OPAQUE MINERALS IN THE PRECAMBRIAN PLUTONIC ROCKS OF BORNHOLM AND THEIR RELATION TO THE DEVELOPMENT OF THESE ROCKS

By

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Abstract

All the Precambrian plutonic rocks of Bornholm contain less than three per cent opaque minerals, but the opaque minerals reflect very well the petrographic development of these rocks.

The opaque minerals consist mainly of Fe-Ti-oxides, but several sulphide minerals are present in small amounts. Pyrite and chalcopyrite have the most widespread occurrence, and pyrrhotite, which is the predominant sulphide in the least granitised rock, is very scarce or absent in all the other rocks.

The Fe-Ti-oxides are mainly magnetite and ilmenite. The magnetite is generally homogeneous but occasionally contains a few ilmenite lamellae parallel to {111} and sometimes also carries inclusions of rutile and spinel. The ilmenite is generally without exsolution bodies and completely homogeneous, but occasionally contains thin lamellar twins on the rhombohedron. Part of the ilmenite however shows a faint heterogeneity, and in the Vang granite, and to some extent also in the Svaneke granite, there is ilmenite showing an extremely fine pattern of small exsolution bodies of hematite.

Ilmenite is frequently found altered to sphene. Other types of ilmenite alteration such as alteration to hematite and rutile and the type of alteration characteristic of ilmenite in beach sands from tropical and subtropical climates are also found. In the more granitised rocks magnetite shows martitisation.

Comparisons with the different degrees of granitisation established by MICHEELSEN (1961 b) show that with increasing granitisation the amount of opaque minerals and the ratio between the amounts of ilmenite and magnetite decrease, whereas the degree of martitisation increases. The decrease in the ratio of ilmenite to magnetite is caused mainly by alteration of ilmenite to sphene.

INTRODUCTION

Precambrian plutonic rocks, mainly of granitic composition, constitute the major part of the island of Bornholm. Bornholm, which covers 600 km^2, constitutes the south-eastern part of Denmark and lies in the Baltic Sea, at approximately lat. 55°N and long. 15°E.

The Precambrian of Bornholm has been thoroughly described by CALLISEN (1934) and more recently by MICHEELSEN (1961 b). The work of these authors is summarised by NOE-NYGAARD (1963). The major part of the plutonic rocks is developed as a greyish or reddish gneiss of granitic compo-

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sition. At Maegård in the north-western part of the gneiss area a small area of dark grey hypersthene-granodiorite occurs within the gneiss. The south-western part of the Precambrian area is formed by the dark grey Rønne granodiorite, which contains plagioclase and potassium feldspar in about equal amounts, but with plagioclase slightly more abundant. The mineralogical composition of the Rønne granodiorite thus places it very close to the granite-granodiorite border. The northernmost part of the island is made up of the most siliceous of the granitic rocks of Bornholm, the reddish Hammer granite. A similar granite is found in the middle of the island, completely surrounded by gneiss. Between the northern Hammer granite area and the gneiss area there is a belt of Vang granite which, in its mineralogical composition, is intermediate between Hammer granite and Rønne granodiorite. East of the gneiss area there is a belt of migmatitic gneiss, the Paradisbakke migmatite. Finally there is the reddish or greyish Svaneke granite, which covers the area between the migmatite and the coast. The Svaneke granite is younger than the other plutonic rocks and has a somewhat larger grain size.

In these Precambrian plutonic rocks pegmatites, leucogranites and aplites are rather common. The pegmatites and the leucogranites are described in separate papers by MICHEELSEN (1960, 1961 a).

The distribution of the different Precambrian rocks is shown in Fig. 1, p. 81.

As CALLISEN and MICHEELSEN in their work did not use reflected light, the author decided to study the content of opaque minerals in the Precambrian plutonic rocks of Bornholm.

The distribution of the different Precambrian rocks is shown in Fig. 1, p. 65.
specimens collected by the author.

THE HYPERSTHENE-GRANODIORITE FROM MAEGÅRD

The percentage of opaque minerals present in the hypersthene-granodiorite is estimated to be 2.7 %.*) This is based on the counting of more than 46 000 points.

Most of the opaque minerals are Fe-Ti-oxides, but there are also some sulphide minerals present.

The Fe-Ti-oxides are represented by ilmenite and by magnetite containing lamellae of ilmenite. Furthermore there are some composite grains, i.e. grains consisting partly of magnetite and partly of ilmenite which is not arranged in lamellae but forms larger masses. These composite grains are generally considerably larger than the other ore grains, but not as numerous. Most of the ore grains consist of ilmenite. In some of the polished sections

* Although sphene is frequently dealt with as it is rather easily identified in reflected light and constitutes a common alteration product of Fe-Ti-oxides, it is not included in the percentages of opaque minerals given. These percentages are all volume percentages.

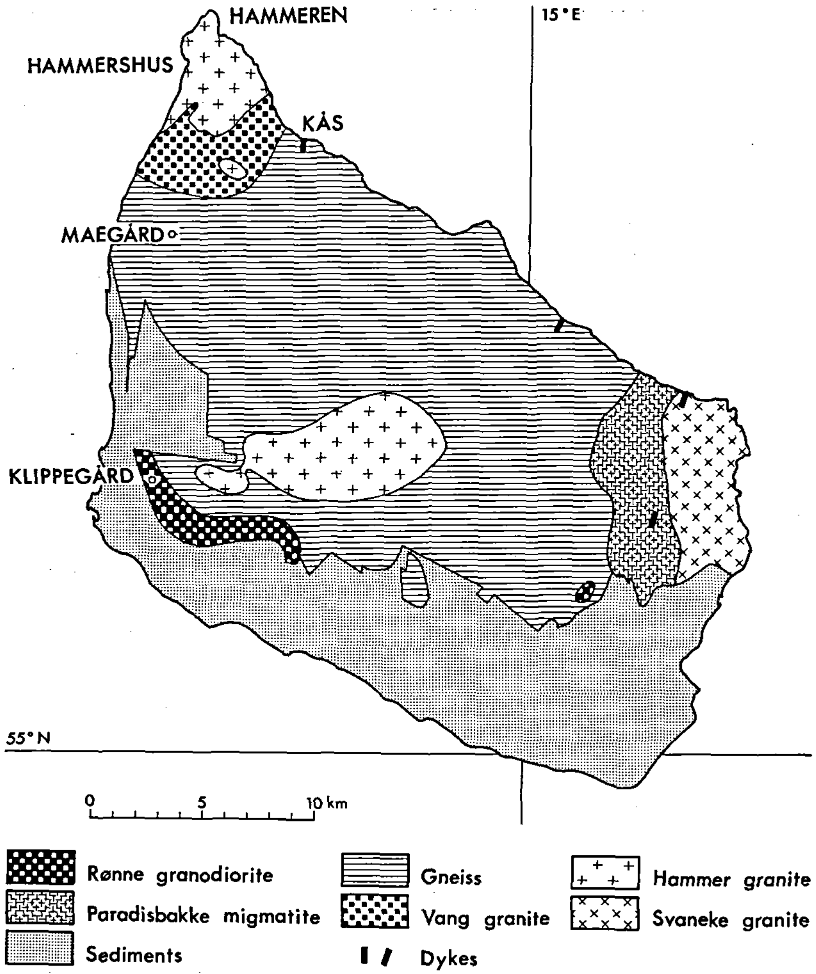

Fig. 1. Sketch map of Bornholm showing the distribution of the different Precambrian plutonic rocks. After CALLISEN (1934) and MICHEELSEN (1961 b).

there is about twice as much ilmenite as magnetite, whereas other polished sections contain ilmenite and magnetite in about equal amounts.

The appearance of the ilmenite, greyish brown colour, reflection pleochroism, strong anisotropy and the lack of internal reflections, indicates that the composition is probably rather close to pure $FeTiO_3$. The ilmenite is generally untwinned and quite homogeneous, but very occasionally a single twin lamella is found in ilmenite from composite grains. Occasionally idiomorphic inclusions of apatite can be seen in the ilmenite.

With a few exceptions the ilmenite is all fresh and completely without alteration. However in a few grains, mainly composite grains, part of the ilmenite attains a faint bluish tint but retains the anisotropy. This faint bluish material is found in rather large areas which are generally clearly localised by cracks. This phenomenon has earlier been described, but not explained, from dolerite dykes from Bornholm (JENSEN 1966, p. 440–441). There are also a few ilmenite grains in which the ilmenite along the borders is weakly altered to sphene, and one ilmenite grain was found completely surrounded by a thin rim of sphene. It should however be emphasised that sphene in connection with ilmenite is found only very occasionally, and that sphene is relatively scarce in the hypersthene-granodiorite anyway.

Most of the magnetite grains contain some ilmenite lamellae arranged parallel to {111} of the magnetite. These lamellae are of two different types: some rather broad and with regular straight borders, and some rather thin and somewhat irregularly shaped. Magnetite with irregular ilmenite lamellae is shown in Plate 1 Fig. 1.

The magnetite part of the composite grains does not carry ilmenite lamellae proper. It does, however, contain some very fine plates. The smallest of these plates are just discernible with the highest magnification, but the largest can be seen to have the colour, the reflection pleochroism and the anisotropy of ilmenite. These ilmenite plates are also arranged parallel to {111} and show a rather regular spacing (Plate 1 Fig. 2).

Apart from the above-described lamellae and plates of ilmenite the magnetite in the hypersthene-granodiorite appears quite homogeneous. Inclusions of idiomorphic apatite are occasionally found in the magnetite.

Five different sulphide minerals are found in the hypersthene-granodiorite: pyrrhotite, pyrite, marcasite, chalcopyrite and sphalerite. Pyrrhotite is strongly predominant. It occasionally contains inclusions of chalcopyrite, which mineral is not found as independent grains. Pyrite occurs as a few rather large grains. Marcasite and sphalerite are found only occasionally. The sphalerite carries numerous small exsolution bodies of chalcopyrite. Similar sphalerite from the Rønne granodiorite is shown in Plate 1 Fig. 3.

RØNNE GRANODIORITE

The percentage of opaque minerals present in the Rønne granodiorite is estimated to be 2.0 %. This is based on the counting of more than 57 000 points.

The most abundant of the opaque minerals is ilmenite, which is strongly predominant. Besides ilmenite, there also occur magnetite and some sulphides. The amount of magnetite present is about the same as that of sulphides.

The appearance of the ilmenite, greyish brown colour, reflection pleochroism, strong anisotropy and the lack of internal reflections, indicates that the composition is probably rather close to pure $FeTiO_3$. The ilmenite is generally untwinned and quite homogeneous, but in a very few grains a number of thin twin lamellae on the rhombohedron were observed. The ilmenite grains rather frequently contain idiomorphic inclusions of apatite. (See Plate 2 Fig. 1.)

Some of the ilmenite grains are surrounded by a thin rim of sphene (Plate 1 Fig. 4), and occasionally a somewhat more advanced alteration of ilmenite to sphene is seen. The majority of the ilmenite grains however do not show a relationship with sphene.

Apart from this alteration to sphene the ilmenite is generally quite fresh, but occasionally three other types of alteration are found; these types, however, are scarce and not very well developed.

1) Alteration of ilmenite to rutile. A few grains of ilmenite were found with alteration to rutile along the grain boundaries. The rutile shows numerous strongly luminous internal reflections, and between the rutile grains there are numerous holes indicating dissolution (Plate 1 Fig. 3).

2) Alteration of ilmenite to hematite and rutile. In a few grains some of the ilmenite was seen to be altered to an extremely fine-grained mixture of hematite and rutile. The internal reflections of the rutile in this type of alteration are not so conspicuous as in the above-described alteration to rutile accompanied by holes. The alteration of ilmenite to hematite and rutile generally starts in the interior of the ilmenite grains. This type of alteration is best seen in Plate 7 Fig. 1 which shows ilmenite from the Svaneke granite where the alteration products have a somewhat larger grain size.

3) Ilmenite alteration of beach sand type. Ilmenite alteration of this type was until recently known only from beach sands occurring in tropical and subtropical climates and is described in detail by LYND, SIGURDSON, NORTH & ANDERSON (1954) and by BAILEY, CAMERON, SPEDDEN & WEEGE (1956). These last-named authors recognise three different stages in this type of ilmenite alteration, and alteration of ilmenite corresponding to Stage 1 of BAILEY et al. has recently been found in rocks in place (JENSEN 1966) as well as in beach sand from a temperate climate (JENSEN 1967). In the Rønne granodiorite a few grains of ilmenite containing typical Stage 1 alteration of beach sand type were found. Plate 5 Fig. 1 shows this type of alteration in ilmenite from dark-coloured gneiss.

The magnetite in the Rønne granodiorite frequently contains a few rather broad lamellae of ilmenite arranged parallel to {111}. Occasionally the number of ilmenite lamellae in the magnetite is somewhat larger, but this increase in number is generally accompanied by a decrease in the width of the individual lamellae.

Apart from these ilmenite lamellae the magnetite looks homogeneous and no alteration of the magnetite was observed.

There are some composite grains of magnetite and ilmenite. These composite grains sometimes carry lamellae of ilmenite as well as ilmenite in masses, whereas small plates of ilmenite as found in the composite grains in the hypersthene-granodiorite from Maegård were not observed in the Rønne granodiorite. Idiomorphic apatite was observed in the magnetite part of one of the composite grains.

The Rønne granodiorite contains the same five sulphide minerals as were found in the hypersthene-granodiorite, but the relative amounts of these minerals are different in the Rønne granodiorite.

Pyrite predominates strongly and is very often idiomorphically developed. The pyrite sometimes contains small inclusions of other sulphides, mainly chalcopyrite, but to a smaller extent also sphalerite and pyrrhotite. In some of the polished sections marcasite occurs intergrown with pyrite, whereas marcasite is completely absent from other polished sections. Pyrrhotite occurs almost exclusively as inclusions in pyrite, whereas independent grains of pyrrhotite are extremely scarce. Chalcopyrite and sphalerite are more often found as independent grains than pyrrhotite. The independent sphalerite grains contain numerous small exsolution bodies of chalcopyrite (Plate 1 Fig. 3).

PARADISBAKKE MIGMATITE

The Paradisbakke migmatite is made up of two very different portions: a dark-coloured portion which so far as the non-opaque minerals are concerned is almost identical with the Rønne granodiorite, and a light-coloured portion which forms ramifying leucocratic veinlets in the dark-coloured portion.

The dark-coloured portion of the Paradisbakke migmatite

The percentage of opaque minerals present in the dark-coloured portion of the Paradisbakke migmatite is estimated to be 1.4 %. This is based on the counting of more than 64 000 points.

Most of the opaque minerals are Fe-Ti-oxides whereas the amount of sulphide is rather small.

The Fe-Ti-oxides are represented by magnetite and ilmenite, which seem to be present in about equal amounts.

Most of the magnetite occurs as large grains, many of which are composite, i. e. contain ilmenite in larger masses. These large grains, pure magnetite grains as well as composite grains, are generally surrounded by a rather broad rim of sphene. Magnetite also occurs as smaller grains, some of which have a rim of sphene, but many of which are without connection with sphene. In a few of the magnetite grains some thin lamellae of ilmenite arranged parallel to {111} can be seen. Occasionally small inclusions of rutile are found in the magnetite (Plate 8 Fig. 3 shows similar but somewhat larger rutile inclusions in magnetite from pegmatite), and very occasionally a few small plates of ilmenite similar to those described from the magnetite of composite grains in the hypersthene-granodiorite can be seen. In the Paradisbakke migmatite however such plates are rare and very few in number so that no regular pattern is established.

The magnetite is generally completely without any traces of martitisation, but occasionally a weak martitisation is seen in magnetite grains adjacent to light-coloured portions of the Paradisbakke migmatite.

Part of the ilmenite has the same appearance as in the previously described rocks, and accordingly a composition which is probably rather close to pure $FeTiO_3$ is indicated. However, there is also some ilmenite with an extremely fine heterogeneous appearance, which might be due to an almost submicroscopic exsolution of hematite in minute points. The ilmenite is frequently found as larger or smaller replacement remnants in larger sphene areas (Plate 2 Fig. 2 and Plate 3 Fig. 1), and although some ilmenite grains are found without connection to sphene, there is very often a rather broad rim of sphene surrounding the ilmenite grains.

Apart from the alteration to sphene the ilmenite is generally quite fresh, but occasionally more or less progressed alteration to hematite and rutile can be observed.

Inclusions of idiomorphic apatite have been observed in ilmenite as well as in magnetite.

Larger areas of sphene in which separate areas of magnetite and of ilmenite occur can sometimes be observed. This probably indicates the former presence of composite grains.

Areas of sphene without any opaque remnants are also frequently found.

The sulphide minerals in the dark-coloured portion of the Paradisbakke migmatite are represented by pyrite and chalcopyrite. These two minerals are present in about equal amounts, but pyrite is somewhat more abundant. Occasionally larger grains of pyrite are seen to contain a few small inclusions of chalcopyrite.

The light-coloured portion of the Paradisbakke migmatite

In this part of the migmatite the opaque minerals are represented almost solely by strongly martitised magnetite, but some smaller grains of ilmenite are also present.

The percentage of opaque minerals present is estimated to be 0.2 %. This is based on the counting of more than 14 000 points.

VANG GRANITE

The percentage of opaque minerals present in the Vang granite is estimated to be 1.8 %. This is based on the counting of more than 92 000 points.

The opaque minerals are mainly Fe-Ti-oxides, but a small amount of sulphide is also present.

The Fe-Ti-oxides are magnetite and ilmenite, magnetite being the most abundant. Generally magnetite is clearly predominant; one of the polished sections, however, contains magnetite and ilmenite in about equal amounts.

The magnetite generally looks quite homogeneous. Occasionally, however, the magnetite contains one or two ilmenite lamellae arranged parallel to {111} of the magnetite. Magnetite grains are very occasionally found containing several rather thin lamellae of ilmenite (Plate 3 Fig. 2). Besides ilmenite in lamellae there are also small plates of ilmenite as in the hypersthene-granodiorite. These plates in the Vang granite are however not as large as those in the hypersthene-granodiorite. Inclusions of idiomorphic apatite occur in the magnetite and sometimes there are also small inclusions of rutile and some spinel-like inclusions.

There occur some composite grains consisting of magnetite with ilmenite in more or less irregular masses. Such grains are generally surrounded by a rather broad rim of sphene. Some grains of pure magnetite are also found surrounded by a rim of sphene.

In a few of the magnetite grains part of the magnetite has been oxidised to hematite. This martitisation however is not very pronounced (Plate 3 Fig. 2).

In the Vang granite there is some ilmenite with the same homogeneous appearance as the ilmenite in the hypersthene-granodiorite and the Rønne granodiorite, but a very large part of the ilmenite in the Vang granite has a very fine pattern of finely dispersed small exsolution bodies of hematite (Plate 4 Fig. 1). The size of the hematite exsolution bodies is about 1 μ for the largest whereas many are considerably smaller, but they can clearly be seen as discrete bodies, whereas no discrete bodies could be observed in the heterogeneous ilmenite in the Paradisbakke migmatite (p. 85). The ilmenite occasionally contains idiomorphic inclusions of apatite and a few twin lamellae on the rhombohedron (Plate 3 Fig. 3).

Only a small part of the ilmenite occurs intergrown with magnetite; most of the ilmenite is found as free grains. These are generally surrounded by a very broad rim of sphene (Plate 3 Fig. 3). Large areas of sphene in which only small rounded blebs of ilmenite are left as replacement remnants are common.

In the sphene connected with ilmenite there are sometimes areas of strongly luminous leucoxene, the mineralogical composition of which cannot be determined with the microscope (Plate 3 Fig. 3).

Occasionally there are larger areas of sphene in which separate areas of magnetite and of ilmenite occur. This probably indicates the former presence of composite grains. The magnetite areas are generally considerably larger than the ilmenite areas.

The ilmenite which has not been altered to sphene is generally quite fresh, but the other three types of ilmenite alteration described for Rønne granodiorite have all been found in the Vang granite. The beach sand type of alteration and alteration to rutile accompanied by holes are very seldom, whereas alteration to hematite and rutile is somewhat more widespread than in the Rønne granodiorite (Plate 3 Fig. 3).

The amount of sulphide in the Vang granite seems to be somewhat less than in the Rønne granodiorite. Pyrite is the predominant sulphide, generally occurring in rather small grains, and no inclusions of other sulphides have been found in the pyrite. Chalcopyrite is found less frequently than pyrite and generally occurs in still smaller grains. Pyrite as well as chalcopyrite is most commonly found as free grains, but occasionally these two sulphides are found intergrown with each other. In one of the polished sections pyrite was occasionally seen intergrown with marcasite, whereas no marcasite was observed in the other polished sections.

GNEISS

The major part of the Precambrian of Bornholm is developed as gneiss. This gneiss however varies considerably from place to place even within rather short distances. The author has followed the division into dark-coloured gneiss and light-coloured gneiss made by MICHEELSEN (1961 b).

Dark-coloured gneiss

The percentage of opaque minerals in the dark-coloured gneiss is estimated to be 1.2 %. This is based on the counting on more than 49 000 points.

Magnetite is by far the most abundant opaque mineral. Ilmenite lamellae in the magnetite are extremely rare, except near the contact of the dolerite dyke at Kås (Fig. 1, p. 81), where the magnetite frequently carries numerous very thin lamellae of ilmenite arranged parallel to {111}. In a few of the magnetite grains small inclusions of spinel were observed (Plate 4 Fig. 2), and in some magnetite grains a few small inclusions of an unidentified mineral, probably ilmenite, were observed. Inclusions of idiomorphic apatite are occasionally found in the magnetite. Larger grains of magnetite are frequently rimmed by sphene.

Composite grains of magnetite and ilmenite are rare. However, the former presence of more composite grains is indicated by larger areas of sphene which include small rounded ilmenite islands as well as larger areas of magnetite (Plate 4 Fig. 3).

A weak martitisation of the magnetite grains is rather common, and a few whole grains of magnetite have been oxidised to hematite.

In most of the polished sections investigated ilmenite is present in very small amounts and is found mainly as small rounded islands left as replacement remnants in larger areas of sphene. However, polished sections of gneiss occurring as inclusions in Svaneke granite differ from the other polished sections of gneiss in having ilmenite and magnetite present in about equal amounts with ilmenite slightly more abundant. Alteration of ilmenite to sphene is not less pronounced where ilmenite is present in larger amounts. Thus rather than indicating less alteration of ilmenite to sphene, the sections rich in ilmenite indicate that the original material from which the gneiss in these inclusions was formed was richer in ilmenite than the material from which the gneiss elsewhere was formed.

Most of the ilmenite has the same appearance as the ilmenite in the hypersthene-granodiorite and the Rønne granodiorite, indicating a composition which is probably rather close to pure $FeTiO_3$. The ilmenite is generally untwinned and quite homogeneous, but occasionally a few lamellar twins on the rhombohedron can be seen. There is however also ilmenite which shows a faint heterogeneity like that shown by some of the ilmenite in the Paradisbakke migmatite.

Near the contact of the Kås dolerite dyke ilmenite alteration of beach sand type is rather widespread (Plate 5 Fig. 1), but elsewhere in the gneiss area this type of alteration is very rare. Ilmenite altered to rutile accompanied by holes has only been observed near the contact of the Kås dyke.

Alteration of ilmenite to hematite and rutile is occasionally seen in the gneiss.

Areas of strongly luminous leucoxene are rather frequently found in connection with sphene. The mineralogical composition of the leucoxene cannot be determined with the microscope. Leucoxene is also found in sphene which still contains opaque Fe-Ti-oxides.

The amount of sulphide is rather small. Pyrite is the predominant sulphide mineral. It occurs mainly as rather small grains. Some of the pyrite grains contain inclusions of chalcopyrite and pyrrhotite. A few grains of sphalerite with numerous small exsolution bodies of chalcopyrite have also been observed.

Light-coloured gneiss

The percentage of opaque minerals in the light-coloured gneiss is estimated to be 0.5 %. This is based on the counting of more than 46 000 points.

The opaque minerals in the light-coloured gneiss are rather similar to those in the dark-coloured gneiss, but the martitisation of magnetite is more pronounced (Plate 5 Fig. 2) and ilmenite is still more scarce or almost absent.

HAMMER GRANITE

The percentage of opaque minerals present in the Hammer granite is estimated to be 0.4 %. This is based on the counting of more than 64 000 points.

Magnetite is by far the most abundant opaque mineral. There are occasional rather thin lamellae of ilmenite arranged parallel to {111}, and a few small inclusions of an unidentified mineral which is most probably ilmenite were also observed. Most of the magnetite grains have a broad rim of sphene (Plate 6 Fig. 1).

Composite grains of magnetite and ilmenite are extremely rare, but as in the dark-coloured gneiss (p. 87), the texture of sphene-magnetite-ilmenite intergrowths indicates that composite grains were originally more abundant.

Some of the magnetite grains are completely without martitisation, but where martitisation does occur it is generally much more advanced than in the gneiss, and rather many grains have been completely oxidised to hematite.

The amount of ilmenite is rather small and most of the ilmenite occurs as small rounded replacement remnants in larger masses of sphene (Plate 5 Fig. 3). Somewhat larger grains of ilmenite can be found, but they are always surrounded by large rims or masses of sphene. Occasionally plates of ilmenite parallel to {0001} can be seen, and such plates can be without association with sphene.

Part of the ilmenite is homogeneous, its appearance indicating a composition which is probably rather close to pure $FeTiO_3$. Another part of the ilmenite however shows a faint heterogeneity as described earlier from the

Paradisbakke migmatite and the gneiss. The ilmenite is occasionally altered to hematite and rutile.

Sphene without remnants of opaque minerals, except for areas of strongly luminous leucoxene the mineralogical composition of which cannot be identified with the microscope, occurs frequently. Leucoxene is also found in sphene which still contains opaque Fe-Ti-oxides.

The amount of sulphide is rather small. Pyrite is the predominant sulphide mineral, but some chalcopyrite also occurs. The sulphides are generally found as rather small grains. Galena has not been observed during this investigation but BØGGILD (1943, p. 13–14) mentions that a small veinlet with cubes of galena about 1 mm large has been found in the Hammer granite at Hammershus (Fig. 1, p. 81). BØGGILD (1943, p. 9) also states that molybdenite has been found at Hammeren but does not mention whether the occurrence was in Hammer granite or in pegmatite. No molybdenite has been observed in Hammer granite during the present investigation.

SVANEKE GRANITE

The percentage of opaque minerals present in the Svaneke granite is estimated to be 1.2 %. This is based on the counting of more than 53 000 points.

Magnetite is the most abundant of the opaque minerals. Most of the magnetite is without connection with ilmenite but some of the magnetite grains, especially smaller ones, carry a few thin lamellae of ilmenite arranged parallel to {111}, and composite grains of magnetite and ilmenite can occasionally be seen. These grains are always very large. Magnetite occasionally contains idiomorphic inclusions of apatite.

Most of the large magnetite grains and all the composite grains are surrounded by broad rims, or rather masses, of sphene (Plate 6 Fig. 2), but quite a few of the smaller magnetite grains are without any connection with sphene.

Some of the magnetite grains are weakly martitised and in one case a few grains completely oxidised to hematite were found, but in two of the polished sections investigated the magnetite is without martitisation.

The amount of ilmenite is always considerably less than that of magnetite and in some of the polished sections ilmenite grains are rather scarce. Part of the ilmenite is homogeneous, its appearance indicating that the composition is probably rather close to pure $FeTiO_3$, but there is also ilmenite which shows a heterogeneity somewhat more pronounced than that shown by some of the ilmenite in the Paradisbakke migmatite, the gneiss and the Hammer granite. Occasionally ilmenite in the Svaneke granite shows discrete exsolution bodies of hematite, but they are generally somewhat smaller than those in the Vang granite. Inclusions of idiomorphic apatite can occasionally be seen in the ilmenite. Twin lamellae on the rhombohedron occur but are extremely rare (Plate 7 Fig. 1).

Although occasionally some ilmenite grains without any connection with sphene can be seen, the ilmenite grains are generally surrounded by a very broad rim of sphene, and a rather large part of the ilmenite is found as larger or smaller replacement remnants in large masses of sphene.

Alteration of ilmenite to hematite and rutile is very common (Plate 7 Fig. 1), and several grains with ilmenite alteration of beach sand type were found. Alteration of ilmenite to rutile accompanied by holes also occurs, but is rare.

Large areas of sphene without any opaque remnants except strongly luminous leucoxene are very common. Most of this leucoxene has not been identified but occasionally the leucoxene occurs as relatively large crystals which are identified as anatase (Plate 7 Fig. 2). Leucoxene is also found in sphene which still includes opaque Fe-Ti-oxides.

The amount of sulphide is relatively large and the following sulphide minerals are represented: pyrite, chalcopyrite, marcasite and pyrrhotite. Pyrite is strongly predominant and is rather frequently found as idiomorphic grains, although the larger grains in particular are often irregular and without crystal faces. Some pyrite grains carry inclusions of chalcopyrite. Chalcopyrite is also found as independent grains. Whereas pyrite and chalcopyrite are found in all the polished sections, only about half of them carry marcasite. Marcasite is found in free grains as well as intergrown with pyrite. One independent grain of pyrrhotite was found and the mineral was also found as an inclusion in a grain of pyrite together with chalcopyrite and an unidentified brownish mineral. Both these occurrences of pyrrhotite are found in polished sections which do not carry marcasite.

PEGMATITES AND APLITES

The percentage of opaque minerals in pegmatites has not been estimated because of the large grain size. However, as pegmatite specimens for preparation of polished sections must be carefully selected to ensure that at least some ore is present, the percentage of opaque minerals is believed to be very low – possibly lower than in any of the other Precambrian rock types of Bornholm. The counting of more than 60 000 points gives an ore percentage of 0.4 % in aplites; thus the aplites can contain the same amount of opaque minerals as the Hammer granite.

The most abundant opaque mineral in pegmatites and aplites is magnetite. Generally, however, the magnetite is strongly martitised (Plate 7 Fig. 3 and Plate 8 Fig. 1). Frequently only some small triangular areas of unaltered magnetite remain in grains which otherwise are completely martitised, and grains consisting purely of hematite without any remnants of magnetite are common. The texture of these hematite grains clearly indicates that the hematite has originated by martitisation of magnetite. In spite of this evidently strong oxidation there also occur some magnetite grains without any trace of martitisation.

Some of the magnetite grains are surrounded by a rim of sphene, but the majority of the grains are without any connection with sphene. Sphene is in any case rather scarce in pegmatites and aplites.

Ilmenite in free grains was not observed but ilmenite occurs as thin lamellae arranged parallel to {111} of some of the magnetite grains, and also occurs as irregular masses in a few of the larger magnetite grains.

Alteration of ilmenite to sphene is found in the irregular masses of ilmenite, and alteration of ilmenite to hematite and rutile is found in ilmenite lamellae parallel to {111} as well as in ilmenite in irregular masses.

In pegmatite a few examples were found of a special type of ilmenite alteration, the mineralogical components of which have not been identified with certainty. The alteration is developed as a coarse network of a mineral which has a certain resemblance to anatase but in two respects it fails to fit the description of anatase given by RAMDOHR (1960): it has reddish brown internal reflections as well as white, and the internal reflections do not prevent the observation of anisotropy with crossed polars. On the other hand this anisotropy is certainly not as strong as that of rutile. The areas intervening between this "anatase-rutile" network are probably sphene. In one of the examples the network and the intervening areas are peppered with small white spots which are probably hematite. This type of alteration is shown in Plate 8 Fig. 2.

Some short and broad but generally more or less elongate bodies of rutile are occasionally found included in relatively weakly martitised magnetite in pegmatite (Plate 8 Fig. 3).

In magnetite from pegmatite a few small inclusions of an unidentified mineral which is probably ilmenite have also been observed.

In strongly martitised magnetite in aplite a mineral was found which resembles perovskite in colour, reflectivity and hardness, and contains yellowish to brownish-red internal reflections. This mineral however differs from perovskite in being distinctly anisotropic. A similar bluish grey mineral has been described, but not identified, earlier (JENSEN 1967, p. 30 and Plate 20 Fig. 1).

The amount of sulphide present in pegmatites and aplites is extremely small. The sulphide minerals consist almost entirely of pyrite and marcasite and occur mainly as small grains. In pegmatite, marcasite as well as pyrite is also relatively frequently seen filling thin cracks. Molybdenite has been found in pegmatite in Rønne granodiorite from Klippegård (Fig. 1, p. 81) and Plate 8 Fig. 4); the occurrence of molybdenite here however has been known for a long time (BØGGILD 1943, p. 9). During the present investigation molybdenite has only been observed in pegmatite from Klippegård, but ØRSTED & ESMARCH (1819, p. 17) describe molybdenite from a pegmatite in Paradisbakke migmatite. Galena has not been observed during the present investigation but CALLISEN (1934, p. 93) has noticed one occurrence of pegmatite in gneiss which contains some galena.

RUTILE-LIKE NEEDLES AND MINUTE EPIDOTE CRYSTALS

The rutile-like needles and the minute epidote crystals occurring as inclusions in quartz and feldspars of the Rønne granodiorite (JENSEN 1965) are also found in the other plutonic rocks of Bornholm.

Rutile-like needles are as common in the hypersthene-granodiorite, the Paradisbakke migmatite, the Vang granite and the Svaneke granite as they are in the Rønne granodiorite, and the triangular pattern described for the needles in the Rønne granodiorite can also be observed in these rocks.

In the gneiss, the Hammer granite and in aplites and pegmatites, rutile-like needles are extremely scarce to absent, and the triangular pattern has not been observed.

Minute epidote crystals are as common in the hypersthene-granodiorite as in the Rønne granodiorite, and they are developed with the same typical triangular pattern. In the hypersthene-granodiorite, however, many of the minute epidote crystals are still smaller than in the Rønne granodiorite.

In the Vang granite minute epidote crystals are as common as in the Rønne granodiorite and the hypersthene-granodiorite. They are similar in size to those found in the Rønne granodiorite, but no triangular pattern is developed.

The Svaneke granite contains fewer minute epidote crystals than the Rønne granodiorite, but some of the crystals attain a larger size. Triangular pattern has not been observed in any of the polished sections of Svaneke granite, but in one thin section minute epidote crystals arranged in a triangular pattern were observed; they were similar in size to those found in the Rønne granodiorite. Alignment in single rows however has been observed several times.

The gneiss and the Paradisbakke migmatite contain considerably fewer minute epidote crystals than the Rønne granodiorite, and no triangular pattern was observed.

In pegmatites and aplites minute epidote crystals are extremely scarce to absent, and more than two or three crystals were never seen together; hence the triangular pattern is also lacking here.

The above description shows that in general the number of inclusions of rutile-like needles and minute epidote crystals decreases with increasing degree of granitisation of the host rock (Table I, p. 93). This fact might indicate an increasing degree of reorganisation of the feldspars and the quartz with increasing degree of granitisation.

However, the content of minute epidote crystals in the Hammer granite, which apart from pegmatites and aplites is the most highly granitised rock in Bornholm, does not fit in the trend. The number of minute epidote crystals in the Hammer granite is somewhat variable but in places these crystals are as numerous as they are in the Rønne granodiorite. Some of the crystals in the Hammer granite attain a size somewhat larger than that in the Rønne granodiorite, but triangular pattern is not observed.

Furthermore the number of minute epidote crystals seems to be larger in the light-coloured gneiss than in the dark-coloured gneiss.

These facts make an interpretation of the occurrence of these inclusions rather difficult.

CONCLUSIONS

On the basis of various investigations such as recording differences in the amounts of microcline, plagioclase, quartz and dark minerals present in the different plutonic rocks, the Ba content of the potassium feldspar, the An content of the plagioclase and the norms of the feldspars, MICHEELSEN (1961 b) has estimated the average degree of granitisation for each of the Precambrian plutonic rock types of Bornholm. His results are reproduced in Table I together with the percentages of opaque minerals in the rock types as given in the present paper.

Table I.

	Average degree of granitisation	Percentage of opaque minerals
Hypersthene-granodiorite from Maegård	20 %	2.7 %
Rønne granodiorite	40 %	2.0 %
Paradisbakke *migmatite*, dark-coloured portion	40 %	1.4 %
Vang granite	55 %	1.8 %
Dark-coloured gneiss	55 %	1.2 %
Light-coloured gneiss	65 %	0.5 %
Hammer granite	80 %	0.4 %
Svaneke granite	60 %	1.2 %
Aplites	100 %	0.4 %
Leucogranites (includes the light-coloured portion of the Paradisbakke migmatite)	100 %	0.2 %
Pegmatites	100 %	

Table I clearly reveals that there exists a relation between the amount of opaque minerals present and the degree of granitisation, in that the amount of opaque minerals decreases with increasing degree of granitisation. The only discrepancy is found between the Vang granite and the dark-coloured portion of the Paradisbakke migmatite. It is noticeable that areas of sphene without remnants of Fe-Ti-oxides are much more common in the dark-coloured portion of the Paradisbakke migmatite than in the Vang granite. Thus this discrepancy is probably due to the alteration of Fe-Ti-oxides to sphene which, at a given degree of granitisation, was farther advanced in the migmatised rocks in the Paradisbakke area than in the Vang granite which underwent more homogeneous granitisation. The migmatisation therefore has had a considerably greater effect on the amount of opaque minerals in the dark-coloured portion of the Paradisbakke migmatite than on those properties of the non-opaque minerals upon which the degree of granitisation is based.

Comparisons between Table I and the descriptive part of this paper show that there is also a relation between the development of the opaque minerals and the different degrees of granitisation.

This is clearly shown by the Fe-Ti-oxides. The ratio between the amounts of ilmenite and magnetite decreases with increasing degree of granitisation, except that a discrepancy exists between the hypersthene-granodiorite from Maegård and the Rønne granodiorite. The decrease in ilmenite relative to magnetite is caused mainly by alteration of ilmenite to sphene, and although ilmenite is more abundant in the Rønne granodiorite than in the hypersthene-granodiorite, the ilmenite in the hypersthene-granodiorite is fresher and less altered than the ilmenite in the Rønne granodiorite. The discrepancy is therefore thought to have been caused by original differences in the material subjected to granitisation, which the relatively low degrees of granitisation have not been able to obliterate.

Martitisation of magnetite starts when the degree of granitisation reaches about 55 % and increases rather strongly with increasing degree of granitisation.

Amongst the sulphide minerals, which constitute only a small part of the opaque minerals, pyrrhotite is strongly predominant in the hypersthene-granodiorite from Maegård, whereas in all the other plutonic rocks pyrite is the predominant sulphide mineral and pyrrhotite is very scarce or absent. It is thus seen that already with a comparatively small increase in the degree of granitisation pyrite becomes the predominant sulphide at the expense of pyrrhotite. The fact that sphalerite is found in the hypersthene-granodiorite, the Rønne granodiorite and the dark-coloured gneiss is in agreement with the results obtained by LUNDEGÅRDH (1948) who found Zn to be more abundant in granodiorite than in granite. The amount of sulphide present is largest in the somewhat younger Svaneke granite.

Although some discrepancies do exist it has now been shown that in the Precambrian plutonic rocks of Bornholm both the development and the amounts of the opaque minerals present are clearly related to the varying degrees of granitisation.

ACKNOWLEDGEMENTS

Thanks are due to Dr. H. I. MICHEELSEN for fruitful discussions during the work. The sketch map Fig. 1 was prepared by Mrs. R. LARSEN, and the photographic work was done by Mr. P. NIELSEN and Mr. C. HALKIER. Mr. G. HENDERSON kindly corrected the English manuscript.

DANSK RESUMÉ

De granitiske bjergarter på Bornholm indeholder alle mindre end tre volumenprocent opake mineraler. Mængden af opake mineraler er således ret ringe, men udviklingen af disse mineraler afspejler meget tydeligt den petrografiske udvikling af Bornholms graniter.

Langt den største del af de opake mineraler er Fe-Ti-oxider, men desuden er forskellige sulfidmineraler til stede i mindre mængde. Fe-Ti-oxiderne er ganske overvejende magnetit og ilmenit. Magnetiten er i regelen homogen, men indeholder undertiden enkelte ilmenitlameller, der er arrangerede parallelt med oktaederretningerne. Enkelte magnetitkorn indeholder et større antal ilmenitlameller (tavle 1, fig. 1 og tavle 3, fig. 2). Endvidere er der i sjældne tilfælde fundet indeslutninger af rutil (tavle 8, fig. 3) og spinel (tavle 4, fig. 2) i magnetiten. Ilmeniten er

i regelen uden afblandinger og fuldstændig homogen, bortset fra enkelte tynde tvillinglameller efter romboedret (f. eks. tavle 2, fig. 1). Imidlertid har en del af ilmeniten et ganske svagt heterogent udseende, og i Vang-graniten (samt i mindre grad også i Svaneke-graniten) forekommer der ilmenit med et yderst fint mønster af små afblandingslegemer af hæmatit (tavle 4, fig. 1). Reflektionsevnen og anisotropien af den homogene ilmenit tyder på, at sammensætningen er ret nær ren $FeTiO_3$. Såvel magnetit som ilmenit ses undertiden at have indeslutninger af idiomorf apatit (tavle 1, fig. 2 og tavle 2, fig. 1).

Ilmenit er hyppigt i større eller mindre udstrækning omdannet til titanit (f. eks. tavle 1, fig. 4 og tavle 2, fig. 2). Der ses desuden tre andre former for ilmenitomdannelse. Hyppigst af disse er omdannelse til hæmatit og rutil (tavle 7, fig. 1), medens omdannelse til rutil ledsaget af huller (tavle 1, fig. 3) og den omdannelsesform der er karakteristisk for ilmenit i tungsandsforekomster i tropisk og subtropisk klima (tavle 5, fig. 1) er sjældnere forekommende. Magnetitkornene kan også være mere eller mindre omdannede til titanit, og i de stærkere granitiserede bjergarter forekommer der martitisering af magnetiten (f. eks. tavle 4, fig. 3 og tavle 6).

De almindeligst forekommende sulfider er svovlkis og kobberkis. Magnetkis er det dominerende sulfidmineral i hypersthen-granodioriten fra Maegård, men forekommer ellers ret sjældent. Foruden disse tre sulfider ses undertiden markasit, og i enkelte tilfælde er der fundet korn af zinkblende indeholdende talrige små afblandingslegemer af kobberkis (tavle 1, fig. 3). Molybdænglans er kun fundet i pegmatit fra Klippegård (tavle 8, fig. 4).

Af tabellen side 93 fremgår det tydeligt, at mængden af opake mineraler falder med stigende granitiseringsgrad. Der er dog en enkelt afvigelse, idet Vang-graniten indeholder en større mængde opake mineraler end den mørke del af Paradisbakkemigmatiten. Denne afvigelse skyldes sandsynligvis omdannelse af Fe-Ti-oxider til titanit i forbindelse med tilførslen af materialet i den lyse del af Paradisbakkemigmatiten, og migmatiseringen har således tilsyneladende haft en større indvirkning på mængden af opake mineraler, end på de egenskaber hos de nonopake mineraler hvorpå granitiseringsgraden er beregnet.

Ikke alene mængden af de opake mineraler, men også deres udvikling er knyttet til forskellene i granitiseringsgrad. Således falder forholdet mellem mængderne af ilmenit og magnetit med stigende granitisering, bortset fra at der her er en afvigelse mellem hypersthen-granodiorit og Rønne-granodiorit. Faldet i ilmenit i forhold til magnetit skyldes især omdannelse af ilmenit til titanit, og selv om ilmenit er noget rigeligere i Rønne-granodiorit end i hypersthene-granodiorit, så er ilmeniten i hypersthen-granodioriten mere frisk og mindre omdannet end ilmeniten i Rønne-granodioriten. Det formodes derfor, at afvigelsen skyldes oprindelige forskelle i sammensætningen af udgangsmaterialet for granitiseringen, som de relativt lave granitiseringsgrader ikke har været i stand til at udslette.

Martitisering af magnetit begynder ved en granitiseringsgrad omkring 55 % og breder sig ret stærkt med stigende granitiseringsgrad.

Blandt sulfidmineralerne er magnetkis stærkt dominerende i hypersthen-granodioriten, medens svovlkis er det dominerende sulfid i alle de øvrige bjergarter, og magnetkis her er yderst sjælden eller mangler helt. Det ses således, at allerede ved en relativ lille stigning i granitiseringsgrad bliver magnetkis næsten fuldstændigt afløst af svovlkis. Mængden af sulfid er størst i den noget yngre Svanekegranit.

Selv om der forekommer enkelte afvigelser, er det således nu tydeligt vist, at mængden såvel som udviklingen af de opake mineraler i graniterne fra Bornholm er knyttet til forskellene i granitiseringsgrad.

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Færdig fra trykkeriet 2. maj 1968.

Fig. 1.

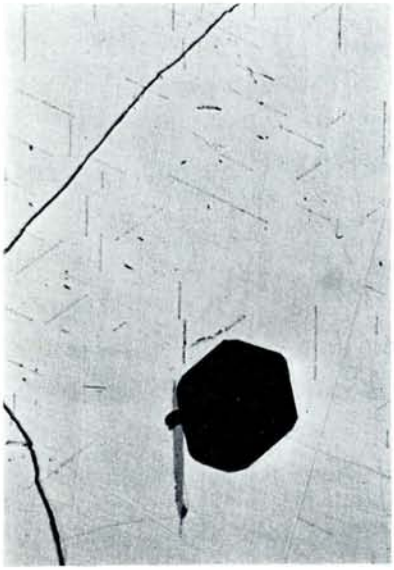

Fig. 2.

Fig. 1. Polariser only. × 700. Oil immersion. Hypersthene-granodiorite (Maegård). Magnetite with many rather thin and somewhat irregularly shaped lamellae of ilmenite arranged parallel to {111}.
Fig. 2. Polariser only. × 700. Oil immersion. Hypersthene-granodiorite (Maegård). Magnetite from a composite grain. Numerous very fine plates of ilmenite arranged parallel to {111} are seen regularly spaced throughout the magnetite. The magnetite also contains an idiomorphic grain of apatite to the left of which is seen a larger plate of ilmenite.

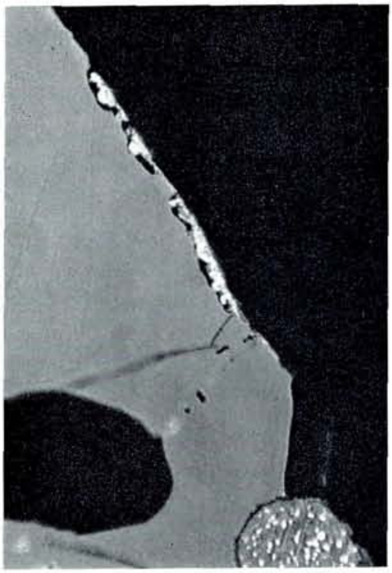

Fig. 3.

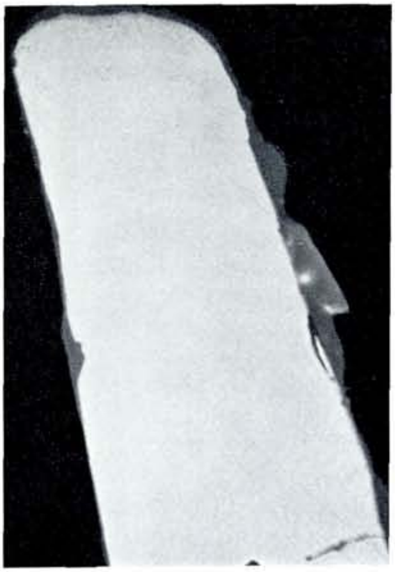

Fig. 4.

Fig. 3. Polariser only. × 700. Oil immersion. Rønne granodiorite (Rønne). Ilmenite with alteration along the border of the grain to rutile accompanied by holes. In the lower right corner the ilmenite is partly intergrown with sphalerite containing numerous small exsolution bodies of chalcopyrite.
Fig. 4. Polariser only. × 700. Oil immersion. Rønne granodiorite (Rønne). Ilmenite with a thin rim of sphene.

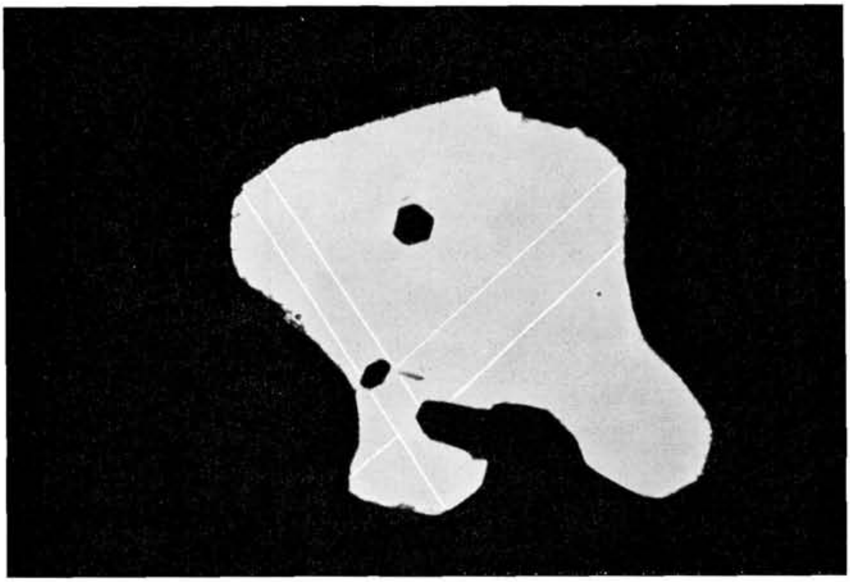

Fig. 1. Polariser only. × 700. Oil immersion. Rønne granodiorite (Rønne). Ilmenite with a few thin lamellar twins on the rhombohedron and inclusions of idiomorphic apatite.

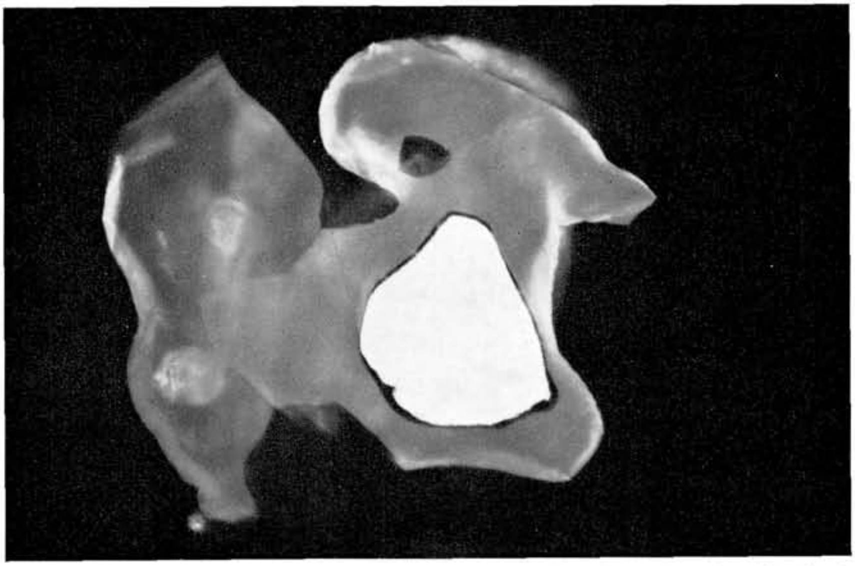

Fig. 2. Polariser only. × 700. Oil immersion. Paradisbakke migmatite (Grydesø). Remnant of ilmenite in a mass of sphene.

Fig. 1

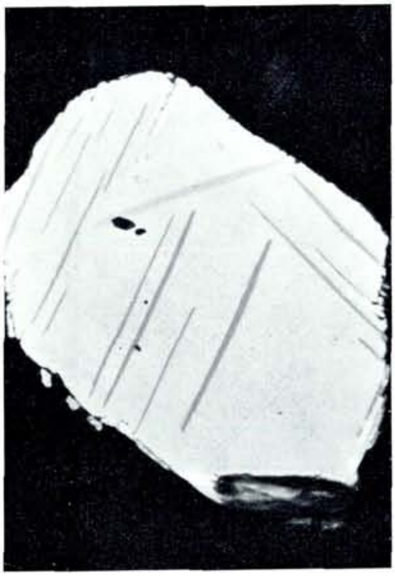

Fig. 2.

Fig. 1. Polariser only. × 190. Paradisbakke migmatite (Grydesø). Small ilmenite islands as replacement remnants in sphene.

Fig. 2. Polariser only. × 700. Oil immersion. Vang granite (Vang). Magnetite with an unusually large number of ilmenite lamellae. Along some of these there is a weak martitisation. The magnetite also contains inclusions of idiomorphic apatite.

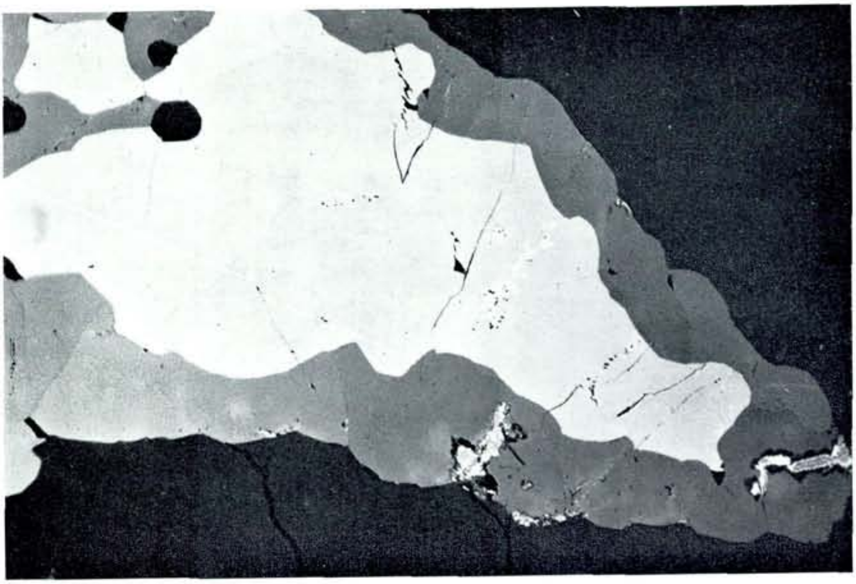

Fig. 3. Polariser only. × 190. Vang granite (Vang).
Ilmenite with broad rim of sphene containing strongly luminous leucoxene. The ilmenite has two thin lamellar twins and an inclusion of idiomorphic apatite. Furthermore the ilmenite shows a weak alteration to hematite and rutile.

Fig. 1.

Fig. 2.

Fig. 1. Polariser only. × 700. Oil immersion. Vang granite (Vang). Ilmenite with a very fine pattern of small exsolution bodies of hematite.
Fig. 2. Polariser only. × 700. Oil immersion. Dark-coloured gneiss (Knarregård). Magnetite with inclusions of spinel.

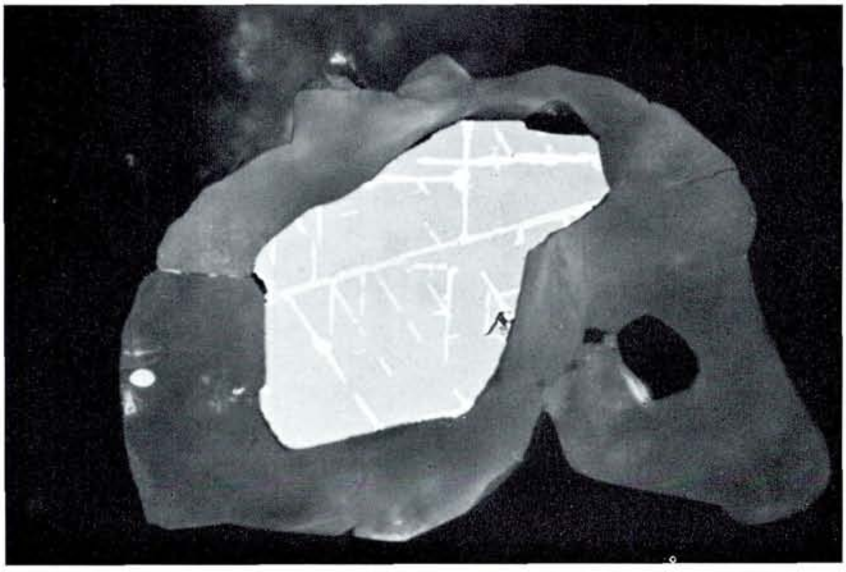

Fig. 3. Polariser only. × 700. Oil immersion. Dark-coloured gneiss (Bølshavn). Magnetite enclosed in sphene which also contains a small rounded island of ilmenite. The magnetite shows a weak martitisation following {111}.

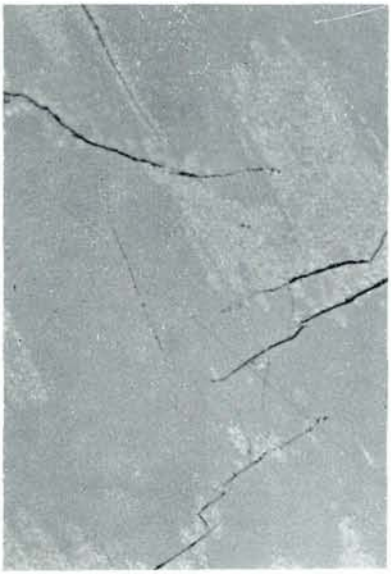

Fig. 1 A.

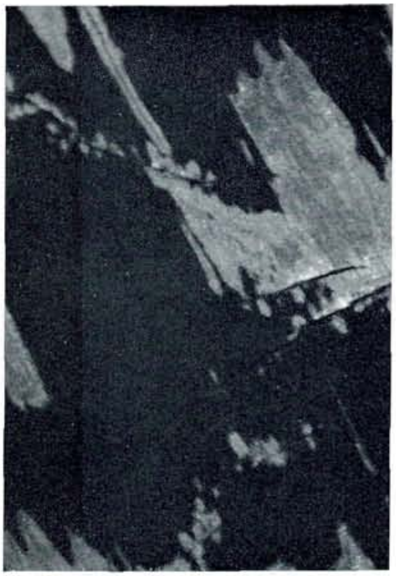

Fig. 1 B.

Fig. 1. Dark-coloured gneiss (Kås).
A. Polariser only. × 700. Oil immersion.
B. Polars 6° from crossed position. × 700. Oil immersion.
Ilmenite with alteration of beach sand type. The alteration is localised by cracks and follows {0001}.

Fig. 2.

Fig. 3.

Fig. 2. Polariser only. × 700. Oil immersion. Light-coloured gneiss (Sandkås).
Martitised magnetite with a few lamellae of ilmenite which is completely altered to hematite and rutile.
Fig. 3. Polariser only. × 700. Oil immersion. Hammer granite (Hammeren).
Two small rounded islands of ilmenite as replacement remnants in a mass of sphene.

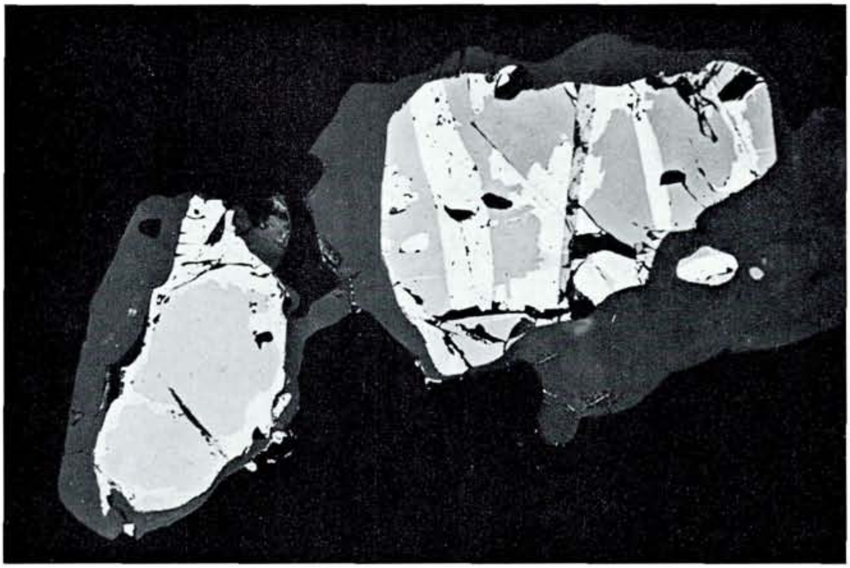

Fig. 1. Polariser only. × 150. Oil immersion. Hammer granite (Hammeren). Martitised magnetite surrounded by a broad rim of sphene. The magnetite contains an ilmenite lamella which shows alteration to sphene (almost black) as well as alteration to hematite and rutile.

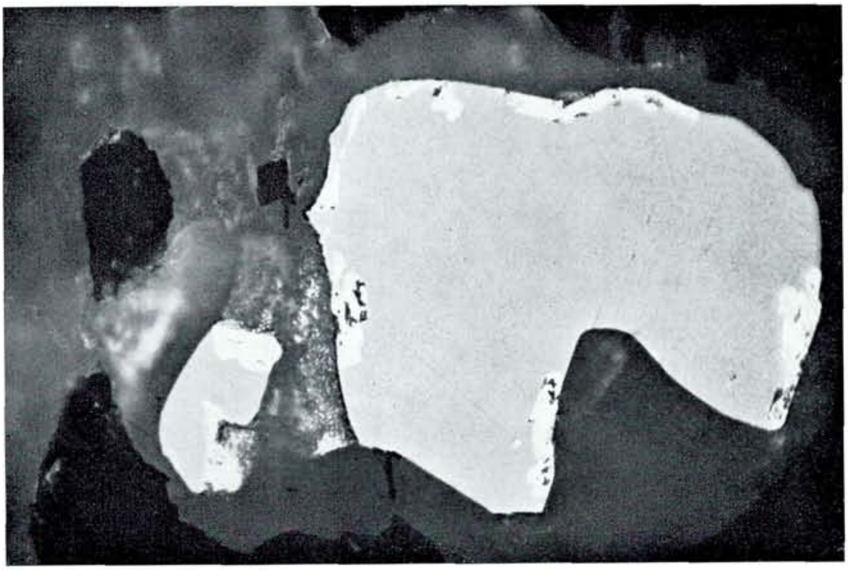

Fig. 2. Polariser only. × 700. Oil immersion. Svaneke granite (Helletsgård). Magnetite with martitisation, enclosed in a mass of sphene.

Fig. 1.

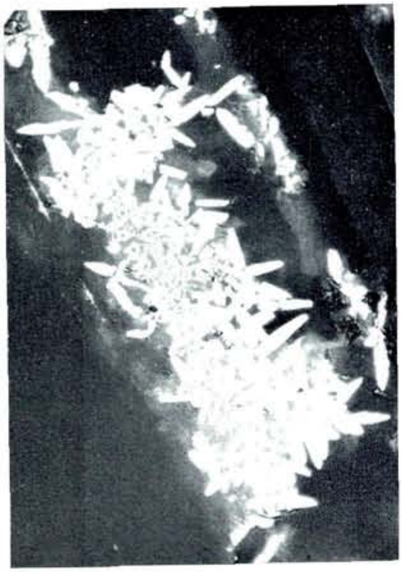

Fig. 2.

Fig. 1. Polariser only. × 700. Oil immersion. Svaneke granite (Helletsgård). Ilmenite with alteration to hematite and rutile. Above and below are twin lamellae.
Fig. 2. Polariser only. × 550. Svaneke granite (Helletsgård). Anatase.

Fig. 3. Polariser only. × Oil immersion. Aplite (Gudhjem).
Martitised magnetite with a few lamellae of ilmenite strongly altered to hematite and rutile. The ilmenite lamella in the upper left corner has been almost completely dissolved.

Fig. 1.

Fig. 2.

Fig. 1. Polariser only. × 700. Oil immersion. Aplite (Gadegård).
Strongly martitised magnetite with lamellae of ilmenite completely altered to hematite and rutile.
Fig. 2. Polariser only. × 700. Oil immersion. Pegmatite (Lobbæk).
Coarse network of "anatase-rutile" with intervening areas of a sphene-like material. Network as well as intervening areas are peppered with small white hematite-like spots. See text p. 91.

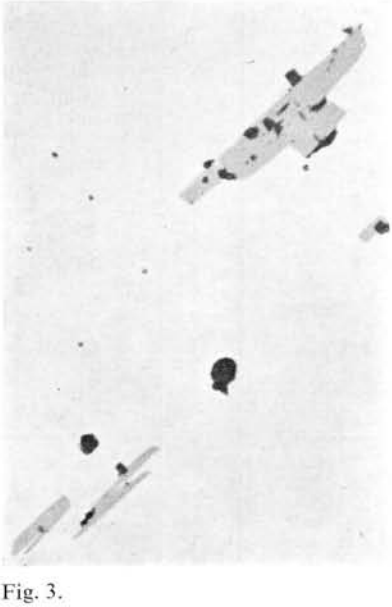

Fig. 3.

Fig. 4.

Fig. 3. Polariser only. × 700. Oil immersion. Pegmatite (Lobbæk).
Magnetite with inclusions of rutile.
Fig. 4. Polariser only. × 150. Oil immersion. Pegmatite (Klippegård). Molybdenite.