

WHITE CAST IRON WITH COHENITE, SCHREIBERSITE, AND SULPHIDES FROM TERTIARY BASALTS ON DISKO, GREENLAND

By

HANS PAULY*

Abstract.

In a short historic review some observations from the works of STEENSTRUP and TÖRNEBOHM are presented. Even though they were published 90 years ago they seem to contain the essential features of the iron occurrences on Disko.

Tiny grains of iron are found scattered through the rock of basalt sheets covering hundreds of square kilometres. The iron was formed in the basalts through interaction with bituminous shales. This is further supported by recent isotope determinations revealing C^{12}/C^{13} ratios which point to an organic origin of the graphite in these basalts.

From an unpublished field report by Dr. FISCH the setting of the iron basalts is illustrated.

Examinations of polished samples bring out first and foremost the "white cast iron nature" of the massive iron from Uivfaq so often described in the literature. From the fineness of the pearlite structure the cooling of the masses is shown to have been extraordinary rapid.

The stabilization of cohenite might be due to the quenching of the rocks.

In the description attention is drawn to several details to be studied in the future work on these deposits. Among these details the occurrences of lowmelting systems containing Fe-C-P-S are stressed.

INTRODUCTION

Massive blocks of cast iron ranging in size from kilograms to many tons have been known for more than 100 years from the west coast of Greenland (BØGGILD, 1953).

FORCHHAMMER (1854) described a 10 kg lump brought to Denmark by H. RINK from his expeditions in 1848–50. It was collected at Niakornak, east of Disko, on the Greenland mainland (see map fig. 1). FORCHHAMMER characterized it as cast iron, because it contained carbon in great amounts and because it was very hard and brittle. The interest in these Greenlandic finds was greatly increased when NORDENSKIÖLD in 1871 brought to Scandinavia the huge boulders from Blaafjæld, where they were found on the shore at Uivfaq. These uncommon products of nature were at first regarded as meteorites, but K. J. V. STEENSTRUP, who joined the expedition

*) Mineralogical Institute

Technical University of Denmark, Lyngby, Denmark.

in 1871 and carried out a long sequence of expeditions to the basalt region in the following years, argued for their origin from the enclosing basalts. In his opinion (STEENSTRUP, 1876) the fact that iron is a rare mineral does not necessarily mean that it has been formed through extraordinary circumstances.

At Uivfaq small lumps and grains of iron had also been found in the basalt, but NORDENSKIÖLD postulated that a meteor shower had been caught up in the molten lava. Arguments against this theory were thus difficult to find at this locality. In 1872 however STEENSTRUP succeeded in finding iron grains disseminated in basalt from Asuk on the north coast of Disko, and his expedition of 1880 was even more successful in that he found iron at many localities along the west coast of Disko. He was able to prove that iron occurred in lava sheets as a fine-grained dissemination, usually as a minor constituent of the rock. As some of the lava sheets are of great extension, ca. 30 m in thickness, and can be followed for many kilometres, STEENSTRUP certainly demonstrated the intimate relation between the rock and the mineral, (STEENSTRUP, 1883).

STEENSTRUP's samples from Mellemfjord and Asuk (see map fig. 1) were examined both chemically and microscopically. Together with the examination of the Uivfaq rocks and iron nodules carried out by TÖRNEBOHM (1878), they give a very detailed picture of the nature of these occurrences.

TÖRNEBOHM's description of the iron-bearing rocks from Uivfaq and his remarks on the Asuk rocks clearly show that a good understanding of the problem was obtained in those years up to 1878. The Uivfaq rocks are both coarser-grained "Dolerit" and fine-grained to dense "Basalt" in TÖRNEBOHM's terminology. The mineralogy is that of a common feldspar basalt: plagioclase, augite, olivine, ilmenite, and glass. This is valid both for the coarser and the fine-grained rock type. In the description of the relations between these rock types TÖRNEBOHM remarked: "Beide Gesteine waren mit einander vollständig verwachsen, und am Kontakt zeigte sich der Basalt noch feinkörniger denn sonst". He concluded that the fine-grained rock was later than the coarse-grained and that it either constitutes dykes in the coarse-grained rock or represents a matrix cementing xenoliths of the "Dolerit". He preferred the latter view. In both rock types occur inclusions of plagioclase characterized by a certain content of graphite and spinel. These plagioclase xenoliths in the "Dolerit" are also found very irregularly intergrown with the rock, wherefore TÖRNEBOHM regards them as older than the "Basalt". He states that the native iron belongs together with the inclusions in the "Basalt" mainly to the "Dolerit".

Apart from the common constituents in the basaltic rock TÖRNEBOHM pointed out iron, pyrrhotite, and an iron-rich silicate. He stressed their common intergranular position with regard to the main constituents of the "Dolerit". Even the glass of the rock seems to have consolidated before these three components – iron, sulphide, and iron-rich silicate. The last is a greenish to brownish "Chlorophäit"-like substance. In places it shows sphaerulitic structure or zones built up of radiating fibres. Within these masses TÖRNEBOHM noted the occurrence of magnetite in many cases.

The three intergranular constituents may also be found as crack in-

fillings. Whereas the "Basalt" was found not to contain iron, it carries sulphide and the iron-rich silicate as rounded inclusions and grains.

The Asuk rock is quite distinct from the rocks from Uivfaq, according to TÖRNEBOHM. The minerals are feldspar, enstatite, and scattered iron grains, besides glass. Only the metal can be seen macroscopically, the other constituents are hardly 0.1 mm in size.

In an attempt to explain the complicated features exhibited at Uivfaq TÖRNEBOHM assumed that the molten basalt masses had assimilated chalk-aluminous and bituminous rocks such as bituminous marl or marly shale. He regarded the graphite-plagioclase xenoliths as anorthite (this seems to be wrong; according to MELSON and SWITZER (1966) it is An 70-75), and found it reasonably explained by interaction of magma with the mentioned sedimentary rocks. In such a process the magma got an opportunity to assimilate bituminous matter which later could serve as a reducing agent leading to the formation of the native iron and the graphite. He had, however, the idea that the reduction took place after the consolidation of the rock, through circulating solutions. The idea about reduction through addition of organic carbon has been corroborated through isotope determinations on graphite from the iron basalts (see MÜNTHER, 1951).

It has been thought worthwhile to summarize some of TÖRNEBOHM's main

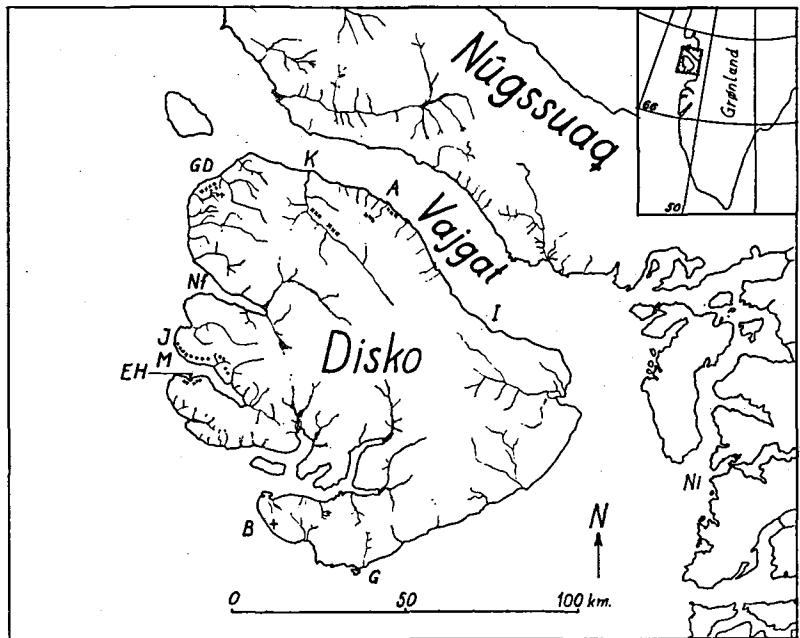


Fig. 1. Sketch map of the island Disko and its surroundings.

B = Blaafjæld with Uivfaq. M = Mellemfjord. EH = Enoks Havn. J = Jernpynten. Nf = Nordfjord. GD = Gieseckes Dal. K = Kuganguaq. A = Asuk. I = Igdrukúnguaq. Ni = Niaqornaq. G = Godhavn.

observations and ideas because in spite of being 90 years old they seem to be extremely helpful in an attempt to understand the Disko iron problem even today. One might in passing remark that TÖRNEBOHM carried out his examinations on an invitation from NORDENSKIÖLD, who generously placed the material at his disposal. STEENSTRUP's urgently pleaded case for a "natural" terrestrial origin of the iron was the result of investigation. Apart from this TÖRNEBOHM's paper is remarkable through its beautifully coloured and extremely detailed microphotos in which everything to be found with the modern microscopes can be seen. (It is only a pity that he has not been able to identify the cohenite which he calls schreibersite, because it did not stain with copper solutions.)

Reading STEENSTRUP's and TÖRNEBOHM's papers with slight reinterpretation of some of the phenomena described allows an interpretation of the occurrences in close keeping with modern views.

Our present knowledge about steel and cast iron contains clues to the cooling history not hitherto drawn from the investigations. Electron microprobe analysis likewise gives us a tool likely to elucidate details in the complex history of development of these occurrences. Finally mapping of the whole basalt complex will be crucial in the attempt to understand the nature of the magma which underwent the hybridization leading to the formation of the iron. Geochemical studies of the basalts and the sediments of the region represent an important part of these investigations.

FIELD WORK

In 1938 all known localities for native iron on Disko were visited by Dr. W. FISCH. This work was carried out for *The Greenland Administration* at the suggestion of Dr. LAUGE KOCH. The idea was to make a study of the economic possibilities in these deposits. Due to the war the work was not brought beyond the reconnaissance stage and all we know is contained in a short report (ca. 3.000 words), half of which gives a description of the observed geological and topographical conditions at the various localities (FISCH, 1938). Although no laboratory work is cited, it is clear from the report that FISCH made a preliminary study of the samples collected. The iron-bearing rocks are named andesite, and he mentions observations of microscopic grains of iron in several places.

The most important part of FISCH's report is however his excellent collection of photos from most of the localities where STEENSTRUP and others have reported iron in basalt. Whereas Uivfaq and Asuk have been adequately described earlier, the same cannot be said about the occurrences on the west coast of Disko. FISCH's pictures from the north and south sides of Mellemfjord, figs. 5 and 6, are therefore reproduced here because they very clearly illustrate the mode of occurrence of the iron-carrying layers in the basalt series. In both photos it is apparent that the layer dips to the west. On the north side of Mellemfjord the iron basalt is found at sealevel at the locality Jernpynten, from where the cut and polished sample pictured in fig. 7 is taken.

Based on the work of the *Nûgssuaq Expeditions* 1938 and 1939 (ROSENKRANTZ et al., 1940), *Grønlands Geologiske Undersøgelse* started systematic work in the basalt areas of West Greenland after the second world war. In connection with this work a detailed sampling was carried out in the basalt series where iron-bearing rocks were found. V. MÜNTHER, the leader of the team working with these problems, discovered ironbearing rocks in several places in the NW part of Disko. Apart from the systematic sampling and mapping of the occurrences his observations of iron basalts connected with volcanic necks in Gieseckes Dal is of great importance for the current work on the relations between iron-bearing rocks and the other rocks belonging to the basalt series. A paper on these discoveries and on the setting of the iron basalts on Disko is to appear shortly from V. MÜNTHER, but he has kindly allowed the communication of a few general observations. It should be mentioned that many of the samples on which the following observations have been based belong to MÜNTHER's collections.

Whereas the iron basalts at Asuk and in the Kuganguaq valley belong to the lower basalt series which are picritic basalts, the iron basalts of west Disko belong to the upper tholeiitic basalt series.

The Kuganguaq iron basalts are found at a height of 450 m. According to MÜNTHER the Asuk occurrence may represent a landslipped part of the same layer, outcrops of which have been noted in a few places in the basalt series above Asuk.

Faults have divided the whole Disko area into many blocks, and the correlation of the basalts depends highly on the tectonic pattern. MÜNTHER's analyses of it show that there is a possibility that the iron basalts in Gieseckes Dal and in the Mellemfjord region may be continuous and he has noted iron basalt as boulders along the coast to Nordfjord and in several places in this fjord where STEENSTRUP and FISCH also found corresponding boulders.

In the Mellemfjord region layers with disseminated iron can be followed for up to 25 km. The westward dip of the series sets a limit for the occurrence to the east. About two-thirds of the way into Mellemfjord the iron basalt constitutes the uppermost layer of the basalt series and east of this the iron basalt has not been observed.

The thickness of the iron basalt layer varies between 10–15 metres and 30–40 m. At Gieseckes Dal MÜNTHER reports a thickness of nearly 200 m where the layers are connected with the volcanic necks.

LABORATORY WORK

Apart from STEENSTRUP's and TÖRNEBOHM's work most of what has been published on Disko iron stems from observations made on iron from Uivfaq. This is understandable, because these samples have been spread all over the world.

Modern descriptions of Uivfaq samples have been given by LÖFQUIST and BENEDICKS (1940), HØEG (1945), RAMDOHR (1953), LOVERING (1964), and MELSON and SWITZER (1966); VAASJOKI (1964) has also worked with samples from Asuk.

The old designation of the iron as "cast-iron" is indeed valid for the Uivfaq occurrence and the modern examinations have only brought out a few more details underlining this picture.

The very fine-grained nature of the pearlite has given rise to remarks on the cooling rate of the material. Generally it has been stated that part of the material must have cooled rapidly through the pearlite point.

The grain size of the intergranular cohenite (intergranular relative to the original γ -iron grains) being far above what is found in artificial irons has on the other hand been interpreted as indicating very favorable and perhaps prolonged time of development at temperatures above the pearlite point.

Beside the fine-grained cohenite in the pearlite and the coarse-grained intergranular cohenite, we also find lamellar cohenite transsecting the original γ -iron grains. From the work of LOVERING (1964), we now know that this contains much more Ni and Co than the intergranular cohenite, 3.14 and 0.59 % as against 0.60 and 0.28 % respectively.

With LOVERING's work attention was drawn to the remarkable fact that the virtually unstable compound cohenite is an obviously sound member of the Disko iron paragenesis. Its existence in certain meteorites had recently called for specific explanations and because the commonly invoked stabilizing elements (see later) were not detected, it seemed as if certain high pressure conditions during the formation were necessary in order to stabilize the cohenite. Such conditions are not directly applicable to the Disko iron, as pointed out by RINGWOOD (1965), wherefore the existence here of cohenite seems to call for further examination.

Many analyses have been given of the compact iron from Uivfaq. They show that the lumps contain about 92 % iron and the carbon content varies around 3 %. From a metallurgical point of view this seems to give a good basis for predicting the development of the various possible constituents of the solid masses on cooling from the molten state. The other elements present do not seem to influence the products directly. According to a less well known analysis to be found in HØEG (1945) the amounts of these are:

Ni	2.24%
Cu	0.12%
C	2.68%
P	0.13%
S	0.71%

Other analyses give around 92 % Fe, Co corresponding to Ni/Co about 3/1, and a few percent silicates, oxides etc.

HØEG's analysis is important in that it gives a confirmation of earlier recorded phosphorus contents. We thus find that the Uivfaq iron can be regarded as cast iron containing both sulphur and phosphorus. Together with the formation of carbide and iron it is to be expected that phosphides and sulphides occur in the iron masses. In passing it can be mentioned that the amounts of the various elements correspond roughly to

50 % Fe_3C , 2 % FeS , 1 % Fe_3P , and 47 % Fe.

With 3 % C it is better described as an occurrence of cohenite with iron and other minerals.

The minor components are of importance in the work of unravelling the details in the consolidation history of the iron masses. The systems Fe-C-S and Fe-P-S have been studied by HANEMANN and SCHILDKÖTTER (1929) and VOGEL and DE VRIES (1930). Characteristic for these systems is the existence of a wide field of liquid immiscibility in both. Molten liquids exist down to temperature around 1100°C in the first and under 1000°C in the second system. In the system Fe-P-S steadite, a ternary eutetic appears. A corresponding symplectite is present in the Uivfaq iron, as mentioned by LÖFQUIST and BENEDICKS (1940) and HØEG (1945).

As mentioned earlier cohenite has a singular position among the constituents of the Disko occurrence because this compound easily breaks down to iron and graphite. The Disko basalts are however not unique in carrying cohenite.

The native iron from Bühl near Kassel in Germany also contains cohenite (SCHWARZ, 1937, RAMDOHR, 1953). On average the metal contains 0.2 % C giving rise to pearlite areas within ferrite grains. Nickel, cobalt, and phosphorus seem to be lacking whereas the Bühl iron contains appreciable amounts of sulphur and manganese.

Cohenite is also reported from gabbro dolerites found in Krasnoyarsk District, where native iron occurs, (BAZHENOV et al., 1959). In the abstract of this paper (in C. A. 1959; Vol. 53, 16832) the following is mentioned regarding the occurrence of cohenite:

The native Fe occurs either in isolated grains dispersed over the rock or in compact masses, in most cases covered with a more or less thin shell of pyrrhotite, ilmenite, and very characteristic rims of Fe₃C (cohenite, cementite). Analysis of this iron is:
Fe 97.62, Ni 0.27, Co 0.12, Mn 0.12, Cu 0.21, Ti trace, P none, S 0.03%, Cl trace, Si trace.

The stability of cohenite in iron is influenced by rather many elements. Among the stabilizers Mn is one of the more important. The two mentioned iron occurrences are clearly Mn-bearing and thus not immediately comparable to the Disko irons.

It might in passing be worth noting that metallurgical texts often stress the stabilizing effect of sulphur on "white cast iron". In LÖFQUIST and BENEDICKS' treatment of the Uivfaq iron, they specifically state that the presence of sulphur might be regarded as the cause for the stability of the cohenite in the material.

THE SOLID LUMPS OF IRON FROM UIVFAQ

Fig. 2. illustrates the common appearance of the massive iron lumps from Uivfaq. This unetched area contains cohenite as broad veins separating metallic areas in which a few long and thin lamellae of cohenite are just discernible. When etched the metallic areas are found to consist of ferrite and cohenite in the fine-grained intergrowth called pearlite.

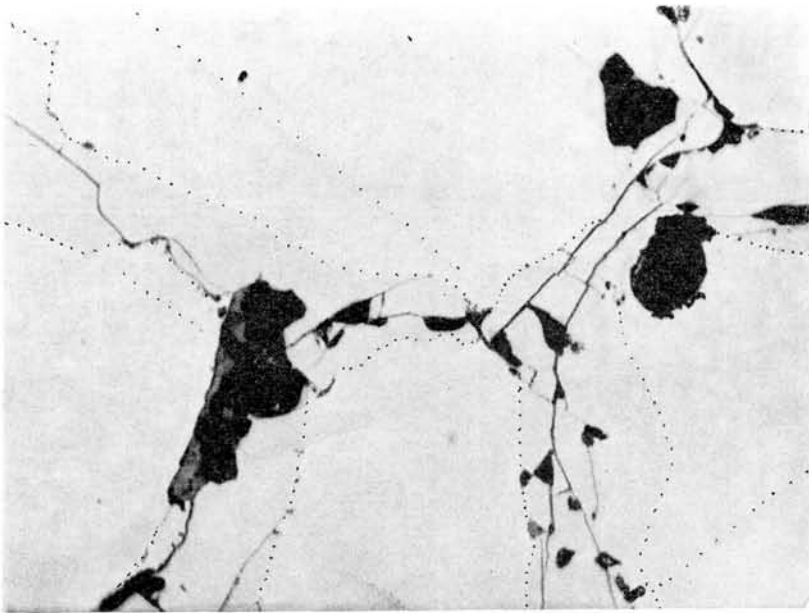


Fig. 2. Pearlite areas separated by intergranular cohenite. In this unetched sample the cohenite is mainly visible through its many cracks and holes (outline marked by dotted line). Grey substance is pyrrhotite. A few cohenite lamellae occur in the pearlite areas. The sample is typical for compact iron from Uivfaq. Magn. 200 X.

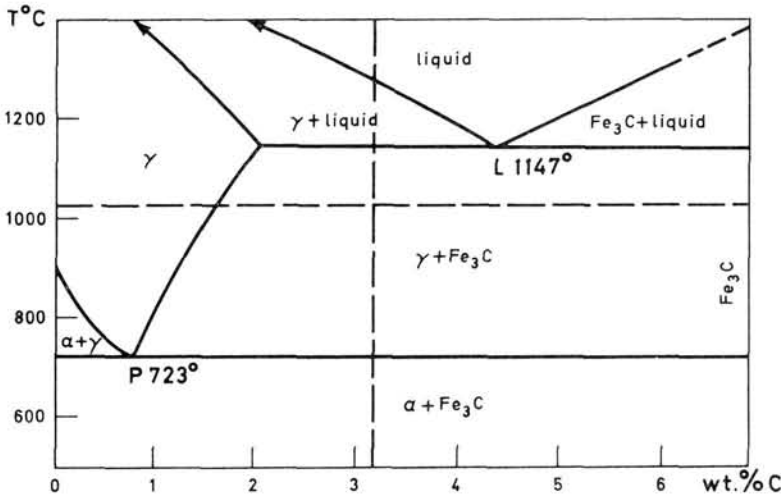


Fig. 3. Fe-C diagram, simplified. Vertical broken line indicates the composition of the Uivfaq iron.

From the composition of the Uivfaq iron it is obvious that knowledge from the Fe-C system cannot be used quantitatively in the interpretation of the paragenesis. A first approximation may however be based on the simplified Fe-C diagram given in fig. 3.

As the Uivfaq iron contains about 3 % C it must have been liquid at temperatures above 1250°C (circa). From all the papers on this material it appears that we have had real molten metal obviously in a silicate melt. As this temperature is close to the temperature at which several of the silicates begin crystallizing, the detailed work on these occurrences should include a study of paragenetic sequences, and analyses of the metallic phases may give important clues to the temperature of initial solidification.

On cooling the metal liquid precipitates γ -iron with a certain content of C in solid solution. These crystals react with the liquid and both are relatively enriched in C. At point L, corresponding to a temperature of 1147° in the pure Fe-C system, the remaining liquid solidifies as a eutectic mixture of cohenite and γ -iron solid solution, the so-called ledeburite. Given enough time at temperatures close to the ledeburite point the C of the γ -iron of the eutectic goes to the cohenite which thereby increases in size. The ledeburite is thus annihilated. Ledeburite has been mentioned by LÖFQUIST and BENEDICKS (1940), but it is obviously a very rare constituent in the material.

The metallic masses are now solid and consist of γ -iron solid solution and in the intergranular spaces between the γ -grains the cohenite is placed. This is the most prominent feature in fig. 2. The destruction of the ledeburite indicates that the Uivfaq masses arrived at this stage through a long period of cooling. This could have been accomplished in the magma chamber.

On further cooling the minor components, sulphides and phosphides occurring as scattered pockets of residual liquids, crystallize. They so-to-speak belong to the intergranular phase, and here we also find the main part of these constituents. They crystallize as ternary or quaternary eutectics analogous to what is found in the ternary systems Fe-S-C and Fe-P-S (see for instance HANEMANN and SCHILDKÖTTER (1929), and VOGEL and DE VRIES (1930)). In a detailed study these compounds should be given special attention, because they represent fairly low melting compositions. For the present work it is of interest to mention the low melting liquids in these systems representing temperatures close to 1100°C and less than 1000° respectively. In all places where these constituents have been observed they occupy undisturbed positions in the intergranular spaces together with cohenite. This might indicate that the development was quiet down such low temperatures.

The cooling results in ejection of C from the γ -iron and at this stage the formation of transsecting lamellae of cohenite in the γ -grains takes place. A certain increase of the intergranular cohenite might likewise take place. LOVERING (1964) reports that the lamellar cohenite contains 3.14 % Ni, whereas the intergranular cohenite only contains 0.60 % Ni. This might be interpreted in relation to cooling rate of the material. The intergranular cohenite developed quietly and had sufficient time to reach equi-

librium with the surroundings, but the high Ni in the lamellar cohenite indicates a rapid fall in temperature. Metallurgical experience has taught us that straight lined lamellae are formed through slow cooling, whereas split and fibrous borderlines indicate rapid fall in temperature. A detailed study of the amounts of this type of cohenite might give informations about where on the curve down to the pearlite point P in the diagram fig. 3 the change in cooling rate took place. It might be at 1000°, but this is plainly a guess.

The third and perhaps most important stage in the development is reached, when the material has cooled to the point P where γ -iron transforms to α -iron with the consequence that most of the carbon is forced into cohenite and the finegrained structure pearlite appears.

Metallurgical experience allows estimates of cooling rate from the grain sizes of the components in this structure, and from the shape of the lamellae. Straight-lined and micron-sized lamellae indicate a rapid chilling or quenching. Gradations between such an appearance and complete separation of the two phases into ferrite and rounded blebs of cohenite exist. This spheroidization, as it is called, can be obtained through a prolonged stay at around 700°C. In 12 hours the pearlite structure is commonly found to be totally annihilated in artificial cast irons. The consequence of this is that the Uivfaq cast iron did not stay for many hours at around 700°C. The extremely fine grains in the pearlite pictured in several of the papers on this iron (e. g. LOVERING, 1964) must indicate a chilling whereby after the pearlite formation the material was taken down to temperatures around 600° in a couple of hours. Moreover we have to reckon with a rather high cooling rate measured in days or maybe in weeks so that the material was brought down to temperatures where effective C-diffusion was no longer possible even in geological time.

In spite of this qualitative approach it seems as if we have in the pearlite an indication of the gradient of the cooling curve – from 723° to perhaps 600° – a hundred degrees in less than 12 hours. As the lamellar cohenite likewise seems to demand a rather steep cooling curve, it seems that rapid cooling already started in the vicinity of 1000°. The event leading to the drastic cooling might well be the extrusion of the partly molten magma. As mentioned by TÖRNEBOHM, the Uivfaq rock contains coarse-grained "Dolerit" in a matrix of fine-grained "Basalt". A study of the proportion of the first to the latter should be valuable, but it can only be undertaken at the locality and on a good collection of well localized samples. An indication of the correspondance between the observations in the metallic masses and the rock can be found in TÖRNEBOHM's own statement that he regards the "Dolerit" as xenoliths in the "Basalt". Further indications that liquid silicate magma could still be present at rather low temperatures can be drawn from the observations pictured in plate 1 fig. 2 and plate 2, fig. 1. They show in polished sections the appearance of secondary silicates mainly representing water-containing minerals of layer-lattice nature. The old papers of TÖRNEBOHM (1878), STEENSTRUP (1883) and others indicate the presence of hisingerite and fibrous, radiating silicates spread all over the preparations of these rocks. The content of

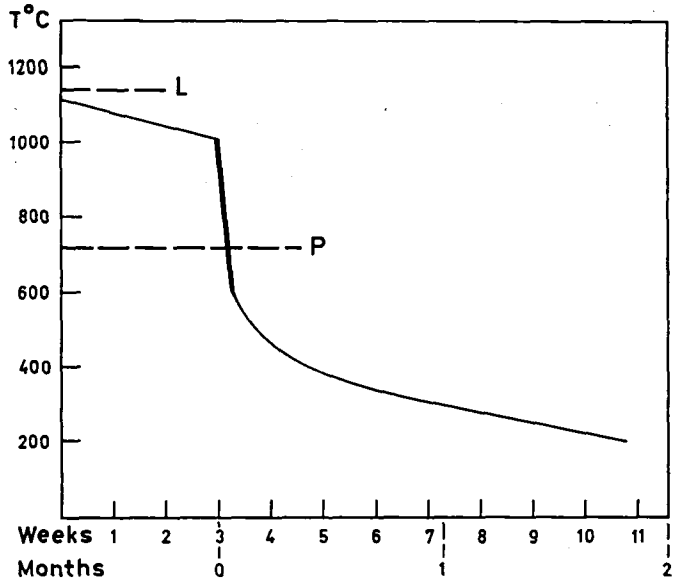


Fig. 4. Cooling-curve proposal for cast iron blocks from Uivfaq.

volatiles, mainly water, has certainly been remarkable. This is in good agreement with the hybridization of the magma through assimilation of bituminous shales.

The observations in the cast iron blocks can be used in constructing the cooling curve. It demands a detailed study of the components. From the above remarks an attempt has been made to visualize such a cooling curve, see fig. 4. The most important observation lies in the pearlite. It indicates a lowering of the temperature after extrusion to about 50 % of the temperature at extrusion within a day or so.

Such a situation might be within bounds of possibility for surface layers of the extrusion. Metallic lumps with good conductivity also seem to fit into such a picture. It is however difficult to understand when the large blocks of metal are considered. The *Nordenskiöld block* examined by LÖFQUIST and BENEDICKS (1940) measured close to 200 cm in length, and not much less in the other dimensions. Metallurgical experience indicates rather that it is very difficult to quench large lumps of metal effectively. From LÖFQUIST and BENEDICKS' paper one can only get the impression that the fineness of the pearlite is roughly the same all over the material examined.

Two points may be mentioned which might contain clues to an understanding of this problem. The block examined showed a rather intense development of cracks in the interior. This was explained with reference to the γ/a transition first taking place in the outer regions of the block.

Due to volume differences of α - and γ -iron the interior comes under heavy tensional strain and develops "flakes", LÖFQUIST and BENEDICKS (1940).

The other point of interest in judging the cooling history from the fineness of the pearlite is the content of Ni in the iron. The distribution of Ni in iron is often somewhat heterogeneous. The presence of Ni inhibits the diffusion of C. Spheroidization of pearlite could therefore be expected to show some variation with Ni content. Examination of the Ni distribution in relation to the pearlite should be carried out in connection with an attempt to gain detailed knowledge about the problem.

DISSEMINATED METAL IN THE ROCK OF UIVFAQ

Disseminated metal grains in the Uivfaq rock are pictured in plate 1, fig. 1 and 2. The grain size is about half a millimetre. Both grains have been corroded. In the grain in plate 1, fig. 2 the corrosion has resulted in total alteration of the ferrite into oxide or hydroxide; only the cohenite is left. In plate 1, fig. 1 parts of the grain are altered in a similar way. In both cases the original pearlite structure can be observed through the preservation of the cohenite lamellae. In plate 1, fig. 1 the grain size in the original pearlite can be seen to be extremely fine. Obviously this pearlite was cooled at a rate corresponding to what was found for the massive iron lumps. In the other grain, plate 1, fig. 2, the pearlite seems to have been somewhat coarser. In addition numerous cohenite lamellae transsecting the original γ -iron grain can be seen together with a thin borderline of cohenite. It looks as if this grain indicates a less drastic cooling rate. The study of such inclusions in the rock gives a variation in pearlite development and thus in cooling history of the material. They can perhaps give an interesting clue to the cooling history of various parts of the rock. A systematic study of these features can only be carried out on well chosen samples from the locality and must therefore be postponed until such samples are available.

The preliminary results obtainable from our present knowledge and the samples at hand are not altered in the main by the picture of the disseminated grains in the rock and their heterogenous character. It is rather what could be expected. In this connection it should be born in mind that closely corresponding pearlite structures are found in the iron from Bühl near Kassel in Germany (SCHWARZ, 1937; RAMDOHR, 1953). As the Bühl iron contains appreciable amounts of Mn it is not directly comparable to the Disko iron.

The corrosion mentioned above seems to be intimately connected with the occurrence of the water-containing silicates formed late in the history of the rock. In plate 1, fig. 2 such a field can be seen in the one corner of the photo. The alteration of the pearlite corresponds closely to the kind of corrosion commonly met with in cast iron construction materials. LÖFQUIST and BENEDICKS term it "oxide pearlite" or rather "hydroxide pearlite" as they found that the dark component replacing the ferrite rather looks like limonite. Together with the water-bearing silicates it is often possible to find magnetite, as pictured in plate 2, fig. 1. This mineral is

always placed in the middle of the area occupied by the late stage products.

The sulphides present comprise pyrrhotite, pentlandite, and a copper-iron sulphide much like chalcopyrite. Microprobe analyses currently undertaken on similar Cu-sulphide occurring as lamellae in FeS in a sample from Asuk indicate low-Cu cubanite compositions corresponding to observations made on sulphides from Hawaiian basalts by DESBOROUGH et al. (1968). The pyrrhotite in the Uivfaq samples contains the other two sulphides as tiny exsolution bodies. The pentlandite occurs as small elongated blebs a few microns in length and the copper sulphide commonly occurs in flame-like lamellae often as three-rayed stars. The directions of these lamellae are obviously determined by the pyrrhotite.

In plate 3, fig. 1 and 2 pyrrhotite grains can be seen containing large lamellae consisting of pentlandite. These pentlandite lamellae are strictly oriented in the pyrrhotite, but the direction diverges by several degrees from the directions of the copper sulphide flames. They merge with pentlandite linings of the pyrrhotite and they are only found where sulphide is in contact with metal grains or lies close to such grains. Mostly one can find the phosphide schreibersite in the metal grains in question. Because the phosphide has been found to contain many percent of Ni, it is found reasonable to regard the pentlandite in the lamellae and in the linings of the pyrrhotite as formed through replacement. Ni liberated from the phosphide in connection with secondary alterations in the metal grains should then have been carried in solution to the sulphide. Ni precipitated in the contact areas and through penetration along cleavage directions the transsecting pentlandite lamellae have been formed. Such a possibility is also in keeping with observations from meteorites (see EL GORESY, 1965).

Plate 3, fig. 2 illustrates a composite grain in the Uivfaq rock. It contains the ternary or quaternary phosphide eutectic where schreibersite together with cohenite and ferrite make up the constituents. Sulphide may be found among the eutectic components and the many dark areas within the eutectic may represent replaced components of the structure thus corresponding to the corrosion illustrated in the pearlite.

Composite grains containing cohenite and pyrrhotite are also found scattered in the rock. It seems probable that such grains represent low-melting local systems. They can obviously give hints about temperatures of formation for the rock.

In plate 1, fig. 2 it is just possible to discern a half spherule of graphite. Plate 2, fig. 2 illustrates a corresponding spherulitic graphite. In other places borders or radiating aggregates of graphite can be found. This is mentioned because it is the most characteristic mode of occurrence of the graphite in these materials. From old times however another type of graphite has been described - disseminated graphite in feldspar which occurs more or less as xenoliths in the rock. These are not however directly connected with the metal containing cohenite. It can thus be stressed that the type of graphite connected with graphitization of cohenite does not seem to exist in these materials. This was also pointed out by LOVERING (1964).

THE COHENITE PROBLEM

The observations on cohenite in the Disko basalts reported in the literature and commented on in the foregoing do not directly contribute anything new to the solution of the stability problem connected with cohenite.

It seems however that the extreme cooling rate inferred from the constituents of the iron blocks from Uivfaq also has a bearing on this problem as suggested by BRETT (1967). Or rather this cooling rate shows that the cohenite may have been cooled down to temperatures where reactions no longer were possible. So far it settles the problem for the Disko material and at the same time excludes this material from elucidating the cohenite problem connected with meteorites.

Analyses of cohenite from Uivfaq have been given by LOVERING (1964) and earlier authors. Attention might be drawn to LÖFQUISTS and BENE-DICKS' work (1940), where they discuss the observation of tiny rectangular bodies included in oriented positions in the cohenite. The bodies are up to 20 times as long as they are wide. The widths are mainly less than one micron, rarely a few microns. They occur dominantly with one orientation but two or three others may be found for a few percent of the bodies. They must be exsolution bodies but their nature is somewhat obscure. In the paper mentioned they are regarded as sulphide (pyrrhotite) and some etch reactions supporting this idea are given. Bodies of exactly the same appearance were found in several of the polished samples examined in the course of the present work. Usually they were only observed in the etched (nital) preparations (see however plate 3, fig. 1). A careful search for these bodies was undertaken in unetched samples, but the only lamellae in cohenite which could be found were of a lighter reflection colour than the cohenite. Several scans with the electron microprobe were made across cohenite grains but sulphur corresponding to the above assumption could not be detected. Neither could phosphide be detected by probing for phosphorus. It is assumed that these light-coloured lamellae in the cohenite consist of ferrite.

Metallurgical studies of cohenite have shown that a certain excess of Fe can exist in cohenite at high temperatures, SCHWARTZ (1938), PETCH (1944). It might be the answer to this puzzle, but it is obvious that the cohenite must be subjected to detailed examinations in order to clear up its peculiar nature in the Uivfaq material.

BASALTS CARRYING DISSEMINATED IRON

The photos given as figs 5 and 6 are reproductions of pictures belonging to FISCH's report (1938). Fig. 5 clearly illustrates the situation of the iron-bearing basalt layer in the lava series on the north side of Mellemfjord. This layer appears at water level at the locality called Jernpynten by STEENSTRUP (1883). Fig. 7 shows a polished rock specimen of the basalt from Jernpynten. The small iron grains are barely visible as white dots here and there in the rock. On examination one finds, together with the iron, cohenite, commonly as rounded inclusions in ferrite. Sulphide,

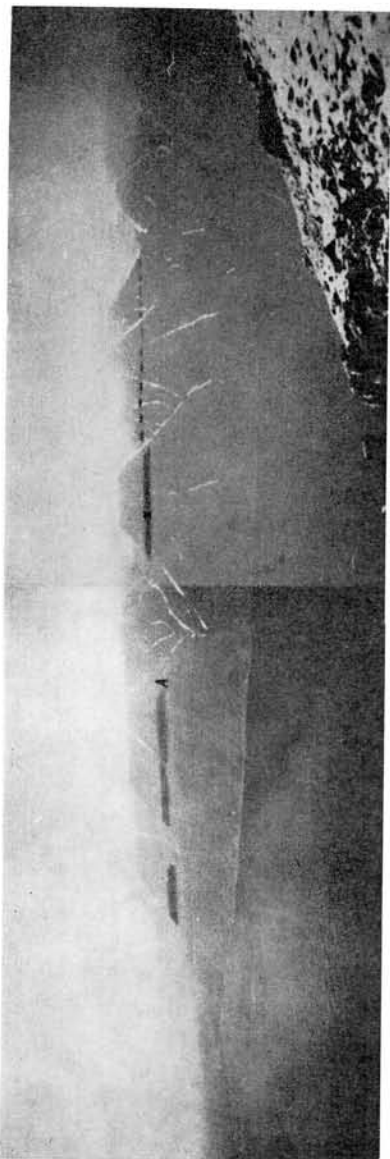


Fig. 5

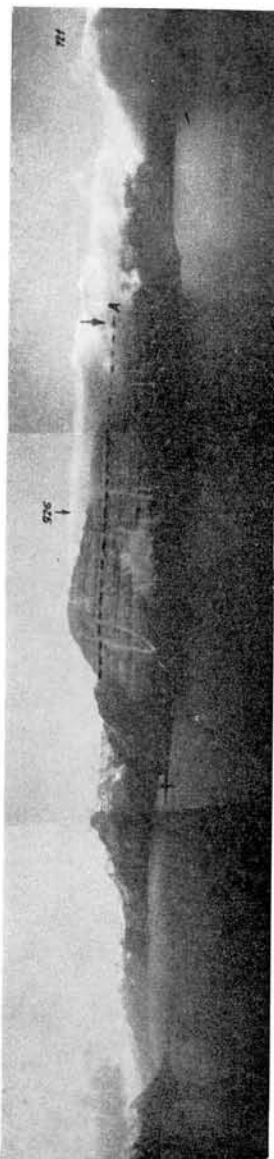


Fig. 6

Fig. 5. Copy of FISCH's photo of the northern side of Mellemfjord viewed from Enoks Havn. The iron-bearing basalt layer has been marked out.

Fig. 6. Copy of FISCH's photo of the southern side of Mellemfjord seen from the place marked "x" in fig. 5. The iron-bearing basalt layer marked by broken line. Enoks Havn to the right.

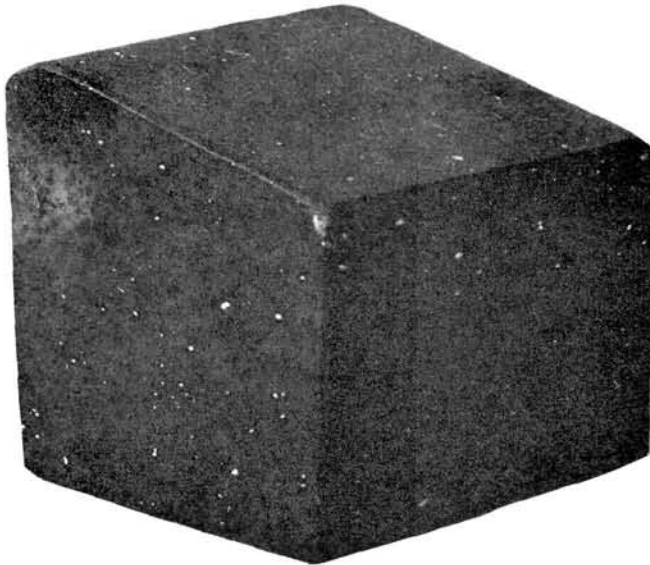


Fig. 7. Cut and polished basalt from Jernpynten. The base measures 33 by 35 millimetres. Tiny white spots are metal grains. Light grey patch in upper left corner is an altered xenolith.

dominantly pyrrhotite, is also present. The rock is very fine-grained. On average the silicates, feldspar laths and pyroxene, are a tenth of the sizes found in the Uivfaq rock, about 0.05 mm in length or diameter.

The rocks connected with the volcanic necks found by MÜNTHER in 1949 are likewise very fine-grained. An impression of these can be gained from plate 4, fig. 1. In addition to the larger iron grains and the scattered tiny iron and sulphide grains is seen a spinel grain. This mineral is usually found in these rocks. In the iron grains cohenite occurs as rounded areas. The amounts of C in the metal grains are difficult to estimate. The intruding plagioclase laths seem to indicate a molten state for part of the metal grains during formation of the silicate. This might place the temperature of solidification under 1300°C, but then the C content should correspond to something like 3 % giving rise to about 50 % cohenite. This is not quite in agreement with observations. Cohenite seems less dominant than 50 % would make it. This problem will be studied in connection with the detailed examination of the profile samples from the many localities where basalt with disseminated iron has been sampled.

SPHERICAL IRON DROPS IN BASALT

In rocks from Jernpynten and Asuk nice round drops of metal have been observed. Plate 4, fig. 2 gives an example of this type of iron grain. Most interesting is the beautiful zoned occurrence of minerals connected with

these drops. The figure shows how the sulphide (pyrrhotite) forms an atoll-like ring round the metallic particle. On closer view a disconnected shell consisting of phosphide in a ternary eutectic can be seen between sulphide and metal. Between crossed nicols or in etched samples the cohenite is easily observed and one often finds that this mineral forms the outer border of the metal grain or part of the outer border. On plate 4, fig. 2 the borderline between cohenite and ferrite has been marked out because the contrast between the ferrite and the cohenite is too faint to show up. The scattered cohenite grains in the interior point to spheroidization of original pearlite. This indicates a cooling rate lower than that of the Uivfaq samples. In spite of the fine-grained silicates this seems more in keeping with a normal cooling history for these basalt sheets.

The drop-like shape of these metallic grains contrasts with the above mentioned metallic grains in the basalt from for instance Gieseckes Dal (plate 4, fig. 1). This is clearly a reflection of the temperature of formation of the solid metal masses and the silicate crystals. The metal grains in the drops have kept their drop shape from the initial liquid state, and it is believed that they solidified before the surrounding silicate melt. Calculation of the content of the various minerals in these grains from the photos of sectioned spheres resulted in the following approximate composition:

Fe: ca. 94%, S: ca. 5%, C: ca. 0.5%, P: ca. 0.1%.

If this is correct (the three dimensional nature of the grains might alter it altogether) it indicates a carbon content in the iron of about 0.6%. Judging from the pure Fe-C diagram this would indicate a solidification temperature above 1400° and implying that the melt had originally a temperature of this high value. It should however be stressed that the drop regarded as a whole contains both S and P in addition to the C. The more reasonable way of looking at this should therefore be on the background of the four-component system. This would certainly give lower temperatures, but really how low can only be stated from a much better knowledge than the existing results from the two ternary system allow. If the temperature of solidification of the surrounding silicates is taken to be between 1200 and 1300°C, the metal grains might have solidified a little above this temperature. It is noted that the pyrrhotite clearly shows borderlines governed by the silicates, thereby illustrating the earlier crystallization of these.

This peculiar zoned structure has an interest beyond the material treated here. As cited p. 14 structure of a similar kind has been observed in the native iron carrying rocks of Krasnoyarsk District.

Comparable zoning including the same compounds can also be found in certain meteorites, (EL GORESY, 1965).

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DANSK RESUMÉ

Forekomsterne af metallisk jern i de tertiære basalter på Disko har været kendt i næsten hundrede år. STEENSTRUP og TÖRNEBOHM offentliggjorde undersøgelsesresultater derom for ca. 90 år siden, og disse arbejder giver i det store og hele en dækkende fremstilling af forholdene.

Nærværende afhandling indeholder en oversigt over hovedtrækkene i disse forekomster, og fra polerprøveundersøgelser af forskellige typer fremhæves flere geologisk interessante detaljer.

Foruden de store blokke af hvidt støbejern finder man små korn af metallisk jern jævnt fordelt i visse basaltlag, der dækker hundreder af kvadratkilometer. Dannelsen af frit jern i basalten er resultatet af reaktioner mellem basaltmelten og bituminøse skifre. Dette understøttes blandt andet af isotopundersøgelser, der viser, at forholdet C^{12}/C^{13} svarer til, hvad man finder i kulstof af organisk oprindelse.

Fra en upubliceret rapport om disse forekomster, af dr. Fisch, bringes et par fotografier, der viser forekomsten af basaltlag med små jernkorn i.

Polerprøveundersøgelser bekræfter først og fremmest, at jernet fra Uivfaq er hvidt støbejern, hvori blandt andet forekommer perlit – en finkornet sammenvoksning af jern og cohenit. Ud fra finkornetheden af denne sammenvoksning kan man skønne, at afkølingen af støbejernet er foregået overordentlig hurtigt, se fig. 4.

Cohenits forekomst her kan netop hænge sammen med en sådan brat afkøling; mineralet er ustabil og omdannes under andre forhold til jern og grafit.

Der er en del detaljer i disse jern-parageneser, der fortjener nærmere studier. Dette gælder blandt andet lavt smeltende forbindelser indenfor systemet Fe-C-P-S.

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Fig. 1. Partly corroded pearlite grains in basalt from Uivfaq. Magn. 200 X.



Fig. 2. Corroded pearlite grain with cohenite lamellae in basalt from Uivfaq. The ferrite of the original pearlite has been transformed into hydroxide. Plagioclase laths transect the metallic grain in the basalt rock. In middle of the grain and at the left border two half-spherules of graphite can be seen. Within the silicates in the one corner secondary silicates constitute a pocket. Magn. 200 X.

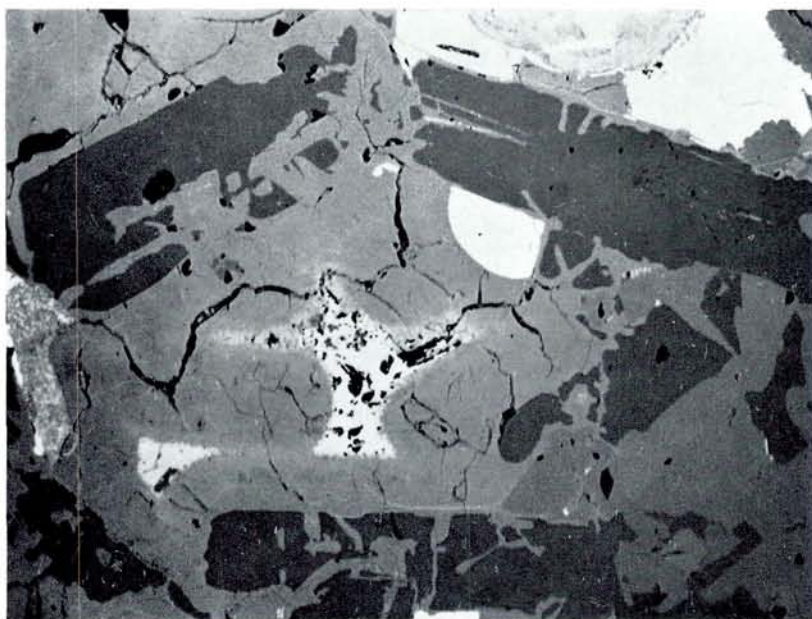


Fig. 1. Magnetite making up the central portion of a pocket of secondary minerals. These are lighter grey than the pyroxenes of the rock. Plagioclase appears darker grey. Light grains are sulphides and metallic phases. Rock sample from Uivfaq. Magn. 200 \times .



Fig. 2. Graphite spherule in cohenite contained in pearlite grains from basalt, Uivfaq. Parts of the pearlite are corroded, whereby compact cohenite stands out. Magn. 500 \times .

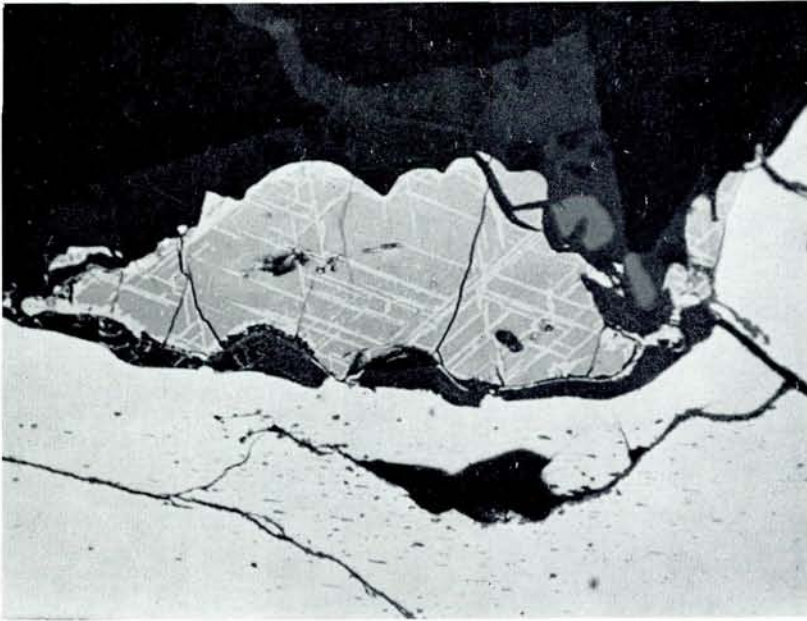


Fig. 1. Sulphides at border of millimetre-sized metal grain in basalt Uivfaq. Main part of metallic phases is cohenite in which tiny rectangular bodies can be seen due to "natural etching" (in other areas giving rise to corroded pearlite). Pyrrhotite containing lamellae of pentlandite and a lining of the same mineral constitutes the sulphide grain. Magn. 500 \times .

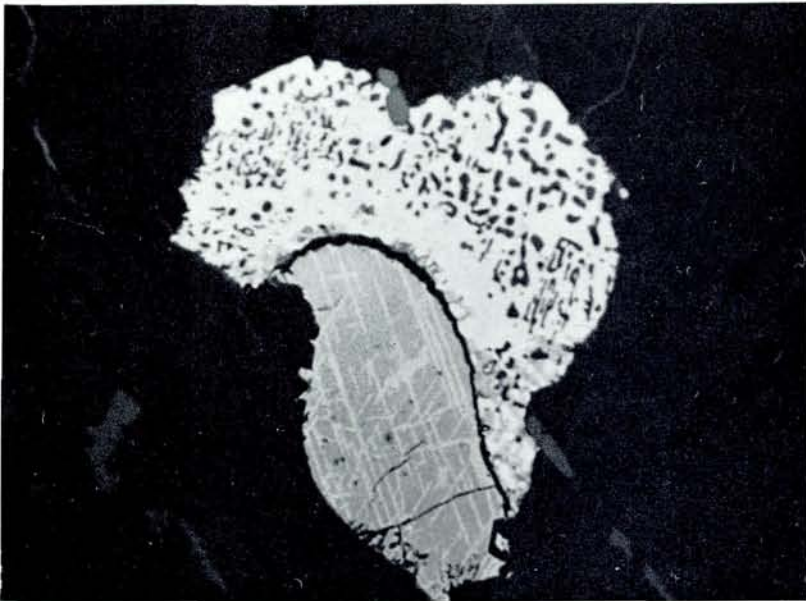


Fig. 2. Composite grain consisting of pyrrhotite with pentlandite lamellae and steadite: a eutectic structure containing schreibersite, cohenite, and ferrite. Dark patches are presumably replacements of ferrite or incorporated silicates. Isolated grain in rock from Uivfaq. Magn. 500 \times .

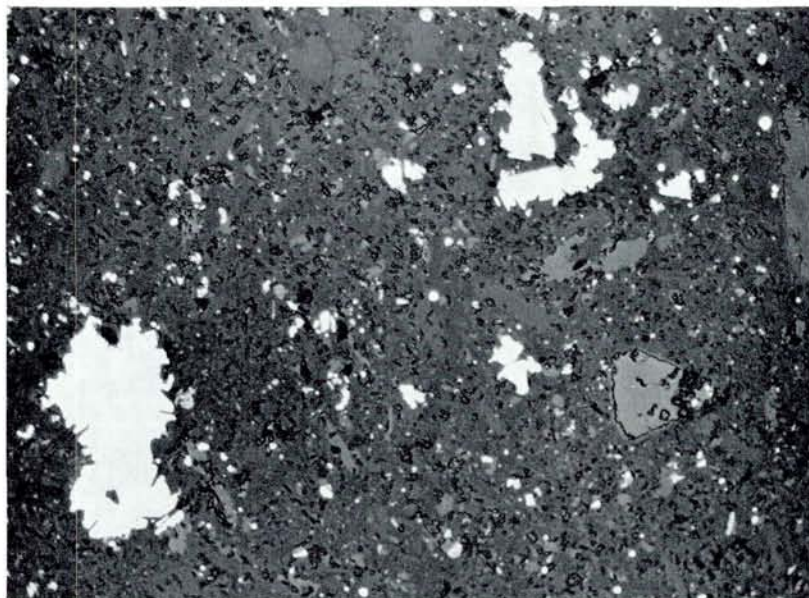


Fig. 1. Polished section of iron-bearing rock from Giesecke's Dal. Plagioclase laths protrude into the large metal grains. Small light grains are sulphides and metallic phases. Light grey smooth grain showing relief is spinel. Other light grey large grains are pyroxenes. Magn. 200 \times .

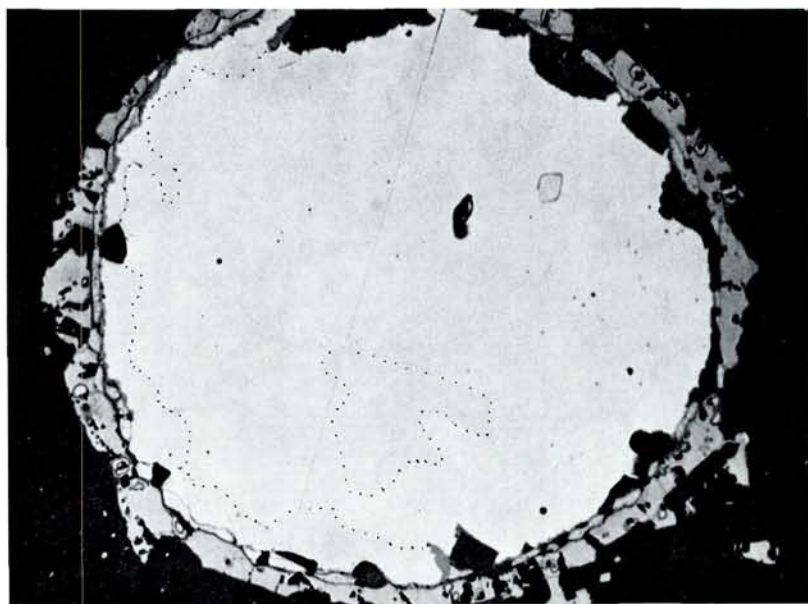


Fig. 2. Metal droplet in Asuk basalt. The light grey grains in the atoll structure are pyrrhotite. Between the sulphide and the metal a thin broken shell of steadite containing schreibersite is seen. Most of the metal is pure iron, but part of its rim consists of cohenite, the border of which has been marked by a dotted line. A cohenite grain in the ferrite has likewise been marked. Magn. 200 \times .