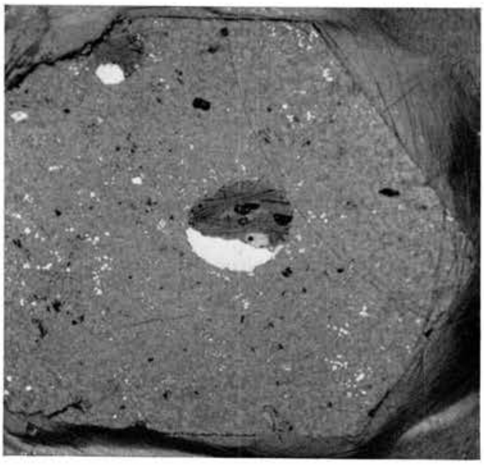

Fig. 4 (2,3×)

Plate XIV.

1. Polished section, × 225, 1 nicol.
   Pyrrhotite with lamellae of chalcopyrite studded with pentlandite, whereby it is just possible to see the chalcopyrite lamellae. Note the "crack" with chalcopyrite-pentlandite along the pyrrhotite on both sides. See page 64. H.P. photo.
2. Polished section, ×183, 1 nicol.
   Sulphides in dike rock. Some ilmenite lamellae visible. From the sample illustrated in Pl. XIII, 4. See page 65. H.P. photo.

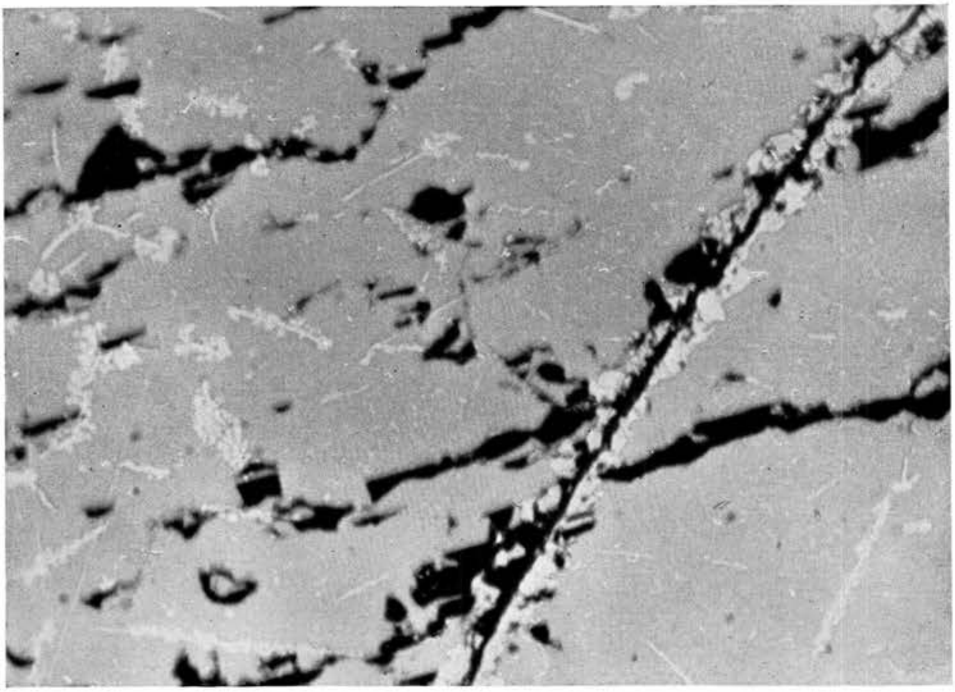

Fig. 1 (225×)

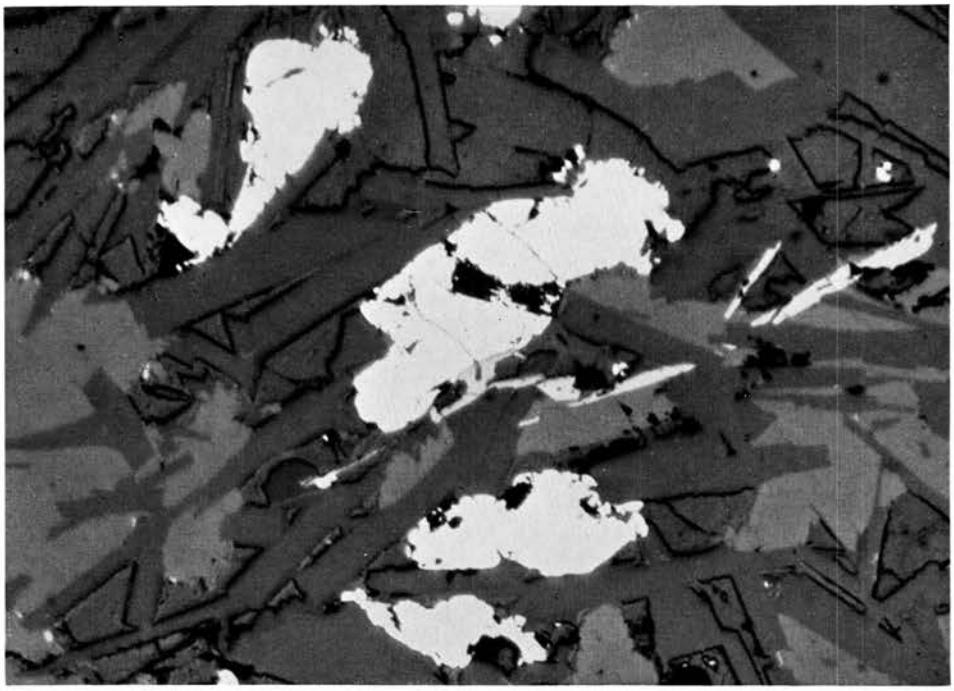

Fig. 2 (183×)

Plate XV.

1. Polished section, × 68, 1 nicol. Beiernfjord.
   Pyrrhotite with intergranular pentlandite. Note several magnetite grains in the pentlandite mass. See page 132, 134. H.P. photo.
2. Polished section, × 115, 1 nicol. Beiernfjord.
   Group of idiomorphic sperrylite grains (relief); on the left and below is pentlandite. See page 132. H.P. photo.
3. Polished section, × 230, 1 nicol. Beiernfjord.
   Chalcopyrite lamellae, flame-like, in pyrrhotite. The (0001) direction indicated by arrow. The dark component of the pyrrhotite surrounds the chalcopyrite lamellae. Chalcopyrite in large area below, right. See page 133. H.P. photo.

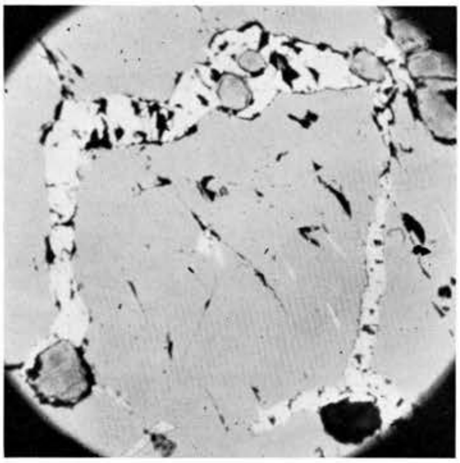

Fig. 1 (68×)

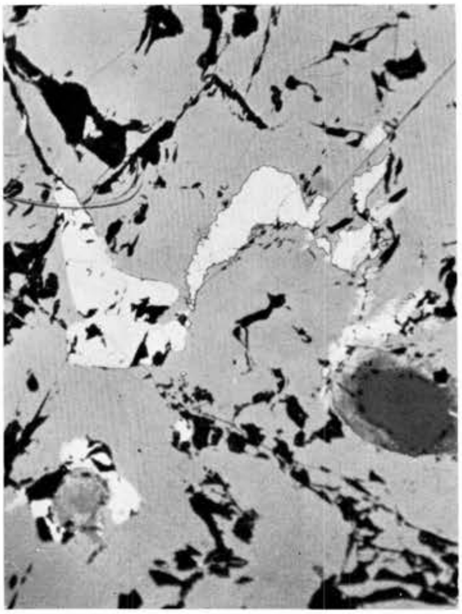

Fig. 2 (115×)

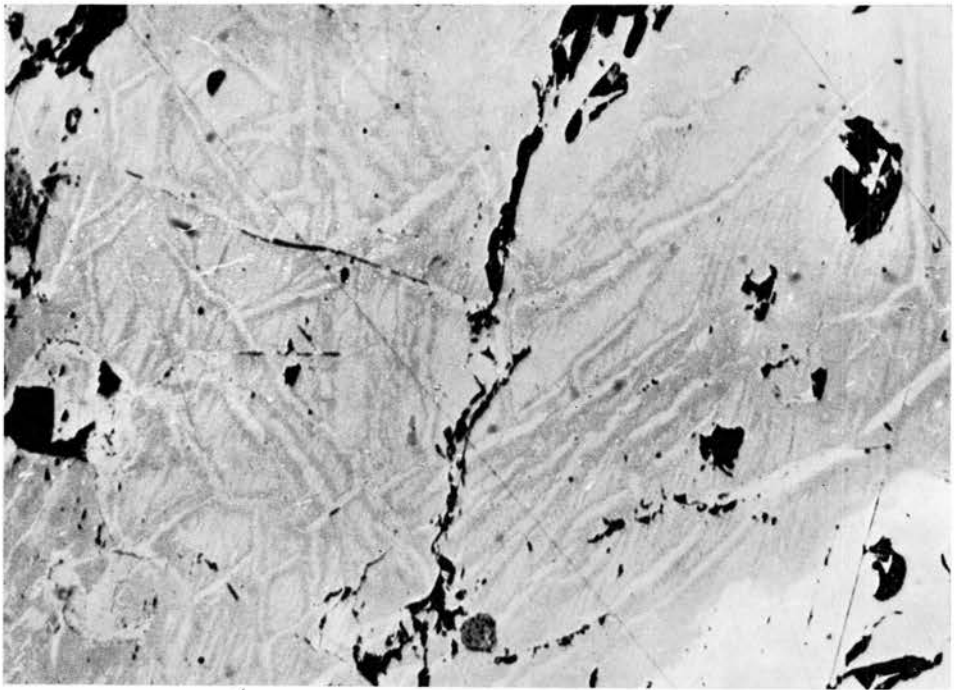

Fig. 3 (230×)

Plate XVI.

1. Polished section, × 350, 1 nicol. Beiernfjord.
   Magnetite with zonal pigmentation or colouring. See page 134. H.P. photo.
2. Polished section, × 410, 1 nicol. Beiernfjord.
   Magnetite grains in pyrrhotite. Incipient transformation to sulphide visible in margin of grains. Against these the pyrrhotite seems to have cracks, indicating a kind of "exfoliation" of the pyrrhotite. See page 134, 135, 136. H.P. photo.
3. Polished section, × 420, 1 nicol. Beiernfjord.
   Almost transformed magnetite grain in pyrrhotite. The FeS replacement in the magnetite is advancing along the (111) directions of the oxide. See page 134 135, 136. H.P. photo.
4. Polished section, × 400, 1 nicol. Beiernfjord.
   Partly transformed and wholly untransformed sharp-edged magnetite grains in pyrrhotite. See pp. 134, 135. H.P. photo.
5. Polished section, × 360, 1 nicol. Beiernfjord.
   Magnetite grain wholly transformed into FeS in pentlandite. See p. 134. H.P. photo.
6. Polished section, × 290, 1 nicol. Beiernfjord.
   Limonite in the pyrrhotite. The pentlandite flames still remain where limonite has replaced FeS. See page 136. H.P. photo.

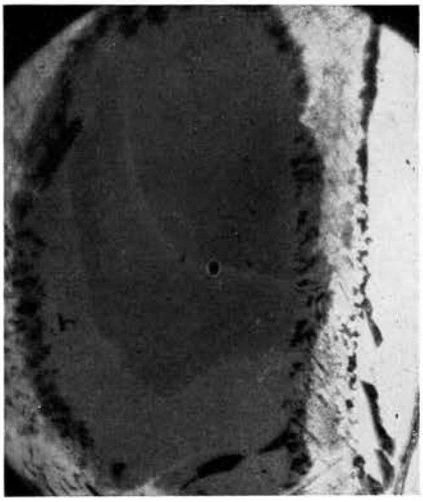

Fig. 1 (350×)

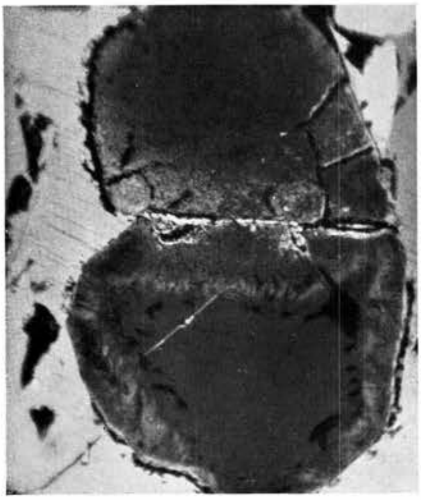

Fig. 2 (410×)

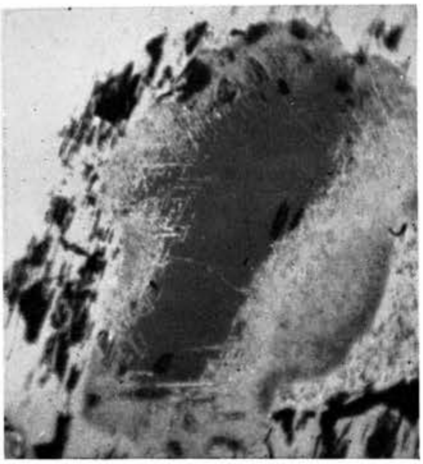

Fig. 3 (420×)

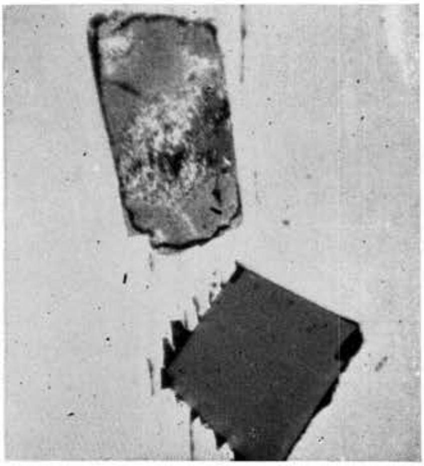

Fig. 4 (400×)

Fig. 5 (360×)

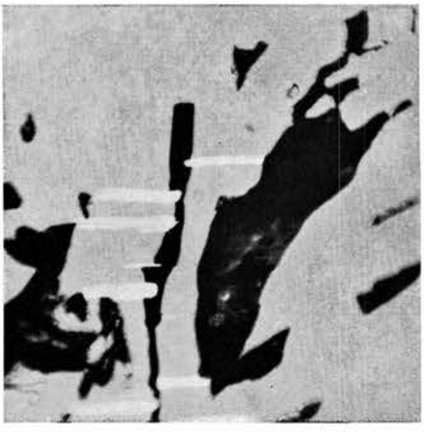

Fig. 6 (290×)

Plate XVII.

1. Polished section, × 160, 1 nicol. Beiernfjord.
   Clusters of magnetite grains in the pentlandite intergranular in pyrrhotite. The oxide exhibits incipient transformation into FeS. Pentlandite flames in the pyrrhotite. See pp. 134, 136. H.P. photo.
2. Polished section, × 450, 1 nicol. Beiernfjord.
   Mustard-brown mineral (cooperite??) replacing magnetite together with other magnetite inclusions in the pyrrhotite. See page 134. H.P. photo.

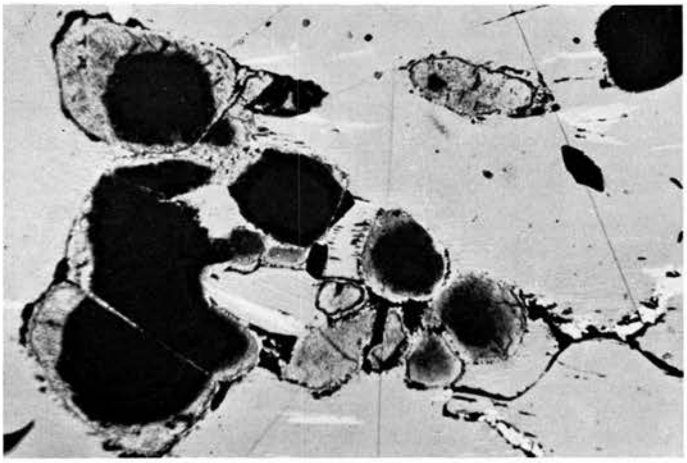

Fig. 1 (160×)

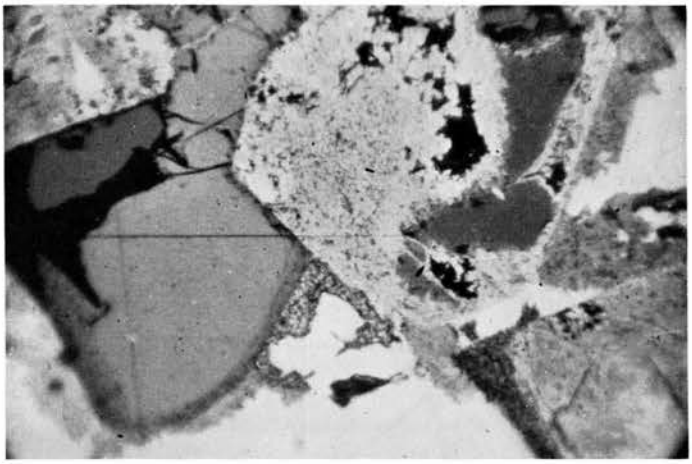

Fig. 2 (450×)

Plate XVIII.

1. Polished section, ×170, 1 nicol. Nivala.
   Pyrite, large area in pyrrhotite. Note the "inherited" structure from the pyrrhotite in the pyrite, the basal parting. See page 125. H.P. photo.
2. Polished section ×120, 1 nicol. Nivala.
   Pyrite surrounded by carbonate in pyrrhotite. See page 125. H.P. photo.
3. Polished section, ×1000, 1 nicol. Nivala.
   Border between pyrrhotite and silicate with border zone of unknown layer-lattice sulphide, following the (0001) direction of the pyrrhotite. See page 127. H.P. photo.

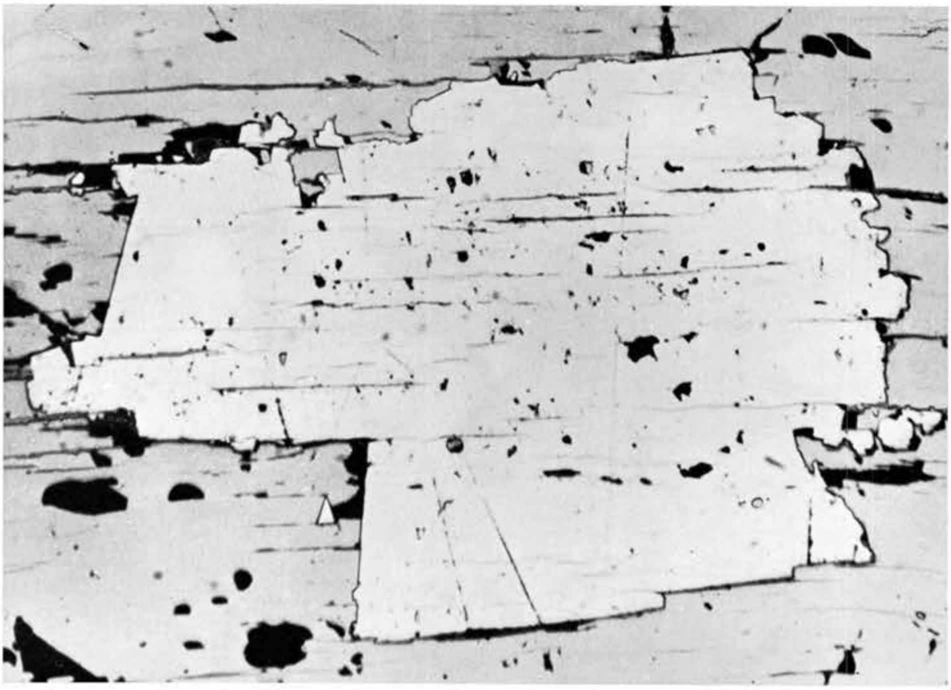

Fig. 1 (170×)

Fig. 2 (120×)

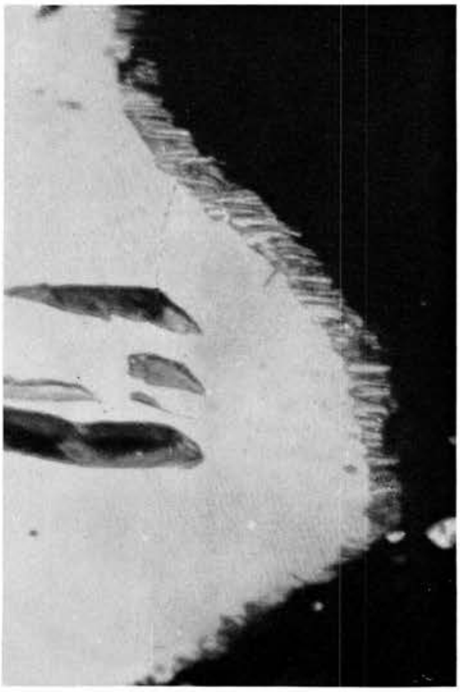

Fig. 3 (1000×)

Plate XIX.

1. Polished section, × 250, 1 nicol. Nivala.
   Bravoitized pentlandite intersected by magnetite veins. In dark areas two rectilinear lamellae of chalcopyrite which do not follow the (111) direction in the original pentlandite. See page 123. H.P. photo.
2. Polished section, ×180, 1 nicol. Kaulatunturi, Petsamo.
   Pyrrhotite with a little pentlandite irregularly distributed in association with imbedded silicates exhibiting movement-conditioned structures. See page 153. H.P. photo.

Fig. 1 (250×)

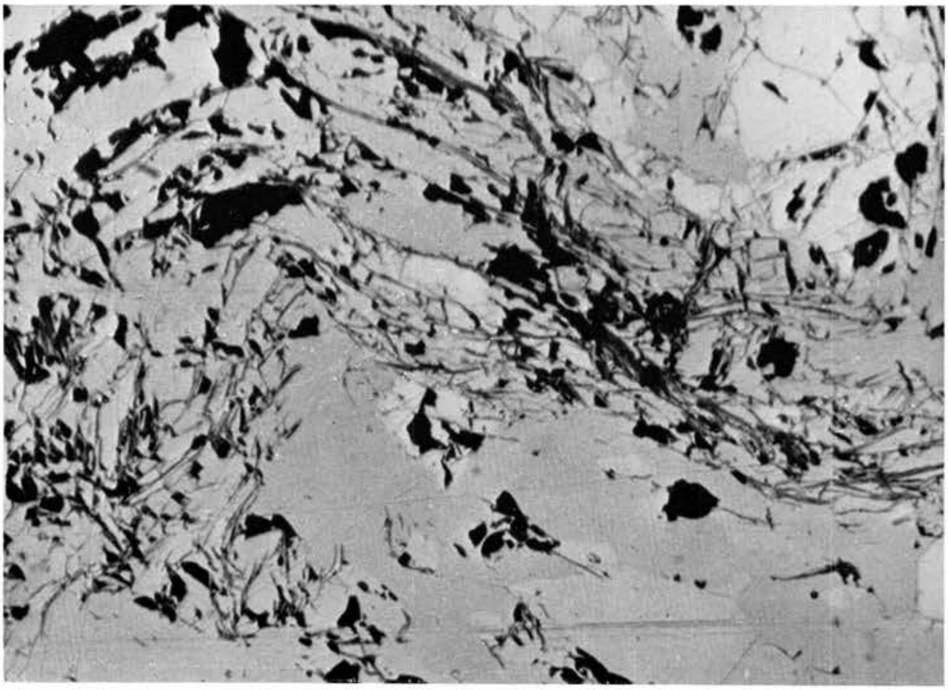

Fig. 2 (180×)

Plate XX.

1. Polished section, × 225, 1 nicol. Basalt with metallic iron, Asuk, Disko. Large grains of iron with cohenite, smaller grains of cohenite or of FeS. See page 159. H.P. photo.
2. Polished section, ×120, 1 nicol. Basalt with metallic iron, Mellemfjord, Disko. In the iron grain are cohenite areas. See page 159. H.P. photo.

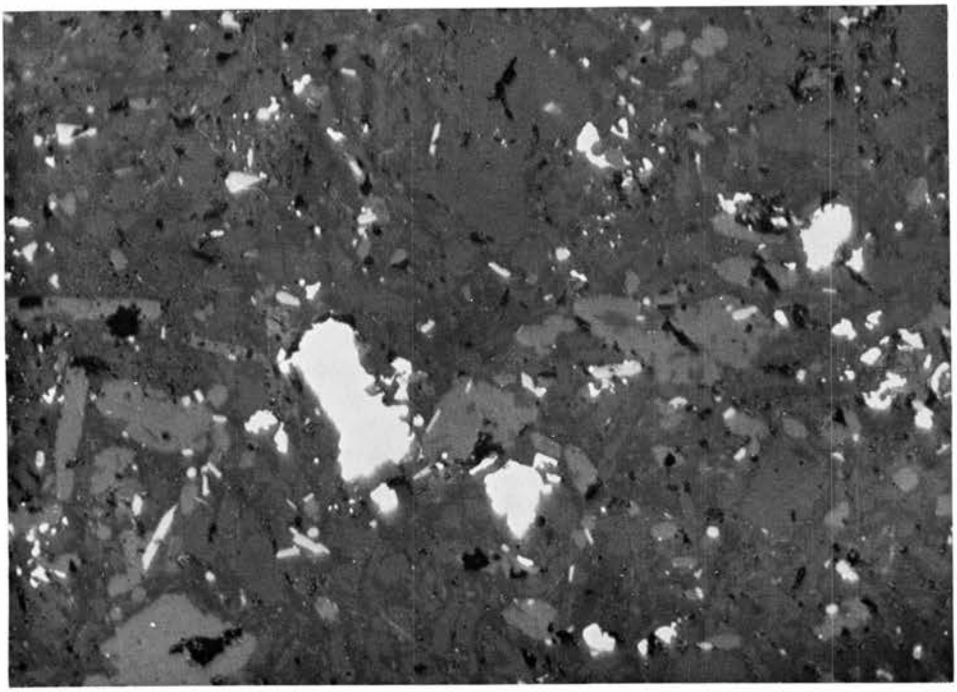

Fig. 1 (225×)

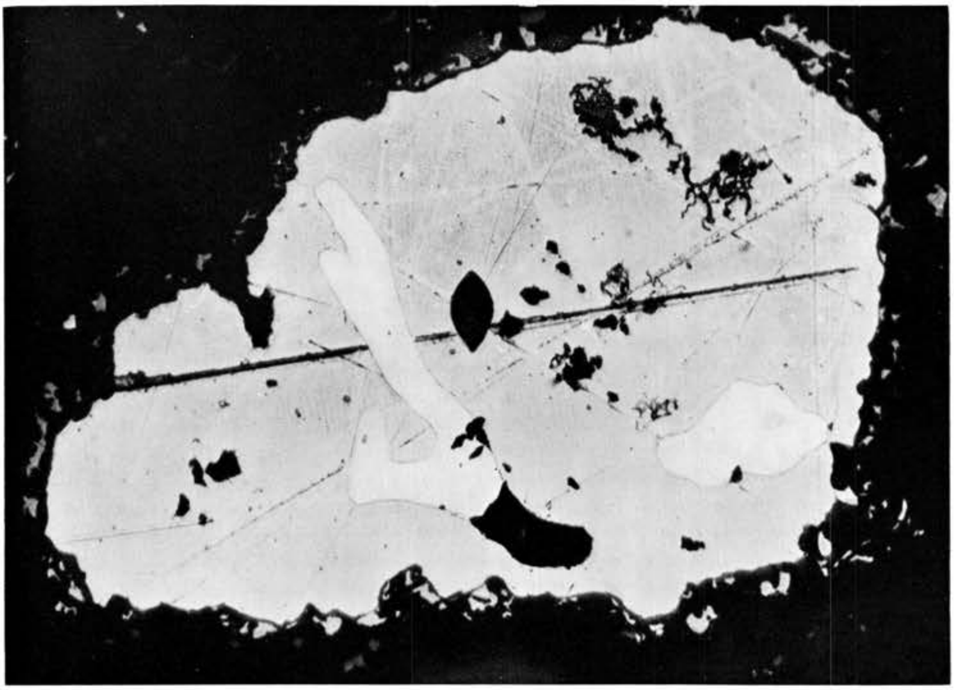

Fig. 2 (120×)