OPAQUE MINERALS IN THE HEAVY BEACH SAND FROM RÅGELEJE, DENMARK

by

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Abstract

The opaque minerals in the heavy beach sand from Rågeleje consist almost entirely of Fe-Ti-oxides, but there is also a small amount of sulphides, generally occurring as inclusions in either Fe-Ti-oxides or in silicates.

The different textures and the types of alteration of the Fe-Ti-oxides are described; the type of ilmenite alteration which is generally considered characteristic of beach sands in tropical and subtropical climates is found.

Neither pseudobrookite nor "Hitzemartit" occurs and the heavy beach sand from Rågeleje clearly belongs to type 1, Magnetite-Ilmenite Sand, of the five types of paragenesis distinguished by STUMPFL (1958). Beach sand of this type originates predominantly from acid plutonic rocks, but several different rock types have contributed to the formation.

INTRODUCTION

Thin layers of heavy beach sand are of fairly common occurrence along the shores of Denmark. Macroscopically these layers are generally characterised by black grains of Fe-Ti-oxides and by red grains of garnet. The maximum thickness of these layers of heavy beach sand is about ten cm; layers of this thickness are encountered on the western coast of Jutland. The majority of the layers however are considerably thinner, and the material investigated here was collected at Rågeleje on the northern coast of Sjælland (Fig. 1, p. 22) from very thin layers the thickness of which does not exceed a few mm.

The occurrence of heavy beach sand in Denmark has previously been dealt with by SØRENSEN (1959) and by CHRISTENSEN & LARSEN (1959, 1960). The last of these papers, which includes a summary in English, is a rather comprehensive work, but the information about the opaque minerals, which is published in it, was obtained mainly from chemical analyses.

It is the aim of the present paper, which however deals with only one occurrence of heavy beach sand, to give a more detailed description of the opaque minerals based on ore-microscopic investigations, and to see if the results obtained can give any clues concerning the parent rocks from which the material in the heavy beach sand has originated.

MAGNETITE AND TITANOMAGNETITE

Grains of magnetite with a homogeneous appearance are relatively numerous. These grains probably consist of rather pure Fe_3O_4 as no devia-

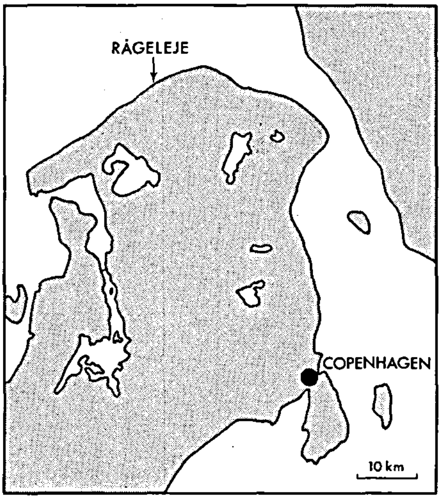

Fig. 1. Sketch map showing the position of Rågeleje.

tion in colour, reflectivity and isotropy from the common descriptions of normal magnetite can be observed.

Besides this homogeneous magnetite there are several different types of heterogeneous titanium-bearing magnetite. These grains of titanomagnetite have been formed from original homogeneous members of the solid solution series Fe_3O_4—Fe_2TiO_4. This series frequently carries small amounts of other elements, as for instance Al, so that cooling may also result in exsolution of spinel. The lamellae of ilmenite which are so frequently found in titanomagnetites are not the direct result of exsolution as their formation depends upon a previous oxidation of part of the Fe_2TiO_4 component in the solid solution to $FeTiO_3$. Upon slow cooling, any remaining unoxidised Fe_2TiO_4 exsolves as ulvöspinel in the temperature range 700–600° C.

With a few exceptions the grains of titanomagnetite in the beach sand from Rågeleje always carry distinct lamellae of ilmenite arranged parallel to {111} of the titanomagnetite. The number and the thickness of these ilmenite lamellae vary considerably from grain to grain, and in some cases also within the same grain (Plate 1 and Plate 2 Fig. 1).

Exsolution of spinel is very common in the titanomagnetites from Rågeleje. This spinel is arranged parallel to {100} and parallel to {111} of the titanomagnetite. In a few of the titanomagnetite grains spinel is strongly predominating, but besides the spinel there are generally found at least some lamellae of ilmenite. One of the rather few exceptions to this rule is shown in Plate 2 Fig. 2 where the titanomagnetite contains lamellae of spinel of different sizes, and although the titanomagnetite groundmass is clearly heterogeneous no distinct ilmenite lamellae can be seen. Growth of the large lamellae of spinel has been achieved at the expense of the surrounding areas, so that exsolution lamellae of spinel here are absent or very scarce.

Plate 3 shows titanomagnetite with exsolution lamellae of spinel parallel to {100} and parallel to {111}, and ilmenite lamellae parallel to {111}. Stereographic solutions according to the methods given by KORN (1933) have shown that the reason that only six spinel directions are seen is not the same for the two figures of Plate 3. In Fig. 1 the reason is that one of the octahedral directions coincides with one of the cube directions, whereas in Fig. 2 it is that two of the cube directions are coincident.

In most of the titanomagnetite grains ilmenite lamellae predominate over spinel lamellae, and spinel exsolution is in many cases completely absent from the titanomagnetites.

In almost all the grains of titanomagnetite the groundmass, i. e. the areas in between the spinel and the ilmenite lamellae, can be seen with high power to be heterogeneous. Some grains of titanomagnetite consisting of a few very broad ilmenite lamellae in a homogeneous appearing groundmass were, however, observed.

The heterogeneity of the titanomagnetite groundmass is probably due to an extremely fine exsolution network of ulvöspinel, but only in some of the grains is this network coarse enough to be identified as the characteristic cloth-like pattern of ulvöspinel exsolution. Ulvöspinel pattern can be seen in Plate 5 and in Fig. 1 of Plate 6.

Because of the extremely fine scale of these exsolution intergrowths of ulvöspinel and magnetite it is not always possible to see if the ulvöspinel part of the network still consists of ulvöspinel, or if it has been oxidised to ilmenite. In some cases however the ilmenite formed by oxidation of the exsolved ulvöspinel has the same orientation in neighbouring areas large enough to permit the observation of anisotropy of ilmenite.

In the heavy beach sand from Rågeleje this is the case with some titanomagnetite grains which contain thin tapering ilmenite lamellae arranged parallel to {111} of the titanomagnetite. These thin tapering ilmenite lamellae seem to have acted as centres for the oxidation of ulvöspinel to ilmenite with the result that each lamella together with the ilmenite in the neighbouring part of the ulvöspinel network forms an optical unit. This phenomenon which is shown here in Plate 4 Fig. 1 has been described earlier in titanomagnetites from dolerites (JENSEN 1966).

Ilmenite formed by oxidation of exsolved ulvöspinel is sometimes rearranged so that tiny indistinct and diffuse lamellae of ilmenite parallel to {111} result. Grains of titanomagnetite showing this rearrangement of ilmenite are found in the heavy beach sand from Rågeleje and one of these grains is shown in Plate 4 Fig. 2. The grain pictured is one of the few cases where the titanomagnetite from Rågeleje does not contain any distinct ilmenite lamellae. Such rearrangement of ilmenite has previously been described from gabbros (VINCENT 1960) as well as dolerites (JENSEN 1966).

Transformation of all the ulvöspinel in the titanomagnetite groundmass to ilmenite, occasionally followed by reorganisation into diffuse and indistinct ilmenite lamellae parallel to {111}, affects larger areas and is probably the result of a thorough oxidation at low temperatures where the rate of diffusion is too slow to permit the newly formed ilmenite to concentrate into larger distinct lamellae.

However, VINCENT (1960) also describes ilmenite lamellae of another type formed by oxidation and reorganisation of exsolved ulvöspinel. This other type is larger and distinct, but tapering; the lamellae are arranged parallel to {111} of the titanomagnetite. These larger and tapering ilmenite lamellae occur spotwise and are confined to areas adjacent to cracks, veinlets and grain boundaries. The titanomagnetite in the vicinity of these ilmenite lamellae is seen to be free of ulvöspinel, which has been used to form the ilmenite lamellae, so that the characteristic ulvöspinel pattern is first met with again some distance away from the lamellae. Such ilmenite lamellae are probably formed as the result of a slight oxidation following cracks and grain boundaries and occurring at temperatures high enough to permit the formation of larger and distinct ilmenite lamellae.

In the heavy beach sand from Rågeleje there are a few grains of titanomagnetite showing ilmenite lamellae of the above-described type. One of these grains is pictured in Plate 5 Fig. 1 which clearly shows the undisturbed ulvöspinel pattern as well as the ulvöspinel-free areas next to the ilmenite lamellae.

Plate 5 Fig. 2 shows ilmenite lamellae with a similar tapering shape, but the ulvöspinel pattern continues right up to the lamellae. These lamellae therefore must have formed above the exsolution temperature of ulvöspinel by oxidation of Fe_2TiO_4 still dissolved as titanomagnetite.

Lamellae of spinel and ilmenite and rods of ulvöspinel occurring in the same grain can be seen in Plate 6 Fig. 1.

ILMENITE AND MUTUAL ILMENITE-HEMATITE EXSOLUTION INTERGROWTHS

Grains of homogeneous ilmenite are rather numerous. 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 $FeTiO_3$.

Besides these grains of homogeneous ilmenite there are also many grains showing mutual exsolution intergrowth of ilmenite-hematite. These grains are formed from original homogeneous members of the complete solid solution series $FeTiO_3$—Fe_2O_3 which, with slow cooling, unmixes to an ilmenite-rich solid solution and a hematite-rich solid solution, each of which upon further cooling continues to unmix so that the final result is a rather intimate intergrowth of two phases the composition of which approaches pure $FeTiO_3$ and pure Fe_2O_3 respectively.

Some of the grains showing mutual exsolution intergrowth of ilmenite and hematite in the heavy beach sand from Rågeleje have these two phases equally well developed (Plate 7 Fig. 1), but most of the grains are richer in either the ilmenite phase (Plate 7 Fig. 2) or the hematite phase (Plate 8). Hematite-rich grains are somewhat predominating over ilmenite-rich grains.

Occasionally some of the grains with mutual exsolution intergrowth of ilmenite-hematite have the texture further complicated by the presence of polysynthetic twin lamellae. Such a grain is shown in Plate 6 Fig. 2.

There are also numerous grains which are not simply mutual exsolution intergrowth of ilmenite-hematite, but which also carry some rutile, generally in the form of straight thin lamellae (Plate 8). In Plate 8 Fig. 2 is shown a grain of ilmenite-hematite exsolution intergrowth, which is extremely rich in hematite and contains numerous lamellae of rutile of different sizes. Plate 9 Fig. 1 shows a grain with an unusually broad rutile lamella which is cut and displaced by medium-sized rutile lamellae, which themselves change their course in passing the broad lamella. Still smaller lamellae of rutile are seen between the medium-sized lamellae.

In the heavy beach sand from Rågeleje rutile is found only in the ilmenite-hematite exsolution intergrowths which are extremely rich in hematite. However, EDWARDS (1954) states that rutile lamellae can also be found in ilmenite-rich members of the ilmenite-hematite series. EDWARDS (1938) has shown that these rutile lamellae are arranged parallel to the rhombohedral directions of the ilmenite-hematite and that they are formed earlier than the ilmenite-hematite exsolution intergrowth. Whether or not this rutile is the result of exsolution is not quite clear yet.

The present author thinks that the formation of rutile in mutual ilmenite-hematite exsolution intergrowths probably bears a similar relation to exsolution as does the formation of ilmenite lamellae in titanomagnetites above the exsolution temperature of ulvöspinel, i. e. it has an oxidation process as a necessary prerequisite. Thus the author believes that the rutile lamellae in the ilmenite-hematite exsolution intergrowths are formed as the result of oxidation of part of the ilmenite component of the solid solution according to the following scheme: $2\ FeTiO_3 + \frac{1}{2}\ O_2 \rightleftharpoons Fe_2O_3 + 2\ TiO_2$. Of the two products of this reaction Fe_2O_3 is accommodated in the structure of the solid solution, whereas TiO_2 forms lamellae of rutile parallel to the rhombohedral directions of the solid solution.

Magnetoilmenite

In some cases there are found in the heavy beach sand from Rågeleje grains of ilmenite-rich ilmenite-hematite exsolution intergrowth in which part of the hematite has been reduced and rearranged into long, straight and regularly spaced lamellae of magnetite parallel to {0001} of the ilmenite as described by RAMDOHR (1956, p. 11 and p. 16). Such a grain is shown in Plate 9 Fig. 2.

The history of this grain however is further complicated because after the reduction which resulted in the formation of the magnetite lamellae there has been a slight oxidation which has transformed part of the magnetite lamellae to martite. Some of the magnetite lamellae, especially in the upper part of the grain, are seen to a large extent to have been dissolved. Finally there are a few twin lamellae in the ilmenite, and one of these is clearly seen to be displaced by a magnetite lamella.

MYRMEKITIC INTERGROWTHS BETWEEN ORE AND SILICATES

In many cases magnetite with a homogeneous appearance is found in myrmekitic intergrowth with silicates. The silicate part of the myrmekites generally carries numerous very strong and luminous internal reflections, which make it somewhat difficult to use the anisotropy effect to distinguish between magnetite and ilmenite, but ilmenite in myrmekitic intergrowth with silicates is found only in a few cases, and the ilmenite myrmekites are developed on a considerably coarser scale than the magnetite myrmekites. Plate 10 shows myrmekitic magnetite, and Plate 11 Fig. 1 shows myrmekitic ilmenite. It should be noted that in Plate 11 Fig. 1 some magnetite with a weak pattern indicating heterogeneity is intergrown with ilmenite in the outermost part of the myrmekite.

ALTERATION OF MAGNETITE AND THE GROUNDMASS OF TITANOMAGNETITES

Martitisation

Martitisation of magnetite is frequently seen, and every gradation from incipient martitisation to completely martitised grains can be found. Incipient and relatively weak martitisation generally follows the {111} directions of the magnetite, whereas more advanced stages of martitisation frequently form compact and somewhat irregular areas of hematite. Occasionally incipient martitisation also advances as compact and irregular areas. Plate 11 Fig. 2 shows a grain with relatively weak martitisation advancing partly along {111} and partly as compact irregular areas, and Plate 13 Fig. 1 shows a grain which is almost completely martitised. Martitisation clearly localised by cracks is shown in Plate 12 Fig. 1. Sometimes the martitisation, although clearly advancing along {111} directions, is seen to be localised mainly by cracks (Plate 12 Fig. 2).

Martitisation is found almost exclusively in originally (i. e. before martitisation) homogeneous magnetites. However in a few cases titanomagnetites are also seen to be martitised. The martitisation of titanomagnetites is generally weak and follows the {111} directions starting adjacent to ilmenite lamellae (Plate 13 Fig. 2). However in one case there is found a grain of titanomagnetite with a net of regularly spaced thin lamellae of ilmenite parallel to {111}, where the groundmass has been completely altered to martite. The ilmenite lamellae are strongly altered to a fine-grained mixture of rutile and hematite. This grain is shown in Plate 1 Fig. 1.

Maghemitisation

In the heavy beach sand from Rågeleje maghemitisation is restricted to titanomagnetites, whereas maghemite formation is never seen in grains of pure magnetite. Furthermore the maghemitisation of titanomagnetites is almost always rather weak, and larger areas affected by maghemitisation are seen in only a few cases. Generally the maghemitisation is confined to thin selvages along tiny cracks in the titanomagnetite groundmass, but occasionally the maghemitisation spreads out as worm-like patches. Maghemite occurring as thin streaks adjacent to ilmenite lamellae can also be found (Plate 2 Fig. 1).

Alteration to turbid sphene

This type of alteration is also restricted to the groundmass of titanomagnetites. Alteration of titanomagnetite to turbid sphene has previously been described from basic rocks in Missouri, USA (Desborough 1963) and from dolerites in the island of Bornholm, Denmark (Jensen 1966).

Alteration to turbid sphene is rather commonly found in the titanomagnetites in the heavy beach sand from Rågeleje, and every gradation can be seen from incipient spotwise alteration, to grains in which the titanomagnetite groundmass is completely altered and only ilmenite lamellae arranged parallel to {111} remain (Plate 2 Fig. 1 and Plate 14). Frequently the alteration is localised by cracks through the titanomagnetite, but alteration proceeding inwards from grain boundaries is also found.

The ilmenite lamellae in the titanomagnetite are not affected by the alteration to turbid sphene, and occasionally it can be seen that such ilmenite lamellae also have been able to protect the titanomagnetite groundmass in their immediate vicinity against the alteration. Thus Plate 15 Fig. 1 shows a grain of titanomagnetite in which the groundmass is completely altered to turbid sphene except for thin rims along the ilmenite lamellae.

ALTERATION OF ILMENITE

Alteration of ilmenite to rutile and hematite

In the heavy beach sand from Rågeleje the most commonly found type of ilmenite alteration is the alteration to rutile and hematite.

The grain size of the rutile and hematite formed by alteration of ilmenite varies strongly and in the heavy beach sand from Rågeleje it ranges from about 1μ to more than 15μ. According to Ramdohr (1960, p. 907) the difference in grain size is caused by different temperatures of formation.

The alteration of ilmenite to rutile and hematite is frequently seen to start rather deep inside the grains, and no relation with cracks and grain boundaries is found. Every gradation from grains with only incipient alteration to grains completely altered to rutile and hematite can be seen.

This type of ilmenite alteration occurs frequently in the heavy beach sand from Rågeleje and comprises ilmenite lamellae in titanomagnetites as well as ilmenite in mutual ilmenite-hematite exsolution intergrowths and ilmenite in originally (before alteration) homogeneous grains.

Alteration of ilmenite to rutile and hematite is shown in Plate 15 Fig. 2, Plate 16 and Plate 17 Fig. 2.

Alteration of ilmenite to rutile and magnetite

The alteration of ilmenite to rutile and magnetite is much rarer in the heavy beach sand from Rågeleje than the alteration of ilmenite to rutile and hematite.

The grain size of the rutile-magnetite alteration product lies in the upper range of that for the rutile-hematite product, i. e. it varies from about 5μ to about 15μ. Plate 17 Fig. 1 shows ilmenite which is strongly altered to coarse-grained rutile and magnetite.

Alteration to rutile and magnetite is found in the ilmenite of mutual ilmenite-hematite exsolution intergrowths as well as in originally (before alteration) homogeneous ilmenite, but is not observed in ilmenite lamellae in titanomagnetite. Sometimes alteration to rutile and magnetite and alteration to rutile and hematite are both found occurring in the same grain (Plate 17 Fig. 2).

Alteration of ilmenite to rutile

Sometimes ilmenite is found partially altered to rutile with a grain size varying from less than 1μ to about 5μ. In this type of alteration no alteration product other than rutile is found, but between the rutile grains there occur several holes indicating dissolution. The rutile here is considerably richer in internal reflections than the rutile in the two types of ilmenite alteration described above. Furthermore the internal reflections in the rutile accompanied by holes are much stronger. Alteration of ilmenite to rutile is shown in Plate 17 Fig. 2.

In the heavy beach sand from Rågeleje alteration of ilmenite to rutile accompanied by holes is found in ilmenite lamellae in titanomagnetites as well as in ilmenite in mutual ilmenite-hematite exsolution intergrowths and ilmenite in originally (before alteration to rutile) homogeneous grains. This type of ilmenite alteration has previously been described from dolerites (JENSEN 1966).

Alteration of ilmenite to sphene

Alteration of ilmenite to sphene is rather frequently seen in the heavy beach sand from Rågeleje. This type of alteration varies in intensity from incipient formation of sphene spotwise along grain boundaries to very advanced alteration of grains in which only small rounded islands of unaltered ilmenite remain as replacement remnants inside large masses of sphene.

The most common way of attack for the alteration of ilmenite to sphene is inwards from grain boundaries, but the alteration can also be seen to follow cracks through the ilmenite.

In incipient stages of the alteration the sphene frequently has a somewhat mottled appearance, but with progressed alteration the appearance becomes homogeneous.

In the heavy beach sand from Rågeleje alteration of ilmenite to sphene is most commonly found in the ilmenite of originally (before alteration) homogeneous grains and in the ilmenite of mutual ilmenite-hematite exsolution intergrowths, but in a few cases alteration to sphene is also seen to have attacked the ilmenite in {111} lamellae in titanomagnetites.

Alteration of ilmenite to sphene is shown in Plate 15 Fig. 2 and Plate 18. Fig. 1.

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).

In the heavy beach sand from Rågeleje several grains are found with ilmenite alteration of beach sand type, and this type of alteration is seen affecting ilmenite lamellae in titanomagnetites as well as originally (before alteration) homogeneous ilmenite grains and the ilmenite part of mutual ilmenite-hematite exsolution intergrowths.

The alteration is found in different gradations ranging from beginning alteration in streaks spreading out from grain boundaries and cracks, to grains which are completely altered. The alteration comprises only Stage 1 of BAILEY et al.

Ilmenite alteration of beach sand type is shown in Plate 18 Fig. 2 and in Plate 19.

Two or more of the different types of ilmenite alteration described above are often found together in the same grain. Thus Plate 15 Fig. 2 shows alteration to sphene as well as alteration to rutile and hematite, and Plate 17 Fig. 2 shows three different types of alteration: alteration to rutile and magnetite, alteration to rutile and hematite and alteration to rutile accompanied by holes.

HEMATITE

In the heavy beach sand from Rågeleje hematite is present mainly in mutual ilmenite-hematite exsolution intergrowths and as martite formed by oxidation of magnetite. However hematite is also formed from ilmenite by the type of ilmenite alteration which results in a mixture of rutile and hematite. Furthermore there are a few grains of homogeneous hematite which do not have a texture indicating formation by martitisation.

LIMONITE

There are a few relatively large grains which are completely altered to limonite so that no suggestion about the original composition of the grains can be made. Furthermore limonite is found as rims around grains of sulphides.

BLUISH-GREY MINERAL

In three cases there was found in partially martitised magnetite a mineral resembling perovskite in colour, reflectivity and hardness, and containing numerous brown to yellowish internal reflections. This mineral however differs from perovskite in being distinctly anisotropic. The reflectivity is definitely high enough to rule out högbomite, and the author is not able to identify this bluish-grey mineral, which is shown in Plate 20 Fig. 1.

SULPHIDES

The opaque minerals in the heavy beach sand from Rågeleje consist almost entirely of Fe-Ti-oxides, but there is also a small amount of sulphides.

These sulphides are generally included in either silicates or Fe-Ti-oxides, whereby they have been protected against alteration, but pyrite and marcasite are also found in free grains, which however are frequently surrounded by a rim of limonite.

Besides pyrite and marcasite chalcopyrite and pyrrhotite are also found. The last two sulphides are frequently found together. For instance in one case a globule observed inside pyrite was found to consist mainly of chalcopyrite, but it also contained a small mass of pyrrhotite, and small points of pyrrhotite were seen to be scattered throughout the chalcopyrite part of the globule (Plate 20 Fig. 2).

Marcasite is found in relatively large masses (diameter about 0.15 mm) with a core of an isotropic mineral with the colour and reflectivity of sphalerite, but without internal reflections.

CONCLUSIONS

CHRISTENSEN & LARSEN (1960, p. 42) in discussing the heavy beach sand in Denmark distinguish ten different regions. One of these regions comprises northern Sjælland and part of northern Fyn, and is characterised by having a large content of opaque minerals, with ilmenite and magnetite being present in about equal amounts, and with garnet being strongly predominant amongst the non-opaque constituents. Although the classification of the opaque minerals as either ilmenite or magnetite from a mineragraphic point of view represents a substantial simplification, the heavy beach sand from Rågeleje investigated here can be said to fit well into the above description by CHRISTENSEN & LARSEN.

STUMPFL (1958) has made a rather thorough mineragraphic investigation of heavy beach sands from all over the world and distinguishes five different parageneses: 1) *Magnetite-Ilmenite Sand,* 2) *Magnetite Sand,* 3) *Pseudobrookite Sand,* 4) *Ilmenite Sand* and 5) *Ilmenite-Hematite Sand.* There is no difficulty by placing the heavy beach sand from Rågeleje in this scheme. It clearly belongs to type 1, Magnetite-Ilmenite Sand.

As to the parent rocks from which sand of this type has originated STUMPFL says that they must comprise rather many different rock types, but consist predominantly of acid plutonic rocks.

It is characteristic for the heavy beach sand from Rågeleje, as well as for the whole group Magnetite-Ilmenite Sand, that pseudobrookite and "Hitzemartit", which originate from extrusive volcanic rocks, are totally absent. In this connection however it is worth noting that the numerous isolated basaltic necks in SW Sweden (NORIN 1933, 1934) do not contain pseudobrookite and "Hitzemartit", but carry magnetite with homogeneous appearance as the main opaque constituent, so that these necks may very well have contributed to the opaque content in the heavy beach sand at Rågeleje.

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DANSK RESUMÉ

Det foreliggende arbejde er en malmmikroskopisk undersøgelse af de opake mineraler i tungsandet fra Rågeleje. Hensigten har været dels at beskrive den ret komplicerede opbygning, som størstedelen af de opake mineraler har, dels at forsøge ud fra sammensætningen af de opake mineraler at få oplysninger om, hvilke bjergarter materialet i tungsandet stammer fra. Langt den største del af de opake mineraler udgøres af Fe-Ti-oxider, men desuden forekommer der en ganske ringe mængde sulfid. I det følgende beskrives de enkelte mineraler hver for sig.

Magnetit og titanomagnetit

Der forekommer talrige korn af magnetit, der fremtræder homogen. Disse korn er isotrope og har den for normal magnetit karakteristiske farve og refleksionsevne, hvorfor deres sammensætning antagelig er ret tæt ved ren Fe_3O_4.

Foruden disse korn af homogen magnetit forekommer der flere forskellige typer af heterogen titanomagnetit. Disse korn er opstået af oprindelige homogene medlemmer af den faste opløsningsserie Fe_3O_4–Fe_2TiO_4, som desuden ofte indeholder små mængder af andre grundstoffer, for eksempel Al, så der ved afkølingen kan opstå afblandingslameller af spinel. Fremkomsten af ilmenitlameller, der næsten altid findes i titanomagnetiter, skyldes ikke direkte afblanding, idet dannelsen af ilmenitlamellerne kræver en forudgående oxidation til $FeTiO_3$ af en del af ulvöspinelkomponenten i den faste opløsning Fe_3O_4–Fe_2TiO_4. Ved langsom afkøling vil eventuel tiloversbleven uoxideret Fe_2TiO_4 afblandes som ulvöspinel ved 700–600°C.

Med enkelte undtagelser indeholder titanomagnetitkornene i tungsandet fra Rågeleje altid tydelige ilmenitlameller, der er arrangerede parallelt med titanomagnetitens oktaederretninger. Antallet og bredden af disse ilmenitlameller varierer betydeligt fra korn til korn, og i nogle tilfælde også inden for samme korn.

Spinelafblandinger forekommer meget almindeligt i titanomagnetitkornene i tungsandet fra Rågeleje. Spinellen er arrangeret dels parallelt med titanomagnetitens terningretninger, dels parallelt med oktaederretningerne. I enkelte af titanomagnetitkornene dominerer spinel over ilmenit, men i de fleste korn er ilmenit stærkt dominerende, og der forekommer mange titanomagnetitkorn med ilmenit men uden spinel, medens korn med spinel men uden ilmenit er sjældne. Et af disse sjældne korn er afbildet i tavle 2, fig. 2, der viser afblandingslameller af spinel i forskellige størrelser. Bemærk, at de store lamellers omgivelser er enten helt fri for eller meget fattige på spinel, der tydeligvis er trukket ind i de store lameller.

Tavle 3 viser titanomagnetit med spinelafblandinger efter {100} og {111}, og ilmenitlameller efter {111}. Stereografiske konstruktioner efter metoden angivet af KORN (1933) har vist, at årsagen til, at der kun ses seks og ikke syv spinelretninger, for fig. 1 er, at en af oktaederretningerne falder sammen med en af terningretningerne, og for fig. 2, at to af terningretningerne er sammenfaldende.

I næsten alle titanomagnetitkornene kan grundmassen, det vil sige områderne mellem spinel- og ilmenitlamellerne, med stor forstørrelse ses at være heterogen. Denne heterogenitet skyldes sandsynligvis et yderst finmasket netværk af ulvöspinelafblanding, men kun i nogle af kornene er netværket groft nok til at kunne genkendes som ulvöspinellens karakteristiske afblandingsmønster, hvor ulvöspinel er arrangeret som små stave efter titanomagnetitens terningretninger.

På grund af den yderst ringe størrelse af de enkelte stave er det undertiden ikke muligt at afgøre, om disse stadig består af ulvöspinel, eller om de er oxiderede til ilmenit. I nogle tilfælde har imidlertid ilmeniten, der er opstået ved oxidation af afblandet ulvöspinel, samme optiske orientering i områder, der er store nok til, at man kan observere anisotropien, således at omdannelsen fra ulvöspinel til ilmenit på denne måde røbes. Tavle 4, fig. 1 viser et sådant tilfælde, hvor tynde, tenformede ilmenitlameller efter {111} har virket som udgangspunkter for oxidationen, med det resultat at hver enkelt ilmenitlamel sammen med ilmeniten i den nærliggende del af ulvöspinelmønsteret udgør en optisk enhed.

Ilmenit opstået ved oxidation af ulvöspinel afblandet efter {100} kan undertiden omlejres til lameller efter {111}. Tavle 4, fig. 2 viser således et korn, hvor ilmenit opstået ved oxidation af afblandet ulvöspinel er omlejret til et tæt mønster af ganske tynde, noget diffuse og utydelige lameller efter {111}. Det afbildede korn viser et af de få tilfælde, hvor titanomagnetiten fra Rågeleje ikke indeholder større, tydelige ilmenitlameller.

Omdannelse som ovenfor beskrevet af al ulvöspinellen i titanomagnetitgrundmassen til ilmenit, undertiden med efterfølgende omlejring til tynde, diffuse ilmenitlameller efter {111}, omfatter større områder og er sandsynligvis resultatet af en ret gennemgribende oxidation ved temperaturer, der er så lave, at diffusionshastigheden ikke er høj nok til, at den nydannede ilmenit kan koncentreres til større, tydelige ilmenitlameller.

Der ses imidlertid også en anden type af ilmenitlameller, dannet ved oxidation af afblandet ulvöspinel. Denne anden type udgøres af større og tydelige, men tenformede lameller, der er parallelle med {111}. Disse større, tenformede lameller forekommer pletvis og er begrænsede til områder nær revner og korngrænser. Det ses tydeligt, at disse ilmenitlameller er opstået ved omdannelse af ulvöspinel i den nærliggende del af titanomagnetitgrundmassen, idet denne nu er helt fri for ulvöspinel, og det karakteristiske ulvöspinelmønster først viser sig i nogen afstand fra ilmenitlamellerne. Sådanne ilmenitlameller er sandsynligvis resultatet af en svag oxidation følgende revner og korngrænser og foregående ved temperaturer høje nok til at tillade dannelsen af større, tydelige ilmenitlameller.

Ilmenit og gensidige ilmenit-hæmatit afblandinger

Der forekommer talrige korn af homogen ilmenit, hvis refleksionsevne og anisotropi viser, at sammensætningen sandsynligvis er ret nær ren $FeTiO_3$.

Foruden disse homogene ilmenitkorn forekommer der mange korn bestående af gensidige afblandinger af ilmenit-hæmatit. Disse korn er opstået af oprindelige homogene medlemmer af den faste opløsningsserie $FeTiO_3$–Fe_2O_3. Ved langsom afkøling afblandes sådanne faste opløsninger i to faste opløsninger, en ilmenitrig og en hæmatitrig, og hver af disse fortsætter ved yderligere afkøling med afblandinger, således at det endelige resultat bliver en ret kompliceret sammenvoksning af to faser, hvis sammensætning nærmer sig henholdsvis ren $FeTiO_3$ og ren Fe_2O_3.

Nogle af kornene med gensidige afblandinger af ilmenit-hæmatit har omtrent lige store mængder af de to faser, men de fleste korn er rigere på enten ilmenitfasen eller hæmatitfasen. Hæmatitrige korn er noget rigeligere til stede end ilmenitrige.

I enkelte af ilmenit-hæmatit kornene er teksturen yderligere kompliceret ved tilstedeværelsen af polysyntetiske tvillinglameller (tavle 6, fig. 2).

Endvidere forekommer der talrige korn, der ikke alene består af gensidige afblandinger af ilmenit-hæmatit, men som yderligere indeholder noget rutil, almindeligvis i form af tynde, lige lameller efter romboederretningerne. Hvorvidt rutilen er opstået ved afblanding eller ej, er endnu ikke helt klarlagt. Forfatteren mener, at rutillamellerne ikke er fremkommet ved direkte afblanding, men at deres dannelse forudsætter en forudgående oxidation til TiO_2 af en del af ilmenitkomponenten i den faste opløsning af ilmenit-hæmatit, således at der er tale om samme forhold som ved dannelsen af ilmenitlameller i titanomagnetiter over ulvöspinellens afblandingstemperatur.

Tavle 9, fig. 2 viser et korn af magnetoilmenit, hvoraf der forekommer ganske få i tungsandet fra Rågeleje. Magnetoilmenit er opstået af ilmenit-hæmatit afblandinger, ved at hæmatiten er blevet reduceret til magnetit, der er omlejret i lange, lige lameller efter basis af ilmeniten. Det afbildede korn af magnetoilmenit er imidlertid senere blevet udsat for oxidation, hvilket ses af, at magnetitlamellerne delvis er martitiserede, det vil sige oxiderede til hæmatit. Bemærk endvidere tvillinglamellerne, hvoraf en er tydeligt forskudt af en magnetitlamel.

Myrmekitiske sammenvoksninger af malmmineraler og silikater

Der forekommer mange korn med myrmekitiske sammenvoksninger af malmmineraler og silikater. Silikaterne i disse myrmekiter er ikke bestemt; malmmineralet er næsten altid homogent udseende magnetit, men der findes enkelte myrmekiter, hvor malmmineralet er ilmenit. Ilmenitmyrmekiterne har en grovere udvikling end magnetitmyrmekiterne (tavle 10 og tavle 11, fig. 1).

Omdannelser af magnetit og af titanomagnetitens grundmasse

Martitisering, der som tidligere nævnt angiver en oxidation af magnetit til hæmatit, forekommer hyppigt, og der findes alle overgange lige fra begyndende martitisering til fuldstændigt martitiserede korn. Begyndende og relativt svag martitisering følger i regelen magnetitens oktaederretninger, medens mere fremskredne stadier af martitisering hyppigt danner kompakte og noget uregelmæssige områder af hæmatit. Undertiden angriber også begyndende martitisering som kompakte, uregelmæssige områder. Tavle 12, fig. 1 viser martitisering, der er tydeligt knyttet til revner. Somme tider ses martitiseringen, selv om den tydeligt trænger frem langs oktaederretninger, at være lokaliseret af revner (tavle 12, fig. 2).

Martitisering forekommer næsten udelukkende i oprindeligt (det vil sige før martitiseringen) homogene magnetitkorn. I nogle få tilfælde ses imidlertid også martitiserede titanomagnetitkorn. Martitiseringen af titanomagnetit er i regelen svag og følger oktaederretningerne, begyndende ved ilmenitlameller. Der er dog i et tilfælde fundet et titanomagnetitkorn, indeholdende et net af tynde ilmenitlameller efter {111}, hvor grundmassen er fuldstændigt martitiseret. Ilmenitlamellerne i dette korn er stærkt omdannede til en finkornet blanding af rutil og hæmatit (tavle 1, fig. 1).

Maghemitisering, det vil sige oxidation af magnetit til kubisk Fe_2O_3, er i tungsandet fra Rågeleje udelukkende begrænset til titanomagnetitkorn. Ydermere er maghemitiseringen af titanomagnetiten næsten altid temmelig svag, og større områder af maghemit ses kun i få tilfælde. I regelen er maghemitiseringen begrænset til tynde rande langs små revner i titanomagnetitgrundmassen, men undertiden spreder maghemitiseringen sig ud som et ormelignende mønster. Maghemit forekommer også som smalle striber langs ilmenitlameller (tavle 2, fig. 1).

Grundmassen af titanomagnetitkornene i tungsandet fra Rågeleje er meget ofte omdannet til titanit, der fremtræder så grumset, at mineralet vanskeligt kan genkendes i gennemfaldende lys. Dette grumsede udseende skyldes antagelig uomdannede rester af magnetit og ilmenit, der forekommer finfordelt i titaniten.

Af denne omdannelsesform ses i tungsandet fra Rågeleje alle overgange fra begyndende pletvis omdannelse til korn, hvor grundmassen er fuldstændig omdannet, således at der kun er ilmenitlameller efter {111} tilbage. Omdannelsen til grumset titanit er ofte lokaliseret af revner gennem titanomagnetiten, men fremtrængen fra korngrænser ses også.

Ilmenitlamellerne i titanomagnetiten angribes ikke af denne form for omdannelse, og tilmed kan man undertiden se, at disse lameller også har været i stand til at beskytte titanomagnetitgrundmassen i deres umiddelbare nærhed mod omdannelse. Tavle 15, fig. 1 viser således et korn af titanomagnetit, hvor grundmassen er fuldstændig omdannet til grumset titanit med undtagelse af tynde rande langs ilmenitlamellerne.

Omdannelser af ilmenit

Den almindeligst forekommende omdannelsesform af ilmenit i tungsandet fra Rågeleje er omdannelse til rutil og hæmatit. Denne omdannelse ses ofte at begynde ret langt inde i kornene, og udbredelsen af omdannelserne udviser ikke nogen sammenhæng med revner og korngrænser. Alle overgange fra begyndende omdannelse til fuldstændigt omdannede korn kan ses.

Omdannelse til rutil og hæmatit omfatter ilmenitlameller i titanomagnetit såvel som ilmeniten i gensidige ilmenit-hæmatit afblandinger og oprindeligt (før omdannelsen) homogene ilmenitkorn.

Omdannelse af ilmenit til rutil og magnetit forekommer i tungsandet fra Rågeleje langt sjældnere end omdannelse til rutil og hæmatit. I nogle tilfælde er begge disse omdannelsesformer fundet i det samme korn.

Ilmenit omdannet til rutil og magnetit er fundet både i ilmenit-hæmatit afblandinger og i oprindeligt (før omdannelsen) homogene ilmenitkorn, men er ikke set i ilmenitlameller i titanomagnetit.

Somme tider ses ilmenit delvis at være omdannet til rutil, der ikke er ledsaget af noget andet omdannelsesprodukt, men mellem rutilkornene forekommer der adskillige huller, der tyder på opløsning af materiale. Rutilen her er betydeligt rigere på indre reflekser end rutilen i de to ovennævnte omdannelsesformer.

Ilmenit omdannet til rutil ledsaget af huller ses såvel i lameller i titanomagnetit som i ilmenit-hæmatit afblandinger og oprindeligt (før omdannelsen) homogene korn.

Ret hyppigt forekommer ilmenit med omdannelse til titanit, der ikke fremtræder grumset, men har sædvanligt udseende i gennemfaldende lys. Graden af denne omdannelsesform varierer fra begyndende pletvis dannelse af titanit langs korngrænser til korn, der er så stærkt omdannede, at der kun findes små afrundede øer af ilmenit som replaceringsrester i titanitmasser. Almindeligvis angriber omdannelsen til titanit langs korngrænser, men omdannelsen kan også undertiden ses at følge revner i ilmeniten.

Omdannelse af ilmenit til titanit er mest almindelig i oprindeligt (før omdannelsen) homogene korn og i ilmeniten i ilmenit-hæmatit afblandinger, men i nogle få tilfælde ses denne omdannelse også at have angrebet ilmenitlameller i titanomagnetit.

I tungsandet fra Rågeleje findes der endvidere adskillige korn med ilmenitomdannelser af en type, der indtil for nylig kun var kendt fra tungsandsforekomster i tropisk og subtropisk klima. Denne omdannelsesform inddeles af BAILEY, CAMERON, SPEDDEN & WEEGE (1956) i tre stadier, og ilmenitomdannelser svarende til det første af disse stadier er nu også kendt fra faststående bjergarter (JENSEN 1966). Ilmenitomdannelserne af denne type i tungsandet fra Rågeleje svarer ligeledes til det første af de af BAILEY med flere beskrevne tre stadier, og omdannelsesgraden varierer fra begyndende omdannelse i striber, udgående fra korngrænser og revner, til fuldstændigt omdannede korn.

Omdannelserne omfatter såvel ilmenitlameller i titanomagnetit som ilmenit i oprindeligt (før omdannelsen) homogene korn og i ilmenit-hæmatit afblandinger.

To eller flere af de her beskrevne former for ilmenitomdannelse træffes ofte i samme korn (tavle 15, fig. 2 og tavle 17, fig. 2).

Hæmatit

Hæmatit er i tungsandet fra Rågeleje til stede væsentligst i ilmenit-hæmatit afblandinger og som martit dannet ved oxidation af magnetit. Desuden forekommer der hæmatit dannet ved omdannelse af ilmenit af den type, der resulterer i en blanding af rutil og hæmatit. Endvidere er der fundet nogle få korn af homogen hæmatit, hvis tekstur ikke viser, at disse korn er opstået ved martitisering.

Limonit

Der forekommer nogle få, men relativt store korn, der er fuldstændigt omdannede til limonit, så kornenes oprindelige sammensætning ikke kan konstateres. Limonit forekommer endvidere som rande omkring sulfidkorn.

Blågråt mineral

I tre tilfælde er der i delvis martitiseret magnetit fundet et blågråt mineral med egenskaber intermediære mellem perovskit ($CaTiO_3$) og högbomit (omtrentlig $Mg(Al, Fe, Ti)_4O_7$).

Sulfider

De få sulfidkorn, der er fundet, er i regelen indesluttet enten i silikater eller i Fe-Ti-oxider, hvorved de er blevet beskyttede mod omdannelse; men svovlkis og markasit forekommer også som frie korn, der imidlertid ofte er omgivet af en limonitrand. Foruden svovlkis og markasit forekommer også kobberkis og magnetkis. Sidstnævnte to findes ofte sammen. Markasit forekommer i relativt store masser med en kerne af et zinkblendelignende mineral.

Konklusioner

CHRISTENSEN & LARSEN (1960, p. 42) opdeler tungsandet i Danmark i ti regionale områder, hvoraf et udgør Nordsjælland og Røgleområdet på Fyn. Dette område karakteriseres ved et stort indhold af opake mineraler med næsten lige dele ilmenit og magnetit, og ved at granat er stærkt fremtrædende blandt de non-opake mineraler. Selv om opdelingen af Fe-Ti-oxiderne i enten ilmenit eller magnetit fra et malmmikroskopisk synspunkt er en stor forenkling, kan det her undersøgte tungsand fra Rågeleje siges at passe udmærket med den af CHRISTENSEN & LARSEN givne karakteristik.

STUMPFL (1958) har lavet en ret omfattende malmmikroskopisk undersøgelse af tungsand fra hele verden og opstiller fem forskellige parageneser: 1) *Magnetit-ilmenit sand,* 2) *Magnetit sand,* 3) *Pseudobrookit sand,* 4) *Ilmenit sand* og 5) *Ilmenit-hæmatit sand.* Tungsandet fra Rågeleje tilhører tydeligvis type 1, om hvilken STUMPFL siger, at moderbjergarterne omfatter temmelig mange forskellige bjergartstyper, men fortrinsvis udgøres af sure dybbjergarter.

Det er karakteristisk for tungsandet fra Rågeleje, såvel som for hele gruppen magnetit-ilmenit sand, at pseudobrookit og "Hitzemartit"*), der er karakteristisk for lavabjergarter, fuldstændig mangler. I denne forbindelse er det imidlertid værd at bemærke, at de talrige basaltudfyldte kraterrør, der forekommer i Skåne, heller ikke fører pseudobrookit og "Hitzemartit", men af opake mineraler væsentligst indeholder homogen magnetit. Disse skånske kraterrør kan derfor udmærket have bidraget med materiale til tungsandet ved Rågeleje.

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*) "Hitzemartit" opstår af titanomagnetit med ilmenitlameller ved genophedning, hvorunder lamellerne vokser i bredde og bliver lysere og Fe-rigere, medens grundmassen tilsvarende indskrænkes og bliver mørkere og Ti-rigere.

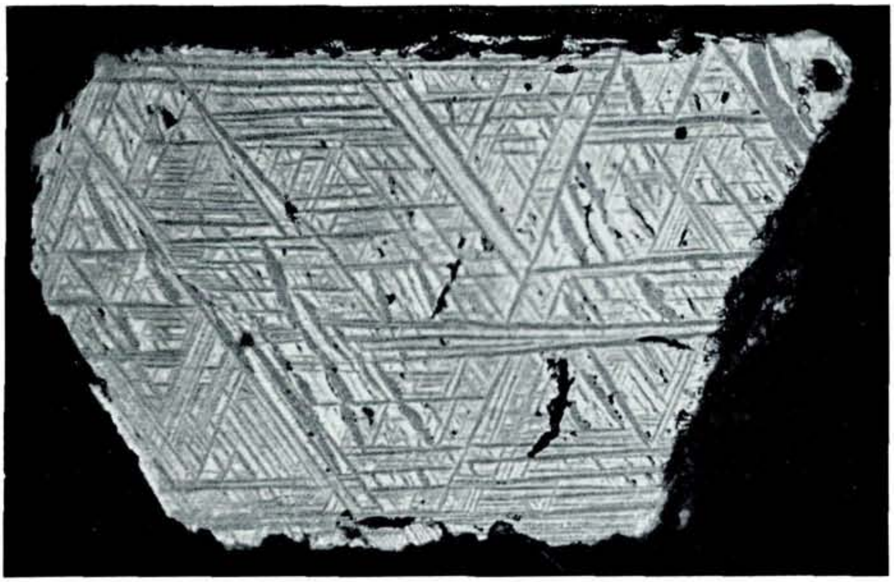

Fig. 1. Polariser only. ×720. Oil immersion.
Titanomagnetite with a dense network of very thin and regularly spaced ilmenite lamellae arranged parallel to {111}. The ilmenite lamellae are strongly altered to a fine-grained mixture of rutile and hematite, and the titanomagnetite groundmass is completely martitised.

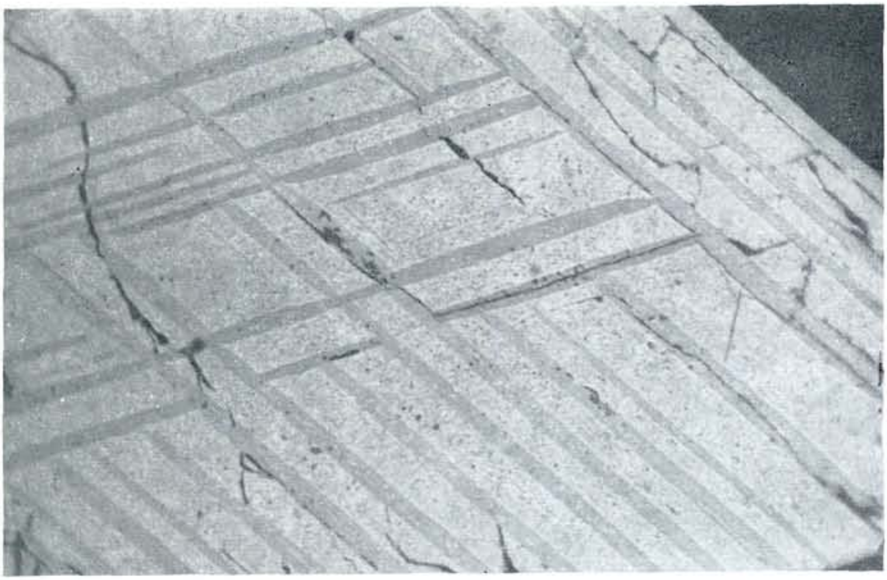

Fig. 2. Polariser only. ×720. Oil immersion.
Titanomagnetite with many thin regularly spaced ilmenite lamellae arranged parallel to {111}. The titanomagnetite groundmass is clearly heterogeneous.

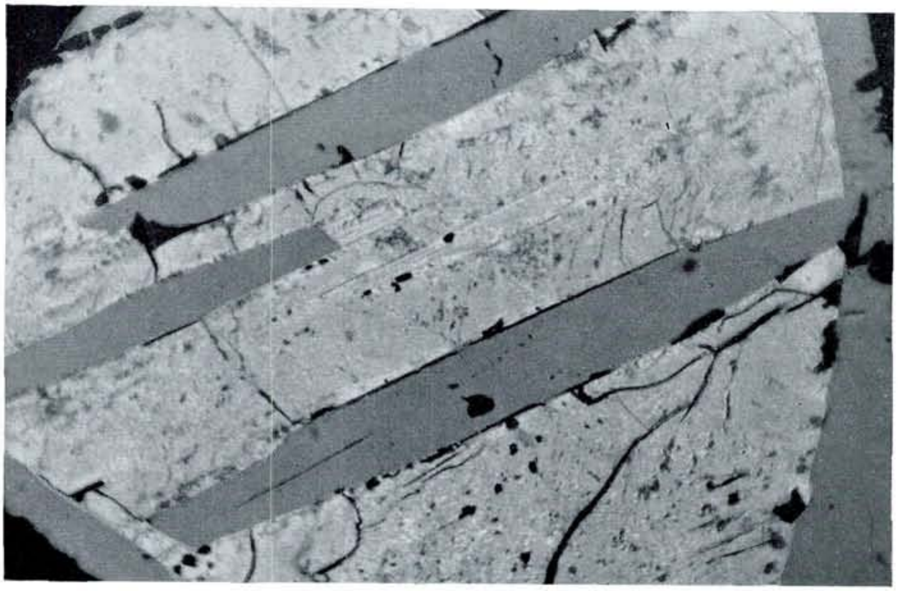

Fig. 1. Polariser only. ×720. Oil immersion.
Titanomagnetite with a few broad and many very thin lamellae of ilmenite arranged parallel to {111}. The mottled dark-grey areas in the titanomagnetite groundmass are incipient alteration to turbid sphene, and the whitish areas, which are scarce and only vaguely seen, are the result of a weak maghemitisation.

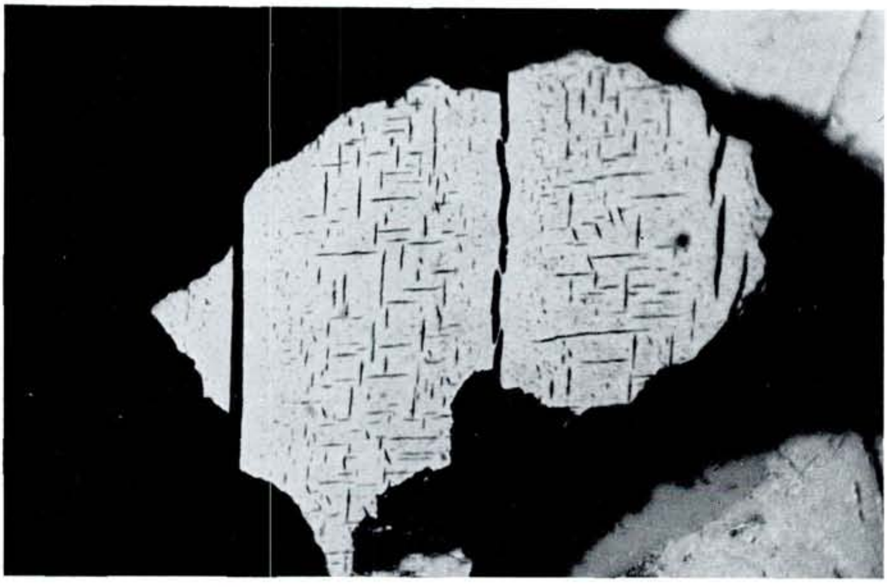

Fig. 2. Polariser only. ×720. Oil immersion.
Titanomagnetite with exsolution lamellae of spinel of different sizes. Growth of the large lamellae of spinel has been achieved at the expense of the surrounding areas, so that exsolution lamellae of spinel here are absent or very scarce.

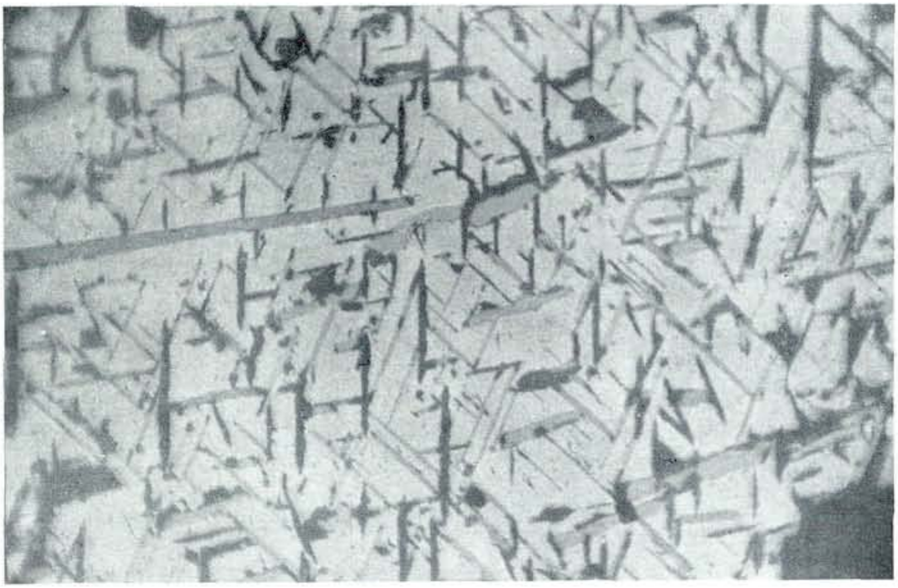

Fig. 1. Polariser only. ×720. Oil immersion.
Titanomagnetite with exsolution of spinel parallel to {100} and {111}, and ilmenite lamellae parallel to {111}.

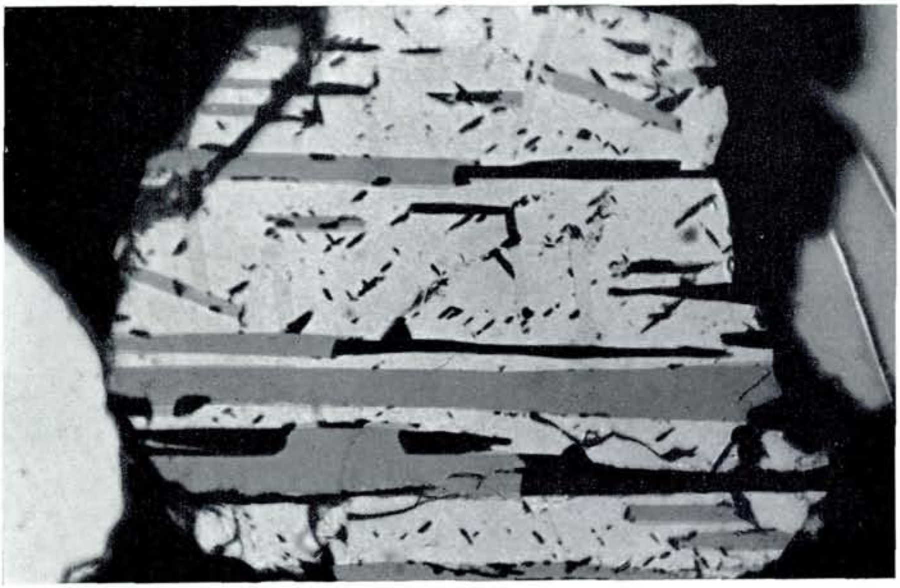

Fig. 2. Polariser only. ×720. Oil immersion.
Titanomagnetite with exsolution of spinel parallel to {100} and {111}, and ilmenite lamellae parallel to {111}.

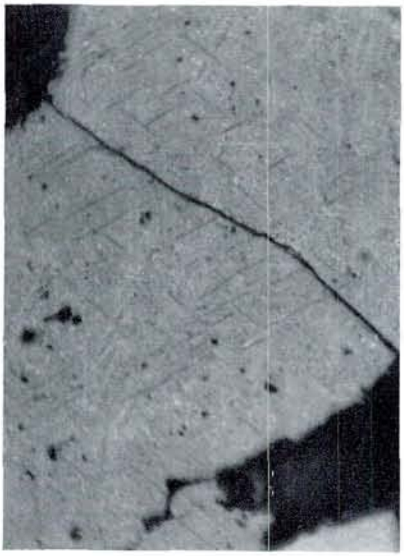

Fig. 1 A

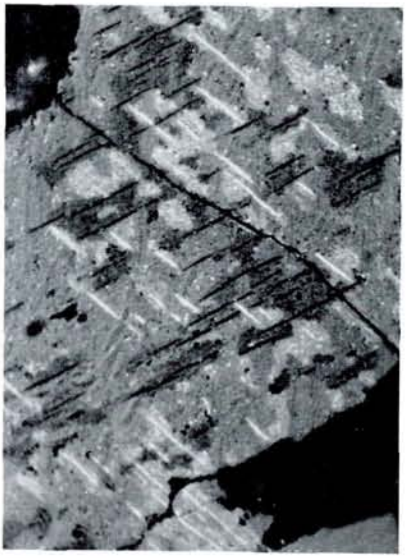

Fig. 1 B

Fig. 1 A. Polariser only. ×720. Oil immersion.
Fig. 1 B. Polars 6° from crossed position. ×720. Oil immersion.
Fig. 1 A shows titanomagnetite with many thin tapering ilmenite lamellae in a heterogeneous groundmass, and in B it is seen that the original ulvöspinel part of the groundmass has been oxidised to ilmenite, and that the tapering ilmenite lamellae have influenced the orientation of this ilmenite in their neighbourhood.

Fig. 2 A

Fig. 2 B

Fig. 2 A. Polariser only. ×720. Oil immersion.
Fig. 2 B. Polars 6° from crossed position. ×720. Oil immersion.
Titanomagnetite in which the ilmenite formed by oxidation of already exsolved ulvöspinel is reorganised from {100} to {111}.

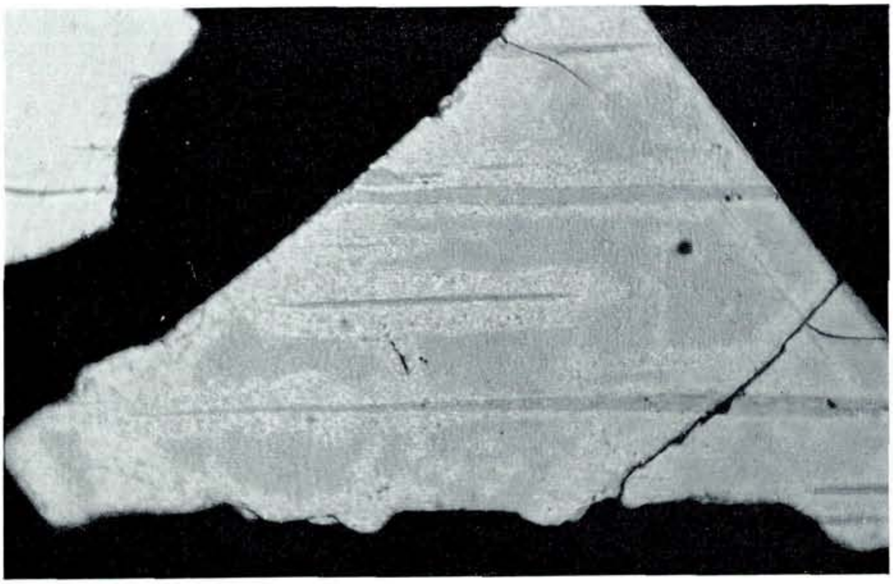

Fig. 1. Polariser only. ×720. Oil immersion.
Titanomagnetite with a few tapering ilmenite lamellae parallel to {111} and a fine pattern of ulvöspinel parallel to {100}. The ulvöspinel pattern is interrupted along the ilmenite lamellae showing that these have formed by concentration of oxidised ulvöspinel from their neighbourhood.

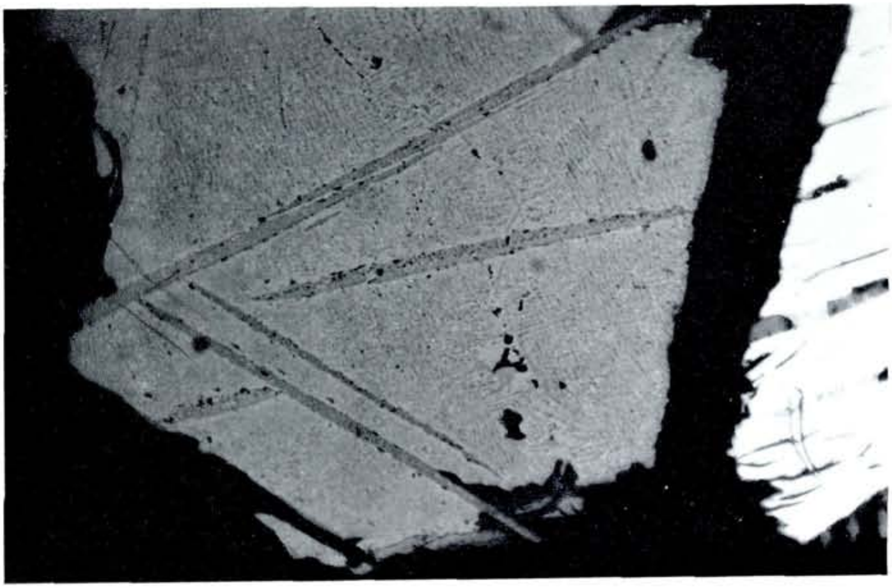

Fig. 2. Polariser only. ×720. Oil immersion.
Titanomagnetite with a few tapering ilmenite lamellae parallel to {111} and a fine pattern of ulvöspinel arranged parallel to {100} and continuing right up to the ilmenite lamellae.

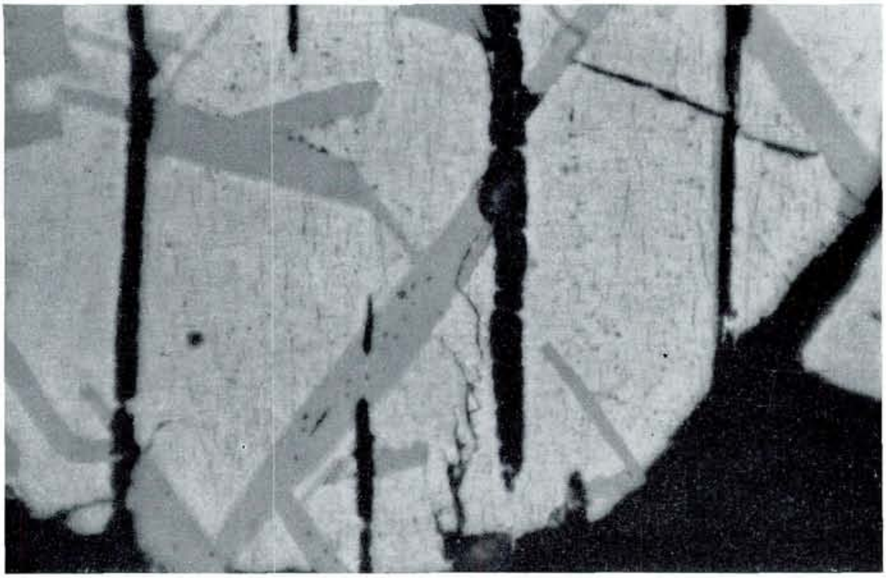

Fig. 1. Polariser only. ×1325. Oil immersion.
Titanomagnetite with spinel lamellae parallel to {100}, ilmenite lamellae parallel to {111} and ulvöspinel in a fine pattern of rods parallel to {100}.

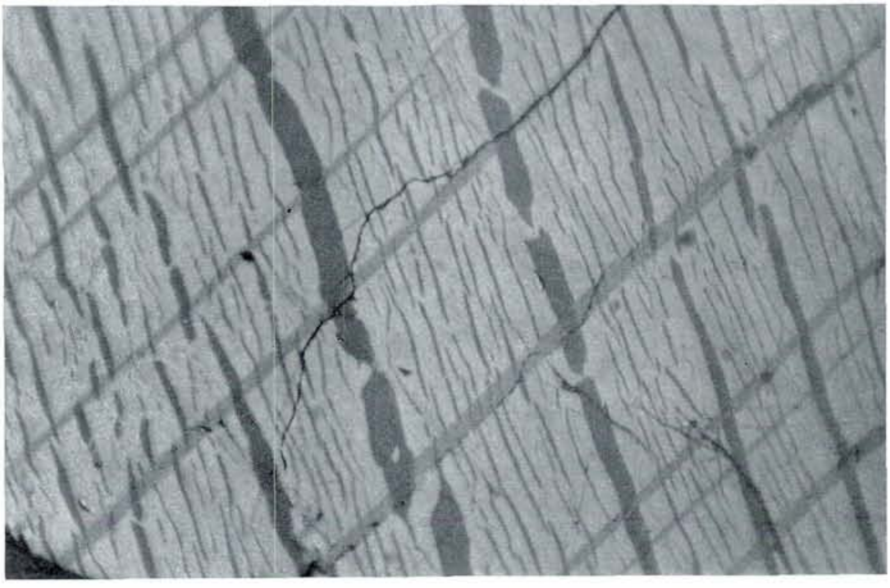

Fig. 2. Polariser only. ×720. Oil immersion.
Ilmenite-hematite exsolution intergrowth with polysynthetic lamellar twins.

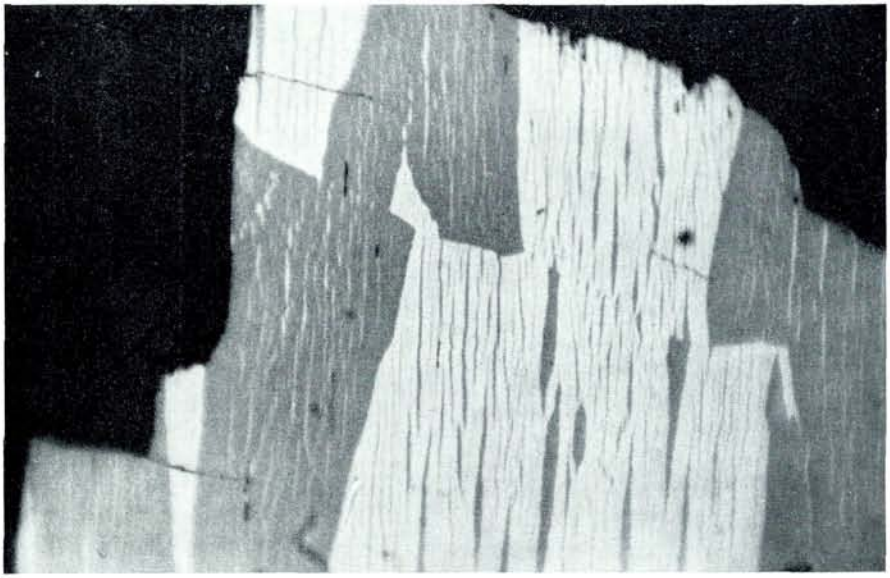

Fig. 1. Polariser only. ×720. Oil immersion.
Ilmenite-hematite exsolution intergrowth.

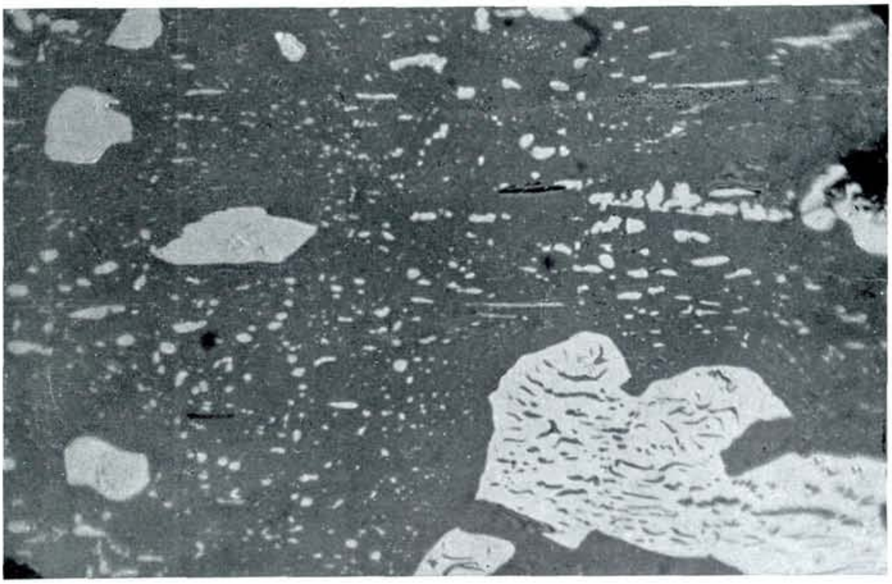

Fig. 2. Polariser only. ×720. Oil immersion.
Ilmenite-rich ilmenite-hematite exsolution intergrowth.

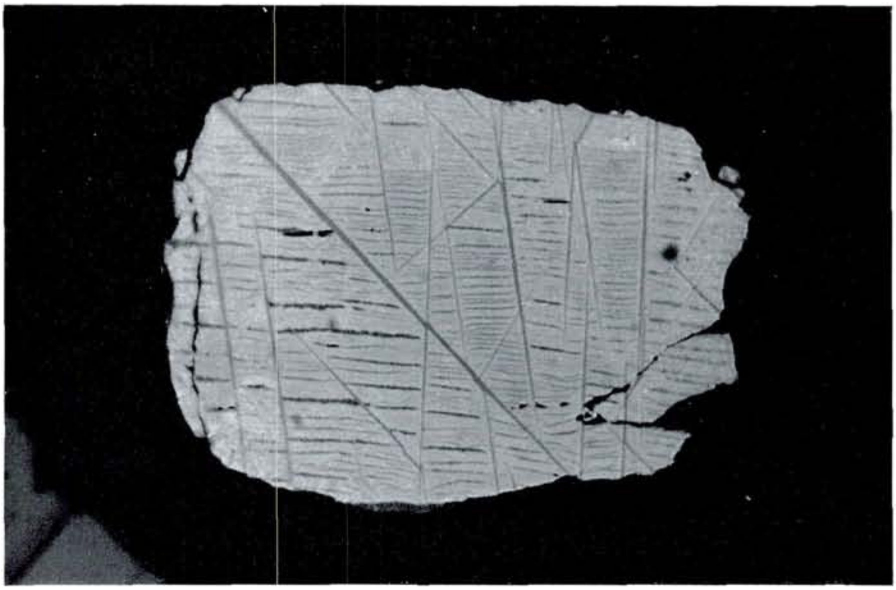

Fig. 1. Polariser only. ×720. Oil immersion.
Hematite-rich ilmenite-hematite exsolution intergrowth with lamellae of rutile.

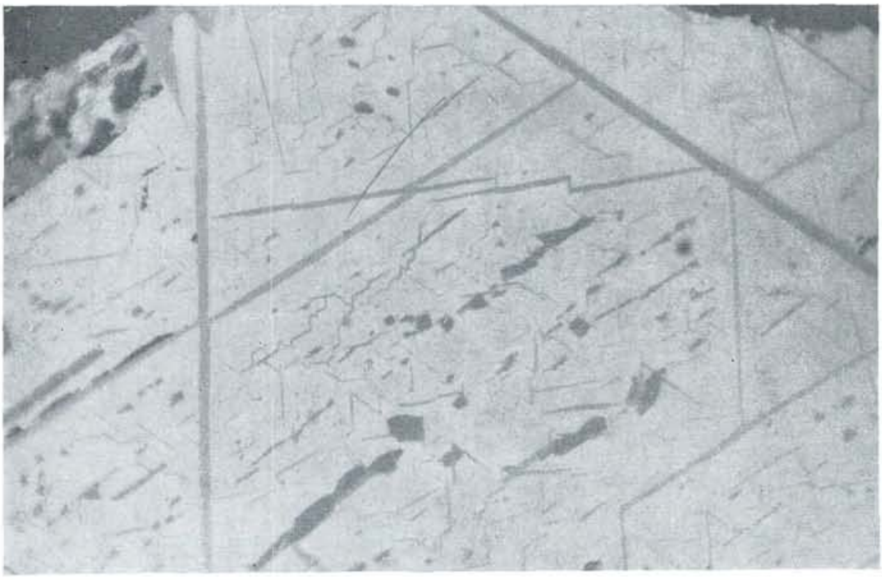

Fig. 2. Polariser only. ×720. Oil immersion.
Hematite-rich ilmenite-hematite exsolution intergrowth with rutile lamellae in varying sizes.

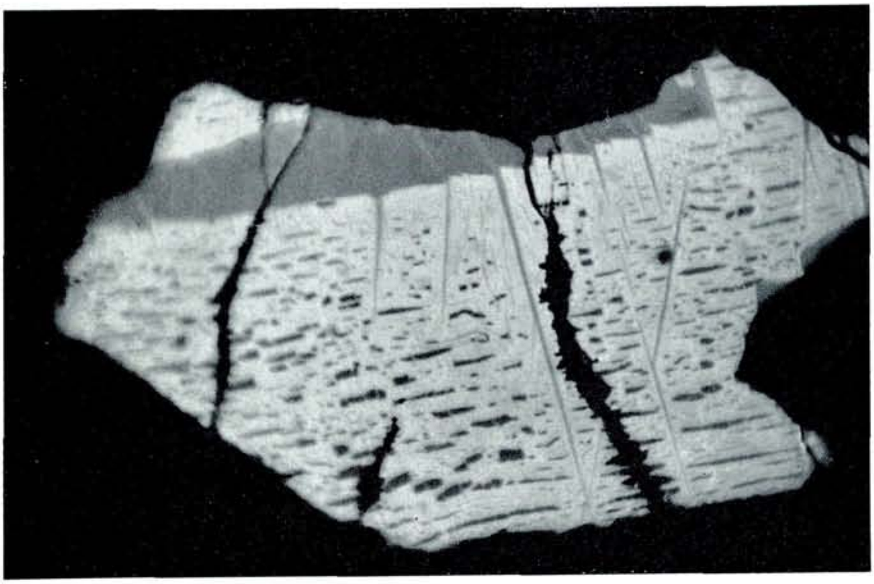

Fig. 1. Polariser only. ×720. Oil immersion.
Hematite-rich ilmenite-hematite exsolution intergrowth with an unusually broad lamella of rutile which is cut and displaced by medium-sized rutile lamellae, which themselves change their course in passing the broad lamella. Still smaller lamellae of rutile are seen between the medium-sized lamellae.

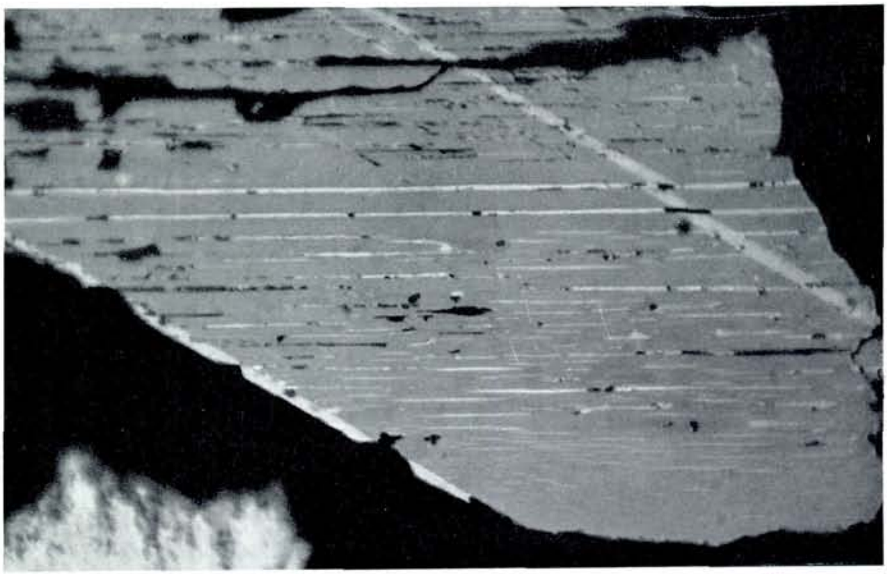

Fig. 2. Polariser only. ×720. Oil immersion.
Magnetoilmenite with a lamellar twin which is displaced by one of the magnetite lamellae. Some of the magnetite lamellae are martitised.

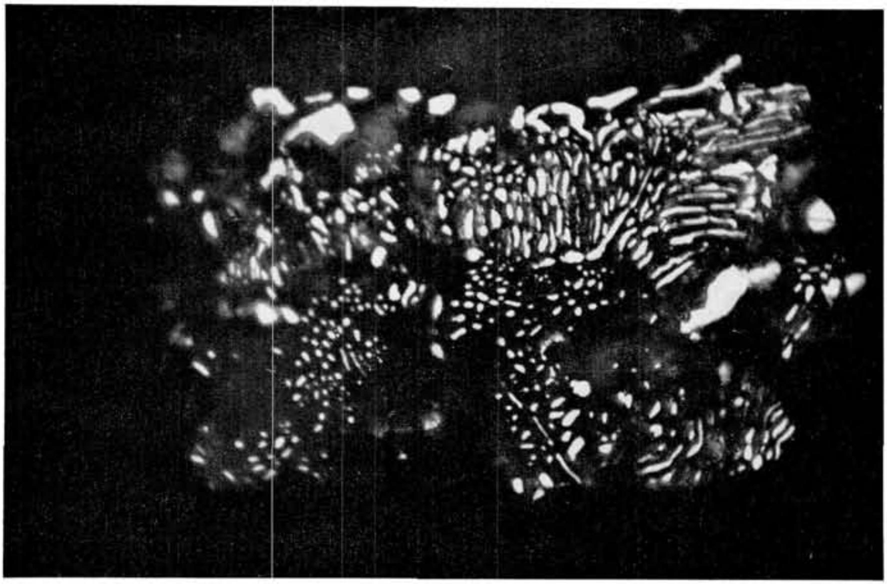

Fig. 1. Polariser only. ×720. Oil immersion.
Myrmekitic intergrowth of magnetite and silicates. The silicate part shows many strong internal reflections.

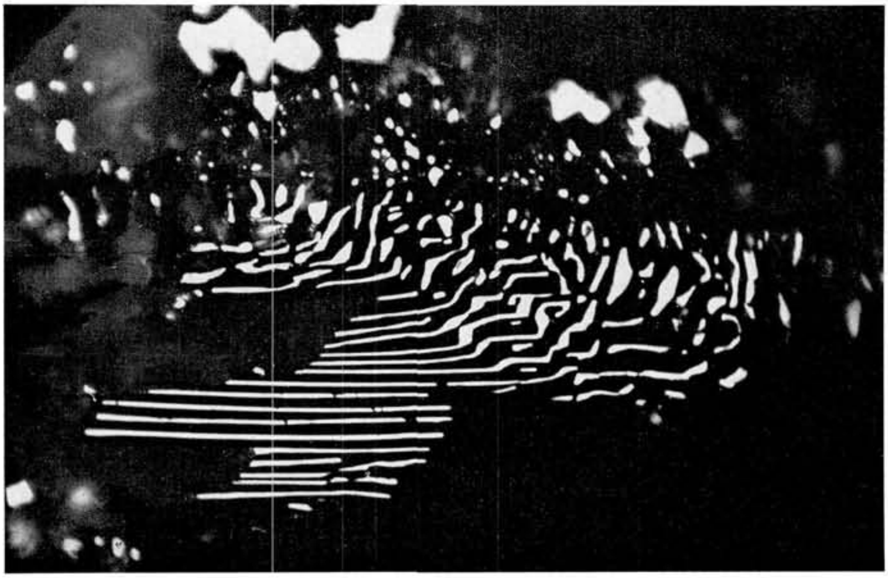

Fig. 2. Polariser only. ×720. Oil immersion.
Myrmekitic intergrowth of magnetite and silicates.

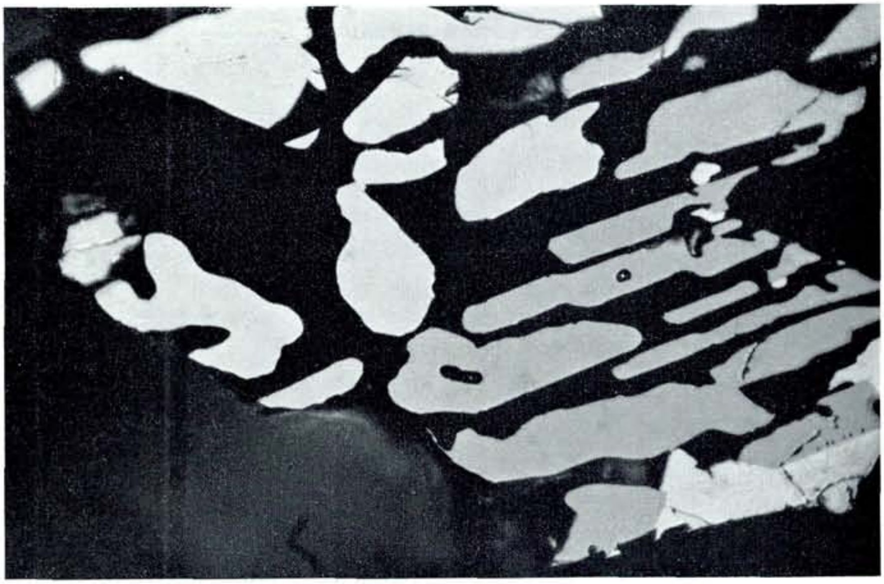

Fig. 1. Polariser only. ×720. Oil immersion.
Myrmekitic intergrowth of ilmenite and silicates. In the lower right corner some heterogeneous magnetite is intergrown with the ilmenite.

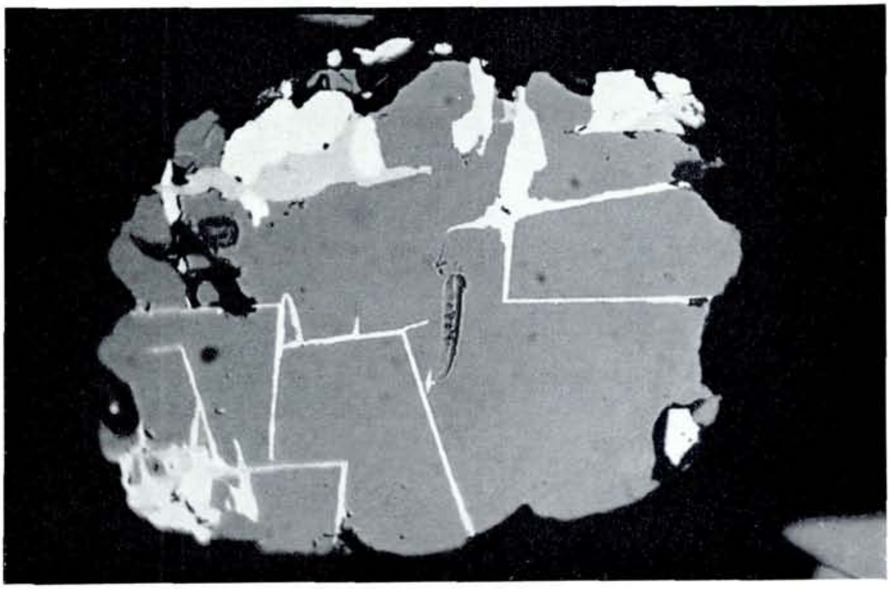

Fig. 2. Polariser only. ×720. Oil immersion.
Magnetite with relatively weak martitisation advancing partly along {111} and partly as compact irregular areas.

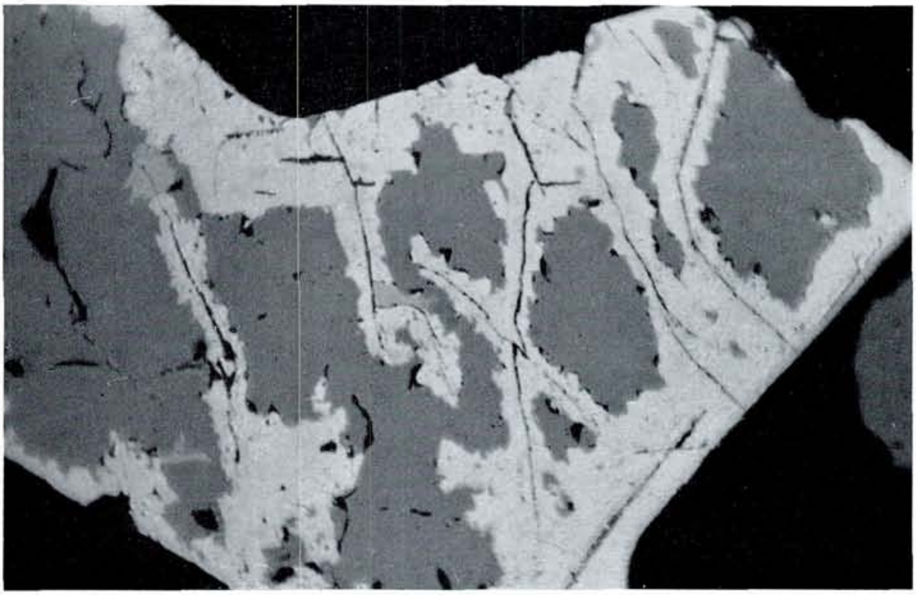

Fig. 1. Polariser only. ×720. Oil immersion.
Magnetite with martitisation clearly localised by cracks.

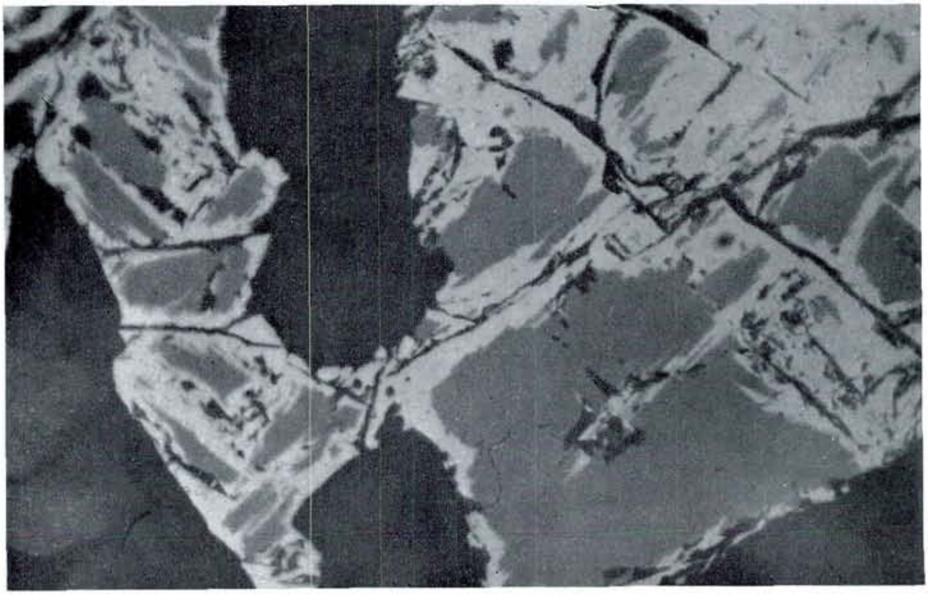

Fig. 2. Polariser only. ×720. Oil immersion.
Magnetite with martitisation which, although mainly localised by cracks, is clearly advancing along {111}.

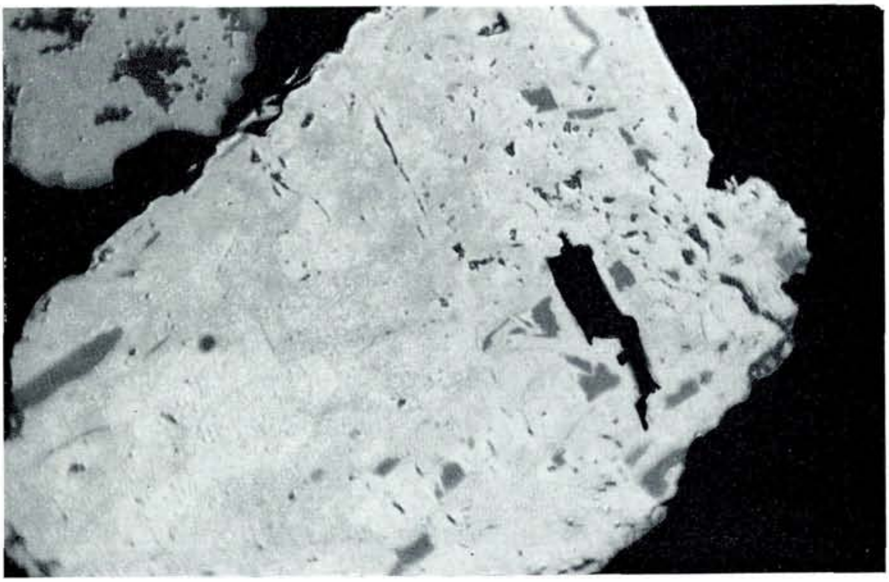

Fig. 1. Polariser only. ×720. Oil immersion.
Magnetite almost completely martitised, so that only small scattered areas of unaltered magnetite are left in the hematite.

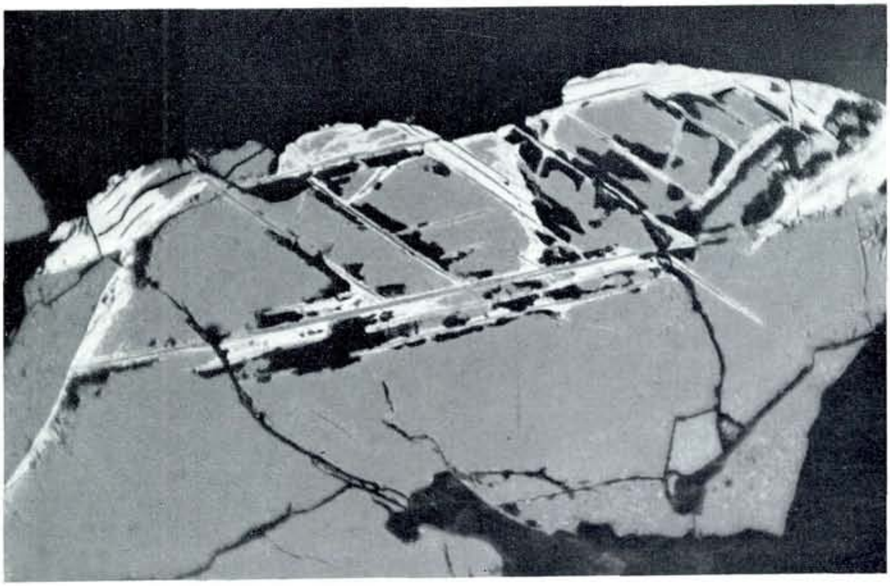

Fig. 2. Polariser only. ×720. Oil immersion.
Titanomagnetite with martitisation along {111} starting adjacent to ilmenite lamellae.

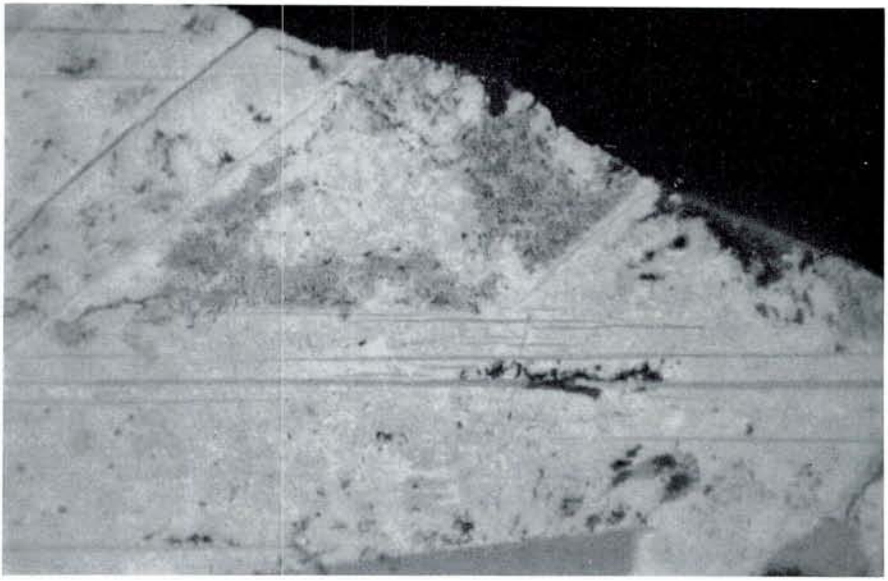

Fig. 1. Polariser only. ×1325. Oil immersion.
Titanomagnetite with weak alteration to turbid sphene (mottled dark-grey areas).

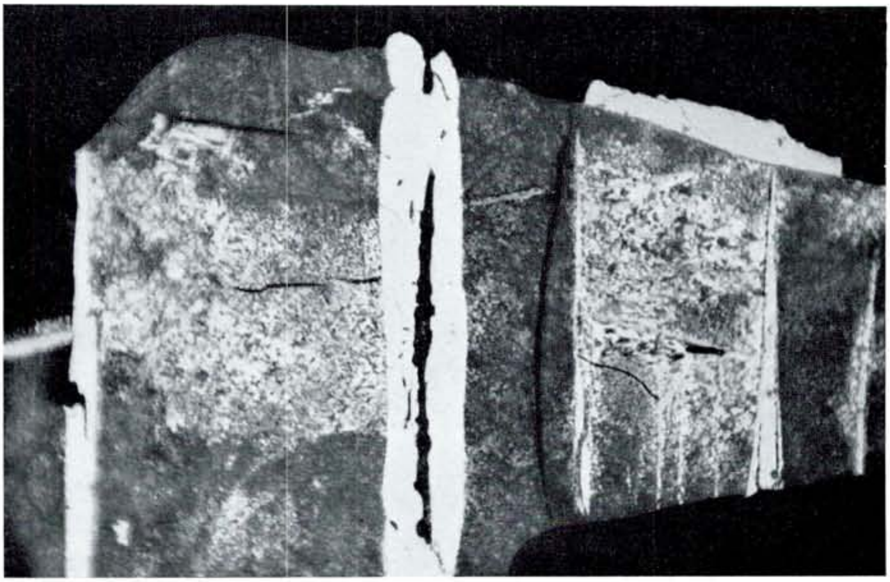

Fig. 2. Polariser only. ×720. Oil immersion.
Titanomagnetite in which the groundmass is almost completely altered to turbid sphene, whereas ilmenite lamellae remain unaltered.

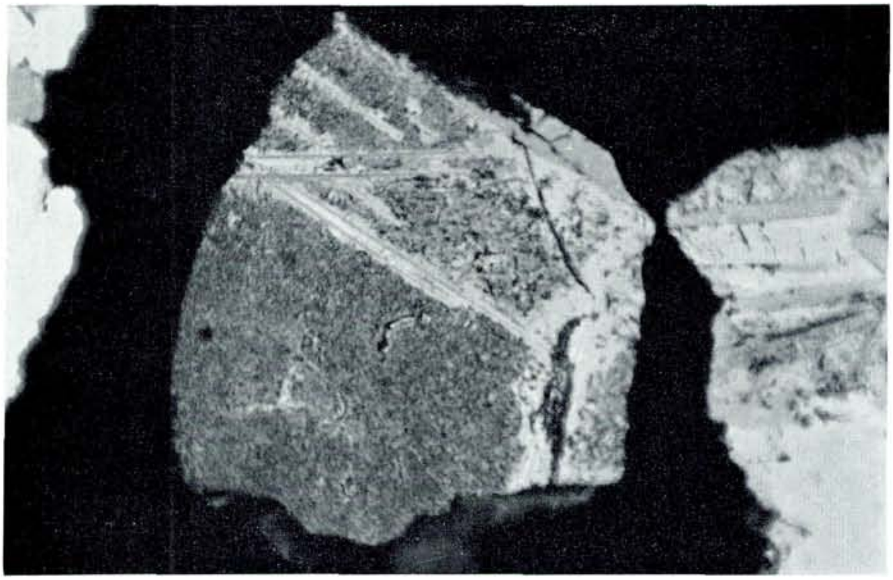

Fig. 1. Polariser only. ×720. Oil immersion.
Titanomagnetite in which the groundmass is completely altered to turbid sphene except for thin rims adjacent to ilmenite lamellae.

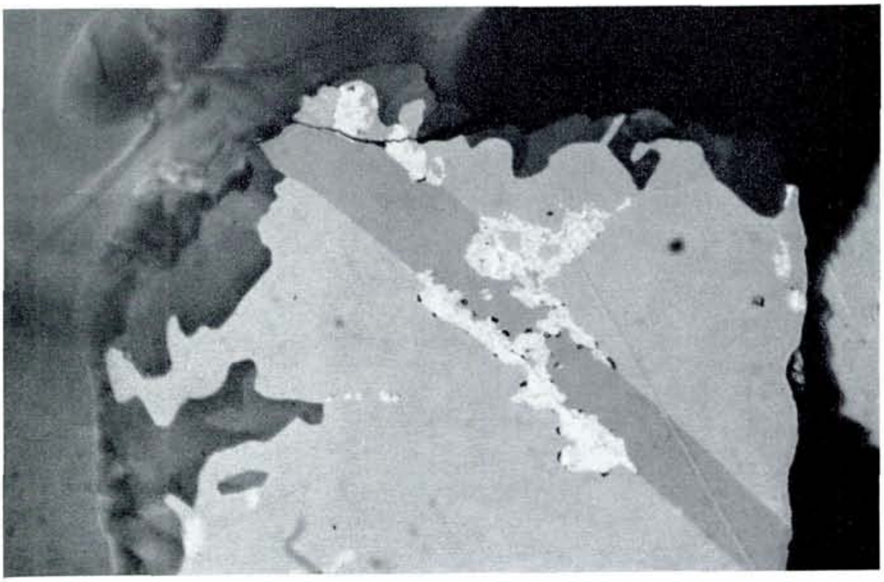

Fig. 2. Polariser only. ×720. Oil immersion.
Ilmenite with alteration to sphene along the borders, and alteration to rutile and hematite, mainly along the twin lamella.

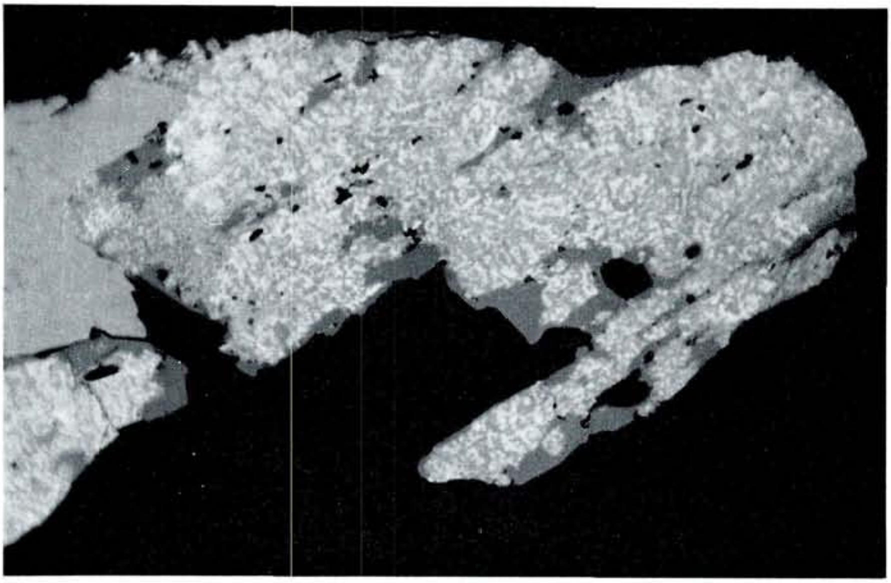

Fig. 1. Polariser only. ×720. *Oil* immersion.
Ilmenite strongly altered to rutile and hematite. It should be noted that unaltered ilmenite is found mainly along the grain boundaries. The light-grey mineral to the left is titanomagnetite.

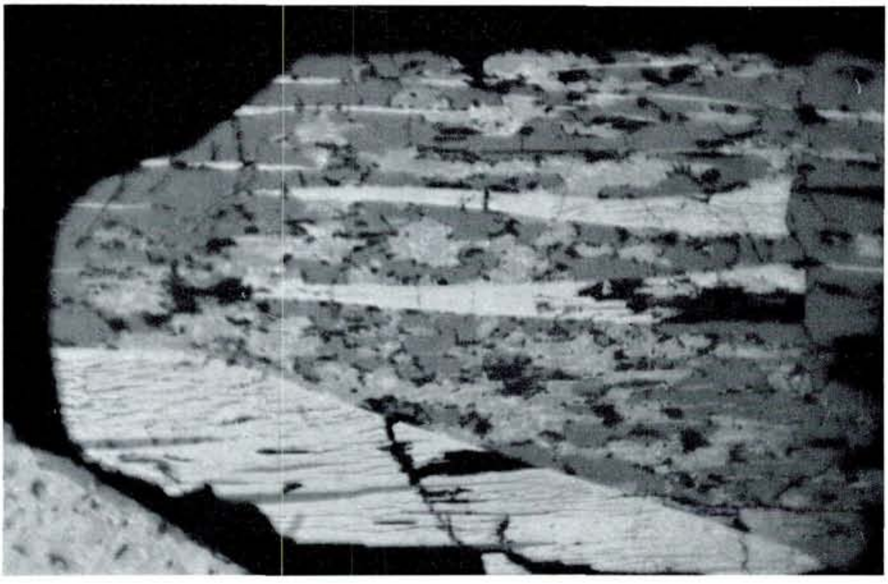

Fig. 2. Polariser only. ×720. Oil immersion.
Ilmenite-hematite exsolution intergrowth; the ilmenite part to a great extent is altered to rutile and hematite.

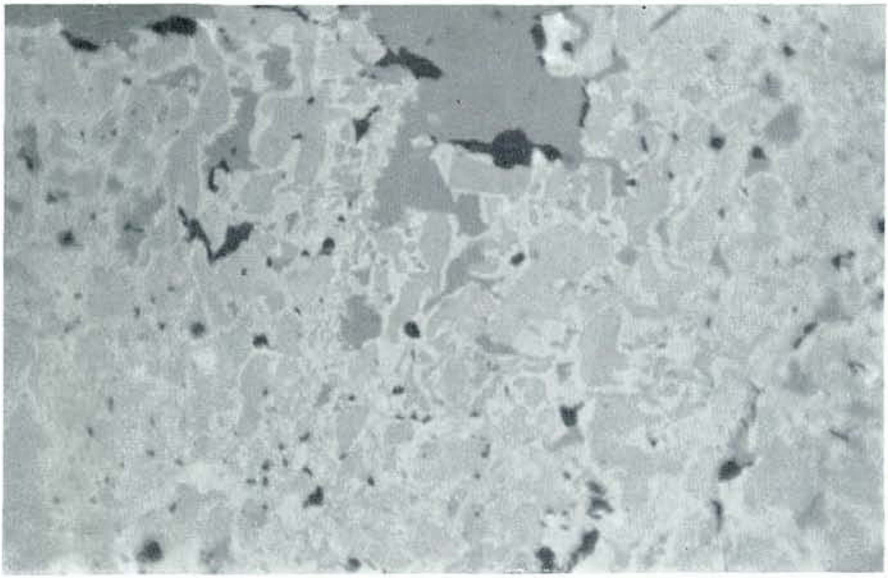

Fig. 1. Polariser only. ×720. Oil immersion.
Ilmenite (dark grey) strongly altered to rutile (medium grey) and magnetite (light grey). The almost black areas are holes.

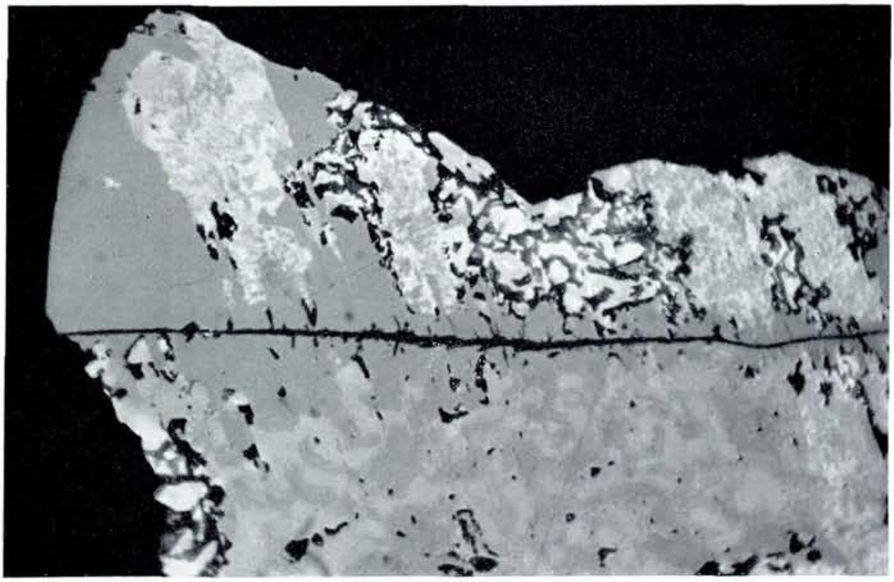

Fig. 2. Polariser only. ×720. Oil immersion.
Strongly altered ilmenite. Below the E–W crack most of the ilmenite is altered to rutile and magnetite; above the crack there is alteration to rutile and hematite, and (mainly in the central part) alteration to rutile accompanied by holes and showing strong internal reflections.

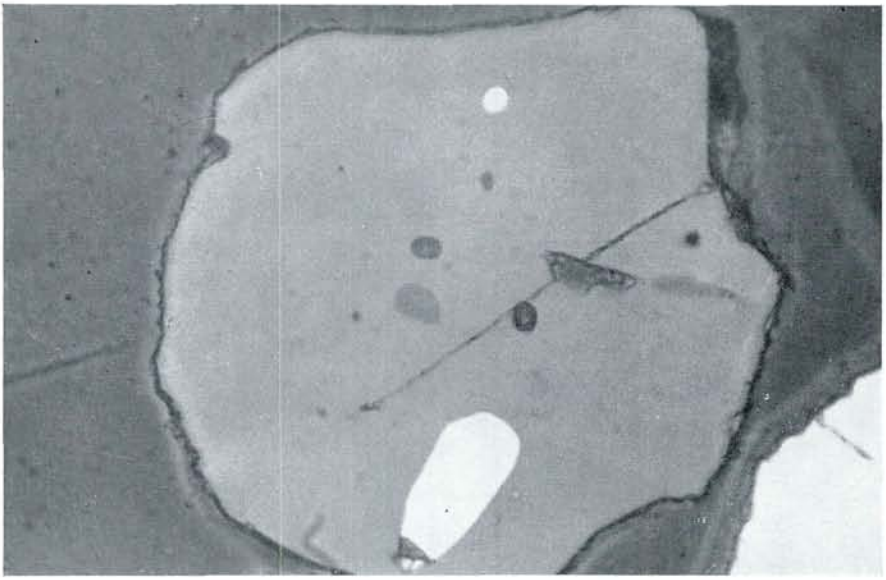

Fig. 1. Polariser only. ×570.
Sphene with two rounded ilmenite islands left as replacement remnants.

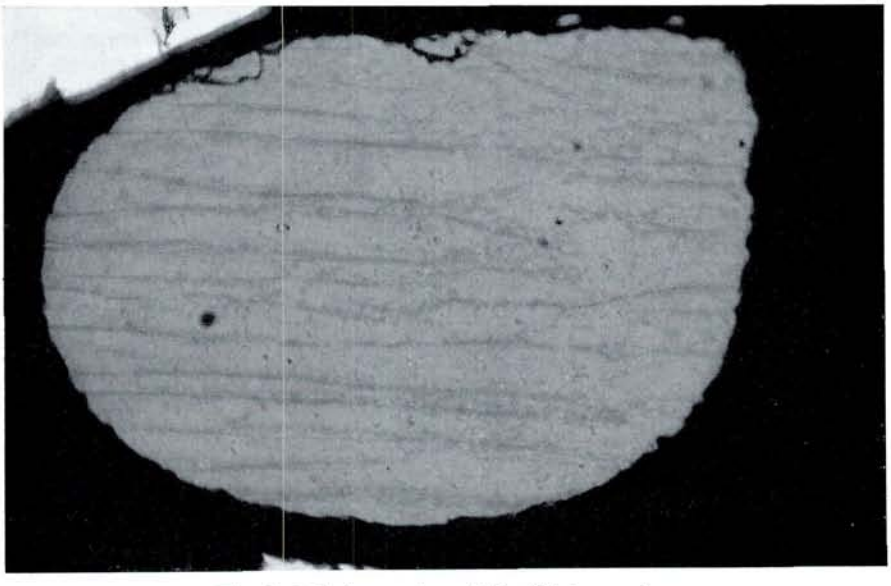

Fig. 2. Polariser only. ×720. Oil immersion.
Ilmenite with strong alteration of beach sand type so that only thin parallel streaks of unaltered ilmenite remain.

Fig. 1. Polariser only. ×720. Oil immersion.
Ilmenite which has been almost completely altered by beach sand type of alteration.

Fig. 2. Polars 6° from crossed position. ×720. Oil immersion.
Ilmenite which has been almost completely altered by beach sand type of alteration.
The same grain as Fig. 1.

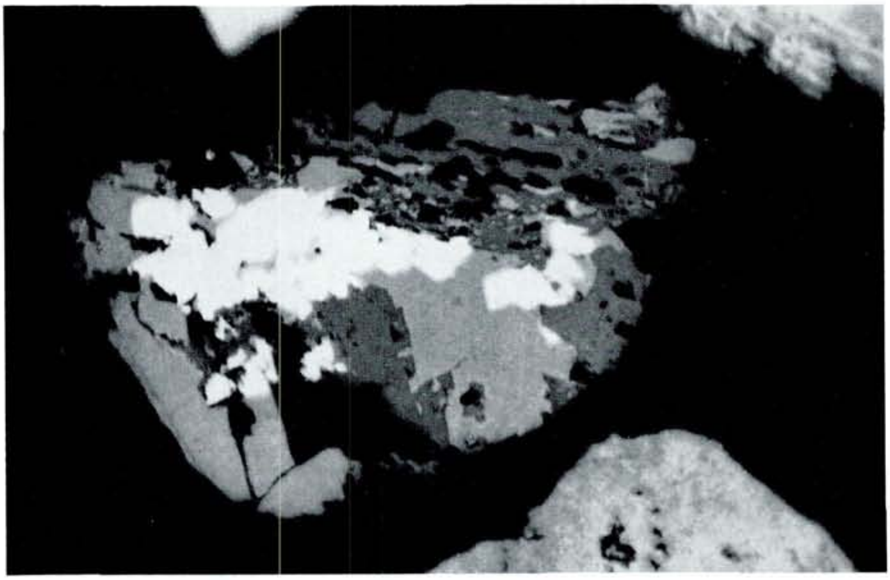

Fig. 1. Polariser only. ×720. Oil immersion.
Magnetite (light grey) with larger areas of hematite (white) and bluish-grey mineral (dark grey).

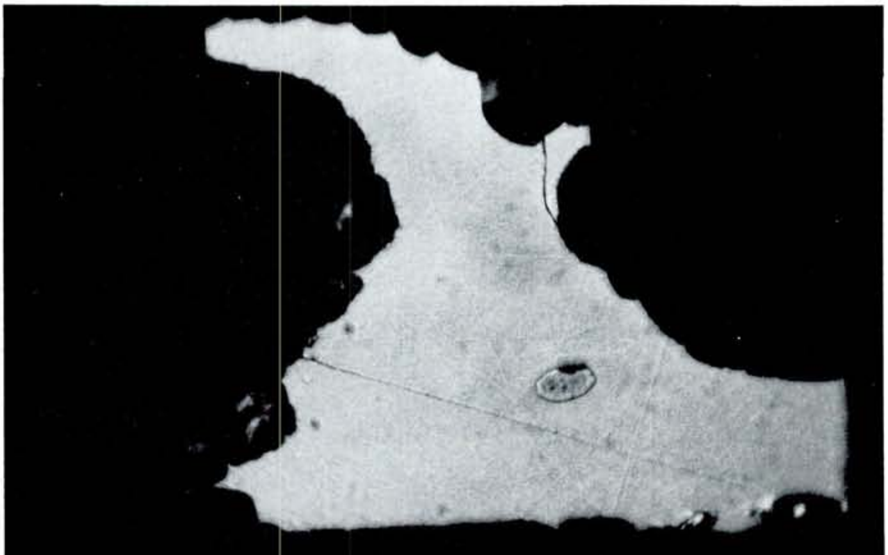

Fig. 2. Polariser only. ×720. Oil immersion.
Pyrite with a globule consisting mainly of chalcopyrite, but also containing some pyrrhotite.