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Mineralogical Variations across two Dolerite Dykes from Bornholm

by

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Abstract

Two Precambrian dolerite dykes, the Kås dyke and the Listed dyke from Bornholm, are described in detail. Modes and norms are given, and the petrography of the dyke rocks is discussed. The variations across the dykes in composition, amounts, and grain size of the different minerals present are investigated.

The variations in Al_2O_3 content of the dyke rocks and in the anorthite content of the plagioclase indicate that the water pressure probably increased with progressing solidification, the increase being considerably higher in the Listed dyke than in the Kås dyke.

The rather complicated development of the titanomagnetite is described, and the composition of the original unexsolved titanomagnetite is estimated. The variations across the dykes in amounts of ilmenite and titanomagnetite indicate an increase in PO_2 towards the end of solidification, the increase being considerably higher in the Listed dyke than in the Kås dyke. The estimated composition of the original titanomagnetite and the composition of the ilmenite are used as a geological thermometer giving values between 950°C and 870°C for the temperature of the magma at the time when ilmenite and titanomagnetite were crystallising together, which was somewhat later than the beginning of crystallisation.

Different types of alteration of the Fe-Ti-oxides taking place after the primary igneous development of the dyke rocks was complete are described in detail. The Kås dyke contains ilmenite alteration of the type hitherto described only from beach sands in tropical and subtropical climates. The most common type of alteration is alteration of titanomagnetite to turbid sphene, the irregular distribution of which is probably the main cause of the rather wide range of density values found in these dykes. Except for the occasional occurrence of thin selvages of maghemite along cracks through titanomagnetite, the different types of alteration are all believed to have been caused by solutions originating from the dykes themselves.

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Introduction

The island of Bornholm constitutes the south-eastern part of Denmark and lies in the Baltic Sea, at approximately lat. 55°N and long. 15°E.

Bornholm covers 600 km^2 and most of the island is built up of Precambrian plutonic rocks of granitic composition. To the west and to the south these are overlain by sediments, the oldest of which are the Eocambrian Nexø sandstone and the Lower Cambrian Balka quartzite.

The plutonites as well as the younger sediments are largely covered by glacial deposits so that outcrops, except in the very northernmost part of the island, are mainly found along the shoreline.

The Precambrian of Bornholm has been thoroughly described by CALLISEN (1934) and more recently by MICHEELSEN (1961). The major part of the plutonic rocks consists of a greyish or reddish gneiss. Besides the gneiss however there are several different types of rather homogeneous granites.

The Precambrian plutonic rocks are at several places cut by dolerite dykes which are generally very thin. According to ROSENKRANTZ (1939) most of the dykes are less than 2 metres thick. A few of the dykes however are some tens of metres thick. The three largest dykes are the Kjeldseå dyke (60 m), the Kås dyke (40 m), and the Listed dyke (30 m).

In some places the dolerite dykes as well as the adjacent plutonic rocks are cut by thin quartzitic "dykes". This is for instance the case at the Listed dyke (Fig. 1). The quartzitic material in these "dykes" belongs to the Lower Cambrian Balka quartzite (USSING 1899 and ROSENKRANTZ & WIENBERG RASMUSSEN 1962) and has been deposited in joints in the plutonites and the dolerite dykes. Accordingly it can be concluded that the age of the dolerite dykes is Precambrian.

The largest of the dolerite dykes, the Kjeldseå dyke, is not well enough exposed to permit a good cross-sectional sampling. This is however possible in both the Kås dyke and the Listed dyke, where they are cut by the shoreline, and the subject of this paper is the mineralogical variations across these two dolerites.

After a brief description of the field relationships and the specimens taken, the general petrography of the dykes is given. This is followed by a short section on variations in alumina content across the dykes, after which a detailed description of the mineralogical variations found across the dykes is presented, and also the conclusions which can be based on these variations. For convenience this main part of the paper is split up into two:

I NON-OPAQUE MINERALS
II OPAQUE MINERALS

II also contains a general description of the opaque minerals, which has been omitted from the section on general petrography.

The location of the dykes and the occurrence of the Precambrian plutonites are shown in Fig. 2 on page 373.

Field description of dykes and general outline of specimens taken

The Kås dyke and the Listed dyke are both situated at the northern coast of Bornholm.

The Kås dyke is found between 8 and 9 km from the northernmost point of

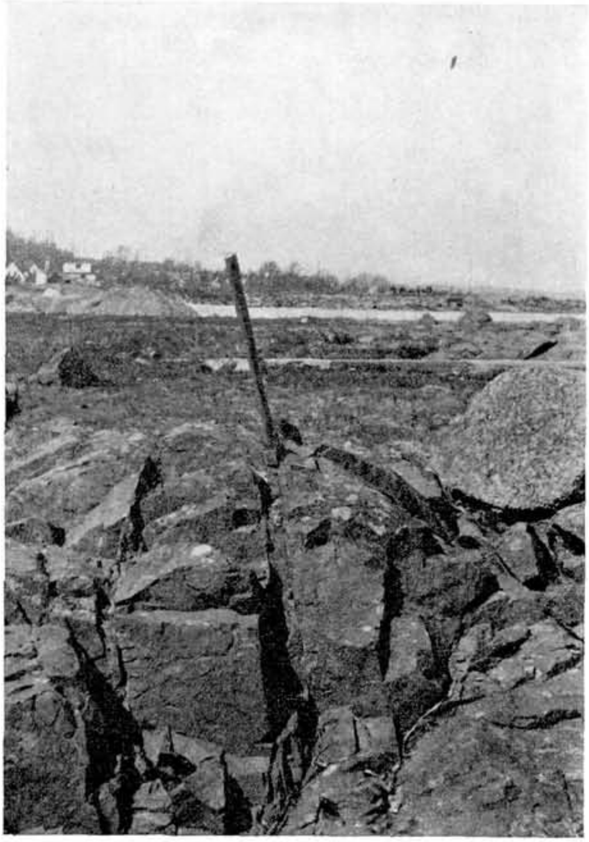

Fig. 1. The Listed dyke seen across the strike.
Beneath the hammer is seen a 4–5 cm thick "dyke" of
Balka quartzite.

the island and cuts through the northern part of the gneiss area. The dyke is steep, with a trend approximately N–S. It is well exposed at the coast and about 40 m thick. At the western contact strike and dip have been recorded at three different exposures. At one of these localities, where the dolerite-gneiss contact can be followed for a little more than $\frac{1}{2}$ m, the strike of the contact is N 6°E. At the two other localities, where gneiss and dolerite are in direct contact for about 5 to 10 cm, the strike is N 6°W. The dip is recorded as 86°E.

In the length direction of the dyke there is a well-developed joint system, the strike of which varies from N–S to N 18°W. The dip is generally almost vertical, varying from 86°E to 86°W. Across the dyke there is also a rather well-developed joint system, which however is somewhat less pronounced than the joint system parallel to the length of the dyke. The strike of the joint system across the dyke is rather variable, but often about E–W. Some of these joints are almost vertical, but there are also two groups of joints with less steep dips, the one group dipping about 60°N and the other about 60°S.

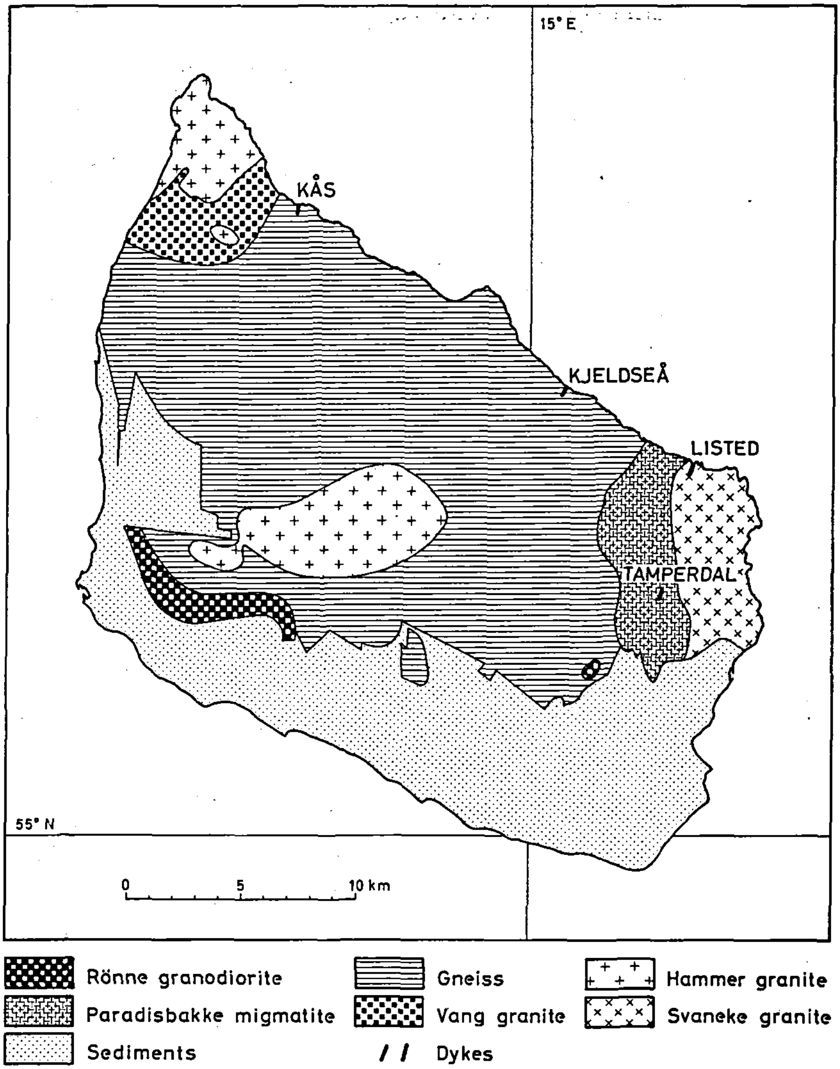

Fig. 2. Sketch map of Bornholm showing the distribution of the different Precambrian plutonic rocks and the positions of the major dykes. After CALLISEN (1934) and MICHEELSEN (1961).

The distance between adjacent joints generally varies between 5 and 20 cm. As far as can be judged there seem to be no differences in intensity of jointing across the dyke.

Some of the joints have been filled with white calcite. The width of these calcite veinlets varies from $\frac{1}{2}$ to 4 cm. Such calcite veinlets have formed in the joint system parallel to the length of the dyke as well as in all three groups of the joint system across the dyke.

Close to the eastern contact there is an area of ½ m² in which the dolerite is transected by numerous thin whitish grey veinlets, striking N 58°W and dipping almost vertically. The veinlets themselves are less than ½ mm thick, but adjacent to each veinlet there is a 1 to 2 mm thick zone in which the dolerite is bleached. The distance between two adjacent veinlets is generally about 1 cm. Under the microscope the veinlets are seen to consist mainly of quartz, but with a thin marginal zone of calcite separating the quartz from the dolerite.

14 specimens have been taken to represent a cross section of this dyke, K1–K14 (Table I). Unfortunately the easternmost outcrop of the dolerite is separated from the country rock by an interval of ½ m in which there is no exposure. Sepcimens K12 and K13 were taken at 3 m and 1 m from the last outcrop and K14 from the outcrop itself. Under the microscope the grain size of K14 is seen to be much larger than that of K2 (5 cm from the west contact). It corresponds fairly closely to that of K3 (1 m from the west contact), but is somewhat finer grained. As the maximum possible distance from K14 to the eastern contact is ½ m, it seems safe to consider K14, K13, and K12 as representing respectively ½ m, 1½ m, and 3½ m from the eastern contact.

The Listed dyke lies approximately 2 km west of the north-eastern corner of Bornholm, and cuts through the Svaneke granite (Fig. 2). A continuation of the Listed dyke is found some 5 km south of Listed in Tamperdal, where the dyke cuts through Paradisbakke migmatite. The present investigation however deals only with the Listed dyke as exposed on the shore, where the dyke is about 30 m thick. The Listed dyke is, like the Kås dyke, steeply dipping with a trend approximately N–S. At the eastern border of the dyke granite and dolerite are found in direct contact for several tens of metres. The strike of the dyke here is N 16°E, and the dip is 86°E.

In the length direction of the dyke there is a well-developed joint system, the strike of which varies between N 16°E and N 20°E, while the dip is approximately 86°E. Across the dyke there is another joint system, which is less well developed. The strike of the joint system across the dyke varies from N 70°W to N 80°W, while the dip is 84°–86°N.

As was found for the Kås dyke the distance between adjacent joints generally varies between 5 and 20 cm. In some cases however this distance is in the Listed dyke as much as ½ m. The distribution of joints across the dyke however appears to be rather homogeneous.

In the Listed dyke small feldspar ovoids, one to three cm in diameter, can be found, and in a zone along the eastern border of the dyke such ovoids are rather numerous. These ovoids are described by COHEN & DEECKE (1891, p. 48–50) and by CALLISEN (1934, p. 167–173). As the ovoids are the result of resorption of part of the granite country rock, the immediate vicinity of ovoids has been avoided in the sampling made for the present investigation.

No calcite veinlets are found in the Listed dyke, but along a joint striking N 70°W and dipping 86°N a 4–5 cm thick "dyke" of Balka quartzite has been formed (Fig. 1).

The Listed dyke is well exposed on the shore. The western part of the dyke however is below sea level, and although the water is only very shallow, the western contact has been made inaccessible and the relationships obscured by a concrete construction.

8 specimens, L1–L8, have been taken to represent a cross section of the Listed dyke (Table I).

Petrography of the centres of the two dykes

The Kås dyke

The centre of the Kås dyke is fine- to medium-grained dark grey dolerite. The dolerite is generally quite fresh, but where weathered surfaces are occasionally found the plagioclase laths attain a brownish colour.

The main components are plagioclase, pyroxene, and ore minerals, with plagioclase constituting more than half of the rock. The other mineral constituents are amphibole (mainly uralite), biotite, chlorite, talc, quartz, and apatite, while olivine-bowlingite and calcite are found as traces.

The texture is doleritic to subdoleritic (KROKSTRÖM 1932).

Table I

List of specimens

The Kås dyke:		
K1	W-contact	Dense greyish black dolerite. Some small plagioclase laths are visible in the dense groundmass.
K2	5 cm E of W-contact	Extremely fine-grained dark grey dolerite.
K3	1 m E of W-contact	Fine-grained dark grey dolerite.
K4	3 m E of W-contact	Fine-grained dark grey dolerite. The length of plagioclase laths may however exceed 1 mm.
K5	5 m E of W-contact	Fine- to medium-grained dark grey dolerite.
K6	10 m E of W-contact	–
K7	15 m E of W-contact	–
K8	20 m from both contacts	–
K9	15 m W of E-contact	–
K10	10 m W of E-contact	–
K11	5 m W of E-contact	–
K12	ca. 3½ m W of E-contact	–
K13	ca. 1½ m W of E-contact	Fine-grained dark grey dolerite.
K14	ca. ½ m W of E-contact	Fine-grained dark grey dolerite.
The Listed dyke:		
L1	E-contact	Dense greyish black dolerite.
L2	1 m W of E-contact	Fine-grained greyish black dolerite.
L3	3 m W of E-contact	Fine-grained greyish black dolerite. The length of plagioclase laths may however exceed 1 mm.
L4	5 m W of E-contact	Fine- to medium-grained dark grey dolerite.
L5	10 m W of E-contact	–
L6	15 m from both contacts	–
L7	10 m E of W-contact	–
L8	ca. 2 m E of W-contact	Fine-grained dark grey dolerite.

Besides these specimens, systematically collected across the dykes, several additional specimens have been collected for special purposes. Such additional specimens are marked with letters instead of numbers, for the Kås dyke KA to KX, and for the Listed dyke LA to LK.

The plagioclase is typically lath-shaped. The largest laths attain 2.70 × 0.50 mm, whereas the average size of laths is 1.50 × 0.30 mm. The laths are built up of thin twin lamellae and generally show a diffuse zoning; only in a few very rare cases is regular zoning visible. The following twin laws are found: Albite, Carlsbad, Albite-Carlsbad, and Ala. The composition of the plagioclase is andesine to labradorite. The difference between core and periphery of the laths never exceeds 7% An. Normal as well as reverse zoning is found, and the average composition is the same for core and periphery, 50% An. In the core the variation is from 46% to 54% An, while the variation in the periphery is from 45% to 56% An. The plagioclase is generally rather fresh, although to some extent it is clouded by sericitisation. Alteration to greenish chlorite also occurs.

The shape of the pyroxene grains is irregular, but they are often somewhat elongated. The largest pyroxene grains attain 2.10 × 0.75 mm, the average grain size being 1.20 × 0.60 mm.

The largest of the pyroxene grains are orthopyroxene, the 2V(−) of which was found to average about 57°, with variation from 52° to 64°. 2V(−) = 57° corresponds to between 35 and 63 mol. per cent ferrosilite, and between 37 and 65 mol. per cent enstatite. The composition is therefore hypersthene to ferrohypersthene. The orthopyroxene has a relatively well-developed cleavage, is faintly pleochroic from pale grey to pale yellowish brown, and occasionally shows a somewhat undulatory extinction.

Besides this orthopyroxene, clinopyroxene is also found. The grain size of the clinopyroxene is generally somewhat smaller than that of the orthopyroxene. The clinopyroxene has an augitic composition. 2V(+) was found to vary from 42½° to 47° and averages 44°. $c \wedge \gamma$ varies between 43° and 46½° and averages 44°. The augite shows a relatively well-developed cleavage, has a brownish grey colour, and occasionally shows twinning on {100}. Very often the augite has a somewhat undulatory extinction.

The majority of the pyroxene is relatively fresh, but alteration to uralite, chlorite-talc, and biotite is frequently found, and some pyroxene grains are strongly altered in the outer portions.

The ore minerals, which are mainly ilmenite and titanomagnetite, will be only briefly mentioned here, a fuller treatment being given later. The size and shape of the ore minerals are strongly variable. Ilmenite frequently forms myrmekitic intergrowths with mafic silicates, the silicate partner often being biotite. Almost all of the ore minerals are primary, although some ore has been formed as the result of alteration of mafic silicates.

Almost all amphibole present is the product of uralitic alteration of pyroxene. In the middle of the dyke where uralitisation is only slight, no optical measurements can be performed on the amphibole. In other parts of the dyke where uralitisation is more pronounced however 2V(−) of the uralite was found to be 70°–75°, and $c \wedge \gamma$ to be about 20°. Besides the uralite some thin needles of colourless amphibole are occasionally seen. The length of the needles may reach ½ mm, but generally the needles are considerable shorter. The width of the needles never exceeds 5 μ.

The biotite is brown, showing pleochroism from dark brown to light yellowish brown. In many cases the biotite has been formed by alteration of pyroxene. In the myrmekitic intergrowths of ilmenite and biotite there are sometimes found remnants of only slightly altered pyroxene, indicating that pyroxene and not biotite was the original partner in the myrmekites. However biotite is also found under circumstances where no evidence of replacement of other minerals is seen. This is the case in many places where biotite occurs together with quartz. Such biotite might very well have formed as a primary late magmatic mineral.

Small remnants of olivine are found in a heavily coloured alteration product, the colour of which varies from yellowish brown to brownish green. The alteration product is fibrous, has a moderate birefringence, and shows a faint pleochroism. It is in good agreement with the olivine alteration product described as bowlingite by WINCHELL & WINCHELL (1961) and DEER, HOWIE & ZUSSMAN (1962) and is therefore termed bowlingite. In the Kås dyke the alteration of olivine to bowlingite is not accompanied by formation of secondary ore minerals. More advanced alteration of the olivine results in the formation of talc and secondary ore. Bowlingite as well as unaltered olivine is found only as traces, while pseudomorphs of talc and secondary ore minerals after olivine are more frequently met with.

Greenish chlorite occurs as an alteration product of pyroxene as well as of plagioclase.

Quartz forms rather irregular grains the average size of which is 0.20 × 0.15 mm. Together with biotite, quartz often fills the interstitial areas between plagioclase and pyroxene. In some cases quartz forms micrographic to granophyric intergrowths with plagioclase.

Apatite occurs as elongated idiomorphic crystals with a width between 0.01 and 0.09 mm. The length is generally about 0.3 mm, but varies from 0.05 to 1.20 mm.

Traces of calcite are found as relatively large grains, the diameter of which may exceed 0.1 mm.

A photomicrograph of the specimen K8 from the centre of the Kås dyke is shown in Plate 1, Fig. 1.

The Listed dyke

The centre of the Listed dyke is fine- to medium-grained dark grey dolerite, macroscopically quite similar to the Kås dolerite. The Listed dolerite is quite fresh, and even when weathered parts are intentionally looked for, they are hard to find in the centre of the dyke.

The main components are plagioclase, pyroxene, olivine, and ore minerals, with the plagioclase amounting to more than half of the rock. The other mineral constituents are biotite, chlorite, talc, bowlingite, quartz, and apatite, while amphibole, potassium feldspar, and calcite are found as traces.

The texture is doleritic to subdoleritic (KROKSTRÖM 1932).

The plagioclase is typically lath-shaped as in the Kås dyke, and the size of the laths is the same. They are built up of thin twin lamellae and generally show a diffuse zoning; only in a few very rare cases is regular zoning visible. The following twin laws are represented: Albite, Carlsbad, Albite-Carlsbad, Aklin, and Manebach. The composition of the plagioclase is labradorite in the cores, but the An content decreases rather strongly outwards. The difference between core and periphery may reach 24% An, and at the periphery the composition of some plagioclase grains lies on the oligoclase-andesine border. No cases of reverse zoning were observed, all measured grains showing only normal zoning. Average composition of cores is 59% An, with variation from 51% to 65% An. In the periphery the plagioclase averages 45% An, and varies from 30% to 59% An. The plagioclase is generally rather fresh, but may be clouded by sericitisation. Alteration of plagioclase to greenish chlorite also occurs.

The shape of the pyroxene grains is irregular, but they are generally somewhat elongated. The largest pyroxene grains are 1.40 × 0.50 mm, the average size being 0.75 × 0.40 mm.

The pyroxene in the Listed dyke is all clinopyroxene with an augitic composition. 2V(+) varies from 41° to 53° and averages 45°. $c \wedge \gamma$ varies from $41\frac{1}{2}°$ to $45\frac{1}{2}°$, the average being $43\frac{1}{2}°$. The augite shows a relatively well-developed cleavage, has a brownish grey colour, and occasionally shows twinning on $\{100\}$. A rather pronounced undulatory extinction is generally found. The augite is usually very fresh, but some alteration is present. Biotite is the commonest alteration product, chlorite being present but in subordinate amounts, and uralite only as traces. Alteration of augite to biotite is so far advanced in some instances that entire grains of augite have been almost completely replaced.

The olivine grains are rather uniform in size, their average diameter being about $\frac{1}{2}$ mm. The grains are frequently rimmed with pyroxene or surrounded by larger pyroxene grains. The olivine is optically negative with 2V(−) varying from 70° to 83°, the average being 75°, i.e. Fa_{48}.

Part of the olivine is very fresh and part is strongly altered to bowlingite. Even the freshest olivine however displays curved cracks and patches along which it is altered to secondary ore minerals and bowlingite. The bowlingite in these patches has a dark brownish colour, whereas the yellowish brown and brownish green colours do not appear until the alteration is more advanced. Contrary to what was found in the Kås dyke, continued alteration of olivine in the Listed dyke results preferentially in the formation of chlorite, while talc formation is more seldom found. This fact might indicate that the olivine in the Listed dyke is more iron-rich than the olivine in the Kås dyke.

The ore minerals are mainly ilmenite and titanomagnetite and have the same general appearance as in the Kås dyke. Ilmenite also forms myrmekitic intergrowths with biotite, and as in the Kås dyke pyroxene rather than biotite was probably the original silicate partner in the myrmekites. The most important difference in the ore minerals between the two dykes lies in the amounts of ore present, as the Listed dyke contains only half as much ore as does the Kås dyke.

Uralitisation of pyroxene is inconspicuous and only traces of uralite are found. No measurements have been performed on the uralite.

Amphibole is also present as a few thin colourless needles, the width of which lies between 2 and 3 μ, while the length is generally about 0.2 mm; occasionally needles considerably longer may be seen.

Greenish chlorite occurs as an alteration product of olivine and pyroxene as well as of plagioclase.

Biotite is brown, showing pleochroism from dark brown to light yellowish brown. Biotite is the most frequent alteration product of pyroxene, but as in the Kås dyke it can not be excluded that some of the biotite, which occurs intergrown with quartz, has formed as a primary late magmatic mineral.

Quartz occurs as rather irregular grains the average size of which is 0.15 × 0.10 mm. Quartz and biotite often occur together and sometimes fill areas interstitial between the plagioclase laths. Quartz can also be found in micrographic to granophyric intergrowths with plagioclase.

Untwinned potassium feldspar is found as traces.

Apatite occurs as elongated idiomorphic crystals with a width between 0.01 and 0.06 mm, and a length which varies from 0.05 to 1.05 mm.

Traces of calcite are found as relatively large grains, the diameter of which may exceed 0.1 mm.

A photomicrograph of the specimen L6 from the centre of the Listed dyke is shown in Plate 1, Fig. 2.

Classification

Chemical analyses have been carried out on K8, the specimen representing the middle of the Kås dyke, and on L6 representing the middle of the Listed dyke. The results are given in Table II. CIPW norm calculations based on these analyses are listed in Table III together with mode determinations based on point countings of thin sections of K8 and L6.

The agreement between norm and mode is fairly good, and the discrepancies which exist between them would largely be removed if the normative orthoclase

Table II

Chemical analysis of Kås (K8) and Listed (L6).
Analyst Miss Me Mouritzen.

	Kås		Listed	
	Weight %	Cation %	Weight %	Cation %
SiO_2	49.66	48.0	50.74	47.6
TiO_2	3.90	2.8	1.86	1.3
Al_2O_3	15.12	17.2	18.19	20.1
Fe_2O_3	4.21	3.1	2.09	1.5
FeO	8.73	7.0	7.84	6.1
MnO	0.14	0.1	0.14	0.1
MgO	3.64	5.3	5.55	7.8
CaO	6.35	6.6	7.33	7.4
Na_2O	3.93	7.4	3.66	6.6
K_2O	1.56	1.9	0.92	1.1
P_2O_5	0.81	0.6	0.50	0.4
H_2O^+	1.47		1.03	
H_2O^-	0.32		0.20	
	99.84	100.0	100.05	100.0
$Na_2O + K_2O$	5.49		4.58	
MgO/CaO	0.57		0.76	
MgO/FeO	0.42		0.71	

Table III

Norm and mode of the dolerite dykes

Kås								Listed							
Norm in cation %					Mode in weight %			Norm in cation %					Mode in weight %		
Q	2.5				Quartz	3		Q	0				Quartz	1	
Or	9.5		66.3		Potassium feldspar	0		Or	5.5		69.5		Potassium feldspar	tr	
Ab	37.0	56.8			Plagioclase	57		Ab	33.0	64.0			Plagioclase	60	
An	19.8							An	31.0						
Wo	3.3	19.4			Pyroxene	14½	26½	Wo	1.0	24.6			Pyroxene	14	32½
En	10.6			(Di 6.6)	Uralite	2½		En	14.8			(Di 2.0)	Uralite	tr	
Fs	5.5			(Hy 12.8)	Biotite	2		Fs	7.7			(Hy 21.5)	Biotite	2½	
Ol	0				Chlorite-Talc	7½		Ol	1.1				Chlorite-Talc	8½	
					Olivine-Bowlingite	tr							Olivine-Bowlingite	7½	
Mt	4.6	10.2			Ore	12		Mt	2.2	4.8			Ore	6	
Il	5.6							Il	2.6						
Ap	1.6				Apatite	1½		Ap	1.1				Apatite	½	
					Calcite	tr							Calcite	tr	
	100.0					100			100.0					100	

An percentage in the plagioclase:

Norm		Mode		Norm		Mode	
With Or	Without Or	Periphery	Core	With Or	Without Or	Periphery	Core
30	35	50	50	45	48	45	59

and part of the normative albite were redistributed in non-opaque mafics. This would also increase the An content of the plagioclase remaining in the norm.

YODER & TILLEY (1962), based on their generalised basalt tetrahedron, divide the basalts into five groups:

1. Tholeiite with normative quartz and hypersthene.
2. Tholeiite with normative hypersthene.
3. Olivine tholeiite with normative hypersthene and olivine.
4. Olivine basalt with normative olivine.
5. Alkali basalt with normative olivine and nepheline.

The Kås dyke belongs to group 1, whereas the Listed dyke just falls in group 3. Hence although both dykes are tholeiitic, the Listed dyke should be closer to alkali basalts than the Kås dyke. This might be reflected in the fact that the Listed dyke shows somewhat higher values of the ratios MgO/CaO and MgO/FeO than does the Kås dyke, whereas the sum of alkalies is higher in the Kås dyke than in the Listed dyke (Table II). The difference in SiO_2 is insignificant. It can be seen that this difference is reversed when the weight percentages are converted to cation percentages. This is partly due to the omitting of water from the cation percentages, and partly due to the Kås dyke being somewhat richer in the heavier cations than is the Listed dyke.

By comparing the Kås and the Listed analyses with the average chemical composition of the rock types given by NOCKOLDS (1954) it is seen that the chemical composition of the Listed dyke shows a greater resemblence to the average normal tholeiitic basalt than to the average tholeiitic olivine basalt. Furthermore, in some respects, especially concerning Mg, Ca, and alkalies, both the Kås dyke and the Listed dyke are closer to the average tholeiitic andesite than to average basalts. The similarity with tholeiitic andesites is more pronounced for the Kås dyke than for the Listed dyke. The An content of the normative plagioclase in the Kås dyke lies in the lower end of the andesine range, while in the Listed dyke it is very close to labradorite.

When the modal composition of the plagioclase is considered it is seen that the plagioclase in the Kås dyke has a composition just on the andesine-labradorite boundary. The modal composition of the plagioclase in the Listed dyke is more difficult to evaluate because of the pronounced difference in An content between the cores and the peripheries of the laths. Whereas the cores of the plagioclase laths lie in the middle of the labradorite range, the peripheries are in the upper end of the andesine range. The author considers it safe to say that the majority of the plagioclase in the Listed dyke is of labradoritic composition. According to the mode, which should be given preference, the Kås dyke is situated on the border between andesite and basalt, whereas the Listed dyke lies just on the basalt side of this border.

Finally it must be noted that the dykes are unusually rich in Al_2O_3, especially the Listed dyke, which carries as much Al_2O_3 as some high-alumina basalts. Except for the high content of Al_2O_3 there is no similarity between the chemical composition of the dykes and that of high-alumina basalts.

With a high Al_2O_3 content the position in the generalised basalt tetrahedron approaches the plagioclase corner, and on approaching the plagioclase corner, the distance between tholeiites and alkali basalts is decreasing.

The Kås and the Listed dykes are situated on each side of the plane of silica saturation, but not very far from it, the Listed dyke being considerably closer to the plagioclase corner than is the Kås dyke.

Variations in alumina content across the dykes

Because of the unexpectedly high amounts of Al_2O_3 found in the centres of the two dykes, it was decided to make a further investigation of the alumina content across the dykes. This was done with X-ray fluorescence using the two chemical analyses as standards. The results are given in Table IV.

It is seen that at the contacts the amount of Al_2O_3 is rather similar in both dykes, although here also the Kås dyke is lower in Al_2O_3 than the Listed dyke. The Al_2O_3 content at the borders of the dykes agrees fairly well with the Al_2O_3 content commonly found in tholeiitic basalts.

Although the values in the Kås dyke fluctuate there is a slight increase in Al_2O_3 in the central part of the dyke, while the Listed dyke shows a much more pronounced increase in Al_2O_3 towards the dyke centre. The extremely low Al_2O_3 value of L3 is probably connected with the fact that L3 is the specimen showing the highest degree of later alteration.

YODER (1954) has shown that high water pressure tends to increase the plagioclase content of residual liquids. Based partly on this study and partly on additional studies in the system diopside-forsterite-anorthite-water YODER & TILLEY (1962) conclude that relatively high water pressure may cause the formation of high-alumina magmas. Thus it seems probable that the increase in Al_2O_3 towards the centres of the dykes is due to an increase in water pressure. If this is so, it can safely be concluded that the increase in water pressure must have been considerably larger in the Listed dyke than in the Kås dyke.

Table IV

Content of Al_2O_3 determined by X-ray fluorescence analysis using the chemically analysed specimens K8 and L6 as standards.

Analyst Mr. Ib Sørensen.

Kås				Listed			
K1	13.4%	Al_2O_3	± 0.3%	L1	14.4%	Al_2O_3	± 0.3%
K2	12.6	–	–	L2	14.3	–	–
K3	13.8	–	–	L3	12.2	–	–
K4	12.9	–	–	L4	14.2	–	–
K5	14.0	–	–	L5	15.6	–	–
K6	14.7	–	–	L6	18.19	–	
K7	14.1	–	–	L7	17.0	–	–
K8	15.12	–		L8	14.4	–	–
K9	14.4	–	–				
K10	15.0	–	–				
K11	14.1	–	–				
K12	13.5	–	–				
K13	13.5	–	–				
K14	14.4	–	–				

Values given are weight percentages.

Non-opaque minerals

Compositional variations across the dykes

Pyroxene

The clinopyroxene with augitic composition found in the middle of the Kås dyke can be followed across the dyke until one metre from the contact. No measurements were possible within the one metre marginal zone because of strong later alteration, and only one measurement was obtained at one metre from the contact.

The measured values of 2V(+) and $c \wedge \gamma$ of augite are listed in Table V, where it can be seen that 2V(+) and $c \wedge \gamma$ remain constant throughout the dyke.

The hypersthene with 2V(−) about 57° found in the middle of the Kås dyke can be followed until ten metres from the contact, but five metres from the contact hypersthene can no longer be seen. It therefore disappears somewhere between five and ten metres from the contact.

Five metres from the contact, where no hypersthene is seen, a few grains of pigeonite are found. Pigeonite grains are also found at three metres and one metre from the contact, whereas no pigeonite can be found at ten metres from the contact.

Although the augite and the pigeonite are rather similar in appearance, pigeonite can often be distinguished by a faint pleochroism from pale grey to pale brown. Because of the strong later alteration in the part of the dyke where pigeonite is found it has only been possible to find eight measurable grains of pigeonite. In only two cases was the cleavage sufficiently well developed to permit the determination of $c \wedge \gamma$. These scarce optical measurements of pigeonite are given in Table VI. Although the values in the table might suggest that the optic axial angle of the pigeonite decreases from the border inwards in the dyke, the measurements are certainly not numerous enough to permit such a conclusion.

Thus in the Kås dyke there are two contemporaneous pyroxenes. Near the border augite and pigeonite occur. The augite continues all through the dyke, and without changes in the optical properties, whereas pigeonite between five and ten metres from the contact is succeeded by hypersthene, which then continues to the middle of the dyke.

In the middle of the Listed dyke only one pyroxene, augite with 2V(+) about 45°, was found. No other pyroxene is found elsewhere in the dyke. The measurements of 2V(+) and $c \wedge \gamma$ obtained for the augite across the dyke are given in Table V. No changes in the optical properties occur across the dyke, and furthermore the values obtained are quite similar to those of the augite in the Kås dyke.

Plagioclase

The results of plagioclase determinations across the two dykes are shown in Table VII. The determinations were made by the method of Reinhard (1931), but instead of Reinhard's curves, the new curves of van der Kaaden (1951) were used.

Table V

Optic axial angle and c∧γ of augite

	2V(+)		c∧γ	
	Average	Variation	Average	Variation
K3	One measurement only 44°		No measurements	
K4	44½°	41° –54°	One measurement only 45°	
K5	44½°	37° –56°	43°	38½°–47°
K6	44½°	43° –48°	42°	40½°–44½°
K8	44°	42½°–47°	44°	43° –46½°
L3	43°	40° –48°	One measurement only 43°	
L4	46°	41° –51°	Two measurements only 39° and 46½°	
L5	45½°	41° –49°	Two measurements only 45° and 50°	
L6	45°	41° –53°	43½°	41½°–45½°
L8	45½°	42° –48°	No measurements	

Table VI

Optic axial angle and c∧γ of pigeonite

	2V(+)				c∧γ	
K3	21°	20°	18°		No measurements	
K4	18°				No measurements	
K5	20°	14°	11°	5°	41½°	42½°

Table VII

Per cent An in plagioclase

	Core		Periphery	
	Average	Variation	Average	Variation
K3	46	42–53	43	39–50
K6	46	40–55	45	42–48
K8	50	46–54	50	45–56
L2.........	47	41–51	43	36–48
L4.........	55	49–58	46	40–54
L6.........	59	51–65	45	30–59

In the middle of the Kås dyke reverse as well as normal zoning was seen. This is also the case in K6, ten metres from the contact, whereas in K3, which represents one metre from the contact, no reverse zoning was observed.

The difference in average composition between core and periphery is greatest near the contact where only normal zoning is found, and decreases inwards in the dyke. Finally there seems to be a slight increase in the An content from the contacts of the dyke towards the middle.

In the Listed dyke only normal zoning occurs. Accordingly the difference in average composition between core and periphery is much more pronounced than in the Kås dyke. Furthermore this difference clearly increases from the border inwards contrary to what was found in the Kås dyke. It is also seen that in the cores there is a considerable increase in An content from the contact towards the middle of the dyke, whereas the peripheries of the grains show only minor changes, the trend of which is not quite clear.

It seems curious that, in spite of the fact that only normal zoning is met with, the An content of the plagioclase cores increases towards the middle of the dyke. YODER, STEWART & SMITH (1957) have shown that the melting temperature of plagioclase is greatly lowered by water pressures of a few thousand bars. Based on this work TURNER & VERHOOGEN (1960) conclude that an increase in water pressure will cause an increase in the An content of the crystallising plagioclase. Possibly therefore the increase in the An content of the plagioclase cores towards the middle of the Listed dyke might indicate that the water pressure increased as the crystallisation of the dyke progressed. The fact that L6, which presumably was formed under the highest water pressure, is the only specimen which contains a relatively large amount of unaltered olivine, places an upper limit for the possible water pressure. According to YODER & TILLEY (1962) the maximum water pressure at which an olivine tholeiite can exist is about 1400 bars. As far as can be judged from the existing knowledge it does not seem improbable that the observed increase in An content of 12% could have been caused by a water pressure lower than 1400 bars, provided that the water pressure at the beginning of crystallisation was negligible.

The present author therefore thinks that the increase in An content from the border inwards of the plagioclase in the Listed dyke has been caused by increase in water pressure. He also believes that the much smaller increase in An content found in the Kås dyke is likewise due to an increase in water pressure. If this is so however, the increase in water pressure in the Kås dyke was considerably less than in the Listed dyke, and the increase did not start until much more of the dyke had solidified.

Variations in grain size across the dykes

Table VIII shows the variation in grain size across the dykes for plagioclase, pyroxene, and quartz.

Except for the metre closest to the contact, the grain size of the plagioclase is quite similar in both dykes, and no decrease in size is visible until three metres from the contact. One metre from the contact the size of plagioclase is considerably smaller in the Listed dyke than in the Kås dyke.

Table VIII a

Variations in grain size across the Kås Dyke
Size given in mm

	Dyke centre 20 m from contact	15 m from contact	10 m from contact	5 m from contact	3 m from contact	1 m from contact
Size of largest plagioclase laths........	2.70×0.50	2.70×0.50	2.70×0.50	2.70×0.50	2.00×0.50	1.60×0.20
Average size of plagioclase laths........	1.50×0.30	1.50×0.30	1.50×0.30	1.50×0.30	1.20×0.25	0.80×0.20
Size of largest pyroxene grains.......	2.10×0.75	1.70×0.50	1.70×0.50	1.70×0.50	1.10×0.35	0.60×0.15
Average size of pyroxene grains.......	1.20×0.60	1.00×0.50	1.00×0.50	0.75×0.40	0.40×0.20	0.35×0.10
Average size of quartz grains.......	0.20×0.15	0.20×0.15	0.20×0.15	0.20×0.15	0.20×0.15	0.15×0.10

Table VIII b

Variations in grain size across the Listed Dyke
Size given in mm

	Dyke Centre 15 m from contact	10 m from contact	5 m from contact	3 m from contact	1 m from contact
Size of largest plagioclase laths...	2.70×0.50	2.70×0.50	2.70×0.50	2.00×0.50	1.60×0.10
Average size of plagioclase laths...	1.50×0.30	1.50×0.30	1.50×0.30	1.20×0.25	0.50×0.10
Size of largest pyroxene grains ...	1.40×0.50	1.40×0.50	1.40×0.50	0.75×0.20	0.35×0.10
Average size of pyroxene grains ...	0.75×0.40	0.75×0.40	0.50×0.30	0.35×0.15	0.20×0.05
Average size of quartz grains......	0.15×0.10	0.15×0.10	0.15×0.10	0.15×0.10	0.10×0.07

Immediately at the chilled contact of the Listed dyke no grains can be recognised, but already one millimetre from the contact small plagioclase laths, the length of which is generally about 0.03 mm, can be seen.

Although the Kås dyke has also a chilled contact, rather large plagioclase laths can be seen almost up to the contact. Less than one half millimetre from the contact a plagioclase lath almost 1 mm long and with a width only slightly less than 0.2 mm was observed. Generally however the plagioclase laths are considerably smaller; the majority of laths present close to the contact are smaller than 0.25 × 0.03 mm.

The grain size of pyroxene is largest in the Kås dyke. The increase here from fifteen metres inwards is caused by the hypersthene, which generally occurs as very large grains, but does not start to form until somewhere between five and ten metres from the contact. When hypersthene is not taken into account there is thus no decrease in grain size of pyroxene until five metres from the contacts, from where the pyroxene in both dykes continuously decreases towards the contacts.

Quartz also has a somewhat larger grain size in the Kås dyke. No decrease in grain size of quartz is visible until one metre from the contacts.

Apatite in the Kås dyke varies in width from 0.01 to 0.09 mm, and in length from 0.05 to 1.20 mm. In the Listed dyke the width of apatite varies from 0.01 to 0.06 mm, whereas the length varies from 0.05 to 1.05 mm. There is in both dykes a slight decrease in size of apatite from the centre outwards, but between three metres and one metre from the contacts apatite completely disappears.

The decrease in grain size between five metres and one metre from the contacts is generally more pronounced in the Listed dyke, especially concerning plagioclase. This is probably due to a slightly higher rate of cooling because of the smaller width of this dyke.

Variations in amounts of non-opaque minerals across the dykes

Mode determinations have been carried out for all the specimens systematically collected across the dykes except for K1 and L1, the specimens from the immediate contacts of the dykes, where ore minerals and plagioclase are the only identifiable minerals.

A SWIFT automatic point counter with spacings of ⅓ mm between counted points was used for the mode determinations. In each of the specimens K2 and K14 2000 points were counted, each counting consisting of two runs of 1000 points. For all the other specimens 3000 points were counted, each counting consisting of two runs of 1500 points. The agreement between the two runs of each counting is good, although some minor deviations, especially concerning the amounts of uralite, biotite, and chlorite, were found. The results of the countings are given in Table IX, p. 388.

Although there are deviations, especially in the eastern part of the Kås dyke, there is a clear trend in the plagioclase values, so that in both dykes the amount of plagioclase increases from the borders inwards. The maximum amount of plagioclase, which is found in the centres of the dykes, is of the same order of magnitude for both dykes, whereas the amount of plagioclase present near the borders of the dykes is considerably smaller in the Kås dyke than in the Listed

Table IX

Modes in volume percentages

	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	L2	L3	L4	L5	L6	L7	LC	L8
Plagioclase	40½	46	47	51	57½	64	62½	59	56½	60	57½	46	48	53	52	59	60	64½	64	63	59
Potassium feldspar	–	–	–	–	tr	–	–	–	–	–	–	–	–	–	tr	–	tr	tr	–	–	–
Quartz	3½	4	5	4	3½	4½	3½	3½	3	3½	4	4	3	3½	8½	2½	1½	1	1½	2	5
Pyroxene	–	6	1	4	5½	7	12½	3½	–	9	1½	–	–	8	4	7	9	12	14	4	12
Olivine	–	–	–	–	–	–	tr	tr	–	–	–	–	–	–	–	tr	½	5	1	–	–
Uralite	27½	24½	15½	16½	14	3	2½	10½	22	8	12½	27	31½	9	4½	10	3	tr	1½	15	7
Biotite	9½	5½	4	4	3	2	2	3	2½	3½	4	3	4	5½	3½	3	3	2½	2½	4½	5
Chlorite	11	7	16	9	5	6½	6	6½	6	6	8½	9	5	14	20½	10½	13	7½	6½	6	7
Talc	–	–	3	2	2½	3½	2	2	1½	2½	2½	2	–	–	–	1	2	1½	1	–	–
Bowlingite	–	–	–	–	½	½	tr	1½	–	–	½	–	–	–	–	½	2½	1½	2½	tr	–
Ore minerals	8	7	7	6	6½	7	7	8½	7	5½	7	8	8	6½	4½	5½	5	3½	5	5	5
Apatite	–	–	1	2	2	2	1½	1½	1½	1½	1½	½	–	–	½	½	½	½	tr	–	–
Calcite	–	–	tr	1½	tr	tr	tr	tr	tr	½	½	½	½	tr	½	–	–	tr	tr	tr	tr
Sphene	–	–	tr	tr	–	–	–	–	–	–	–	tr	–	tr	1½	–	–	–	–	tr	–
	100	100	99½	100	100	100	99½	99½	100	100	100	100	100	99½	100	99½	100	99½	99½	99½	100
Sum of mafic silicates	48	43	39½	35½	30½	22½	25	27	32	29	29½	41	40½	36½	32½	32	33	30	29	29½	31
Ratio of plagioclase to sum of mafic silicates	0.8	1.1	1.2	1.4	1.9	2.8	2.5	2.2	1.8	2.1	1.9	1.1	1.2	1.5	1.6	1.8	1.8	2.2	2.2	2.1	1.9
"Pyroxene" ratio: $\frac{(\text{Pyr.} + \text{Ur.}) \times 100}{\text{Pyr.} + \text{Ur.} + \text{Plag.}}$	40.4	39.9	26.0	28.7	25.3	13.5	19.4	19.2	28.0	22.1	19.6	37.0	39.6	24.3	14.1	22.4	16.7	15.7	19.5	23.2	24.4
Ratio of primary to secondary mafic silicates	0	0.2	0.0	0.1	0.2	0.5	1.0	0.1	0	0.5	0.1	0	0	0.3	0.1	0.3	0.4	1.3	1.1	0.2	0.6

The specimen LC was taken from an exposure just one metre east of L8, and at the beginning of the work it was thought that L8 alone could represent this part of the dyke. However as it became apparent later that the precise position represented by LC is very important in evaluating the distribution of the primary and secondary *mafic silicates* and also *of the opaque minerals, LC was included amongst the specimens L1–L8 systematically* collected to represent a cross section of the Listed dyke.

dyke. The increase in plagioclase towards the centres of the dykes is thus greater in the Kås than in the Listed dyke. This is surprising when it is remembered that the increase in Al_2O_3 content towards the centres of the dykes is much more pronounced in the Listed dyke than in the Kås dyke. No explanation can be offered for this discrepancy.

Concerning quartz, no trend can be observed in the values for the Kås dyke, whereas the amount of quartz in the Listed dyke seems to decrease from the borders inwards. The extremely high value for quartz in L3 must be seen in connection with the fact that L3 is the specimen showing the highest degree of later alteration.

The fact that olivine, bowlingite, and talc are not found near the borders of the dykes does not mean that no olivine formed here, but that any original olivine has been completely altered to chlorite and uralite.

The average percentage of ore minerals is 7% and 5% for the Kås and the Listed dyke respectively. The variation in ore content is discussed in the section on opaque minerals (p. 408 and p. 410).

The amount of apatite, which is considerably higher in the Kås dyke than in the Listed dyke, seems in both dykes to be rather constant in the central parts of the dykes until three to five metres from the contacts. Thereafter the amount of apatite decreases abruptly towards the contacts, and already at one metre from the contacts apatite can no longer be seen.

The small amount of calcite found in the dykes is rather regularly distributed across the dykes.

Sphene was observed in only a few of the thin sections. The sphene has a somewhat turbid appearance and is always found in connection with ore minerals. The greatest amount of sphene is found in the specimen L3, which as mentioned earlier is characterised by a relatively high degree of later alteration.

Because of later alteration there are serious difficulties involved in evaluating the original amounts of the primary mafic silicates. It is evident that a discussion of the variations in the amounts of pyroxene and olivine now present in the rocks will have more bearing on the distribution of the later alteration than on the primary mineral content of the dykes. In contrast to the alteration of the ore minerals described later, it is impossible in the case of the altered mafic silicates to determine with certainty what minerals were present originally where the alteration products now occur. Bowlingite is the only secondary silicate, the origin of which is without doubt. Bowlingite is always formed by replacement of olivine. Although the talc was probably also formed from olivine it can not be excluded that some talc was formed by alteration of pyroxene. Chlorite has been formed from both pyroxene and olivine as well as from plagioclase, although the majority of the chlorite has clearly originated from the primary mafic silicates, mainly pyroxene.

Biotite does not seem to have formed from olivine, but only from pyroxene. It is however possible that part of the biotite is primary late magmatic (p. 377 and p. 379).

The majority of the uralite has been formed from pyroxene, but in some cases uralite may have been produced from olivine. The thin colourless amphibole needles are counted as uralite in the mode. These needles however do not represent any significant amount, and they seem to be rather regularly distributed across the dykes, although there is some suggestion that they are somewhat scarcer in the centres of the dykes.

The sum of the mafic silicates is listed in Table IX below the modes. It is seen that the amount of mafic silicates decreases from the contacts towards the centres of both dykes, this decrease being much more pronounced in the Kås than in the Listed dyke.

In an attempt to illustrate the relationships between plagioclase and mafic silicates two ratios have been determined. a) The ratio of plagioclase to the sum of mafic silicates. b) The "pyroxene" ratio, which instead of the usual pyroxene ratio $\frac{\text{pyroxene} \times 100}{\text{pyroxene} + \text{plagioclase}}$ gives $\frac{(\text{pyroxene} + \text{uralite}) \times 100}{\text{pyroxene} + \text{uralite} + \text{plagioclase.}}$ The first ratio (a) shows the combined effect of the increase in plagioclase and the decrease in mafic silicates from the contacts to the centres of the dykes, but without any attempt to distinguish between pyroxene and olivine. This is aimed at with the "pyroxene" ratio (b). Uralite has been incorporated in this ratio in view of the widespread alteration of pyroxene to uralite. It is however appreciated that uralite is not the only alteration product of pyroxene and that some of the uralite might have been formed from olivine. The "pyroxene" ratios in both dykes decrease from the contacts inwards, the decrease being much more pronounced in the Kås dyke than in the Listed dyke. The fact that the "pyroxene" ratios for L3 and K4 do not fit the general trend is attributed to the unusually high amount of chlorite present in these specimens. The author is not able to explain the fluctuations in the middle and eastern part of the Kås dyke.

In order to illustrate the variation in amount of later alteration across the dykes the ratio of primary to secondary mafic silicates has been determined. Only pyroxene and olivine are counted as primary mafic silicates, whereas uralite, chlorite, talc, and bowlingite as well as biotite are all counted as secondary minerals. This should give a good expression of the alteration, the only uncertainty lying in the possibility that part of the biotite is primary late magmatic. The ratio of primary to secondary mafic silicates in these dykes is pictured graphically in Figures 3 and 4. It is seen that in both dykes the alteration is concentrated at the immediate borders and in belts along each contact, but at several metres distance from the contacts. The centres of the two dykes are least affected by alteration, and rather close to the borders there are belts of relatively weak alteration. It is worth noting that if a correction could be made for some of the biotite being not secondary but late magmatic, such a correction would probably tend to increase the peak in the centres of the dykes, as a late magmatic mineral must be assumed to increase in amount in the last solidified central parts of dykes.

As only one profile has been made across each dyke it is of course possible that the distribution of the alteration is just casual. However because of the rather symmetrical development of the curve for the Kås dyke, and because of the high degree of similarity between the curves of the two dykes, the author is inclined to believe that the alteration was guided by factors which tended to concentrate the alteration at the immediate contacts and in belts along the contacts but at some distance away from the contacts. The possibility that one

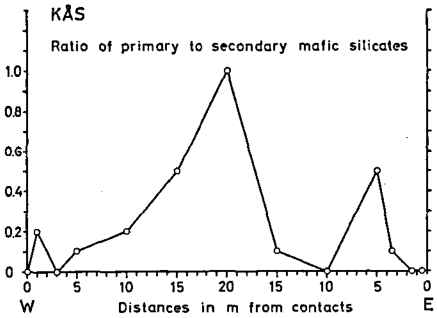

Fig. 3

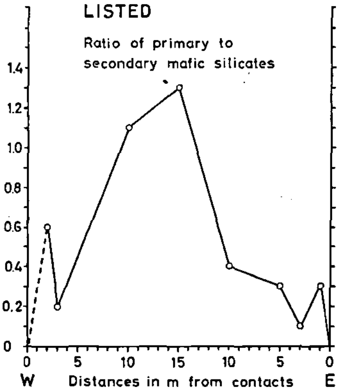

Fig. 4

of the guiding factors might be the degree of jointing seems to be out of the question, since the joints as far as can be judged seem to be rather regularly distributed across the dykes (p. 373 and p. 374).

Sequence of crystallisation

The two dykes show the same sequence of crystallisation and are therefore discussed together.

Based mainly on textural evidence such as idiomorphic outlines and in-inclusions of polycomponental silicate globules, which are described in detail on p. 393, the oxidic ore minerals ilmenite and titanomagnetite, except in the immediate chilled contact (see later), are considered to have been the first minerals to form, and in the order named. The formation of Fe-Ti-oxides however did not cease early but continued together with the formation of silicates. Ilmenite continued to crystallise until the very end of solidification since small ilmenite plates can be found interstitially between plagioclase laths.

The doleritic to subdoleritic texture of the pyroxene-plagioclase intergrowths indicates that these two minerals were formed mainly contemporaneously, and there is no textural evidence indicating which of the two minerals was the first to form.

Olivine is frequently found surrounded by pyroxene, but is never seen interstitially between plagioclase laths. Olivine has therefore formed before pyroxene and plagioclase.

Quartz and some biotite are often found interstitially between plagioclase laths and are believed to have formed as the latest primary minerals.

The fact that the amount of plagioclase increases from the contacts of the dykes inwards, while the amount of pyroxene, when the alteration is taken into account, decreases from the contacts inwards might be taken to suggest that pyroxene started crystallisation earlier than plagioclase. Evidence indicating the contrary is provided by the fact that at the immediate contacts plagioclase in the form of rather large laths is, besides the ore minerals, the only mineral which can be recognised. The grain size of the plagioclase is considerably larger than that of the ore minerals. The relationships found at the immediate contacts therefore indicate that plagioclase was the first mineral formed, preceding even the ore minerals.

Similar conflicting views are obtained concerning the position of apatite in the sequence of crystallisation. Completely idiomorphic crystals of apatite are found as inclusions in the early ilmenite grains indicating that apatite was the first mineral formed. The idiomorphic outlines of apatite need not mean that apatite formed before the surrounding host ilmenite. They could be due to apatite possessing a greater power of crystallisation than ilmenite. Nevertheless the apatite inclusions are still evidence of early formation of apatite, at least contemporaneously with the early ilmenite. This is however in conflict with the fact that no apatite is found at all within the first metre from the contacts.

Faced with this conflicting evidence the author is inclined to believe that the sequence in which the minerals appeared was changed as the solidification progressed.

The author thinks that at the very beginning of crystallisation the magma was practically free of water, and that in this anhydrous magma system plagioclase was amongst the first minerals to form, and most probably the earliest mineral of all. Very soon after however enough water pressure was built up to cause Fe-Ti-oxides to crystallise before plagioclase, and as the water pressure increased, the crystallisation of plagioclase was successively delayed, so that finally plagioclase formed after pyroxene, but still before quartz and biotite. Similarly, conditions prevailing at the very beginning of crystallisation may not have permitted the formation of apatite, but later on apatite was amongst the first minerals to form.

Opaque minerals

The description of the opaque minerals is composed of three major sections. The primary igneous development of the Fe-Ti-oxides is described first. Then follows a short section on the very small amounts of sulphides present in the dykes, and finally the many different types of later alteration of the Fe-Ti-oxides are discussed.

A. Primary igneous development of Fe-Ti-oxides

Ilmenite

Only ilmenite occurring as independent grains is discussed under this heading, while ilmenite intergrown with titanomagnetite is dealt with in the next section.

The ilmenite has the usual greyish brown colour and shows strong anisotropy. Internal reflections are not observed. Apart from some twinning the ilmenite is completely homogeneous, and exsolution textures are totally absent.

The shape of the ilmenite grains is highly variable. There are skeleton crystals, plates parallel to {0001}, myrmekites, and somewhat irregular but generally more or less equidimensional grains. This last category constitutes the bulk of the ilmenite in the dykes.

Skeletons are mostly confined to the borders of the dykes, where beautiful patterns of skeletal ilmenite are seen (Plate 2, Fig. 1).

Ilmenite plates parallel to {0001} have a more widespread distribution. They are terminated by rhombohedral faces and are very thin. Because of the insignificant extension normal to {0001} the plates are most frequently met with as cross sections. Here the appearance of the ilmenite plates is rather irregular, due to a characteristic way of growth. Within a narrow zone above and below the main plate there are quite frequently smaller plates, also parallel to {0001} and terminated by rhombohedral faces. The small plates are often connected to the main plate by means of a slender bridge, although the connection with the main plate is sometimes more substantial resulting in protuberances. With further growth the intervening areas between the protuberances have become filled with ilmenite generally containing some rounded inclusions of silicates. The final result therefore is a thickening of the main plates (Plate 2, Fig. 2).

This characteristic way of growth is probably caused by conditions of growth very similar to those which produce skeleton crystals, and all transitional stages can be found between skeleton crystals and typical plates. Plate 3, Fig. 1 shows clearly the development from skeleton crystals to plates step by step from left to right. The transition from skeleton crystals to plates parallel to {0001} is very smooth, and the plates may well be termed skeletons also. They are however skeletons of a special kind and deserve a special mention. In many places ilmenite plates are arranged parallel to each other in small groups.

Not infrequently ilmenite forms myrmekitic intergrowths with pyroxene. The pyroxene however is generally strongly altered to biotite. Whereas some of the ilmenite in the myrmekitic intergrowths has the typical worm-like nature which justifies the use of the term myrmekitic, part of the ilmenite is generally developed as the characteristic protuberanced plates parallel to {0001}. It is therefore suggested that these myrmekites were also formed under conditions similar to those producing skeleton crystals, i.e. mainly fast growth.

Most of the ilmenite however is not developed as myrmekites, plates, or skeletons, but as larger more or less equidimensional grains. These grains, although generally somewhat irregular, are partly developed with their own crystal faces, and completely idiomorphic ilmenite grains are not uncommon. Ilmenite is considered to have been the first of the main components to crystallise. The only mineral which may have started to grow before ilmenite is the accessory apatite, as in some cases completely idiomorphic crystals of apatite are found as inclusions in the ilmenite grains (Plate 14, Fig. 1). Such inclusions are however rather seldom met with. More common are rounded inclusions of silicates. Although some of these are elongated others appear to be completely globular, and in the following these inclusions will all be termed globules (Plate 3, Fig. 2).

It is characteristic of the globules that they are not built up of a single silicate, but of two or more different silicates. In some cases although very rare there is also some sulphide present in the globules. The globules are believed to be original droplets of magma, which were captured and included in the ilmenite during its growth, and then later separated into different silicates. The existence of these globules therefore, together with the idiomorphic development of ilmenite towards all other constituents except apatite, is taken as evidence of the ilmenite being among the first minerals to crystallise.

The ilmenite is generally untwinned. In some rather rare cases however a few very thin twin lamellae arranged parallel to the rhombohedral faces occur. It is generally the case that ilmenite twin lamellae on the rhombohedron are characterised by a great variation in the width of the lamellae. In the Kås and the Listed dyke a few grains are seen with twin lamellae varying in width from ½ to 5 μ, but generally the width does not vary much and lies between 1 and 2½ μ. The twin lamellae here however show another characteristic feature: they often taper out in one direction. Twin lamellae are shown in Plate 4, Fig. 1 and Plate 15, Fig. 1.

These lamellar twins are the only kind of ilmenite twin observed in the Listed dyke. In the Kås dyke however, single twins are more frequent than polysynthetic lamellar twins. The two different types of twin are never found in the same ilmenite grain. The twin law of the single twins found in the Kås dyke has not yet been exactly determined, but the author hopes in co-operation with H. I. MICHEELSEN from the Geological Institute of the University of Copenhagen to be able to solve this problem in the near future. At present there seem to be two possibilities as to the twin law of the single twins.

1. They have the rhombohedron $\{10\bar{1}1\}$ as twin plane as have the polysynthetic lamellar twins.
2. The single twins have $[21 \cdot 1]$ as twin axis.

Case 2 if true would represent a new twin law for ilmenite. In case 1 the twin law as such is not new, but hitherto only polysynthetic lamellar twins of ilmenite have been described with $\{10\bar{1}1\}$ as twin plane, whereas single twins of ilmenite are so far known only on $\{0001\}$.

Single ilmenite twins are shown in Plate 4.

The ilmenite grains are often cut by a few small cracks. They are often confined to the ilmenite grains, but some cracks, especially the broader ones, continue through the surrounding silicates. The number of cracks cutting ilmenite grains is much less than the number cutting the titanomagnetite, and the cracks in ilmenite are probably solely due to volume changes occurring as a result of cooling of the rock.

Titanomagnetite

The shape of the titanomagnetite grains is generally very irregular, although the grain boundaries are often linear in parts, but completely idiomorphic grains are not uncommon.

Inclusions of idiomorphic apatite are occasionally seen in the titanomagnetite, whereas silicate globules have been formed only in ilmenite.

It is characteristic that the titanomagnetite very seldom occurs as independent grains but almost always in composite grains of ilmenite and titanomagnetite. These composite grains contain not only lamellae of ilmenite arranged parallel to $\{111\}$ of the magnetite, but also contain more or less irregularly shaped masses of ilmenite, the distribution of which is independent of the crystallographic orientation of the magnetite.

Such ilmenite masses could be the results of exsolution*) at a temperature high enough to permit the newly formed ilmenite to concentrate in masses by solid diffusion, and possibly some of the ilmenite masses here were formed in this way. However, for reasons which follow, the author considers it impossible that all the masses of ilmenite were formed as the result of exsolution.

If the ilmenite masses were all the product of exsolution it would be expected that grains formed at the same time and hence at the same temperature would show the same ratio of ilmenite to magnetite. Making the assumption that grains starting to grow at the same time will reach about the same size, it would thus be expected that composite grains of ilmenite and titanomagnetite with about equal size would have the same ratio of ilmenite to magnetite, and this is not so in these dykes.

In some cases ilmenite masses show idiomorphic outlines against the surrounding parts of the titanomagnetite, indicating successive deposition, not exsolution.

Rather large ilmenite grains are in some cases, especially in L7, found with a thin outer rim of titanomagnetite. This case must be the result of overgrowth and not of exsolution. The use of the relative amounts of ilmenite and titanomagnetite as evidence can be extended to many other cases with the help of the following considerations.

There still seem to be some geologists who believe that ilmenite as such or a postulated cubic modification of $FeTiO_3$ is capable of making extensive solid solutions with magnetite. However VERHOOGEN (1962a) has shown on the grounds of physical chemistry that cubic $FeTiO_3$ even if it exists will be only slightly soluble in magnetite: much less than 10% even at 1200°C. On the other hand ulvöspinel Fe_2TiO_4 is capable of forming extensive solid solutions with magnetite. In consistency with VERHOOGEN's calculations, heating experiments by VINCENT, WRIGHT, CHEVALLIER & MATHIEU (1957) show that whereas intergrowths of magnetite and ulvöspinel are rather easily homogenised by heating in vacuo, homogenisation can not be attained in vacuo with intergrowths of magnetite and ilmenite, the homogenisation of which requires reducing conditions.

The ilmenite lamellae actually found in titanomagnetite must therefore be the result of oxidation of ulvöspinel, either while this was still dissolved in magnetite, or after the ulvöspinel had exsolved parallel to {100} of the magnetite. This means that the original material from which titanomagnetites are formed has a composition between Fe_3O_4 and Fe_2TiO_4.

No original homogeneous titanomagnetite could then have a composition richer in Ti than Fe_2TiO_4, and if this is all oxidised to ilmenite, ilmenite and magnetite will form in the molecular proportions 3/1 according to the following scheme: $3\ Fe_2TiO_4 + \frac{1}{2}\ O_2 \rightleftharpoons 3\ FeTiO_3 + Fe_3O_4$. The 3/1 ratio of ilmenite to magnetite expressed in molecules corresponds to a ratio a little less than 2.2/1 expressed in volume, and many of the composite grains have a volume ratio of

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*) Exsolution is not the correct expression for this formation of ilmenite, as it is not ilmenite but ulvöspinel which is in solid solution as titanomagnetite. As will be discussed later ilmenite lamellae in titanomagnetite have been formed as the result of oxidation of ulvöspinel. However as there is no precise short term for this process exsolution is nevertheless used.

ilmenite to magnetite larger than this. These grains accordingly can not have formed from one originally homogeneous phase.

For the sake of completeness in argument it should be mentioned that the composition of the ilmenite is very close to that of pure $FeTiO_3$ (p. 416). The surplus actually found in many of the composite grains, of rhombohedral ilmenite over the amount which possibly could have exsolved from an original homogeneous titanomagnetite, therefore is a real surplus, and can not be attributed to the rhombohedral phase present being a more iron-rich member of the solid solution series between Fe_2O_3 and $FeTiO_3$.

It is thus evident that the composite grains of ilmenite and titanomagnetite at least to a certain extent really are intergrowths, formed by successive – or perhaps partly contemporaneous – deposition of ilmenite and titanomagnetite, the ilmenite being the first mineral to form. It is however still possible that part of the ilmenite masses in the composite grains was formed by exsolution at high temperature. Possibly therefore the number of independent grains of titanomagnetite could be raised somewhat if it were possible to distinguish between primary ilmenite masses and ilmenite masses formed by exsolution from titanomagnetite at high temperature. The author however can see no means of making this distinction.

Composite grains of ilmenite and titanomagnetite are shown in Plate 5.

It is appropriate now to turn to the origin of the part of the composite grains outside the ilmenite masses. This part has evidently formed from an original homogeneous phase of titanomagnetite, or more precisely a solid solution between magnetite and ulvöspinel, although it now appears strongly heterogeneous.

There are many distinct lamellae of ilmenite arranged parallel to $\{111\}$ of the magnetite. These ilmenite lamellae differ from each other in four ways. 1) In size, mainly the width of the lamellae. 2) In form, straight or tapering. 3) With respect to regularity in distribution. 4) Finally some lamellae have had an influence upon the orientation of ilmenite formed by oxidation of already exsolved ulvöspinel, so that each lamella and its immediate surroundings form an optical unit, while other lamellae show no such influence.

The distribution of the above mentioned four characteristics is such, that establishment of a proper classification of the ilmenite lamellae without considerable overlapping in properties between groups is impossible. For the purpose of description it seems most convenient to use size as the primary basis of classification, and to operate with three groups of lamellae.

Group 1 comprises the first-formed and the largest lamellae. Their width is generally between 8 and 20 μ, although some are considerably broader than the upper 20 μ limit. The length of the lamellae is highly variable. They can attain a length greater than the lamellae of the other two groups, although they normally do not so. The lamellae are straight and not tapering, but the larger ones may be somewhat irregular in shape, and grade into ilmenite masses. This fact favours the view that some of the ilmenite masses were formed by exsolution. The distribution of the lamellae is rather irregular and they show no influence on the optical orientation of the neighbouring ilmenite formed by oxidation of exsolved ulvöspinel. Ilmenite lamellae of group 1 are shown in Plate 6, Fig. 1.

The lamellae of group 2 have a width of between 2 and 8 μ. The smaller ones show pronounced tapering, and even some of the broader lamellae, although not really tapering, show some convergence of the distant parts of the lamellae. Generally however lamellae broader than about 4 μ are not tapering. The distribution of the lamellae is much more regular than was the case in group 1. However within the same grain, areas of regularly distributed lamellae, and areas completely without lamellae, are often seen. There also exist some whole grains without lamellae. Occasionally these lamellae influence the orientation of the neighbouring oxidised ulvöspinel, but normally they do not. All the lamellae showing influence have a width of between 2 and 3 μ, but there are many lamellae in this size range without influence on the orientation. Ilmenite lamellae belonging to group 2 are shown in Plate 6, Fig. 2.

Group 3 comprises lamellae with a width ranging from less than ½ μ to about 2 μ. They all show pronounced tapering, and the same degree of regularity of distribution as the lamellae of group 2. Practically all lamellae of group 3 influence the orientation of the surrounding oxidised ulvöspinel. Plate 7, Fig. 1 shows lamellae of group 3.

This description clearly reveals that while there is a striking difference between the lamellae of group 1 and those of group 3, group 2 is in many ways transitional between the other two groups. It might therefore be a wrong approach at all to make attempts to classify the ilmenite lamellae in different groups or generations. This latter term has been avoided intentionally, because the grouping has been made for purely descriptive purposes, and the author does not consider it justified in this case to talk about different generations. It is more probable that the lamellae are all the result of a single continuous long period of exsolution, and that the differences between the lamellae are caused by slowly decreasing rate of diffusion. The ilmenite first formed was able to concentrate in a few large and irregularly distributed lamellae, and probably also to some extent into ilmenite masses, while later lamellae were smaller and more regularly distributed. Finally the rate of diffusion was so slow that the lamellae had to give up their straight form and became tapering.

The author can not explain why some lamellae influenced the orientation of oxidised ulvöspinel, while other ones did not. Apparently however it was only the smaller lamellae which had this influence.

Plate 7, Fig. 2 shows a very strange lamella of ilmenite. The lamella goes NE–SW across the picture. The north-eastern third of the lamella has the right orientation i.e. the ordinary ray is parallel to the length direction, whereas the south-western two thirds of the lamella has the extraordinary ray parallel to the length direction which therefore could not possibly lie in {0001}. The wrongly orientated part of the lamella is more irregular than the part with the right orientation. It is to be noted that both parts of the lamella influence the orientation of the surrounding oxidised ulvöspinel. No explanation can be offered for this phenomenon.

The groundmass of the titanomagnetite (i.e. the areas between the ilmenite lamellae) is seen under high power to possess an extremely fine cloth-like texture, indicating exsolution of ulvöspinel. The cloth-like pattern is so fine that all homogeneous areas in the titanomagnetite groundmass are considerably less than 1 μ in diameter. This ulvöspinel pattern occupies the whole area between the ilmenite lamellae without any interruption, and there is no change in the pattern on approaching the ilmenite lamellae: the pattern is homogeneous throughout. As far as can be judged from the cloth-like pattern magnetite and ulvöspinel have been present in about equal amounts, possibly with ulvöspinel slightly predominating. Plate 8, Fig. 1 shows the cloth-like ulvöspinel pattern.

Although there is no doubt that this pattern originated by exsolution of ulvöspinel, there is however no longer any ulvöspinel present. The former ulvöspinel has all been completely oxidised to ilmenite. This fact is seen immediately when crossed polars are applied (Plate 7, Fig. 2). The oxidation of ulvöspinel to ilmenite has originated from many different centres, and in such a way that ilmenite formed from the same centre has the same optical orientation. Because of the very small grain size in the extremely fine pattern it is almost impossible to see that the material consists of a dense network of isotropic magnetite and anisotropic ilmenite, but the whole groundmass appears like a lobal aggregate of one single anisotropic mineral, where material belonging to the same oxidation centre acts as single mineral grains. By intense study however it is possible to see that the material of an oxidation centre is heterogeneous and consists of strongly anisotropic small rods and points, in a mass which at least is much less anisotropic, but that this mass really is isotropic can not be stated with certainty.

The distribution of the oxidation centres is regular, and there is no sign of the distribution being influenced by cracks or grain boundaries. Disturbances in the lobal pattern formed by the areas of differently orientated ilmenite arise however very often where the titanomagnetite contains tapering ilmenite lamellae with a width of less than 3 μ. Very often each of these tapering lamellae together with the ilmenite in the immediate surrounding part of the ulvöspinel pattern constitutes an optical unit. The lobal pattern formed by the oxidation centres, which are not connected to ilmenite lamellae, is by far the most common, and can be seen uninterrupted over large areas. Therefore it is impossible that the optical units could all have formed in connection with ilmenite lamellae and that the lobal pattern is merely the consequence of sections so orientated that the ilmenite lamellae themselves are not intersected.

The fact that many of the thin tapering ilmenite lamellae form optical units with the titanomagnetite groundmass in their immediate vicinity offers two alternative interpretations. One is that the thin tapering ilmenite lamellae formed before the exsolution of the ulvöspinel and behaved as centres for the oxidation of the subsequently exsolved ulvöspinel to ilmenite, and that all the resulting ilmenite developed with the same optical orientation as the lamellae from which the oxidation started. According to this the oxidation of ulvöspinel to ilmenite should therefore partly have been localised by the thin tapering ilmenite lamellae, and partly performed from many oxidation centres evenly spaced in the groundmass of the titanomagnetite. The alternative interpretation is that the tapering ilmenite lamellae themselves are the result of concentration and reorganisation from {100} to {111} of ilmenite formed by oxidation of exsolved ulvöspinel.

The tapering ilmenite lamellae therefore are either older than the oxidation of ulvöspinel and have influenced the orientation of the resulting ilmenite, or they have first formed by concentration and reorganisation of ilmenite resulting from the oxidation of exsolved ulvöspinel.

In both cases the tapering ilmenite lamellae would have been formed by oxidation of ulvöspinel, but in the first case the formation of lamellae would have taken place at temperatures above 600–700°C and as the result of oxidation of ulvöspinel still in solid solution as titanomagnetite, whereas in the second case the lamellae would have been formed at temperatures below 600–700°C and by oxidation of ulvöspinel already exsolved as a fine network parallel to {100} of the magnetite, with consequent concentration and reorganisation into tapering {111} lamellae.

If the lamellae were formed as the result of concentration and reorganisation, one would expect to find a depletion of ilmenite in the immediate vicinity of the lamellae, and as this is never found the author considers that the tapering lamellae are older than the oxidation of ulvöspinel and that they to a certain extent influenced the orientation of ilmenite formed by the oxidation of ulvöspinel.

Vincent (1960) describes titanomagnetites from the Skaergaard intrusion, East Greenland, which in many respects show similarities to the titanomagnetites from the Kås and the Listed dyke. He describes tapering ilmenite lamellae in an ulvöspinel exsolution pattern, and concludes that these lamellae were formed by concentration and reorganisation of ilmenite formed by oxidation of exsolved ulvöspinel.

Besides studying the excellent photomicrographs in Vincent's paper, the author has had the opportunity of studying the Skaergaard material under the microscope, and fully agrees with Vincent's interpretation. As the present author in interpreting the titanomagnetites in the dykes from Bornholm prefers the alternative interpretation it seems appropriate to point out some significant differences between these otherwise very similar titanomagnetites.

In the Skaergaard material the distribution of the tapering ilmenite lamellae is very irregular. They occur sporadically, being confined to zones bordering cracks and veinlets, and to the margins of crystals. The immediate vicinity of the tapering ilmenite lamellae is free of ulvöspinel and consists of pure magnetite, while the characteristic ulvöspinel pattern first shows up some distance away from the lamellae. There are areas where the presence of tapering ilmenite lamellae with the surrounding zones free of ulvöspinel is the only sign of alteration of ulvöspinel, whereas in other areas there has been a more general oxidation of the ulvöspinel, although frequently there is still unaltered ulvöspinel left besides the ilmenite and the magnetite.

In contrast to this the tapering ilmenite lamellae in the titanomagnetite of the dykes from Bornholm are rather regularly distributed. They are much more regular in their distribution than the broader non-tapering ilmenite lamellae, which could not be suspected to have formed by oxidation of already exsolved ulvöspinel. The tapering lamellae from the dykes are never surrounded by a zone of pure magnetite; the ulvöspinel pattern continues unchanged right up to the boundary of the tapering ilmenite lamellae. The ulvöspinel in the dykes has all been completely oxidised to ilmenite, which provides a further point of difference from the Skaergaard rocks described by Vincent.

The regular distribution of the tapering lamellae in the dykes from Bornholm, and the absence near these lamellae of zones free of ulvöspinel, or free of ulvöspinel oxidised to ilmenite, from which material could have concentrated into the lamellae, strongly suggest that the tapering ilmenite lamellae in these dykes have formed at temperatures above the exsolution of ulvöspinel, and consequently by oxidation of ulvöspinel still in solid solution as titanomagnetite.

The tapering ilmenite lamellae in the Skaergaard titanomagnetites were probably formed as the result of a weak oxidation following cracks and to a minor extent also grain boundaries, at a temperature which must have been below the 700–600°C which is the exsolution temperature of ulvöspinel, but still high enough to permit the newly formed ilmenite to concentrate into tapering {111} lamellae by solid diffusion. The absence of tapering ilmenite lamellae originating in such a manner from titanomagnetite in the dykes from Bornholm might indicate that in these dykes there was possibly a standstill in oxidation for a period after the exsolution of ulvöspinel, and when the oxidation was resumed, an oxidation not confined to cracks and grain boundaries but really extensive, affecting all of the ulvöspinel, the temperature had attained values low enough to prevent the resulting ilmenite from concentrating into distinct {111} lamellae.

With the oxidation to ilmenite of the exsolved ulvöspinel, with maintenance of the ulvöspinel pattern, the primary history of genesis of the major part of the titanomagnetite in these dykes was complete.

RAMDOHR (1953b) has shown that ilmenite formed in this way and occupying the position of former ulvöspinel, will show oblique extinction, contrary to the parallel extinction of ilmenite arranged parallel to {111} of the magnetite host. Because of the very fine nature of the exsolution network it is unfortunately impossible to verify that this is so in the material from Bornholm.

Ilmenite arranged parallel to {100} could however later be transformed to ilmenite lamellae parallel to {111} and with parallel extinction. In the dykes from Bornholm this process is in some cases seen to have progressed so far that the result is the formation of a set of regularly spaced, but very fine, indistinct and somewhat diffuse lamellae parallel to {111} and with parallel extinction (Plate 9).

This transformation of ilmenite from {100} to {111} has also been described by VINCENT (1960), and in this respect the Skaergaard material and the Bornholm material are quite similar (compare Plate 9, Fig. 2 of this paper with VINCENT's Fig. 16). VINCENT believes that the main oxidation of exsolved ulvöspinel not confined to cracks took place at temperatures down to 200–100°C. If this is so, the transformation from {100} to {111} of the resulting ilmenite therefore must have taken place at even lower temperatures.

In their account of the titaniferous iron ore of Susimäki VAASJOKI & HEIKKINEN (1962) show a photomicrograph (Plate III, Fig. 1) of a magnetite grain showing a faint worm-like texture, which the authors tentatively suggest might indicate the presence of ulvöspinel. Somewhat similar worm-like textures are occasionally seen in the titanomagnetites of the dykes from Bornholm (Plate 11, Fig. 1). The present writer suggests that such faint worm-like textures are probably formed as a result of a tendency towards a reorganisation from {100} to {111} of ilmenite formed by oxidation of exsolved ulvöspinel.

In the dykes from Bornholm the fact that there is no decrease in the ilmenite content of the ulvöspinel exsolution pattern towards the borders of the tapering ilmenite lamellae indicates that these lamellae were formed by oxidation of ulvöspinel still dissolved as titanomagnetite, and not by concentration and reorganisation of ilmenite formed by oxidation of already exsolved ulvöspinel. The optical continuity between the tapering ilmenite lamellae and the ilmenite in the surrounding part of the ulvöspinel pattern need not be primary and formed simultaneously with the oxidation of ulvöspinel to ilmenite. These optical units arranged around tapering ilmenite lamellae could also have formed as the result of incipient reorganisation from {100} to {111} of the ilmenite in the ulvöspinel pattern. However the optical units around tapering ilmenite lamellae are found both in areas without reorganisation of the main mass and in areas with advanced reorganisation, and in both cases the appearance of the optical units is identical. Hence the author considers that these units around tapering ilmenite lamellae are primary as are the units around regularly spaced oxidation centres in the main mass.

The grains are cut by many small cracks, which are generally confined to the ore grains. Some of the cracks are curving, but many of them follow ilmenite lamellae for part of their course. It is not uncommon that a straight crack the main direction of which makes an acute angle with an ilmenite lamella on its path, in passing this follows the lamella for some length before cutting through the lamella and taking up the former direction again. Curving cracks when meeting ilmenite lamellae are often seen to straighten and follow the ilmenite lamellae. In some cases cracks can be seen situated between two parallel ilmenite lamellae (or between a grain boundary and an ilmenite lamella parallel to the boundary) like ladder veins in a dyke (Plate 6, Fig. 1 and Plate 11, Fig. 2). Cracks connected with ilmenite lamellae in this manner are thus clearly younger than these. This is the normal relationship between cracks and ilmenite lamellae. In some very rare cases however a few short and broad lamellae can be seen clearly originating from a curved crack, and in one case thin tapering ilmenite lamellae are seen localised by a crack, but it must be emphasised that in such cases there are also ilmenite lamellae rather regularly spaced and clearly independent of cracks (Plate 10). The textural relationship between ilmenite lamellae and cracks therefore reveals that the cracks are generally younger than the lamellae, although a few cracks can be seen to be older than ilmenite lamellae. The cracks probably formed partly because of cooling and partly as the result of volume changes caused by the development of ilmenite lamellae in the titanomagnetite. The cracks therefore generally formed in areas where the formation of ilmenite corresponding to the oxidation potential at that stage was already completed, and only very rarely did the cracking result in a renewal of the formation of ilmenite lamellae.

It is interesting to note that the cracks show no influence either on the oxidation of exsolved ulvöspinel to ilmenite, or on the later reorientation of the resulting ilmenite from {100} to {111}, and had it not been for the rare cases of ilmenite lamellae clearly originating from cracks the author would have been inclined to consider the cracking as younger than all these events.

Summary of the development of the titanomagnetite

The titanomagnetite began crystallisation somewhat later than the ilmenite. At least to some extent the grains of titanomagnetite used already formed, but probably still growing, grains of ilmenite as starting points for their growth.

Originally the titanomagnetite was a homogeneous solid solution of Fe_3O_4 and Fe_2TiO_4, the composition being closer to Fe_2TiO_4 than to Fe_3O_4.

Contemporaneously with the cooling of the rock there was a slight oxidation, so that part of the Fe_2TiO_4 was oxidised according to the following scheme: $3\ Fe_2TiO_4 + \frac{1}{2}\ O_2 \rightleftharpoons 3\ FeTiO_3 + Fe_3O_4$. Of the two products of this reaction only Fe_3O_4 can be accommodated in the structure of the titanomagnetite, whereas $FeTiO_3$ can not. The result therefore was the formation of ilmenite lamellae arranged parallel to {111} of the titanomagnetite. This process began at temperatures where the rate of diffusion was high enough to permit the newly formed ilmenite to concentrate in rather large and irregularly distributed lamellae, and probably also in irregular masses of ilmenite. Later however the oxidation resulted in the formation of smaller and regularly spaced ilmenite lamellae, and finally the lamellae became tapering.

As a result of the cooling, or probably partly because of volume changes in connection with the formation of the ilmenite lamellae, many small cracks occurred. The cracks were to a large extent localised by ilmenite lamellae.

When the temperature reached 700–600°C the solid solution of titanomagnetite still contained about 50% Fe_2TiO_4 despite the preceding extensive formation of ilmenite. Below this temperature however a solid solution of magnetite and ulvöspinel is no longer stable, and hence ulvöspinel was exsolved forming a very fine pattern of points and small rods arranged parallel to {100} of the magnetite.

After the exsolution of ulvöspinel there was possibly a standstill in the oxidation (this suggestion arises from comparison with the Skaergaard titanomagnetites), but ultimately the ulvöspinel was completely oxidised to ilmenite, so that now only the texture indicates the former presence of ulvöspinel. The alteration of ulvöspinel to ilmenite started from many different oxidation centres, mainly evenly spaced throughout the titanomagnetite, but to a lesser extent small tapering ilmenite lamellae acted as oxidation loci.

VINCENT (1960 p. 1011) suggests that this process probably takes place at temperatures down to 200–100°C. At this stage the primary development ended for the most part of the titanomagnetite in the Bornholm dykes. In some cases however the ilmenite in the ulvöspinel pattern parallel to {100} is reorganised into a set of very fine and diffuse lamellae arranged parallel to {111} of the magnetite.

Variations in size and shape of Fe-Ti-oxides across the dykes

It is somewhat difficult to express size and shape in concise terms because of the irregularity of the grains of Fe-Ti-oxides. Examination has however shown that the size of the largest grains with about equal extensions in the two dimensions which can be observed on the polished surface is a useful measure of the variation in grain size, at least when care is taken also to notice the size of larger irregular grains. Plates of ilmenite parallel to {0001} are of course a clear exception to this rule.

The largest grains of the Fe-Ti-oxides are composite grains of titanomagnetite and ilmenite. Ilmenite in free grains, i. e. grains consisting purely of ilmenite, occurs frequently throughout both dykes, whereas grains consisting purely of titanomagnetite without masses of ilmenite are, on the whole, very rare. Their size generally does not exceed the size of ilmenite in free grains in the same polished section. In order to simplify the description these rare grains of pure titanomagnetite will not be further commented on and they are omitted from Table X which gives the size and shape of the Fe-Ti-oxides.

No decrease in grain size is seen until five metres from the contacts. From here the grain size decreases continuously towards the contacts. At the immediate contacts of both dykes practically only ilmenite grains are present. The

Table X a

Size and shape of Fe-Ti-oxides in the Kås dyke
Size given in mm

	Central part	5 m from contact	3 m from contact	1 m from contact
Diameter of largest equidimensional composite grains	0.50	0.30	0.20	0.15
Size of largest irregular composite grains..........	1.25×0.50	0.65×0.25	0.35×0.20	0.20×0.10
Diameter of largest equidimensional ilmenite grains ..	0.25	0.20	0.15	0.10
Size of largest irregular *ilmenite grains*............	0.50×0.35	0.40×0.15	0.35×0.10	0.20×0.10
Size of largest ilmenite plates....................	0.35×0.03	0.75×0.05	0.75×0.05	0.30×0.02

Table X b

Size and shape of Fe-Ti-oxides in the Listed dyke
Size given in mm

	Central part	5 m from contact	3 m from contact	1 m from contact
Diameter of largest equidimensional composite grains	0.50	0.30	0.20	0.10
Size of largest irregular composite grains..........	0.75×0.35	0.50×0.25	0.35×0.20	0.15×0.05
Diameter of largest equidimensional ilmenite grains ..	0.25	0.20	0.10	0.05
Size of largest irregular ilmenite grains............	0.70×0.25	0.55×0.10	0.25×0.10	0.10×0.05
Size of largest ilmenite plates....................	0.75×0.05	0.75×0.05	0.55×0.05	0.15×0.01

largest equidimensional grains reach about 0.003 mm in diameter. Elongated grains are not much longer, but have considerably less width.

The decrease in grain size between five metres and one metre from the contacts is somewhat more pronounced in the Listed dyke. This is probably due to a slightly higher rate of cooling because of the smaller width of this dyke. The difference in width between the dykes however does not seem to have had any noticeable influence on the grain size in the central parts of the dykes. The larger dimensions of the irregular composite grains in the Kås dyke, which can be noticed already five metres from the contacts and is rather striking in the central parts of the dykes, is caused by the fact that in the Listed dyke a considerably greater proportion of the Fe-Ti-oxides crystallised as ilmenite in free grains (Table XI and Figures 6 and 8).

Plates of ilmenite parallel to {0001} are common throughout the Listed dyke, and in the central part broader plates grade imperceptibly into larger elongated grains.

In the Kås dyke ilmenite plates are rather scarce and small in the central part, and do not start to occur more frequently until five metres distance from the contacts. They attain their largest size between five and three metres from the contacts.

In K2, five centimetres from the contact, the Fe-Ti-oxides to all intents and purposes comprise only ilmenite developed as skeleton crystals. The single parts of the skeletons as seen on the polished surface do not exceed 0.03 × 0.02 mm, and generally reach only about one third of this size. These single parts however are organised in larger units and are probably connected in the third dimension (Plate 2, Fig. 1). In some places the single parts of the skeletons have coalesced to serrated plates, constituting transitional stages between skeletons and plates parallel to {0001}. They can attain sizes up to 0.07 × 0.005 mm.

Such transitional stages are also met with at one, three, and five metres distance from the contacts of the Kås dyke; at five and three metres distance however the transitional stages are much less conspicuous than is the case at one metre from the contacts.

In the Listed dyke transitional stages between skeleton crystals and plates parallel to {0001} of ilmenite can be found all the way from contact to the centre of the dyke.

Variations in amounts of original rhombohedral ilmenite phases and original cubic titanomagnetite phases

In the point countings made on thin sections it was established that the content of ore minerals in the Kås and the Listed dyke amounted to about 7% and 5% respectively. In order to see how these percentages were distributed amongst the different opaque minerals present, point countings were also carried out on polished sections. In this case also a SWIFT automatic point counter with spacings of ⅓ mm between counted points was used. For the polished sections representing the central parts of the dykes, the use of a ×16 objective was generally found satisfactory, but in a few cases the Fe-Ti-oxides were so strongly altered that the use of a ×60 oil objective was necessary for proper identification of the ore minerals. The polished sections from nearer the borders of the dykes were also counted in oil with a ×60 objective.

In the countings the following grouping was used:

Silicates (Non-opaque minerals)
Ilmenite in free grains (Grains consisting purely of ilmenite)
Ilmenite in composite grains
Titanomagnetite in free grains (Grains of titanomagnetite without masses of ilmenite)
Titanomagnetite in composite grains
Sulphides

The distinct ilmenite lamellae parallel to {111} were specially noted, but as the main purpose of the countings was to establish the relationship between the part of Fe-Ti-oxides which originally crystallised as rhombohedral ilmenite phases, and the part which originally crystallised as cubic titanomagnetite phases, the ilmenite lamellae were counted as titanomagnetite.

As discussed earlier in the section on titanomagnetite (p. 394–396) it is impossible that all the ilmenite masses in the composite grains could have developed from an original cubic titanomagnetite phase, although part of this ilmenite could perhaps have originated in this way. In the section on titanomagnetite it was also stated that there are no means by which a distinction can be made in every case between ilmenite with the one or the other origin. Masses of ilmenite in the composite grains therefore could not be split up into original rhombohedral phases and original cubic phases, but were counted together in a common group: ilmenite in composite grains. Ilmenite in distinct lamellae parallel to {111} is not placed under this heading, because this is a clear case where the ilmenite certainly has developed from an original cubic titanomagnetite phase, and these lamellae were therefore transferred to the titanomagnetite.

Besides these distinct lamellae the countings under titanomagnetite comprise both the magnetite and the ilmenite formed by oxidation of exsolved ulvöspinel. Regardless of whether this ilmenite is still arranged parallel to {100} or has been reorganised to small diffuse indistinct lamellae parallel to {111}, the intergrowth between magnetite and ilmenite originating from exsolved ulvöspinel is always so fine and intimate that the centre of the cross-hairs covers both some magnetite and some ilmenite. The countings therefore could not be used to estimate the ratio of magnetite to ulvöspinel in the exsolution pattern, and both components have to remain unspecified as titanomagnetite.

The titanomagnetite as well as the ilmenite has been subjected to alteration. The various types of alteration are very interesting and are dealt with in detail later. During the countings cases of alteration were specially noted, but in every case it was possible to see whether it was original titanomagnetite or original ilmenite which had been altered, and the alteration products were counted under these respective headings.

The first countings were made on K8 and K3, L6 and L2, representing the centre and a position near the margin of each dyke. A marked difference was found between K8 and K3, while L6 and L2 were rather similar. In order to obtain a further elucidation of these relationships, all the other sections were also counted, except for K1 and L1, where the Fe-Ti-oxides to all intents and purposes are made up of ilmenite phases only.

From the figures in the countings the ratio of ilmenite to titanomagnetite was computed as a measure of the variation in amounts of rhombohedral ilmenite and cubic titanomagnetite phases.

For each polished section 3000 points were counted. Stops were made after 1500 points, so that comparisons could be made between the two halves of each counting.

In the main there is a good agreement between the two 1500 points runs. The values for the single runs often deviate less than five per cent from the average value for the 3000 points.

Independently of the countings the average ratio of ilmenite to titanomagnetite in the composite grains has been estimated for each section.

In the Kås dyke this average ratio is about 3/4. Although there is a strong variation in the ratio from grain to grain within the same section, no variation was seen in the average ratio from section to section across the dyke. If any variation does exist it can therefore only be slight.

The Listed dyke shows an average ratio of around 1/2, and also here no variation was found across the dyke, except that L7 deviates markedly from all the other sections. The average ratio for L7 is close to 1/1. The reason for this deviation is obvious from the microscopic examination of the section. In L7 a weak overgrowth of titanomagnetite on large ilmenite grains is rather common, while such overgrowths are practically absent in all the other sections examined. The increase in the average ratio of ilmenite to titanomagnetite in composite grains in L7 is therefore balanced by a corresponding decrease in the amount of ilmenite in free grains.

Apart from L7 which constitutes a special case there is thus no observable variation across the dykes in the average ratio of ilmenite to titanomagnetite in the composite grains. It is therefore seen that variations in the overall ratio of ilmenite to titanomagnetite could not be due to variations in the ilmenite-titanomagnetite ratio in the composite grains, but must be caused by changes in proportions between ilmenite in free grains and the rest of the Fe-Ti-oxides.

Therefore in addition to the ratio of ilmenite to titanomagnetite, the ratio of ilmenite in free grains to the rest of Fe-Ti-oxides was also computed. In this latter ratio both components of the composite grains go into the denominator, and because of the constancy of the average ratio of ilmenite to titanomagnetite in the composite grains, the ratio with only free ilmenite in the numerator is also a measure of the variation in amounts of rhombohedral and cubic phases. The only difference between using this ratio with only free ilmenite in the numerator and the ratio of total ilmenite to titanomagnetite is that the first ratio will show the variations between rhombohedral and cubic phases less markedly than the second, because the first ratio is formed from the second by transferring part of the ilmenite from the numerator to the denominator of the ratio.

Thus there are two ratios available as measures of the variations in amounts of original rhombohedral and cubic phases. As the possible sources of error are not the same for both ratios, the two ratios can well serve to verify each other.

The results of the countings and the computed ratios are shown in Table XI, p. 407.

Table XI

Results of point counting of polished sections
Percentages listed are all volume percentages

	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	L2	L3	L4	L5	L6	L7	LC	L8
Silicates	2820	2825	2797	2826	2759	2778	2781	2796	2812	2889	2759	2806	2815	2866	2872	2881	2889	2874	2849	2856	2839
Ilmenite total	160	140	157	130	159	126	141	116	116	151	165	143	147	104	73	81	76	92	98	80	113
Ilmenite in free grains	156	112	131	100	103	69	86	70	85	106	119	106	121	87	53	64	63	78	66	63	84
Ilmenite in composite grains	4	28	26	30	56	57	55	46	31	45	46	37	26	17	20	17	13	14	32	17	29
Titanomagnetite total	10	29	44	44	69	80	71	73	64	59	61	44	29	31	52	47	29	29	40	59	48
Titanomagnetite in free grains	3	0	0	4	1	1	0	4	3	9	3	1	9	7	0	3	2	0	9	13	3
Titanomagnetite in composite grains	7	29	44	40	68	79	71	69	61	50	58	43	20	24	52	44	27	29	31	46	45
Sulphides	10	6	3	0	14	16	7	15	8	4	15	7	10	0	3	1	10	6	13	5	2
	3000	3000	3001	3000	3001	3000	3000	3000	3000	3103	3000	3000	3001	3001	3000	3010	3004	3001	3000	3000	3002
Ratio of ilmenite to titanomagnetite	16.00	4.83	3.57	2.95	2.30	1.58	1.99	1.59	1.81	2.56	2.70	3.25	5.07	3.35	1.40	1.72	2.62	3.17	2.45	1.36	2.35
Ratio of ilmenite in free grains to rest of Fe-Ti-oxides	11.14	1.96	1.87	1.35	0.82	0.50	0.68	0.59	0.90	1.02	1.11	1.31	2.20	1.81	0.74	1.00	1.50	1.81	0.92	0.83	1.09
Ore percentage from opaque countings	6.0	5.8	6.8	5.8	8.1	7.4	7.3	6.8	6.3	6.9	8.0	6.5	6.2	4.5	4.3	4.3	3.8	4.2	5.0	4.8	5.4
Ore percentage from non-opaque countings	8	7	7	6	6½	7	7	8½	7	5½	7	8	8	6½	4½	5½	5	3½	5	5	5

Average ore percentage from opaque countings	The Kås dyke	6.8	The Listed dyke	4.5
Average ore percentage from non-opaque countings	The Kås dyke	7.1	The Listed dyke	5.0
Average sulphide percentage (opaque countings only)	The Kås dyke	0.3	The Listed dyke	<0.2

Kås

The percentage of ore minerals found by point counting of polished sections varies from 5.8 to 8.1, while the percentage of ore minerals found by counting of thin sections varies from 5½ to 8½. The differences in ore percentage between opaque and non-opaque countings are of the same magnitude as the differences in ore percentage between different specimens, and there is no trend in the variations of ore percentage found across the dyke. The variations therefore are considered to be just casual and not related to the different distances from the contacts.

As mentioned earlier K1 was not subjected to point counting together with the other specimens because the Fe-Ti-oxides here to all intents and purposes are only ilmenite phases. Proper counting is moreover very difficult for that section because of the extremely small grain size. However in order to see if there was an increase in the ore percentage at the immediate contact of the dyke, 1500 points were counted in oil with a ×105 objective. This gave an ore percentage of 8.3. During the counting two composite grains of ilmenite and titanomagnetite and some few grains of sulphide were seen, but none of these grains fell at the centre of the cross-hairs. Although the ore percentage of 8.3 found at the immediate contact is the highest value obtained by the opaque countings, this value is in no way conspicuously high, being only 0.3% higher than the value obtained from the thin section of K2. It can therefore be safely concluded that if there is an increase in the content of ore minerals at the immediate contact of the dyke, such an increase can be only very slight.

The ore percentages dealt with here represent almost entirely Fe-Ti-oxides, as the average sulphide content is only 0.3%.

It is to be noted that grains of free titanomagnetite are very scarce. The table might on first inspection suggest that these grains are concentrated in the eastern half of the dyke, but the number of grains is certainly too small for such a conclusion to be statistically valid.

The variations across the dyke in the ratios of ilmenite to titanomagnetite, and of ilmenite in free grains to the rest of Fe-Ti-oxides are shown graphically in Fig. 5 and Fig. 6 respectively. The two curves are consistent. The only difference between the curves is that the one with only free ilmenite in the numerator naturally has a somewhat lower slope than the curve representing the ratio with total ilmenite in the numerator. If the scale on the ordinate for the curve with only free ilmenite in the numerator is expanded 2½ times the two curves will be identical, except for some minor discrepancies. Therefore there can be no doubt as to the validity of the main trend of the curves.

There is a rapid decrease in the amount of ilmenite relative to titanomagnetite from the contacts of the dyke inwards for the first metre, after which the relative decrease in ilmenite is less abrupt but still pronounced, until in the very middle of the dyke there is some increase in the amount of ilmenite relative to titanomagnetite.

As already explained, and as shown clearly in Fig. 6, the variations are due to changes in the proportions of free ilmenite and the rest of the Fe-Ti-oxides.

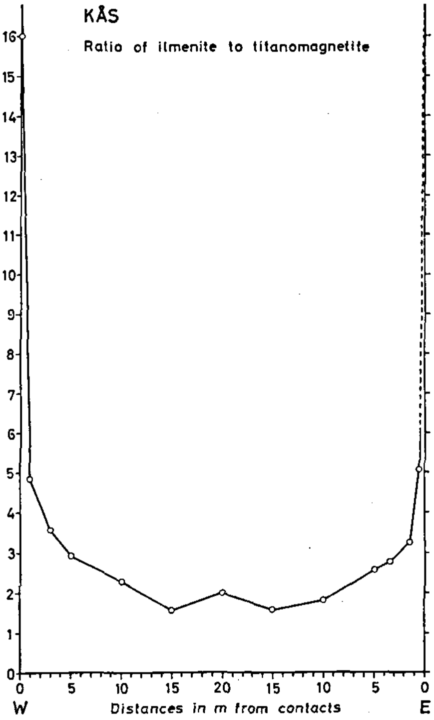

Fig. 5.

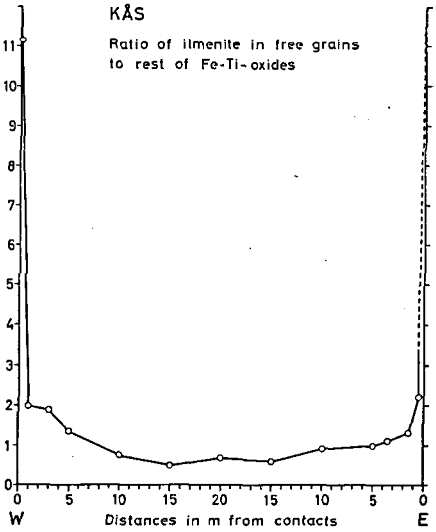

Fig. 6.

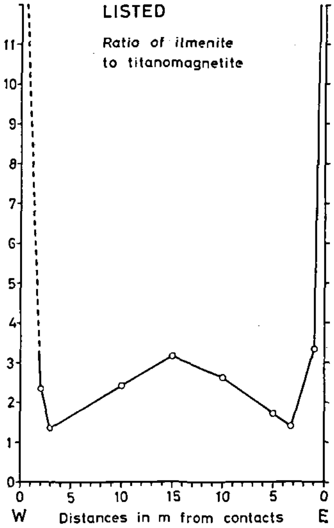

Fig. 7.

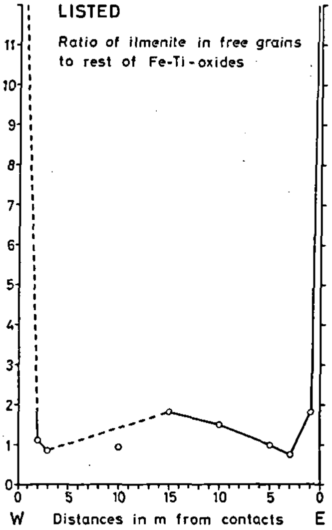

Fig. 8.

Listed

In this dyke the percentage of ore minerals found by the opaque countings varies from 3.8 to 5.4, while the percentage of ore minerals from the non-opaque countings varies from 3½ to 6½. The values from the opaque countings show a trend, with the highest ore percentages at the borders and decreasing values inwards. This trend however finds no substantial support from the values of the non-opaque countings, and the differences in ore percentage between opaque and non-opaque countings are of the same magnitude as the differences in ore percentage between different specimens. The author therefore thinks that in this dyke also, the variations found across the dyke are merely casual and unrelated to the different distances from the contacts.

The counting of 1500 points in L1 using a ×105 oil objective resulted in an ore percentage of 4.8. No titanomagnetite was seen. Sulphide grains were met with, but none of these fell at the centre of the cross-hairs. Although the ore percentage of 4.8 found at the immediate contact fits well into the trend of the other opaque countings, this value is only 0.3% higher than the opaque value for L2, and it is more than 1½% lower than the non-opaque value for L2. The possibility of an increase in the content of ore minerals at the immediate contact of the Listed dyke can therefore be ruled out.

In this dyke also the ore percentages dealt with represent almost solely Fe-Ti-oxides, as the average percentage of sulphides is less than 0.2%.

Grains of free titanomagnetite are very scarce as was the case in the Kås dyke, but in the Listed dyke it is clearly seen that there is no trend in the distribution of these grains.

The variation across the Listed dyke in the ratios of ilmenite to titanomagnetite and of ilmenite in free grains to the rest of Fe-Ti-oxides are shown graphically in Fig. 7 and Fig. 8 respectively. The reason for the failure of L7 to fit the curve with only free ilmenite in the numerator has already been explained (p. 406). The two curves are consistent in trend, and if the scale on the ordinate for the curve with only free ilmenite in the numerator is expanded twice, the two curves are almost identical. The main trend of the curves therefore can not be doubted.

The curves show that there is a rapid decrease in the amount of ilmenite relative to titanomagnetite from the contact inwards for about the first three metres, but already at three metres from the contact this decrease stops, and from here until the centre of the dyke ilmenite increases in amount relative to titanomagnetite.

The curves for the Kås dyke and the Listed dyke are rather similar. The only difference between the two dykes is that whereas the reversal in trend from ilmenite decreasing relative to titanomagnetite, to ilmenite increasing relative to titanomagnetite, in the Kås dyke did not set in until three quarters (30 m of the dyke's 40 m) of the magma had solidified, this reversal in the Listed dyke started already when a fifth (6 m of the dyke's 30 m) of the magma had solidified. Consequently this reversal in trend has had a greater influence on the development of the Listed dyke. It should also be noted that in the Kås dyke the scale on the ordinate had to be expanded 2½ times in order to make the curves for the two different ratios coincide, while for the Listed dyke an expansion of 2 times was sufficient. This clearly reveals that in the Listed dyke a greater proportion of the ilmenite is developed as free grains. The preponderance of free ilmenite in the Listed dyke relative to the Kås dyke is also reflected by the fact that small ilmenite grains, mostly plates, are much more common in the centre of the Listed dyke than in the central parts of the Kås dyke.

The outermost parts of the curves where ilmenite shows a decrease relative to titanomagnetite obviously reflect the fact that ilmenite was the first mineral to crystallise, and first somewhat later was joined by titanomagnetite. The central parts of the curves however could mean either that the proportions of ilmenite and titanomagnetite crystallising were changed, or that towards the end of solidification ilmenite again became the only stable Fe-Ti-oxide.

The factors influencing the sequence of crystallisation and the changes in proportions of the components are: temperature of crystallisation, rate of cooling (influences the degree of equilibrium reached), amount of Ti present, the reduction-oxidation potential, and finally the ease of nucleation.

Before a proper discussion of the possible influence and importance of these different factors can be undertaken, it is however necessary to determine the composition of the ilmenite phases and the titanomagnetite phases, and see if there are any changes in the compositions across the dykes. This is dealt with in the following sections of the paper.

Composition of the rhombohedral ilmenite phases

The determination of the composition of the ilmenite phases has been carried out mainly by X-rays. The results obtained from X-ray investigations have been supplemented by two microprobe analyses.

According to PALACHE, BERMAN & FRONDEL (1946) the lattice parameters a and c for pure ilmenite are 5.083 Å and 14.04 Å respectively, and those of pure hematite are 5.029 Å and 13.73 Å.

If there is no break in the variation of the cell dimensions in the solid solution series between ilmenite and hematite it should therefore be possible to judge the position within this solution series for any member by determination of its cell dimensions.

BASTA (1953 quoted by NICHOLLS 1955) has determined a and c values for some intermediate members of the ilmenite-hematite solid solution series. BASTA's a and c values and the ratios of c/a are reproduced here as Table XII.

Table XII

	a	c	c/a
Ilmenite $FeTiO_3$	5.083 Å	14.04 Å	2.762
2 $FeTiO_3$. Fe_2O_3	5.0657 Å	13.928 Å	2.749
$FeTiO_3$. Fe_2O_3	5.0636 Å	13.895 Å	2.744
$FeTiO_3$. 2 Fe_2O_3	5.0481 Å	13.829 Å	2.7395
Hematite Fe_2O_3	5.029 Å	13.73 Å	2.730

Although some of the values, especially the a value for ilmenite-hematite in equal proportions, are somewhat aberrant, the variations in cell dimensions seem to be continuous and without breaks.

There is however a difficulty in using cell dimensions for determination of the composition of rhombohedral ilmenite phases occurring in natural rocks. The rhombohedral phases in natural rocks are not always pure solid solutions between $FeTiO_3$ and Fe_2O_3, but may also contain some $MnTiO_3$ and $MgTiO_3$. Palache, Berman & Frondel (1946) give the values 5.126 Å and 14.333 Å for a and c of $MnTiO_3$, and 5.086 Å and 14.093 Å for a and c of $MgTiO_3$. While therefore the presence of Fe^{+++} decreases the a and c values of pure ilmenite, the presence of Mn and Mg will increase these values.

Vincent, Wright, Chevallier & Mathieu (1957) have determined the cell dimensions of ilmenite lamellae intergrown with magnetite in rocks from the Skaergaard intrusion and found values for a and c and the ratio c/a, which are all higher than the values generally quoted in the literature. The authors suggest that the reason for their high values is that most of the Mn and Mg revealed in their analysis of the magnetite-ilmenite intergrowth is concentrated in the ilmenite lamellae. There is no direct evidence of this, but their suggestion is based on the fact that Vincent & Phillips (1954) have shown the elements Mn and Mg to be significantly concentrated in discrete ilmenite crystals as compared with the accompanying magnetite-ilmenite intergrowth in rocks from the Skaergaard intrusion. Accordingly it is highly probable that most of the Mn and Mg found in analyses of magnetite-ilmenite intergrowths is to be found in the ilmenite lamellae and not in the magnetite base.

From Basta's data on cell dimensions of the solid solution series between $FeTiO_3$ and Fe_2O_3, Vincent *et al.* (1957) have constructed a diagram which they use for determination of the position in this series of members they have produced by heating experiments. Partly because their initial ilmenite has a larger cell than Basta's ilmenite, and partly because one of the phases produced by heating falls in the range where Basta's values are somewhat aberrant, they can however only give the positions approximately. The cell dimensions of heated and unheated samples together with the estimated positions in the solid solution series given by these authors are reproduced here as Table XIII.

In the dyke material from Bornholm cell dimensions have been determined for the ilmenite grains in K3, K7, K8, and K13 from the Kås dyke, while in the Listed dyke L4, L5, and L6 were chosen.

Table XIII

	a	c	c/a
E.G. 4359 unheated..........	5.088 ±0.001 Å	14.092 ±0.002 Å	2.770
E.G. 2569 unheated..........	5.087 ±0.001 Å	14.09 ±0.01 Å	2.770
E.G. 4359 heated Contains 30–40% Fe_2O_3......	5.068 ±0.001 Å	13.92 ±0.01 Å	2.749
E.G. 2569 heated Contains about 10% Fe_2O_3...	5.082 ±0.001 Å	14.04 ±0.01 Å	2.760

The material for the X-ray investigation was drilled out of the polished sections by the method described by Williams (1962) using an object marker as a drill. The instrument available however could in no position produce a hole with a diameter of less than 0.2 mm. Hence for the smaller grains it was in many cases found more satisfactory not to rotate the object marker, but to place the point of the diamond in the optic axis of the microscope and then rotate the microscope table. In this way a hole with a diameter of only slightly more than 0.1 mm could be produced, but it was found to be rather difficult to make the point of the diamond and the microscope axis coincide exactly.

This method of preparing the samples for X-ray investigation has the advantage over the generally used method of mineral separation by magnet and heavy liquids, that the material is extremely pure as every bit of material has been examined under the microscope. It must however be admitted that with the smaller grain sizes, notably in K3, some contamination with silicates is unavoidable. The disadvantage of the method used here lies in the fact that the amount of material produced is rather limited and does not permit the use of an X-ray diffactometer. Hence the determination of the cell dimensions was carried out with a Guinier camera, which gave somewhat less accurate values because of the few and rather weak lines in the available range of 2 θ. Thus for instance while Vincent *et al.* (1957) give their a values with ±0.001 Å, and their c values generally with ±0.01 Å, the determinations in the present work are given to an accuracy of ±0.005 Å for a values, and ±0.02 Å for c values.

The material taken for analysis was drilled out from grains of free ilmenite, as well as from larger ilmenite areas in composite grains.

The results of the cell determinations are given in Table XIV.

The variations in the values are no greater than the limits of experimental error. If there are indeed any variations in the cell dimensions they can only be very slight. That the considerable range in values obtained from the Kås dyke probably is only due to experimental error is shown by the fact that the highest a value and the lowest c value were obtained from the same specimen (K13).

It is evident that the cell dimensions for the rhombohedral ilmenite phases in the dykes indicate a composition very close to that of pure ilmenite. Comparison of Table XII with Table XIII shows that Basta's values for pure ilmenite are

Table XIV

Cell dimensions of ilmenite from the Kås dyke
and the Listed dyke

	a	c	c/a
K3	5.084 ± 0.005 Å	14.08 ± 0.02 Å	2.769
K7	5.079 –	14.07 –	2.770
K8	5.082 –	14.08 –	2.771
K13	5.087 –	14.06 –	2.764
L4..................	5.081 –	14.06 –	2.767
L5..................	5.080 –	14.05 –	2.766
L6..................	5.079 –	14.04 –	2.764

quite similar to the values given by VINCENT *et al.* (1957) for an Mn- and Mg-containing ilmenite phase with about 10% Fe_2O_3 (E.G. 2569 heated). As long as nothing is known about the content of Mn and Mg in the ilmenite phases from the Kås and the Listed dyke, the values in Table XIV only allow the conclusion that the content of Fe_2O_3 in the rhombohedral ilmenite phases present in these dykes is 10% or less.

Table XIV shows that the sample with the lowest values of a, c, and c/a, and consequently the sample which permits the highest amount of Fe_2O_3 in the rhombohedral ilmenite phases, is L6. Therefore L6 was chosen for further investigation concerning the composition, especially the content of Mn and Mg. These further investigations were done by microprobe analysis.

There was another reason for undertaking a further investigation of the rhombohedral ilmenite phases in L6. L6 represents the very middle of the Listed dyke, and compared with K8, which represents the very middle of the Kås dyke, L6 contains rather many smaller ilmenite plates. The elongated form of these plates makes them unsuited for sampling by an object marker, and hence the material for X-ray investigation of the ilmenite in L6 was all taken from the larger ilmenite grains. It was therefore of great interest to find out whether the composition of the ilmenite plates was the same as that of the larger ilmenite grains or not. This interest is so much greater as a difference in composition between the large ilmenite grains and the ilmenite plates in L6 might explain why the increase in the amount of ilmenite phases in the middle of the dykes is so much more pronounced in the Listed dyke than in the Kås dyke.

Microprobe analysis was therefore made on both a large ilmenite grain and on a small ilmenite plate in L6. The results of the microprobe analyses are given in Table XV.

Table XV

Microprobe analysis of large ilmenite grain and small ilmenite plate in L6

Analyst Dr. J. V. P. Long, Cambridge

	Large grain	Small plate	$FeTiO_3$ theoretical
Fe	34.5 ± 1	33.3 ± 1	36.8
Ti	28.1 ± 1	27.2 ± 1	31.6
Al	<1	n.d.	
Mg	<0.8	n.d.	
Mn	0.4 ± 0.1	0.4 ± 0.1	
Cr	<0.1	n.d.	
V	<0.2	n.d.	
Total metal	63.0	60.9	68.4

The values given are weight percentages

The presence of Al, Mg, Cr, and V has not been proved, but if these elements are present the amounts are less than the figures given for the respective elements.

The figures are corrected for absorption, but not for atomic number effect. Atomic number correction could possibly increase the metal content by 2–3%.

If the small amount of Mn and the small possible amount of Mg are not taken into account the content of Fe_2O_3 in the ilmenite could be determined from the ratio of Fe/Ti. This ratio is 1.17 for pure $FeTiO_3$. For the large ilmenite grain and for the small ilmenite plate the values of 1.23 and 1.22 respectively were obtained for this ratio. A Fe/Ti ratio of 1.23 corresponds to a solid solution of 97% $FeTiO_3$ and 3% Fe_2O_3 expressed in weight percentages, while the ratio 1.22 corresponds to 97½% $FeTiO_3$ and 2½% Fe_2O_3. The composition of the large ilmenite grain is accordingly practically the same as that of the small ilmenite plate.

The above figures need a correction because of the content of Mn and Mg. At first only the proved 0.4% of Mn is considered. The 0.4% Mn combines with 0.35% Ti and 0.35% O_2 to form 1.10% $MnTiO_3$. When the 0.35% Ti is subtracted from the amount of Ti found in the analyses there remains 27.75% Ti and 26.85% Ti for the large grain and the small plate respectively. The 27.75% Ti combines with 32.36% Fe in forming $FeTiO_3$, and the 26.85% Ti with 31.31% Fe in forming $FeTiO_3$. When these amounts of Fe are subtracted from the respective amounts of total Fe found in the analyses, there remains for the large grain 2.14% Fe, and for the small plate 1.99% Fe. Combined with oxygen these amounts of Fe are able to form respectively 3.06% Fe_2O_3 and 2.85% Fe_2O_3. It is clearly seen that the difference from the values of the Fe_2O_3 contents obtained from the Fe/Ti ratio alone is only very small. If only the amounts of Fe, Ti, and Mn are taken into account it may be concluded that the rhombohedral ilmenite phase present in L6 is composed of 96% $FeTiO_3$, 3% Fe_2O_3, and 1% $MnTiO_3$.

This picture however is somewhat blurred by the possible presence of small amounts of Mg, Al, Cr, and V. Concerning the possible small amounts of Cr and V, the author intends to leave these out of consideration. In the opinion of the author the small amounts of these two elements often quoted in chemical analyses of Fe-Ti-oxides are preferentially, if not completely, contained in spinel phases of Fe-Ti-oxides. The author therefore considers that Cr and V are not present at all in this rhombohedral ilmenite phase. The possible presence of Mg and Al must however be taken into consideration, as these elements in the form of $MgTiO_3$ and Al_2O_3 respectively are generally accepted as components of rhombohedral ilmenite phases.

Mg if present is less than 0.8%. Therefore it will be shown how the presence of the maximum possible amount of 0.8% Mg would influence the composition of the rhombohedral ilmenite phase. 0.8% Mg combines with 1.58% Ti and 1.58% O_2 to form 3.96% $MgTiO_3$. When the 1.58% Ti and the 0.35% Ti combining with Mn are subtracted from the total of 28.1% Ti found in the analysis, there remains 26.17% Ti. This combines with 30.51% Fe to form $FeTiO_3$. After subtraction of this amount of Fe from the total Fe found in the analysis, there remains 3.99% Fe, which is sufficient for the formation of 5.70% Fe_2O_3. The presence of 0.8% Mg therefore will change the composition of the rhombohedral ilmenite phase to 89% $FeTiO_3$, 6% Fe_2O_3, 4% $MgTiO_3$, 1% $MnTiO_3$.

The maximum possible amount of Al, 1%, will, combined with oxygen, be able to form 1.89% Al_2O_3. If this amount of Al is present, the above composition will be further changed by the addition of 2% Al_2O_3 and a corresponding decrease in the content of $FeTiO_3$ from 89% to 87%.

Finally therefore it can be concluded that a = 5.079 Å, c = 14.04 Å, c/a = 2.764 are the cell dimensions of a rhombohedral ilmenite phase very close to pure ilmenite in composition, but which contains 1% $MnTiO_3$ and at least 3% Fe_2O_3, and which may also contain a further 3% Fe_2O_3 and from 0–4% $MgTiO_3$ and from 0–2% Al_2O_3.

The spectral analyses dealt with later indicate that Al and Mg almost certainly are not present in the ilmenite (p. 420). The composition of the rhombohedral ilmenite phase should therefore be taken as 96% $FeTiO_3$, 3% Fe_2O_3, 1% $MnTiO_3$.

This result was obtained from L6. X-ray analyses of the other samples all show apparently higher values of the cell dimensions, except that K7 has the same a value as L6, and K13 the same c/a ratio as L6. If these somewhat higher values of cell dimensions are not due solely to experimental error in the determinations they indicate that these samples contain a little less Fe_2O_3, a little more $MnTiO_3$ or $MgTiO_3$, or some combination of these possible ways of increasing the cell dimensions.

The variation in the values of the cell dimensions is within the limits of experimental error. It can therefore be stated that the rhombohedral ilmenite phases in all the samples from both dykes are of about the same composition, close to pure $FeTiO_3$, but some variation is possible, for instance to the extent of a few per cent of Fe_2O_3 on both sides of the 3% established for L6 if no Mg is present. This applies to ilmenite in free grains, including the small ilmenite plates, and also to the larger ilmenite areas in the composite grains. It was also necessary to determine the composition of the ilmenite lamellae, the larger lamellae formed by oxidation of ulvöspinel still in solid solution as titanomagnetite, as well as the small ilmenite lamellae formed by oxidation of already exsolved ulvöspinel.

These ilmenite lamellae are all so narrow that they prevent the preparation of selective ilmenite samples by an object marker. This method however has been used to prepare samples of titanomagnetite from the composite grains, avoiding the larger areas of ilmenite. The material so sampled consists of a magnetite phase and the above mentioned ilmenite lamellae. The X-ray films of these samples permit the determination of the cell dimensions of both the magnetite phase and the ilmenite phase intergrown with the magnetite as lamellae. As only one ilmenite phase is seen on the films, all lamellae must have the same cell dimensions.

These determinations of cell dimensions have been carried out on K7, K8, and K12 from the Kås dyke, and on L5 and L6 from the Listed dyke. The reason that only two specimens from the Listed dyke have been investigated, and the reason that the specimens investigated from the Kås dyke are not quite the same as those used in the determination of cell dimensions of the ilmenite grains, is that in places the titanomagnetite has been subjected to rather strong alteration. This alteration will be dealt with later. Only completely unaltered material was investigated here. The cell dimensions obtained for the ilmenite phases represented by the lamellae are shown in Table XVI.

Table XVI

Cell dimensions of ilmenite lamellae from the Kås dyke and the Listed dyke

	a	c	c/a
K7	5.086 ± 0.005 Å	14.07 ± 0.02 Å	2.766
K8	5.086 –	14.07 –	2.766
K12	5.082 –	14.06 –	2.767
L5	5.083 –	14.05 –	2.764
L6	5.082 –	14.06 –	2.767

The values in this table show that there can be almost no variation in the composition of the ilmenite lamellae across the dykes, and that the composition is the same in both dykes. Furthermore comparison with Table XIV shows that the ilmenite lamellae have the same composition as ilmenite in free grains and the larger areas of ilmenite in the composite grains.

Composition of the cubic titanomagnetite phases

The most complete investigation of the composition of the cubic titanomagnetite phases has been carried out on the specimen K8. This specimen was chosen, partly because it represents the middle of the one of the two dykes where the most complete sampling was possible, and partly because the titanomagnetite groundmass in this specimen is generally completely unaltered.

The first step was to prepare a sample of the titanomagnetite groundmass for X-ray investigation by a Guinier camera, by using an object marker as drill as described on p. 413.

X-ray investigation revealed the presence of only two phases. Furthermore only one of these is a cubic phase, while the other is a rhombohedral ilmenite phase with a = 5.086 Å, c = 14.07 Å, and c/a = 2.766. This ilmenite phase probably represents both the ilmenite lamellae parallel to {111} of the titanomagnetite, and the ilmenite part of the titanomagnetite groundmass (p. 416).

The cubic phase was found to have a lattice parameter of 8.395 ± 0.005 Å, which is very close to that of pure magnetite, which Basta (1957) gives as 8.3963 ± 0.0005 Å.

No other phases could be detected on the Guinier film, and as the texture of the titanomagnetite groundmass seen under the microscope clearly indicates that ulvöspinel has once been present, although it now appears to be completely oxidised to ilmenite, it was decided to prepare a sample large enough to permit the use of a diffractometer. A sample that large however could not be produced using an object marker, but was prepared by traditional mineral separation. The result showed that not even with the diffractometer could any traces of ulvöspinel be found. It is therefore concluded that the oxidation to ilmenite of the exsolved ulvöspinel has been completed to the extent that no relict ulvöspinel can be found by X-ray. Its former presence is indicated only by the texture of the titanomagnetite groundmass.

The diffractometer gave the following values for the rhombohedral ilmenite phase: a = 5.085 Å, c = 14.05 Å, c/a = 2.763. For the cubic phase a lattice parameter of 8.394 Å was obtained.

While the accuracy of the determination of the rhombohedral phase in this case seems to be the same for Guinier camera and diffractometer ±0.005 Å for the a value, and ±0.02 Å for the c value, the accuracy of ±0.005 Å for the cube edge of the cubic phase as determined by Guinier camera can, by using the diffractometer, be reduced to ±0.002 Å because of the greater number of reflections.

The rhombohedral phase has already been dealt with in the preceding section, the lattice parameters of the rhombohedral phase being given here only for comparisons between Guinier and diffractometer values.

The two values of the cube edge of the cubic phase agree well. It has therefore been shown that in the specimen K8 only one cubic phase is present in the titanomagnetite groundmass, and that it has a lattice parameter similar to that of pure magnetite.

In order to see if the result obtained for K8 was representative of the titanomagnetite groundmass in other parts of the Kås dyke, and of the titanomagnetite groundmass in the Listed dyke, some further specimens were examined by X-rays. Unfortunately however the titanomagnetite in these dykes is rather often attacked by later alteration, which prevents a systematic investigation of the titanomagnetite in the full width of the dykes. Furthermore the specimens taken near the contacts of the dykes contain only very small amounts of titanomagnetite. Hence only the following specimens have been chosen for further investigation by X-rays: K7, K12, L5, and L6. In all these specimens the titanomagnetite is generally unaltered. The results in no case revealed more than one cubic phase. The lattice parameters obtained for this are listed in Table XVII.

From the values in this table it is concluded that apparently the lattice parameter of the cubic phase in the titanomagnetite groundmass does not vary either with position in the dyke, or between the two dykes.

Accordingly it has now been shown that the lattice parameter of the cubic phase in the titanomagnetite apparently has the same value overall in the dykes, and that this value is similar to the value of the lattice parameter of pure magnetite. Unfortunately however the lattice parameter alone is not sufficient to determine the cubic phase as being pure magnetite. BASTA (1957) reports a

Table XVII

Lattice parameter of the cubic phase in the titanomagnetite groundmass

K7	8.396±0.005 Å (Guinier)	
K8	8.395 – –	8.394±0.002 Å (Diffractometer)
K12	8.393 – –	
L5	8.396 – –	
L6	8.396 – –	

cubic titanomagnetite phase from Magnet Cove, Arkansas, U.S.A. with a cube edge of 8.3960 ± 0.001 Å but containing 6.98% TiO_2, 7.18% MgO, 1.82% MnO, 3.62% Al_2O_3, and small amounts of Ca, Si, V, and Cr. Although Si, Ca, and part of the Al and Mg are probably due to contamination with silicates, it is clear that even when the cube edge coincides with that of pure magnetite, the composition of the phase may differ considerably from Fe_3O_4.

The presence of Ti and Mn in magnetites will increase the lattice dimensions, while Mg, Al, and Cr will cause a decrease. Surplus of Fe^{+++} in magnetites, that is formation of maghemites, phases intermediate between Fe_3O_4 and γ-Fe_2O_3, will also cause a lowering of cell dimensions. As far as the author knows the effect of V on the lattice dimensions of magnetite is still unknown.

As the ulvöspinel exsolution pattern of the titanomagnetite groundmass is so extremely fine that homogeneous areas of the magnetite phase are considerably less than 1 μ in diameter, it is very difficult to determine the chemical composition of the magnetite phase. However as it has just been shown that no ulvöspinel at all remains in the titanomagnetite, the only other phase intergrown with the magnetite is the rhombohedral ilmenite phase formed by oxidation of the former ulvöspinel. This ilmenite phase has been shown to have the same cell dimensions as the larger ilmenite grains, the composition of which was determined by microprobe analysis, and it is assumed that the composition is the same. Provided that this assumption is correct, there is a possibility of determining the composition of the magnetite phase by analysing the whole titanomagnetite groundmass, and from the results found deduce the amounts which are due to the ilmenite phase present.

The titanomagnetite material separated from K8 for diffractometer analysis was known to be very impure and highly contaminated with silicates. This material therefore had to be treated further before it could be used for analysis of composition. Before such further treatment was undertaken however the material was spectrally analysed for Si, Ca, Al, Mg, and Mn. The results of this analysis are given in Table XVIII as column I.

In spite of the strong contamination with silicates, clearly indicated by the 7% Si found in the material, all attempts to concentrate the titanomagnetite by mechanical means were unsuccessful, so the preparation of the material for analysis was finally done by hand picking under microscope, a task which was very difficult because the strong magnetism of the ore grains made it almost impossible to disperse the particles. This phenomenon explains why all other means of separation failed. The results of the spectral analysis of the hand picked material are given in column II of Table XVIII.

Before a proper evaluation of the results found could be undertaken it was necessary to determine the ratio between magnetite and ilmenite in the material analysed. Point counting of a polished section prepared of the separated material reveals that titanomagnetite groundmass and ilmenite in either masses or distinct lamellae are present in the ratio of 4 to 1. As far as can be judged from the ulvöspinel exsolution pattern, the titanomagnetite groundmass was once composed of about equal amounts of ulvöspinel and magnetite, although ulvöspinel might have been predominating. (It is not considered possible to give the composition closer than 40–50% Fe_3O_4, 60–50% Fe_2TiO_4). When ulvöspinel is oxidised ilmenite and magnetite are formed in the ratio of 3 to 1

Table XVIII

Spectral analyses of the titanomagnetite groundmass in K8
Analyst Mrs. H. J. Bollingberg

	I	II	III
Si	7%	1.5%	
Ca	0.6–1%	tr	
Al	1%	0.15%	<1%
Mg	2%	0.15%	<0.8%
Mn	0.25%	0.3%	0.4±0.1%
V		0.3%	<0.2%
Cr		ca. *0.013*%	<*0.1*%

Column I : Titanomagnetite groundmass before hand picking.
Column II : Titanomagnetite groundmass after hand picking.
Column III: Microprobe analysis of large ilmenite grain from L6.

The values given are weight percentages.

The accuracy of the values determined by spectral analysis is ±10%.

according to the following scheme: $3\ Fe_2TiO_4 + \frac{1}{2}\ O_2 \rightleftharpoons 3\ FeTiO_3 + Fe_3O_4$. It follows that $\frac{3}{4}$ of the original ulvöspinel of the titanomagnetite groundmass is now ilmenite, and accordingly the ratio of magnetite to ilmenite in the material analysed is about 1/1.

For convenience in comparison Table XVIII giving the results of the spectral analyses has in column III the corresponding values of the microprobe analysis of the large ilmenite grain from L6 given on page 414.

Comparison between columns I and II of Table XVIII shows that contemporaneously with the drop in Si content from 7% to 1.5%, Ca practically disappears and the amounts of Al and Mg are strongly reduced. The small amounts of Al and Mg left in column II do not exceed what could be accommodated by forming silicates with the 1.5% Si found. The author therefore considers that all of the Al and Mg, as well as the trace of Ca, are due to the unavoidable contamination with silicates, and that probably no Al, Mg, and Ca are present in either the magnetite phase or the ilmenite phase.

The 0.3% Mn found in the titanomagnetite groundmass is of the same order of magnitude as the Mn found by microprobe analysis of the ilmenite phase, and accordingly the magnetite phase must contain about 0.3% Mn.

The titanomagnetite groundmass contains 0.3% V, while the microprobe analysis shows that less than 0.2% V is present in the ilmenite phase. As stated earlier V is not likely to occur in ilmenite phases, but must be expected in small amounts in cubic magnetite phases. Assuming therefore that no V at all is present in the ilmenite phase, it can be concluded that about 0.6% V must be present in the magnetite phase.

Cr like V is not to be expected in ilmenite phases, and a deduction analogous to the one carried out above for V leads to the conclusion that about 0.03% Cr is present in the magnetite phase.

As the influence of V on the lattice parameter of magnetite is not known, and Mn and Cr influence the lattice parameter in opposite ways, it is not possible to make an exact evaluation of how the presence of these elements has influenced the magnetite lattice. It seems however safe to conclude that these small amounts could not have caused any appreciable change in the lattice dimensions of pure magnetite.

There are still two possibilities for changes in the lattice parameter of magnetite which have not so far been taken into consideration. These are the possible formation of maghemites, and the possible content of Ti which might have escaped exsolution.

In material like the present where the intergrowth between ilmenite and magnetite phases is so extremely fine, it is impossible to determine the content of Ti in the separate phases. The formation of maghemite phases however should be detectable under the microscope. In a few very rare cases there have been observed along small cracks through titanomagnetite, thin selvages in which the magnetite part of the titanomagnetite groundmass attains a bluish colour, indicating the formation of maghemite. This phenomenon is dealt with later (p. 432). Such cases are extremely rare and seem to be connected with weathering, while the titanomagnetite groundmass in fresh rock is without traces of maghemite formation.

As stated earlier (p. 419) maghemitisation lowers the lattice parameter of magnetite, while the presence of Ti increases the parameter. When no maghemite is present to counterbalance the effect of the Ti content in the magnetite, the presence of Ti must result in the value of the lattice parameter being greater than that of pure magnetite, and as the lattice parameter found corresponds closely to that of pure magnetite, it can be concluded that practically no Ti is left in the magnetite phase.

It has thus been shown that the magnetite phase present is very close to pure magnetite in composition, but contains about 0.6% V, 0.3% Mn, and 0.03% Cr.

It is interesting to note that the exsolution of ulvöspinel from the titanomagnetite was so complete that practically no Ti remained in the final cubic magnetite phase, and that the oxidation which later transformed the exsolved ulvöspinel to ilmenite was not strong enough to affect the magnetite phase, which remained unoxidised.

The magnetite phase, the composition of which has now been determined, is however not the cubic magnetite phase which crystallised in equilibrium with the rhombohedral ilmenite phase, the composition of which was discussed in the previous section of this paper.

The cubic magnetite phase which crystallised together with the rhombohedral ilmenite phase, i.e. the original unexsolved titanomagnetite, was very rich in Ti. It is very difficult to make an exact evaluation of the composition of the original titanomagnetite, because it can not in all cases be proved that the ilmenite masses present in the composite ore grains are primary ilmenite, but some of these masses might have formed by oxidation of part of the ulvöspinel dissolved in the original titanomagnetite at temperatures high enough to permit the resulting ilmenite to concentrate into masses. Furthermore, although the composition of the rhombohedral ilmenite phase has been shown to have been constant throughout the crystallisation of the dykes, the composition of the primary titanomagnetite may have changed during the crystallisation. The author however considers it most probable that the composition of the titanomagnetite remained the same throughout the crystallisation. This assumption is based on the fact that there is no detectable difference in the ulvöspinel pattern, either from grain to grain within the same section, or with different positions within the dykes. It would indeed be curious if original titanomagnetite phases with different positions in the Fe_3O_4–Fe_2TiO_4 solid solution series were oxidised in such a way that the richer the original phase was in Fe_2TiO_4 the more the phase was oxidised with the resulting formation of ilmenite, so that when the temperature of exsolution of Fe_2TiO_4 was reached, all grains had reached a position about midway between Fe_3O_4 and Fe_2TiO_4.

Provided the composition of the original titanomagnetite phase remained constant throughout the crystallisation, there is a possibility of evaluating this composition by determining the ratio of titanomagnetite groundmass to distinct ilmenite lamellae in those grains where the masses of ilmenite can be proved to be all primary ilmenite. Although few in number there are also grains which totally lack ilmenite masses and they can also be used for evaluation of the ratio of titanomagnetite groundmass to distinct ilmenite lamellae. Estimation of the average amount of ilmenite present as distinct lamellae in the titanomagnetite is a difficult task, but as far as can be judged the ratio of titanomagnetite groundmass to ilmenite in distinct lamellae seems to average about 6 to 1. This applies to both the Kås dyke and the Listed dyke, as no difference can be detected between the two dykes.

In evaluating the composition of the original titanomagnetite it must be remembered that by oxidation of ulvöspinel, ilmenite and magnetite are formed in the ratio of 3/1. Therefore in addition to the amount of ilmenite actually found as distinct lamellae, a further $\frac{1}{3}$ of this amount must be added to arrive at the original amount of ulvöspinel, and this $\frac{1}{3}$ must be subtracted from the magnetite part of the titanomagnetite groundmass.

The composition of the titanomagnetite groundmass before the exsolved ulvöspinel was oxidised to ilmenite is estimated as between 50% Fe_3O_4, 50% Fe_2TiO_4 and 40% Fe_3O_4, 60% Fe_2TiO_4.

If the composition was 50% Fe_3O_4, 50% Fe_2TiO_4 it can be computed that the original titanomagnetite was composed of ca. 38% Fe_3O_4, 62% Fe_2TiO_4, while the composition 40% Fe_3O_4, 60% Fe_2TiO_4 of the titanomagnetite groundmass gives an original titanomagnetite of ca. 29½% Fe_3O_4, 70½% Fe_2TiO_4.

Probably therefore the original titanomagnetite had a composition somewhere in the range 30–40% Fe_3O_4, 70–60% Fe_2TiO_4, but furthermore containing minor amounts of V, Mn, and Cr.

It has now been shown that the ore minerals in the Kås and the Listed dyke consist mainly of a pair of Fe-Ti-oxides, a cubic titanomagnetite and a rhombohedral ilmenite. The composition of this pair does not show any detectable change across the dykes, and accordingly the composition of the pair must have remained constant throughout the crystallisation. The composition of the ilmenite phase is very close to pure $FeTiO_3$ and this phase has not been subjected to any kind of later exsolution. The composition of the original titanomagnetite phase was considerably closer to Fe_2TiO_4 than to Fe_3O_4, and this original titanomagnetite phase underwent an exsolution so complete that the cubic phase now present has a composition very close to pure Fe_3O_4.

Chemical investigations carried out on rock samples

For attempts to evaluate the reasons for the changes in amounts of rhombohedral ilmenite and cubic titanomagnetite, which have been established across the dykes, information concerning the partial pressure of oxygen and the amounts of Ti relative to Fe at the time of formation of the Fe-Ti-phases would be of great value. If the dyke rocks, after the primary igneous development, had not been subjected to any kind of later alteration involving reduction-oxidation processes and introduction or removal of Ti or Fe, the author considers that determination of the ratios of FeO to Fe_2O_3 and of Ti to Fe on total rock samples would give information about respectively the PO_2 and the concentration or activity of Ti relative to Fe at the time of formation of the Fe-Ti-oxides. Unfortunately however the dyke rocks have suffered severely from later alteration, which in particular has changed the reduction-oxidation conditions, but some of the different types of alteration of the Fe-Ti-oxides might also have caused appreciable changes in the ratio of Ti to Fe in different places in the dykes.

Although the information which could be expected from determination of the ratios of FeO to Fe_2O_3 and of Ti to Fe on total rock samples is therefore limited, the author can see no other possible way of gaining knowledge about the conditions prevailing during the formation of the Fe-Ti-phases. Accordingly chemical determinations of FeO, Fe_2O_3, and TiO_2 have been carried out on rock samples representing the best sampled sections of the two dykes from one of the contacts to well beyond the centres of the dykes.

The results of these determinations are listed in Table XIX, and the ratios of FeO to Fe_2O_3 and of Ti to Fe which are computed from the values of Table XIX are given in Table XX. The Ti/Fe ratios obtained have been confirmed by X-ray fluorescense analyses.

Inspection of Table XX reveals that Ti as well as Fe is somewhat more abundant in the Kås dyke than in the Listed dyke. The values of the Ti/Fe ratio in the Kås dyke are generally higher than in the Listed dyke.

The Ti/Fe ratio of the Listed dyke decreases from the contact inwards towards the centre (L6). The value for L3 is a little too high to fit the trend. This is obviously due to the fact that L3 is the specimen showing the highest degree of alteration of the titanomagnetite groundmass with resulting removal of iron.

In the Kås dyke the Ti/Fe ratio is constant in the middle of the dyke and increases towards the contact, whereas the contact shows the lowest Ti/Fe ratio found in the dyke.

Comparison with the Fe-column shows that the low value at the contact is probably due to the presence of an unusually high amount of iron. The contact specimen K1 contains some thin veinlets filled with limonite. These veinlets, which are evidently younger than the primary igneous development of the rock, must obviously have caused an increase in the amount of Fe. Accordingly the Fe now present in K1 must exceed the amount present at the end of the primary igneous development. It is believed that were it not for these limonite veinlets K1 would have shown the highest Ti/Fe ratio in the dyke. If the assumption is made that before the entrance of the limonite, the amount of Fe in

Table XIX

Chemical determinations of FeO, Fe_2O_3, and TiO_2

Analyst Miss Me Mouritzen

	FeO	Fe_2O_3	Total iron as Fe_2O_3	TiO_2
L1...........	4.49%	4.48%	9.46%	2.43%
L2...........	6.62%	2.44%	9.79%	2.21%
L3...........	6.64%	2.39%	9.76%	2.21%
L5...........	6.87%	3.02%	10.65%	2.27%
L6...........	7.84%	2.09%	10.79%	1.86%
L7...........	6.42%	3.32%	10.45%	2.31%
K1	9.46%	3.89%	14.40%	3.97%
K3	9.39%	1.94%	12.36%	3.75%
K5	9.24%	2.65%	12.90%	3.67%
K7	9.73%	3.75%	14.55%	4.08%
K8	8.73%	4.21%	13.90%	3.90%
K9	9.28%	3.73%	14.03%	3.93%

Table XX

Ratios of FeO to Fe_2O_3 and of Ti to Fe based on the values of Table XIX

	FeO/Fe_2O_3	Ti	Fe	Ti/Fe
L1...........	1.00	1.46%	6.62%	0.221
L2...........	2.71	1.32%	6.85%	0.193
L3...........	2.78	1.32%	6.83%	0.193
L5...........	2.27	1.36%	7.45%	0.183
L6...........	3.73	1.12%	7.55%	0.148
L7...........	1.93	1.38%	7.31%	0.189
K1	2.43	2.38%	10.07%	0.236
K3	4.84	2.25%	8.65%	0.260
K5	3.49	2.20%	9.02%	0.244
K7	2.59	2.45%	10.18%	0.241
K8	2.07	2.34%	9.72%	0.241
K9	2.49	2.36%	9.81%	0.241

K1 did not exceed the amount of Fe found in K3, the Ti/Fe ratio for K1 must be at least 2.75.

The author therefore suggests that if the effect of the veinlets could be excluded the ratio of Ti to Fe in the Kås dyke would decrease from the contact inwards as in the Listed dyke. While however in the Listed dyke the decrease continues as far as the centre of the dyke, the Ti/Fe ratio in the Kås dyke remains constant through at least 10 metres in the central part of the dyke.

The ratio of FeO to Fe_2O_3 in the Kås dyke clearly decreases from the contact inwards, except that again the value for K1 does not fit the trend. The reason for the aberrant value for K1 is obviously the same as put forward under the discussion of the Ti/Fe ratio, namely the presence of thin limonite veinlets. Inspection of Table XIX reveals that the extraordinarily high amount of Fe in K1 is present as Fe_2O_3 and not as FeO, the value of which does not seem to deviate unusually from the FeO values found for the other specimens from the Kås dyke. Assuming that the amount of Fe_2O_3 present in K1 before the entrance of the limonite did not exceed the Fe_2O_3 value found for K3, the minimum value of 4.88 would be obtained for the FeO/Fe_2O_3 ratio of K1. Furthermore the trend in the Fe_2O_3 values for the Kås dyke indicates that the proper Fe_2O_3 value for K1 should be appreciably lower than for K3. It is therefore likely that if the effect of the limonite veinlets could be excluded the Kås dyke would show a continuous decrease in the ratio of FeO to Fe_2O_3 from the contact to the centre of the dyke.

The establishment of a trend in the FeO/Fe_2O_3 ratios found in the Listed dyke is obviously difficult, and the author admits the subjectivity of the following interpretation. Considering first the extremely low value for L1, this could as in the case of K1 be due to the presence of thin limonite veinlets. Such veinlets are in fact found in L1. Contrary to K1 however L1 does not show an extraordinarily high value of total iron. The presence of limonite veinlets therefore does not offer the full explanation. It is striking that L1 is the only specimen from the Listed dyke in which a considerable alteration of ilmenite is found, and alteration of ilmenite to rutile is not found at all in the Listed dyke except in L1. The alteration of ilmenite to rutile is considered to imply some removal of iron (p. 435), and this process therefore might have counterbalanced the effect of the limonite veinlets with the result that total iron in L1 does not attain an extraordinarily high value. If therefore the combined effects of the limonite veinlets and the ilmenite alteration could be excluded, the FeO/Fe_2O_3 ratio would show a considerably higher value, which might be the maximum for the dyke.

In considering the high value of the FeO/Fe_2O_3 ratio found for L6 it must be remembered that L6 has the highest ratio of primary to secondary mafic silicates found in the two dykes, and that L6 is the only specimen containing an appreciable amount of unaltered olivine. It is thus evident that L6 has undergone markedly less alteration after the completion of the primary igneous development. This later alteration is believed to have caused an appreciable change of Fe^{++} to Fe^{+++}. It is not possible to evaluate the effect of the later alteration more exactly, but the author considers it possible that at the end of the primary igneous development L6 had an FeO/Fe_2O_3 ratio, which was not higher, and might possibly have been lower, than the ratios for L5 and L7 at that time. Provided the assumptions made are valid, it is thus possible to interpret the FeO/Fe_2O_3 ratios so that a trend from high values at the contact to low values in the centre of the dyke is established.

Although the support given by the figures found admittedly is very limited, the author thinks that in the Listed dyke also the ratio of FeO/Fe_2O_3 at the end of the primary igneous development showed a decrease from the contacts inwards in the dyke.

Finally it can be noticed that except for L6–K8 the FeO/Fe_2O_3 ratios are somewhat higher in the Kås than in the Listed dyke, indicating a higher degree of oxidation in the Listed dyke.

Conclusions

It has been shown that the primary Fe-Ti-oxides in the Kås dyke and the Listed dyke consist of two phases, a rhombohedral ilmenite and a cubic titanomagnetite, the composition of which remained about constant throughout the crystallisation, while the relative amounts of the two phases vary with position in the dykes as shown by Figures 5 to 8.

It has also been shown that ilmenite was the first of the Fe-Ti-phases to form. Ilmenite probably continued to form as the sole Fe-Ti-phase for some time before the first titanomagnetite appeared. The appearance of the titanomagnetite did not mean that the crystallisation of ilmenite ceased, but the two phases then crystallised together, forming a pair of coexisting Fe-Ti-oxides.

It is to be expected that as long as the two phases crystallised in equilibrium they were formed in a fixed proportion. The proportions of the final amounts of the two phases clearly vary across the dykes. It is therefore assumed that the conditions prevailing while the two phases were crystallising in equilibrium were changed in such a way that cubic magnetite phases, no matter what composition, were no longer stable, and ilmenite accordingly again became the only Fe-Ti-phase to form. This will explain satisfactorily the form of the curves in Figures 5 to 8, which further show that the period in which the two phases crystallised in equilibrium was obviously much longer in the Kås dyke than in the Listed dyke.

As far as can be judged from the accuracy of the methods of investigation used, the ilmenite formed before the crystallisation of titanomagnetite started, the ilmenite formed contemporaneously with the titanomagnetite, the ilmenite formed after the formation of titanomagnetite had ceased, the ilmenite formed by oxidation of ulvöspinel dissolved as titanomagnetite, and the ilmenite formed by oxidation of ulvöspinel exsolved from titanomagnetite, all have the same composition.

As to the reason that titanomagnetite started crystallisation later than ilmenite it has been shown in the preceding section that the ratio of Ti/Fe decreases from the contacts inwards, and hence it is possible that titanomagnetite was stabilised because of decreasing concentration of Ti in the melt. However the ease of nucleation may have played an even more important role. The fact that grains of pure titanomagnetite are extremely scarce, and that titanomagnetite preferentially used ilmenite grains as starting points for its growth, indicates that the nucleation of ilmenite may take place more easily than the nucleation of titanomagnetite.

Concerning the fact that ilmenite later again became the only Fe-Ti-phase forming, it is evident that this could not have been due to a later increase in Ti concentration, as the Listed dyke, which shows the most pronounced increase in ilmenite towards the end of crystallisation, has continuously decreasing ratios of Ti/Fe from the contact to the centre. The reason for the cessation of titanomagnetite formation is likely to be an increase in the partial pressure of oxygen, making ilmenite, which is the richest in oxygen of the two phases, the only stable phase. Because of the later alteration a decrease in the ratio of FeO/Fe_2O_3 towards the central part could not be convincingly shown for both dykes. The theory of increasing partial pressure of oxygen towards the end of crystallisation however is strongly supported by the evidence from the variation in Al_2O_3 content, and from the variation in An content in the plagioclase, which point to an increase in water pressure towards the end of crystallisation. According to OSBORN (1959) dissociation of water is the principal source of oxygen in a crystallising magma. The increase in water pressure indicated by the plagioclase and by the Al_2O_3 content therefore probably also caused an increase in the partial pressure of oxygen.

Both the Al_2O_3 content and the composition of the plagioclase indicate that the increase in water pressure was considerably larger in the Listed dyke than in the Kås dyke. This is in good agreement with the fact that the increase in the amount of ilmenite towards the end of crystallisation is more pronounced in the Listed dyke than in the Kås dyke, indicating that the cessation of titanomagnetite formation because of increasing partial pressure of oxygen took place considerably earlier in the Listed dyke.

The coexisting pair of Fe-Ti-oxides as a geological thermometer

If the interpretation is correct that the ilmenite and the titanomagnetite for some time crystallised together in equilibrium, these two phases constitute a pair of coexisting Fe-Ti-oxides.

Thanks to the work of LINDSLEY (1963) such coexisting pairs can now be used both as geological thermometers and as oxygen barometers.

The composition of the coexisting pair present in the Kås and the Listed dyke falls within an area where LINDSLEY considers his curves accurate to ±30°C and within one order of magnitude for the oxygen fugacity. The greatest source of uncertainty in determining the temperature when ilmenite and titanomagnetite crystallised together therefore evidently lies in the rather loose determination of the composition of the original titanomagnetite phase. The composition of the ilmenite phase has been determined as 96% $FeTiO_3$, 3% Fe_2O_3, 1% $MnTiO_3$, while the composition of the original titanomagnetite could not be given closer than 30–40% Fe_3O_4, 70–60% Fe_2TiO_4.

Although the influence of impurities such as for instance $MnTiO_3$ is not exactly known, it seems reasonable to count $MnTiO_3$ as Fe_2O_3, which gives an ilmenite phase of 96% $FeTiO_3$, 4% Fe_2O_3. This phase together with a titanomagnetite of 40% Fe_3O_4, 60% Fe_2TiO_4 would crystallise in equilibrium at 870°C and an oxygen fugacity close to 10^{-14} atm, and the pair 96% $FeTiO_3$, 4% Fe_2O_3 and 30% Fe_3O_4, 70% Fe_2TiO_4 at a temperature of 950°C and an oxygen fugacity between 10^{-13} and 10^{-12} atm (LINDSLEY 1963).

The temperature range obtained, 950°C–870°C, seems reasonable for a magma of basaltic to andesitic composition crystallising under hypabyssal conditions. These temperatues do not indicate the beginning of crystallisation, as ilmenite crystallised alone for some time, before it was joined by titanomagnetite.

B. Sulphides

The amounts of sulphides found in the dykes are extremely small, 0.3% in the Kås dyke and less than 0.2% in the Listed dyke. The sulphide minerals present are the same in both dykes: pyrrhotite, pyrite, marcasite, chalcopyrite, and pentlandite.

The sulphides were formed very late. Thus cracks through the titanomagnetite and through the silicates are occasionally partly filled with sulphide, and pyrrhotite, which probably is the first-formed sulphide mineral, is sometimes seen to replace secondary magnetite, formed by alteration of silicates.

Pyrrhotite, most of the chalcopyrite, and possibly some of the pyrite are primary. The diameter of more or less equidimensional grains of pyrrhotite varies from 2 to 75 μ. Frequently however the pyrrhotite forms elongated grains the dimensions of which can reach 100 × 50 μ. Chalcopyrite generally occurs as more or less equidimensional grains with diameters between 2 and 6 μ, but is occasionally found as considerably larger grains.

All the pentlandite and part of the chalcopyrite have been exsolved from pyrrhotite. The pentlandite exsolutions are flame-shaped and attain sizes up to 25 × 2½ μ. The chalcopyrite exsolutions are partly developed as more or less rounded masses the diameter of which can exceed 10 μ, and partly as flame-shaped bodies about 10 μ in length and about 2 μ in width. The flame-shaped chalcopyrite probably corresponds to the type described by PAULY (1958, p. 37).

Although it can not be excluded that part of the pyrite might be primary, most of the pyrite and all the marcasite are secondary, formed as the result of breakdown of pyrrhotite.

Chalcopyrite is rather evenly distributed across the dykes. As far as can be judged, pyrrhotite was originally also fairly regularly distributed. Now however the amount of pyrrhotite is greatest in the central parts of the dykes, because the breakdown to marcasite and pyrite here is less pronounced.

These regularly distributed primary sulphides are thought to be late magmatic.

In addition to the sulphides hitherto described, the development and distribution of which are similar for both dykes, the Listed dyke contains some irregularly shaped grains of pyrite, the diameter of which can reach 1 mm. These large pyrite grains are found irregularly distributed within the three metres closest to the eastern contact and probably constitute a later hydrothermal pyrite generation.

Finally it should be mentioned that in the centre of the Listed dyke a 0.2 mm large cluster of covellite grains was observed. This must be of supergene origin.

C. Later alteration of the Fe-Ti-oxides

Alteration of titanomagnetite to turbid sphene

Alteration of the groundmass of the titanomagnetite to turbid sphene is the most widespread alteration, and the only type equally well developed in both dykes. This type of alteration however has a rather irregular distribution across the dykes, and even within the same polished section it is possible to find strongly altered areas of titanomagnetite alternating with completely fresh areas.

Every gradation from incipient spotwise alteration along cracks (Plate 11) to strong alteration where all the titanomagnetite of the ore grains has been completely altered (Plate 8, Fig. 2) is found. The alteration is evidently younger than the cracks through the titanomagnetite, and the most common way of attack is by spreading out from these cracks, but alteration proceeding inwards from grain boundaries is also found.

The whole groundmass of the titanomagnetite, the magnetite phase as well as the ilmenite phase, is affected by the alteration. Apparently however these two phases are altered in different ways, with the result that even in the most strongly altered areas the characteristic ulvöspinel pattern of the titanomagnetite groundmass can often still be recognised (Plate 8, Fig. 2).

As previously described the ilmenite of the titanomagnetite groundmass was formed by oxidation of already exsolved ulvöspinel. It is remarkable that while the groundmass ilmenite formed in this way is changed by the alteration, distinct ilmenite lamellae, even the most tiny ones, arranged parallel to {111} of the titanomagnetite are always completely unaffected by this kind of alteration, even when the ilmenite lamellae are found in the middle of strongly altered titanomagnetite. Such distinct ilmenite lamellae are only found altered in areas where, in addition to the titanomagnetite alteration dealt with here, one of the types of ilmenite alteration which are described in the following sections occur, and these types of ilmenite alteration all seem to be quite independent of the alteration of the titanomagnetite.

The ilmenite lamellae arranged parallel to {111} of the titanomagnetite are not only themselves completely unaffected by the alteration of the titanomagnetite groundmass, but it is very often seen that these ilmenite lamellae have also been able to protect the titanomagnetite in their immediate vicinity from being altered. This is shown in Plate 12, Fig. 1. The border between unaltered and altered titanomagnetite is strongly serrated. With progressed alteration however these rims of unaltered titanomagnetite finally disappear and only the ilmenite lamellae themselves remain. Rims of unaltered titanomagnetite are found around all types of distinct ilmenite lamellae, not only around those forming optical units with the surrounding titanomagnetite. This indicates that the rims of unaltered titanomagnetite are not preserved because they have any property, orientational or compositional, different from the rest of the titanomagnetite, but probably just because the ilmenite lamellae offered a shielding effect so that the titanomagnetite in their immediate surroundings could not be attacked from all directions as could the rest of the groundmass. The alteration in the immediate vicinity of the lamellae was therefore retarded.

In air the reflectivity of the alteration product is considerably lower than that of ilmenite, but still higher than the reflectivity of any of the common translucent constituents of the rock. The colour is dark grey in different shades. There is a pronounced mottled appearance, and the alteration product is porous and obviously rather inhomogeneous. Reflection pleochroism is not observable. Anisotropy is easily seen. With polars crossed internal reflections are seen but are not very pronounced. The internal reflections are generally whitish, but sometimes especially in more porous parts of the alteration, brownish red and greenish internal reflections are also seen. In contrast to the whitish internal reflections the brownish red and the greenish ones, which are always found together, can also be observed with polariser only. These colours are possibly not due to genuine internal reflections, but may be caused by some sort of Newton phenomenon in the porous material.

In oil the reflectivity of the alteration product is difficult to judge because of a wealth of internal reflections. Apparently however the reflectivity is not much higher than that of the pyroxene in the rock. The alteration product is coloured in different shades of dark grey, and the mottled and porous appearance is even more pronounced in oil than was the case in air. The colours of the internal reflections as seen with polariser only are whitish, light yellow, brownish red, and greenish. Reflection pleochroism is often easily visible. With crossed polars part of the alteration product is completely covered with whitish internal reflections with a cloudy appearance, which to some extent mask the anisotropy, but nevertheless the anisotropy in many cases is easily observed. The cloudy whitish internal reflections are absent from part of the alteration product, which on the other hand contains abundant brownish red and light yellow internal reflections, which are not cloudy but distinct in their appearance. Also in these parts of the alteration product anisotropy is often easily observable.

Examination of polished thin sections reveals that in many cases even strongly altered areas are completely opaque in transmitted light and can hardly be discerned from unaltered titanomagnetite, except that altered areas have a somewhat darker appearance than unaltered areas. In thin sections which are not polished such altered areas are dull brownish black in contrast to the pure black colour of unaltered titanomagnetite. Besides this completely opaque alteration there are cases where the alteration shows a rather dark brown colour in transmitted light but is translucent enough to show that the alteration product has a high relief and a strong birefringence. A number of black completely opaque spots can often be seen peppered throughout this dark brown and somewhat translucent material. In a few rare cases it is possible to find areas of alteration which in transmitted light are grey and translucent, and which can be recognised as being composed of sphene.

The alteration product was drilled out from L3, which shows the highest degree of alteration of the titanomagnetite groundmass. Although great care was taken when the material was drilled out it was impossible to avoid contamination with the ilmenite lamellae arranged parallel to {111} of the original titanomagnetite. Therefore although most of the sample prepared was composed of the alteration product, the ilmenite phase from the lamellae was also represented. X-ray investigation by Guinier camera of the prepared sample reveals that sphene constitutes a large part of the alteration product. Besides sphene the presence of a magnetite phase with a cube edge of 8.398 ± 0.005 Å and an ilmenite phase with $a = 5.092 \pm 0.005$ Å, $c = 14.06 \pm 0.02$ Å, $c/a = 2.761$ is also shown. The presence of rutile is not shown, but it can not be completely excluded that small amounts of rutile might be present, since it is possible for the strongest line of rutile to be hidden behind one of the diffuse lines of sphene. The weaker lines of rutile however are all absent. Similarly the presence of a rhombohedral phase close to pure hematite in composition can neither be proved nor completely excluded.

In the hope of obtaining indisputable results concerning the presence or absence of rutile and hematite a larger amount of altered titanomagnetite from L3 was separated and investigated by X-ray diffractometer.

The diffractometer also showed sphene to be the main component of the alteration product, and gave a magnetite with a cube edge of 8.396 ± 0.002 Å and an ilmenite with a = 5.088 ± 0.005 Å, c = 14.07 ± 0.02 Å, c/a = 2.765. The diffractometer however was as unsuccessful as the Guinier camera concerning rutile and hematite, which minerals can neither be proved to be present nor to be absent.

Both the Guinier and the diffractometer values of the cube edge of the magnetite phase found in the alteration product are in good agreement with the cube edge values given in Table XVII for the magnetite phase in unaltered areas of the titanomagnetite groundmass. Hence the magnetite phase present in the alteration product is believed to be remnants of the magnetite phase formed at the end of the primary igneous development. Such unaltered remnants seem to be present even in the most strongly altered areas.

The ilmenite phase in the alteration product has a values slightly higher than the a values of the ilmenite in Table XIV and Table XVI. As however the c values lie in the middle of the range of c values in the Tables XIV and XVI, and the values of the ratio of c/a lie in the lower end of the range given in these tables, it is concluded that the composition of the ilmenite phase in the alteration product is the same as that of the ilmenite found elsewhere in the dykes. The ilmenite phase in the alteration product probably represents both ilmenite in distinct lamellae arranged parallel to {111} of the original titanomagnetite and unaltered remnants of ilmenite from the titanomagnetite groundmass.

Considering that the ilmenite lamellae and the ilmenite part of the titanomagnetite groundmass had the same composition before any alteration took place, it is surprising that the one form is strongly altered, while the other form is not altered. The reason for this difference probably lies in the fact that the ilmenite in the titanomagnetite groundmass, because of the extremely fine intergrowth with magnetite, must have a larger surface area than the distinct ilmenite lamellae. Although most of the ilmenite in the titanomagnetite groundmass is not reorganised from the {100} to the {111} directions of the titanomagnetite, it does have this tendency. This fact also might make it more prone to alteration than ilmenite already arranged parallel to the {111} directions. With this possibility in mind the author has especially studied the texture of unaltered parts of titanomagnetite occurring in areas where most of the titanomagnetite is strongly altered, to see if these unaltered parts could be preferentially such parts of the titanomagnetite where the reorganisation from {100} to {111} is most advanced. This seems however not to be the case. The reason for the strongly irregular distribution of the alteration even within the same polished section therefore can not be the different degrees of reorganisation of the ilmenite in the titanomagnetite groundmass.

DESBOROUGH (1963) has described similar alteration of magnetite-ulvöspinel intergrowths in basic rocks from Missouri, U.S.A. His identification of the turbid sphene is also based on X-rays, and he states that in thin sections and polished thin sections the sphene could easily be mistaken for an opaque ore mineral. He also states that the apparent opacity in thin section may be due to finely disseminated impurities, but if such impurities are present in the sphene, either they are present in amounts insufficient to be indicated on X-ray powder photographs or they are too fine grained to give rise to lines on the X-ray film.

Thus both DESBOROUGH and the present author expected other components besides sphene to be present in the alteration product. The present investigation failed to prove or disprove the presence of rutile and hematite, but it is shown that even in the most strongly altered areas some unaltered magnetite remains. Probably therefore the apparent opacity of the turbid sphene is caused by the presence of small unaltered spots of titanomagnetite finely dispersed throughout the sphene alteration product.

DESBOROUGH suggests that the amount of iron removed during this kind of alteration is sufficient to account for the formation of ore deposits of magnetite and/or hematite. The present author agrees with DESBOROUGH in that iron is removed from rocks subjected to this kind of alteration. Closer inspection of Table XX reveals that the values for L3 do not fit into the otherwise clearly established trend that the content of Fe in the total rock increases while the ratio of Ti/Fe decreases from the contacts inwards. Very strikingly the specimens L2 and L3 represent extremes with respect to the alteration of titanomagnetite to turbid sphene, in such a way that in L2 the titanomagnetite is practically unaltered, while in L3 the titanomagnetite is all more or less strongly altered. With this fact in mind the values of the table present rather strong evidence for the removal of iron during this kind of alteration of titanomagnetite.

The present author believes that iron mobilisation by large scale alteration of this kind might very well lead to the formation of significant amounts of iron ore with low titanium content, especially if the removal of iron from the titanomagnetite is accompanied by a similar removal of iron from the mafic silicates of the rock. HAGNER, COLLINS & CLEMENCY (1963) on the basis of very detailed investigations conclude that the source of the magnetite ore of the Scott mine in the Sterling Lake District, New York, is the pyroxene amphibolite host rock. They are able to show how the percentage of iron in the mafic silicates of the rock, as well as the iron content of the total rock, decreases with proximity to the ore zone.

Alteration og the magnetite part of the titanomagnetite groundmass to maghemite

In a very few cases there were found along small cracks through the titanomagnetite thin selvages in which the magnetite part of the extremely fine magnetite-ilmenite intergrowth in the titanomagnetite groundmass attains a bluish colour, indicating the transformation of magnetite to a maghemite phase. These selvages generally have a width between 2 and 5 μ, but sometimes the maghemitisation spreads out from the cracks affecting larger parts of the neighbouring titanomagnetite. Such alteration is generally found in titanomagnetite which is completely unaffected by the alteration to turbid sphene, although in some cases traces of this type of alteration might also be present.

If the maghemite selvages represent the very incipient stage of the alteration to turbid sphene they ought to have a more widespread occurrence, and even incipient stages of alteration to turbid sphene are almost always found without microscopically visible maghemite. Furthermore maghemite selvages are found in only four polished sections, three of which were prepared from specimens intentionally taken from weathered parts of the dykes in order to evaluate the relationship between the different types of alteration and atmospheric weathering.

It is therefore concluded that the development of maghemite along cracks in the titanomagnetite is independent of the alteration of titanomagnetite to turbid sphene, and is most probably related to atmospheric weathering.

DESBOROUGH (1963) in his investigation of alteration to turbid sphene has in two specimens found cracks in the titanomagnetite showing selvages of a mineral, which he says may be titanomaghemite. He states that the alteration of titanomagnetite to turbid sphene apparently is a type different from the alteration of titanomagnetite to titanomaghemite.

Alteration of ilmenite to sphene

The most widespread of the different types of ilmenite alteration is that of ilmenite to sphene. This type is most strongly developed in the Listed dyke, but even here it is generally restricted to grain boundaries and the immediate vicinity of small cracks through ilmenite. Only very rarely are whole grains of ilmenite altered to sphene.

The typical development of this kind of alteration is shown in Plate 13.

The sphene here is not of the turbid type, but is recognisable as sphene in transmitted light also. In reflected light the sphene is grey with a reflectivity clearly higher than that of pyroxene and the other silicates in the rock, but much lower than that of ilmenite.

In oil the reflection pleochroism is in many cases seen to be distinct, and judging from the reflection pleochroism the grain size is rather large with diameters exceeding 5 μ, but the grains have a pronounced mottled appearance, so that without the reflection pleochroism the grain size would appear to be much less. With crossed polars the sphene is generally completely covered with more or less luminous internal reflections of whitish colour. Part of the sphene however, especially along the cracks, has a darker grey colour and shows fewer and less luminous internal reflections. This may be due to the presence of unaltered ilmenite just below the polished surface.

In air it is practically impossible to see reflection pleochroism, but under crossed polars the internal reflections are weak enough to permit the anisotropy to be easily seen, while the observation of anisotropy under crossed polars is impossible in oil because of the complete covering with internal reflections.

The alteration of ilmenite has resulted only in the formation of sphene, and no other alteration product is seen. The alteration therefore not only implies supply of calcium and silica, but also removal of iron. Sphene has essentially the composition $CaTiSiO_5$, and although substitution of both Fe^{+++} and Fe^{++} for Ti is possible, Ti will always be strongly predominating. In the table of sphene analyses in DEER, HOWIE & ZUSSMAN (1962) the two most iron-rich sphenes have Fe/Ti ratios of 0.11 and 0.08 respectively. As the Fe/Ti ratio in the ilmenite in the dykes from Bornholm is about 1.22, removal of iron by the alteration of ilmenite to sphene is clearly shown.

However part of the Ti content has evidently also been removed. The alteration of ilmenite to sphene is obviously the result of volume-by-volume replacement, as no cracks and no holes have been created during the alteration. The maximum content of Ti in the sphene analyses listed in DEER, HOWIE & ZUSSMAN (1962) is 24.24%. The specific gravity of sphene is 3.5 and that of ilmenite 4.7. The 24.24% Ti in sphene therefore corresponds to 18% Ti in the ilmenite. The percentage of Ti in the original ilmenite in the Listed dyke is known from the microprobe analyses to be around 28%. The X-ray investigations showed the composition of the ilmenite to be the same in the Kås dyke and the Listed dyke. Of this 28% only 18% has been retained in the alteration product, while the remaining 10% has obviously been removed. Accordingly about ⅓ of the Ti content in the ilmenite has been carried away during the alteration process.

For comparison the same calculation is carried out for the Fe content. The most iron-rich of the sphene analyses in DEER, HOWIE & ZUSSMAN (1962) contains 2.43% Fe, which corresponds to 1.8% Fe in the ilmenite. The percentage of Fe in the original ilmenite according to the microprobe analyses is around 34% Fe. Of this 34% a maximum of 1.8% could have been retained in the alteration product, while at least 32% has been removed. This means that at least 94% of the Fe content of the ilmenite has been carried away during the alteration process.

Alteration of ilmenite to rutile

This type of ilmenite alteration is most strongly developed at the immediate contacts of both dykes. Here many ilmenite grains are completely altered to rutile, and partially altered grains are common. Where ilmenite grains are only partially altered to rutile there are generally many holes in the rutile, while no holes are seen where the alteration has advanced so far that entire grains have been replaced. No alteration product other than rutile can be seen.

In the Listed dyke alteration of ilmenite to rutile is found only at the immediate contact, and not even traces of this type of alteration are seen in any other part of this dyke.

Contrary to this, alteration of ilmenite to rutile occurs rather widely in the Kås dyke. Away from the immediate contacts alteration of ilmenite to rutile is however generally found in incipient stages, and only very rarely are whole grains of ilmenite altered to rutile. The alteration mainly attacks from grain boundaries, but also follows small cracks.

The colour of the rutile is grey with a faint violet-blue tint, and the reflectivity is somewhat higher than that of ilmenite. The grains vary in size from minute to relatively large grains with a diameter of about 5 μ.

In oil the minute rutile grains are almost completely covered by strong and luminous internal reflections. These are generally yellowish white, but also light red and bluish green internal reflections occur. The larger grains contain fewer and less luminous internal reflections, and both reflection pleochroism and anisotropy can easily be seen.

In air the internal reflections are not so pronounced without crossed polars. Reflection pleochroism can hardly be observed, while anisotropy is easily seen.

Very often the rutile nearest to unaltered ilmenite occurs as larger grains with relatively few and less luminous internal reflections, while the rutile closer to the grain boundaries from where the alteration started is minute in size and filled with strong and luminous internal reflections. This seems to indicate that the rutile with progressed alteration diminishes in grain size and becomes more translucent.

As mentioned no alteration product other than rutile was observed. There are however several holes between the rutile grains, and no matter how carefully the polishing is carried out these holes persist. The question then arises whether these holes could be due to Fe having been dissolved and carried away during the alteration. This seems quite possible, but can not be proved. The occurrence of holes in rutile is however not unusual. RAMDOHR (1960, p. 918) states: "grössere Partien mancher Vorkommen behalten hartnäckig Löcher".

In the dykes described here it is characteristic that the more minute the rutile grains are, the less pronounced are the holes.

The typical development of the incipient stages of the alteration of ilmenite to rutile is shown in Plate 14, and the more progressed stages of this type of alteration are shown in Plate 15.

As mentioned in the section on alteration of titanomagnetite to turbid sphene, distinct ilmenite lamellae arranged parallel to {111} of the titanomagnetite are generally completely unaffected, even when the surrounding titanomagnetite is completely altered. Occasionally such ilmenite lamellae are seen to be altered to rutile.

It is not possible to carry out more precise calculations of the chemical changes involved in the alteration. The presence of the holes in the alteration product indicates that the alteration was probably not a volume-by-volume replacement, and furthermore the Fe content in the resulting rutile can not be estimated. The iron content of rutile can vary strongly. HENRIQUES (1963) states that the iron content of stable ferriferous rutile is low, while that of unstable rutile may be fairly high. Although the rutile in the Kås and the Listed dyke might well be unstable, the present author considers this rutile to be low in iron because of the strong development of internal reflections, which indicate a rather translucent rutile, while iron-rich rutiles are generally considered to be more opaque.

Thus the strengthening in internal reflections connected with the decrease in grain size of rutile with progressed alteration probably indicates a continued removal of iron. The alteration of ilmenite to rutile implies at least some removal of iron, and probably most of the iron content of ilmenite is carried away. No removal of Ti is implied in the alteration, and most probably all the Ti is retained in the rutile formed. The alteration does not imply any introduction of material.

Ilmenite alteration of beach sand type

Rather locally in the Kås dyke a third type of ilmenite alteration is found, which bears a striking resemblance to the one described from beach sands from tropical and subtropical climates.

Contrary to the types of ilmenite alteration described in the previous sections this alteration of beach sand type very often comprises whole grains of ilmenite, and all forms of transitional stages from incipient spotwise alteration along cracks or grain boundaries to completely altered grains are found.

Incipient stages of this type of ilmenite alteration are clearly related to grain boundaries and cracks, and the connection with cracks is more pronounced for this type than for the types previously described. Besides the relationship with grain boundaries and cracks there is a striking tendency for the alteration to follow a certain crystallographic direction of the ilmenite, probably {0001}.

Plate 16 shows two grains of ilmenite which are attacked by alteration to about the same extent. Fig. 1 shows very clearly the connection of alteration with grain boundaries and cracks, while Fig. 2 shows a rather pronounced formation of parallel layers of alteration, starting from grain boundaries (including the boundaries of silicate inclusions in the ilmenite) and from cracks, and probably following the basal plane of ilmenite. With progressed alteration the parallel layers of alteration, which earlier were alternating with layers of fresh ilmenite, merge into one another forming larger areas of alteration. This way of attack is similar to that found by BAILEY, CAMERON, SPEDDEN & WEEGE (1956) in beach sand alteration of the type they call Stage 1, patchy ilmenite. These authors however state that the arrangement of parallel stringers of alteration alternating with fresh ilmenite in many grains is interrupted along cracks, from which the alteration appears to have spread laterally. Contrary to this the present author very often finds that this arrangement is developed just because the alteration is attacking from cracks. This is clearly seen in Plate 17, both figures of which show the same grain. Fig. 1 is taken with polariser only and shows the position of cracks very clearly, while the stringers of alteration are more indistinct. Fig. 2 is taken with polars crossed and shows the distribution of alteration very clearly, while the cracks can only be seen with difficulty. The two figures combined show that parallel stringers are formed by alteration attacking out from cracks, and are developed irrespective of whether the cracks are sub-parallel to the direction of the stringers or cut this direction at high angles.

In air the reflectivity of the alteration product appears somewhat higher than that of unaltered ilmenite. The colour is greyish with a faint bluish tint, and the alteration product has a very pronounced extremely fine mottling. Reflection pleochroism is generally not visible, but where the altered ilmenite contains polysynthetic twin lamellae on the rhombohedron, it is just discernible. No internal reflections are seen with polariser only. Anisotropy is easily observed and with crossed polars numerous minute brownish red internal reflections are seen.

In oil the reflectivity of the alteration product is clearly higher than that of unaltered ilmenite. The alteration product has an extremely fine mottled appearance, which is due mainly to the presence of innumerable minute internal reflections of weakly bluish and reddish colours, which cover the altered areas completely. The main colour impression is bluish grey. Also in oil reflection pleochroism is only observable where the altered ilmenite contains polysynthetic twin lamellae, but it is more distinct than in air. The bluish grey colour impression is probably due to a predominance of the bluish internal reflections. With polars crossed however brownish red internal reflections are strongly predominating. Anisotropy is easily observed. The patchy development of the alteration can often be seen clearly with crossed polars, even where, with the polariser only, the grains appear to be homogeneously altered.

Where areas of fresh ilmenite remain in the alteration product, the altered areas nearest to fresh ilmenite are, under crossed polars, often darker and contain fewer internal reflections than the other altered areas. With polariser only the altered areas appear quite homogeneous. The phenomenon described can be due to the presence of unaltered ilmenite just below the surface in the immediate vicinity of fresh ilmenite, but it may also indicate that the alteration product becomes more translucent with progressed alteration.

The ilmenite alteration described here shows pronounced similarity to that in beach sands described and pictured by LYND, SIGURDSON, NORTH & ANDERSON (1954) and by BAILEY *et al.* (1956).

According to LYND *et al.*: "The appearance of the altered ilmenite varied, depending on the degree of alteration. Some grains appearing grayish white and granular in bright light were dark in polarized light, as was fresh ilmenite. Other grains showed dark brown to bright yellow reflections in polarized light, in a wide variety of patterns: light and dark alternating bands, mottled areas, diffuse brown grains of various tones, or rims of light alteration products around a core of fresh or less altered material."

BAILEY *et al.* recognise three different stages in the alteration of ilmenite. Stage 1 is called patchy ilmenite and comprises the appearance of elongated stringers, rims, or rounded patches of a grey material having a reflectivity near that of rutile but slightly lower. With progressed alteration the altered areas become enlarged and merge into one another, and ultimately unaltered ilmenite is no longer seen. This first stage of alteration is accompanied by progressive decrease of anisotropy. Various substages are recognised, but finally the grains become homogeneous, isotropic, and opaque without any internal reflections, and Stage 2 which is called amorphous iron-titanium oxide is now reached. The reflectivity of the material at Stage 2 is close to that of rutile and the colour is slightly greyer. Stage 3 is called leucoxene and marks the development of leucoxene at the expense of amorphous iron-titanium oxide. The leucoxene is finely crystalline and has a colour like rutile. Under crossed polars it shows mass internal reflections ranging from brown to white. The leucoxene of Stage 3 differs microscopically from ordinary rutile only in texture.

Except for a few very rare cases described later (p. 439) the ilmenite alteration in the Kås dyke is clearly anisotropic, and no amorphous or isotropic stage is observed. The internal reflections of the alteration product are certainly not the bright luminous ones characteristic of rutile, but are much duller. It seems therefore evident that the ilmenite alteration in the Kås dyke does not reach either Stage 2 or Stage 3, but corresponds closely to Stage 1, of BAILEY *et al.*

BAILEY *et al.* show photomicrographs with very early phases of Stage 1 alteration, where most of the alteration product has already reached Stage 2. These authors however stress that there is a considerable overlapping between the different stages, and that all three stages as well as unaltered ilmenite may often be found in the same grain. It is therefore probable that alteration at Stage 1, because of stronger degree of alteration, is not so well preserved in the material investigated by BAILEY *et al.*, as is the case in the Kås dyke, where Stage 2 and Stage 3 were never reached.

Various substages of the Stage 1 alteration were recognised by BAILEY *et al.* In the Kås dyke such substages are recognised only with crossed polars, while the alteration product as seen with polariser only, generally appears quite homogeneous. This is seen in Plate 18, both figures of which show the same grain. Fig. 1 is taken with polariser only, while Fig. 2 is taken with polars crossed. Fig. 2 shows various substages in the alteration, and although the grain is completely altered, twin lamellae on the rhombohedron are easily seen. With the polariser only the alteration appears quite homogeneous except that some of the broader twin lamellae are vaguely seen, which fact however is lost in Fig. 1. Along the upper border of the grain some small groups of strongly luminous internal reflections are seen. They are whitish to yellowish and mark the spotwise development of small rutile grains. Such rutile grains are sometimes found in this type of ilmenite alteration, but are always surrounded by clearly anisotropic and typical Stage 1 alteration. This rutile is therefore believed to have developed independently of the beach sand type of ilmenite alteration.

Where alteration of titanomagnetite to turbid sphene and ilmenite alteration of beach sand type occur together, distinct lamellae of ilmenite arranged parallel to {111} of the titanomagnetite are generally attacked, as well as ilmenite in masses or free grains, by the beach sand type of alteration (Plate 12, Fig. 2).

The alteration product was drilled out and investigated by X-rays. The results of this investigation show that neither hematite nor rutile is present. LYND *et al.* (1954, p. 823) have found that in material of this kind the principal lines at 2.68 Å and 3.25 Å for respectively hematite and rutile may be absent, while broad weak maxima can be found at 1.69 Å and other spacings common to both hematite and rutile. Even with this possibility taken into account it can be stated that neither hematite nor rutile is present in the beach sand type of alteration in the Kås dyke, as no lines at 1.69 Å were seen either. The two other modifications of TiO_2, anatase and brookite, are likewise absent from the alteration product. It follows that the lines needed to build up the postulated mineral arizonite are also absent, as the lines of arizonite are very similar to those of hematite, anatase, and rutile.

The only lines found all fit together to give an ilmenite-like structure with $a = 5.063 \pm 0.005$ Å and $c = 14.05 \pm 0.02$ Å*). The corresponding value of the ratio of c/a is 2.775, which is somewhat higher than that obtainable for any member of the normal solid solution series between $FeTiO_3$ and Fe_2O_3.

To ensure that the ilmenite subjected to the beach sand type of alteration was of the same composition as is generally found throughout the Kås dyke and the Listed dyke, the unaltered ilmenite from partly altered ilmenite grains was also sampled for X-ray investigation. The unaltered ilmenite gave $a = 5.087 \pm 0.005$ Å, $c = 14.06 \pm 0.02$ Å, and $c/a = 2.764$; this ilmenite has therefore the same composition as all the other ilmenite in the dykes.

The alteration thus seems to have changed the ilmenite structure so as to cause a considerable decrease in the a value, while the c value remains almost constant.

This alteration has resulted in the formation of a more translucent material with somewhat higher reflectivity and with a disturbed ilmenite lattice. These changes could be due to leaching of the Fe content of the ilmenite. It is known

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*) The line 110 is however three times as broad as usual, whereas 104 has the normal thickness.

that ilmenite alteration of beach sand type results in an increase in Ti and a decrease in Fe content. Analyses of magnetically separated subfractions of beach sand ilmenite carried out by BAILEY *et al.* indicate however that most of the iron is removed first at Stage 3, while only a very minor amount of Fe is leached during Stage 1 and Stage 2.

Near the eastern border of the Kås dyke a small area ($\frac{1}{2}$ m^2) is found in which the dyke rock is transected by rather many thin veinlets which are more or less parallel (p. 374). In the immediate vicinity of these veinlets most of the ilmenite is altered, partly to rutile and partly to Stage 1 of beach sand type.

The alteration of beach sand type found in connection with these veinlets differs from the previously described alteration of beach sand type in that whitish and not brownish red internal reflections are predominating. Apart from this there is generally no difference in the appearance.

Amongst the altered grains connected with veinlets there are however a few grains with a type of alteration which differs from the alteration of beach sand type found elsewhere in the dyke in yet another way. With crossed polars these particular grains can be seen to contain some small, more or less rounded, dark spots. The spots are rather closely spaced and evenly distributed throughout the grains in which they occur. The diameter of the spots is about 1 μ. Their colour with crossed polars is black, and in contrast to the surroundings the spots are opaque and isotropic. With the ×60 oil objective the spots are only visible with crossed polars. With the ×105 oil objective the spots can be discerned also with polariser only as areas slightly darker than the surroundings. The author suggests that these small opaque and isotropic spots indicate that the alteration of beach sand type here is just reaching the very beginning of Stage 2.

Altered ilmenite containing such small rounded opaque spots is shown in *Plate 19, Fig. 1.*

Relationship between ilmenite alteration to rutile and ilmenite alteration of beach sand type

In many cases alteration of ilmenite to rutile is absent in the areas of the Kås dyke where ilmenite alteration of beach sand type is found, and vice versa. At some places however these two types of ilmenite alteration are found together. Near the eastern border of the Kås dyke both kinds are found in connection with thin veinlets (p. 374), and occasionally spotwise development of rutile along the borders of ilmenite grains, which are strongly attacked by beach sand type of alteration, can be found in areas where beach sand type is generally the only kind of ilmenite alteration present. In the immediate vicinity of the calcite veinlets (p. 373) both types are often found together. Besides these cases these two kinds of ilmenite alteration are also found together in K5, five metres from the western contact of the Kås dyke. In this specimen alteration to rutile is strongly predominating, and alteration of beach sand type occurs in only a few grains.

Where both kinds of alteration occur together in grains which still contain fresh ilmenite, the alteration of beach sand type is generally separated from fresh ilmenite by a zone of ilmenite altered to rutile (Plate 19, Fig. 2). BAILEY *et al.* (1956) state that in beach sands rutile (leucoxene) representing Stage 3 is always separated from fresh ilmenite by amorphous material of Stage 2. Accordingly the relationship between alteration to rutile and alteration of beach sand type at Stage 1 in the Kås dyke can not be the one generally found in beach sands.

The fact that the rutile in the Kås dyke is found between fresh ilmenite and alteration of beach sand type is not considered to represent a sequence of alteration: *fresh ilmenite → rutile → beach sand type alteration* for the following reasons. 1) Such a succession of events would be in contradiction to that generally found in beach sands. 2) In the Kås dyke rutile is in most cases completely absent from alteration of beach sand type, even where such alteration is only incipient. 3) It is unlikely that ilmenite would be altered, first to tetragonal rutile, and thereafter to beach sand type alteration with a lattice structure very similar to that of ilmenite.

The author therefore considers that in the Kås dyke alteration of ilmenite to rutile and ilmenite alteration of beach sand type have developed independently of each other. The alteration of beach sand type probably was the first to develop, and when later alteration to rutile occurred, this started from the grain boundaries of fresh ilmenite grains and of completely altered grains, while in partially altered grains the border between fresh ilmenite and alteration of beach sand type was the starting point for the alteration to rutile (Plate 14, Plate 18, and Plate 19, Fig. 2).

Blue colouring of ilmenite along cracks

Sometimes ilmenite, which in all other respects is completely unaltered, attains a faint bluish tint in thin zones along cracks through the ilmenite. The width of the blue coloured zones varies from about 1 μ to about 5 μ. The reflectivity is very close to that of ilmenite but might be just slightly lower. The anisotropy is at least considerably lower than for ilmenite, and the blue coloured zones might be isotropic.

The possibility that these blue coloured zones represent the very beginning of alteration of beach sand type has been considered, but is discarded because even very incipient stages of beach sand type alteration have a reflectivity clearly higher than ilmenite and show anisotropy not much weaker than ilmenite.

The author considers that the blue coloured zones may be perovskite, and were it not for the lack of internal reflections there would not have been much hesitation in the determination*).

These blue coloured zones are rather widespread in the Kås dyke, but are not observed in the Listed dyke.

There are also rare cases of still another kind of blue colouring of ilmenite, in which the bluish tint is somewhat weaker than in the cases just described. This even fainter blue colouring is also found connected with cracks through the ilmenite. It is not confined to thin zones along the cracks but spreads out from the cracks affecting larger areas, which grade rather imperceptibly into ilmenite with the normal brownish colour. The reflectivity of this material with slight blue colouring is very close to that of normal ilmenite, and in contrast to

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*) In K11 three small grains (0.02 × 0.01 mm) of idiomorphic perovskite is found included in pyroxene, and in L2 a single grain, 0.03 × 0.01 mm, of perovskite associated with titanomagnetite is seen.

the above described thin zones of blue colouring the material here is strongly anisotropic to about the same extent as normal ilmenite. No satisfactory explanation of this phenomenon is offered.

Although these faintly bluish areas are very rare, they have been observed in both dykes.

Distribution and nature of the different types of alteration

Alteration of titanomagnetite to turbid sphene

Besides the specimens systematically collected across the dykes in order to evaluate the differences which are dependent on position within the dykes, specimens were also collected of the most weathered dyke rock, of dyke rock adjacent to joints, and of dyke rock adjacent to veinlets cutting through the dykes, so that any possible dependence of the alteration on such phenomena could be elucidated.

Investigation of this material (KA–KX and LA–LK) showed that in no case was alteration of titanomagnetite to turbid sphene found to be more strongly developed in weathered specimens of the dyke rock, or in specimens adjacent to joints, than in the systematically collected specimens from the corresponding positions in the dykes. In the case of veinlets it was found in some instances that there is a certain increase in the degree of alteration with proximity to the veinlets. This is however never very pronounced, and characteristically no veinlets are found in the parts of the dykes which show the strongest degree of alteration. This is in good agreement with DESBOROUGH (1963) who finds that rock adjacent to different kinds of veinlets, all less than 1 mm wide, which transect all minerals of the rocks, is altered. As however other altered areas do not contain such veinlets, he concludes that no essential relation exists between veinlets and alteration.

The central parts of the dykes and thin belts adjacent to the contacts are the least affected areas, while rather strong alteration is found in zones extending from about two metres to about five metres from the contacts. In the Kås dyke the specimens K10 and KE which were both taken at ten metres from the eastern contact show considerably stronger alteration than the adjacent specimens. When the fact that no titanomagnetite is present at the immediate contacts of the dykes is taken into consideration, it is seen that the alteration to turbid sphene is mainly coincident with the alteration of mafic silicates, which is shown graphically in Fig. 3 and Fig. 4 on page 391.

Concerning the zone about two metres wide of only weak alteration of titanomagnetite adjacent to the contacts, it is of interest to note that DESBOROUGH, in investigating the distribution of alteration to turbid sphene in a sill with a thickness of a little less than 50 metres, found that altered and unaltered specimens apparently were not restricted to any particular part of the sill except that no alteration was detected within three metres of the upper and lower contacts. He also states that there can be strong variation in the degree of alteration even within the same polished section.

There is apparently no difference either in the degree of alteration or in the distribution of the alteration between the two dykes.

As to the nature of the solutions causing the alteration it has been shown that the alteration is not related to atmospheric weathering, and although the alteration spreads out from cracks through the titanomagnetite, no suitable channelways have been seen which could have guided the solutions through the rock to the ore grains. It is therefore presumed that the solutions causing the alteration were hypogene and possessed a rather high penetrating power. DESBOROUGH emphasises that the solutions which altered the basic rocks in southeastern Missouri were probably in the temperature range of high-temperature hydrothermal solution.

Alteration of ilmenite to sphene

This type of ilmenite alteration is clearly found not to be related either to weathered parts of the dykes, dyke rock adjacent to joints, or dyke rock adjacent to veinlets.

Excluding L1, the specimen from the eastern contact, alteration of ilmenite to sphene has been found in all other specimens from the Listed dyke and is the only form of ilmenite alteration in these specimens apart from one case of faint blue colouring found in L5.

Near the contacts and in the central part of the dyke (L6) the alteration is weak and scanty. It attains its strongest development at about three metres from the contacts.

Although alteration of ilmenite to sphene was first found in the Listed dyke, where this type of alteration is best developed, very careful inspection of the specimens from the Kås dyke has revealed that in some cases it is possible to find a few grains of ilmenite which show a weak alteration to sphene. In many of the Kås specimens however it has not been possible to detect this form of ilmenite alteration. No alteration is found closer than three metres to the western contact, closer than five metres to the eastern contact, and none in the central part of the dyke (K8), while weak and scanty alteration can be observed in the intervening parts of the dyke.

As in the case of the alteration of titanomagnetite to turbid sphene, and for the same reasons, the alteration of ilmenite to sphene is thought to have been caused by hypogene solutions with a rather high penetrating power.

Alteration of ilmenite to rutile

Alteration of ilmenite to rutile is unrelated to weathered parts of the dykes, and unrelated to dyke rock adjacent to joints, but the immediate contacts of both dykes are strongly attacked by this kind of alteration.

Except at the very contact alteration of ilmenite to rutile is completely absent from the Listed dyke, while in the Kås dyke this alteration has a rather widespread occurrence. In this dyke the alteration can in part be found clearly related to veinlets, so that in the immediate vicinity of the veinlets the ilmenite is strongly altered to rutile, the degree of alteration decreasing with increasing distance from the veinlets. However not all the veinlets show this relationship, and rather strongly developed alteration of ilmenite to rutile is also found in areas from which veinlets are absent. Accordingly no essential relationship exists between this type of alteration and the veinlets.

Apart from the concentration of alteration in the vicinity of the contacts and of some veinlets, the alteration to rutile shows a pronounced maximum in a zone in the western part of the Kås dyke which is almost coincident with one of the zones of strong development of the alteration of titanomagnetite to turbid sphene, but no similar maximum was found in the eastern part of the dyke corresponding to the other zone of strong alteration of titanomagnetite to turbid sphene.

The alteration of ilmenite to rutile, like the types of alteration previously discussed, is thought to have been caused by hypogene solutions. The penetration of these solutions has in part been guided by the contacts of the dykes and by veinlets. In the Kås dyke the solutions in places were also able to penetrate the rock without any such channelways, while in the Listed dyke the only way of access was along the contacts.

Ilmenite alteration of beach sand type

Ilmenite alteration of beach sand type is found only in the Kås dyke. None of the weathered specimens shows any trace of this type of alteration, and no connection with joints is found.

Alteration of beach sand type, together with alteration of ilmenite to rutile, is found concentrated in the area near the eastern border of the dyke, which is transected by small quartz veinlets, and in the immediate vicinity of some of the calcite veinlets. Concerning the calcite veinlets the strongest degree of alteration, beach sand type as well as rutile type, is found connected with E–W striking veinlets, while the N–S striking veinlets apparently only to a less extent are connected with alteration.

Besides this occurrence related to veinlets ilmenite alteration of beach sand type is found concentrated within the two metres closest to the eastern contact, and to a lesser extent in K5 (five metres from the western contact, where however alteration to rutile is strongly predominating), and is observed nowhere else in the dyke.

However ilmenite alteration of beach sand type is also found in the gneiss country rock unrelated to veinlets as such veinlets are absent from the gneiss. Because of the very restricted occurrence of beach sand type alteration in the dyke, when the immediate vicinity of veinlets is not taken into account, the author is not convinced that the beach sand type of alteration found in the gneiss is connected with the alteration in the dyke.

Concerning the origin of the beach sand type of alteration in the dyke, the connection with quartz veinlets and some of the calcite veinlets, together with the fact that none of the specimens intentionally collected from weathered parts of the dyke shows any trace of this alteration, leads the author to consider that this type of alteration is also caused by hypogene solutions.

Thus not only has ilmenite alteration of beach sand type been found for the first time in rocks in place, but furthermore under such conditions that a hypogene origin is indicated.

Density determinations

Saxov & Abrahamsen (1964) have determined the density of different specimens from the Kås dyke and the Listed dyke and found considerable variation within each of the dykes. They give the density of the Kås dyke as varying from 2.95 to 2.84 g/cm³, and that of the Listed dyke from 2.83 to 2.76 g/cm³.

In the Kås dyke the two extreme values 2.95 and 2.84 g/cm³ were both obtained on weathered specimens, which indicates that the cause of the variation is not different degrees of weathering. The present author thought that the variation was probably caused by the hypogene alteration of the ore minerals, mainly the alteration of titanomagnetite to turbid sphene, and of the mafic silicates, which the present paper has shown to be present in both the dykes.

In order to verify this, density determinations have been made on the specimens L2, L3, and L6. L2 and L3 represent extremes with respect to the alteration of titanomagnetite to turbid sphene in that whereas the titanomagnetite in L2 is practically unaltered, all the titanomagnetite in L3 is more or less strongly altered. The ratio of primary to secondary mafic silicates for L2 and L3 is respectively 0.3 and 0.1, whereas L6 with a ratio of 1.3 represents the least degree of silicate alteration found in the dykes. Most of the titanomagnetite in L6 is unaltered, but some grains show an alteration as strong as found in L3.

The density determination of different pieces all cut from L2 gave values around 2.80 g/cm³. The density of different pieces cut from L3 varies from 2.77 to 2.73 g/cm³, while the density of different pieces cut from L6 varies from 2.87 to 2.82 g/cm³.

The spread in the values of L3 and L6 is believed to be due to the strongly irregular distribution of the titanomagnetite alteration even within very small areas, while the fact that L6 gave higher values than L2 is probably due to the considerably weaker alteration of silicates in L6. Thus the alteration of the mafic silicates as well as the alteration of the ore minerals results in a decrease in the rock density.

Conclusions

The major forms of alteration described all imply the removal of iron. The question therefore arises what has happened to the iron carried away. The dykes are rather narrow and would not be expected to give rise to large concentrations of iron. However no unusual concentration of iron can be found at all in the vicinity of the dykes. Polished sections of the gneiss country rock bordering the Kås dyke and the Svaneke granite country rock bordering the Listed dyke show no evidence of any exceptional iron concentration.

The only sign of late iron concentration met with is found within the dykes themselves. Near the contacts of both dykes is found a network of thin veinlets, the width of which varies from about 10 µ to about 20 µ, and which are filled mainly with limonite. These limonite veinlets however can hardly account for all the iron removed during the alteration, and probably part of this iron was either carried rather far away, or deposited in the part of the rocks later removed by erosion.

Except for the casual formation of maghemite selvages along cracks in the titanomagnetite, the different types of alteration are all considered to have been caused by hypogene solutions, probably in the temperature range of high-temperature hydrothermal solution.

No orogenic, intrusive, or extrusive activity younger than the dolerite dykes is known from Bornholm. Thus there is no major event with which hydrothermal solutions, which could have influenced the dykes, can be connected. Signs of hydrothermal activity other than the alteration in the dykes do exist in the form of calcite veins in the Hammer granite (ROSENKRANTZ 1939), a minor copper mineralisation in the Svaneke granite (ØRSTED & ESMARCH 1819 and BØGVAD 1940), and alteration along veinlets in the Rønne granodiorite (JENSEN 1965). The age of these phenomena relative to the time of emplacement of the dolerite dykes is not known.

The lead mineralisation in the Nexø sandstone (ØRSTED & ESMARCH 1819 and PAULY 1944) and graphite veinlets likewise occurring in the Nexø sandstone (unpublished observation by the author) are however clearly younger than the dolerites.

Although it is thus possible to find signs of hydrothermal activity younger than the dolerite dykes, the author is inclined to seek the source of the altering solutions within the dykes themselves and thinks that the solutions causing the alteration were expelled from still molten parts of the magma at deeper levels and forced into already solidified parts of the dykes at higher levels. The author prefers to term solutions formed as described above hydrothermal, but would emphasise that the source of these solutions was the dolerites themselves.

FINAL REMARKS

The two dykes investigated in the present paper show considerable similarity in chemical composition. The mineralogical differences are clearly due in part to such small differences as do exist in the chemical composition of the dykes, but to a great extent must be attributed to the effect of different rate and degree of increase in PH_2O and PO_2 with progressing solidification.

At the end of this work therefore it seems proper to stress the importance of PH_2O and PO_2 in the development of igneous rocks.

Because of the dependence of the An content of plagioclases on PH_2O, this pressure might under certain circumstances determine whether a magma crystallises as a basalt or as an andesite.

Fe-Ti-oxides are common constituents of igneous rocks and their development is strongly dependent on PO_2. Although different development of Fe-Ti-oxides has not so far resulted in different rock names, the differences in these minerals caused by PO_2 are certainly not less conspicuous than the changes in plagioclase composition due to PH_2O.

The effect of PO_2 on the development of Fe-Ti-oxides however is often not appreciated. The development of titanomagnetites has frequently been stated as being dependent only on temperature of formation and rate of cooling. It is now clearly established that it is not ilmenite, but ulvöspinel, which is capable of forming extensive solid solutions with magnetite as titanomagnetites. Therefore it is necessary to take into consideration not only temperature and rate of cooling, but also PO_2.

When titanomagnetite is cooled sufficiently slowly under oxidising conditions, the ulvöspinel part of the titanomagnetite will oxidise to a three to one mixture of ilmenite and magnetite. Of these two products only magnetite can be accommodated in the cubic titanomagnetite phase, while the ilmenite forms lamellae parallel to {111} of the cubic phase. To what extent the ulvöspinel dissolved as titanomagnetite is subjected to this transformation depends on both PO_2 and rate of cooling. If PO_2 has not been sufficiently high to convert all the dissolved ulvöspinel to ilmenite before a temperature of 700–600°C is reached, the remaining part will exsolve, forming a fine cloth-like pattern in the titanomagnetite. This exsolved ulvöspinel may later be oxidised to ilmenite.

If titanomagnetite is cooled slowly under reducing conditions, no ilmenite will be formed, because the titanomagnetite is then stable until the 700–600°C where exsolution of ulvöspinel will take place.

Although high temperature of formation and slow cooling thus are not the only determining factors in the formation of ilmenite from titanomagnetite, the fact that this formation is not due to true exsolution, but is initiated by an oxidation process, does not affect the basic ideas concerning the effects of temperature and rate of cooling.

However LINDSLEY (1962 and 1963) has shown that when a member of the magnetite-ulvöspinel series is crystallising in equilibrium with a member of the ilmenite-hematite series, the compositions of both members are unique functions of temperature and PO_2. Under such equilibrium conditions therefore the maximum amount of Ti which is available in titanomagnetites for formation of ilmenite as the result of oxidation during cooling depends not only on the temperature of formation of the original titanomagnetite, but also on the original PO_2.

Concerning the effect of the rate of cooling it seems reasonable to assume that a cooling rate, which is high enough to prevent a true exsolution process, must also be high enough to prevent the formation of ilmenite from ulvöspinel in solid solution, because this latter process probably is best characterised as an exsolution process which has a previous oxidation process as a precondition.

RAMDOHR (1960) states that unexsolved titanomagnetites are frequently found in effusive rocks, and the present author has found titanomagnetite with ilmenite lamellae parallel to {111} to be a common constituent of basalts during the examination of more than 100 polished sections. As PO_2 in basalts is obviously high enough not to be a limiting factor (except for extraordinary cases such as basalts containing graphite and native iron), it thus seems reasonable to assume that the rate of cooling in basaltic lavas covers an interval around the critical value, where the cooling rate will prevent the formation of ilmenite from titanomagnetites.

The Fe-Ti-oxides found in the Kås dyke and the Listed dyke are thought to be rather typical of dolerite dykes, although it is not claimed that the cloth-like pattern indicating the former presence of ulvöspinel can be observed in all cases. The author has thus examined dykes where the titanomagnetite shows an extremely fine network of ilmenite lamellae parallel to {111} on such a minute scale that the finest lamellae are hardly discernible with the highest magnification. In these cases no cloth-like pattern could be detected, but the extremely fine ilmenite network could very well be the result of complete reorganisation from {100} to {111} of ilmenite formed by oxidation of exsolved ulvöspinel.

While obviously there are some differences between the Fe-Ti-oxides from individual dykes, and between those of individual basalt flows, there is however a striking difference in the development of Fe-Ti-oxides between dolerites and basalts as groups.

These differences between dolerites and basalts are not only caused by the higher PO_2 generally prevailing in basalts, but are to a great extent due to the fact that basalts are generally subjected to more than one cooling cycle, as each flow is reheated by the outpouring of the next flow.

Basalts are thus characterised by the extensive development of "Hitzemartit". This is produced when titanomagnetite with ilmenite lamellae is reheated, resulting in exchange of molecules between the rhombohedral phase and the cubic phase. From the cubic phase the rhombohedral ilmenite phase receives Fe_2O_3, which is taken into solid solution resulting in a higher reflectivity of the ilmenite lamellae, which also become broader. From the ilmenite phase a corresponding amount of $FeTiO_3$ is given off to the cubic phase, where it reacts with the surplus of FeO created here by the loss of Fe_2O_3 to the rhombohedral phase, forming Fe_2TiO_4 which is taken into solid solution. This results in a darkening of the cubic phase. Heating experiments have shown that further advance of this process results in a decrease in area of the rhombohedral lamellae, which begin to resemble hematite in appearance (VINCENT, WRIGHT, CHEVALLIER & MATHIEU 1957).

Besides this special development of members of the magnetite-ulvöspinel and ilmenite-hematite solid solution series, the Fe-Ti-oxides of basalts are further complicated by the frequent occurrence of pseudobrookite, Fe_2TiO_5. This mineral forms under high temperature and high PO_2, and in basalts intergrowths of pseudobrookite and hematite are frequently found under such conditions that it can be concluded that the intergrowths have originated from previous titanomagnetite with ilmenite lamellae, so that pseudobrookite now preferentially occupies the position of former ilmenite, and hematite the position of former magnetite. Pseudobrookites form a solid solution series, Fe_2TiO_5–$FeTi_2O_5$, the thermodynamics of which however are not very well known, and the series probably continues beyond $FeTi_2O_5$ towards Ti_3O_5.

Ilmenite occurring as free grains in basalts often contains enough Fe_2O_3 to give the grains a reflectivity visibly higher than that of pure ilmenite. Such Fe_2O_3-rich members of the ilmenite-hematite series frequently can be seen to have been oxidised to a mixture of rutile and hematite.

Finally it is worth mentioning that in basalts rather extensive maghemite formation is frequently met with. In this connection however it should be noted that the author has also seen dykes where maghemite formation is more pronounced than in the Kås dyke and the Listed dyke.

The present paper has shown that many interesting mineralogical variations exist between contact and centre of the two dykes investigated.

These variations record the development of the dykes, and it is seen that important parts of this development will not be elucidated, if the sampling is done by taking one specimen from near the contact and another from the central part of the dyke, not even when the dykes in question are less than 40 m wide. Furthermore it is important that investigations are not limited to the non-opaque minerals, as the opaque minerals in many cases present a record of stages in the development, which can not be obtained from the non-opaque minerals. The Fe-Ti-oxides are of special importance in the understanding of the development, as these minerals, when thoroughly investigated, not only give the conditions at the time of their formation, but because of the possibility of continuous reactions by exsolution and reduction-oxidation processes can record the conditions from the moment they were formed until the very end of the igneous development.

In the investigation of these dykes emphasis has been laid on an adequate sampling and the opaque minerals have been studied in detail. However the full story of the development of these two dykes can not be given, because only horizontal variations have been investigated. It would indeed have been interesting if similar cross sections could have been investigated at different levels in the dykes. The need of such investigations is so much more important as it seems possible that those differences which are caused by the differences in PH_2O and PO_2 are the result of different positions with respect to height or depth of the cross sections investigated in the two dykes. It seems reasonable to assume, that from the time when solidification in the uppermost part of a dyke has progressed far enough to prevent the free escape of gases, PH_2O and PO_2 will increase with increasing height in dyke. According to this theory the section through the Listed dyke probably represents a relatively higher level than the section through the Kås dyke.

In the case of the Kås dyke and the Listed dyke unfortunately only one level is accessible, but when adequate samples from other dykes are obtained, the interesting problem of differentiation with height in dykes will be the subject of further studies.

DANSK RESUMÉ

Dette arbejde er en undersøgelse af mineralerne i to diabasgange, Kås gangen og Listed gangen på Bornholm.

Beliggenheden af de undersøgte prøver fremgår af Tabel I, side 375. Gangbjergarternes kemiske sammensætning ses af Tabel II, side 379, norm og modus af Tabel III, side 380. Den mineralogiske sammensætning af Kås gangen ligger lige på grænsen mellem andesit og basalt, medens Listed gangen falder på basaltsiden af grænsen, men tæt ved denne. Gangene er begge tholeiitiske og har doleritisk til subdoleritisk tekstur.

Al_2O_3-indholdet i bjergarterne og anorthitindholdet i plagioklaserne stiger i begge gangene fra kontakterne indefter mod midten. Stigningen er væsentlig mere udpræget i Listed end i Kås gangen (Tabel IV, side 382 og Tabel VII, side 384). Såvel stigningen i Al_2O_3-indhold som stigningen i anorthitindhold i plagioklasen skyldes formentlig en stigning af vanddamptrykket, efterhånden som størkningen skrider frem; er denne tolkning rigtig, kan man slutte, at stigningen i vanddamptryk må have været væsentlig højere i Listed end i Kås gangen.

Kås gangen indeholder tre forskellige pyroxener: augit, hypersthen og pigeonit. Nær kontakterne finder man augit og pigeonit, men mellem fem og ti meters afstand fra kontakterne afløses pigeonit af hypersthen, der sammen med augiten fortsætter til gangens midte. I Listed gangen forekommer kun én pyroxen, en augit af samme sammensætning som augiten i Kås gangen (Tabel V, side 384).

Mineralernes kornstørrelse stiger i begge gange fra kontakterne indefter de første tre til fem meter, hvorefter kornstørrelsen i regelen holder sig konstant (Tabel VIII, side 386).

Mineralvariationen tværs over gangene ses af Tabel IX, side 388.

Bortset fra malmmineralerne er de mørke silikater de mineraler, der har været udsat for de kraftigste sekundære omdannelser. Forholdet mellem primære og sekundære mørke silikater er afbildet grafisk i Fig. 3 og Fig. 4, side 391.

Krystallisationsforløbet er: ilmenit, titanomagnetit, olivin, pyroxen, plagioklas og til sidst kvarts og biotit, hvis indbyrdes aldersforhold ikke er fastslået. Denne rækkefølge har formentlig været gældende under størstedelen af størkningsperioden, men umiddelbart ved størkningens begyndelse, da magmaet antagelig var vandfrit, dannedes plagioklas meget tidligt, muligvis endda som det først udskilte mineral; men efterhånden som vanddamptrykket steg, forsinkedes plagioklasdannelsen. Hvor apatit findes, ses dette mineral at være dannet før de øvrige, men nærmere ved kontakterne end halvanden meter forekommer apatit ikke. Det er derfor sandsynligt, at de forhold, der herskede umiddelbart ved størkningens begyndelse, ikke tillod dannelsen af apatit, men da forholdene senere ændredes, udskiltes apatit sammen med de tidlige malmmineraler.

Titanomagnetiten, der i uafblandet form er en fast opløsning mellem magnetit, Fe_3O_4, og ulvöspinel, Fe_2TiO_4, har gennemgået en ret kompliceret udvikling i disse diabasgange. Den oprindelige, uafblandede titanomagnetit har haft en sammensætning nærmere ulvöspinel end magnetit. På grund af oxidation ved temperaturer over ulvöspinellens afblandingstemperatur, der er 600–700°C, er en del af titanomagnetitens ulvöspinelindhold blevet oxideret til ilmenit, $FeTiO_3$, der ikke kan akkomoderes i titanomagnetiten, men udskilles som lameller efter basis, der er arrangeret efter titanomagnetitens oktaederretninger. Muligvis har en del af ilmeniten kunnet koncentreres til mindre samlede masser af ilmenit i stedet for ilmenitlameller. Da afkølingen nåede ulvöspinellens afblandingstemperatur, omdannedes den resterende del af titanomagnetiten (hovedparten af den oprindelige titanomagnetit) til et meget finmasket netværk af ulvöspinel og magnetit, hvor ulvöspinellen er arrangeret som små stave efter magnetitens terningretninger. I dette netværk har magnetit og ulvöspinel været til stede i omtrent lige store mængder. Kun ulvöspinelafblandingens karakteristiske tekstur viser i dag den tidligere tilstedeværelse af ulvöspinel, idet denne senere er blevet fuldstændig oxideret til ilmenit. Denne oxidation af allerede afblandet ulvöspinel er dels sket ud fra oxidationscentre, jævnt fordelt i titanomagnetitens grundmasse (den oprindelige titanomagnetit minus ilmenit dannet før afblandingen af ulvöspinel), dels ud fra ganske tynde ilmenitlameller, der er dannede ved oxidation af ulvöspinel forekommende i fast opløsning som titanomagnetit.

*Den ilmenit, der er fremkommet ved oxidation af afblandet ulvöspinel, har ind*taget ulvöspinellens plads i afblandingsmønsteret; men nogle steder ses denne ilmenit ganske tydeligt at være blevet omlejret, således at den er blevet arrangeret efter magnetitens oktaederretninger, ligesom ilmenit dannet over ulvöspinellens afblandingstemperatur. Oxidationen af afblandet ulvöspinel må være foregået ved temperaturer under 700°C og ifølge VINCENT (1960) sandsynligvis ved temperaturer helt ned til 200–100°C. Omlejringen fra terningretninger til oktaederretninger af den fremkomne ilmenit må derfor være sket ved endnu lavere temperaturer.

Sammensætningen af den oprindelige, uafblandede titanomagnetit er beregnet til at ligge mellem 30% Fe_3O_4, 70% Fe_2TiO_4 og 40% Fe_3O_4, 60% Fe_2TiO_4. Ilmenitens sammensætning er ved hjælp af røntgenundersøgelser og analyser udført med mikrosonde bestemt til 96% $FeTiO_3$, 3% Fe_2O_3, 1% $MnTiO_3$, og det gælder såvel for ilmeniten i selvstændige korn som for ilmenit dannet ved oxidation af ulvöspinel, og dette sidste uanset om oxidationen er sket over eller under ulvöspinellens afblandingstemperatur.

Fordelingen af malmmineraler tværs over gangene fremgår af Tabel XI, side 407, og forholdet mellem mængderne af ilmenit og titanomagnetit er afbildet grafisk i Fig. 5 og Fig. 7, side 409. Kurvernes form skyldes antagelig, at ilmenit er det først dannede af de to mineraler og først senere ledsagedes af samtidig titanomagnetit*udskillelse, der imidlertid er ophørt igen mod slutningen af størkningen, således* at ilmenit atter er blevet det eneste Fe-Ti-oxid. Årsagen til titanomagnetitdannelsens ophør formodes at være en stigning i ilttryk, der har bevirket, at ilmenit er blevet den eneste stabile fase af Fe-Ti-oxid. Det ses af kurvernes form, at stigningen i ilttryk må have været væsentlig kraftigere og have sat ind tidligere i Listed gangen end i Kås gangen. Dette er i god overensstemmelse med det fundne forhold, at stigningen i vanddamptryk må have været væsentlig kraftigere i Listed end i Kås gangen. Ifølge OSBORN (1959) er nemlig dissociationen af vand langt den vigtigste kilde til ilt i et krystalliserende magma.

Sammensætningen af ilmenit og af den oprindelige titanomagnetit kan anvendes *som geologisk termometer* (LINDSLEY *1963*). *Da sammensætningen af den oprindelige* titanomagnetit kun er tilnærmet bestemt, opnås der i dette tilfælde et ret stort interval, nemlig 950–870°C, for det tidsrum hvor ilmenit og titanomagnetit udskiltes samtidigt. Da ilmenitdannelse har fundet sted i nogen tid, inden den første titanomagnetit fremkom, må størkningen være begyndt ved noget højere temperatur.

Der forekommer fem forskellige sulfidmineraler i gangene: magnetkis, svovlkis, markasit, kobberkis og pentlandit, men det samlede sulfidindhold er meget lavt, 0.3% i Kås gangen og mindre end 0.2% i Listed gangen. Sulfiderne er dannede meget sent, da de blandt andet findes i sprækker gennem silikater og titanomagnetit.

Fe-Ti-oxiderne har i ret stor udstrækning været udsat for senere omdannelse af forskellige former. Mest udbredt er omdannelse af titanomagnetitens grundmasse til titanit, der fremtræder så grumset, at mineralet vanskeligt kan genkendes i gennemfaldende lys. Denne særlige fremtræden skyldes antagelig uomdannede rester af magnetit og ilmenit, der forekommer finfordelt i titaniten. Udbredelsen af denne form for omdannelse veksler stærkt fra sted til sted, således kan man ofte inden for områder mindre end 1 mm^2 finde både fuldstændig uangrebet titanomagnetit og stærkt omdannet titanomagnetit. Det er interessant at se, at selv i de kraftigst omdannede partier kan man ofte endnu tydeligt iagttage mønsteret efter ulvöspinelafblandingen. Dette tyder på, at magnetitdelen og ilmenitdelen af titanomagnetitgrundmassen omdannes på forskellige måder. Selv om omdannelsen veksler stærkt selv inden for meget små områder, kan man iagttage, at omdannelsen stort set er koncentreret i de samme dele af gangene som omdannelsen af de mørke silikater (Fig. 3 og Fig. 4, side 391).

Omdannelsen af titanomagnetit til grumset titanit er formentlig hovedårsagen til de ret forskellige værdier af massefylden, der opnås for disse gange (SAXOV & ABRAHAMSEN 1964).

Langt mindre udbredt end omdannelsen af titanomagnetitgrundmassen forekommer omdannelse af ilmenit til titanit, der er kraftigst udviklet i Listed gangen, men selv her i regelen begrænset til den umiddelbare nærhed af korngrænser og sprækker gennem ilmeniten. Titaniten fremkommet ved omdannelse af ilmenit er ikke grumset og kan let genkendes i gennemfaldende lys.

Ilmenitomdannelse til rutil er kraftigst udviklet langs kontakterne af begge gange. I Listed gangen forekommer omdannelse af ilmenit til rutil kun ved kontakten. I Kås gangen træffes denne omdannelsesform desuden i forbindelse med tynde kvartsslirer og i forbindelse med nogle af de kalkspatårer, der gennemsætter denne gang, samt desuden i et område i den vestlige del af gangen, nogenlunde sammenfaldende med det bælte, der her findes med kraftig omdannelse af titanomagnetitgrundmassen. I det tilsvarende bælte i den østlige del af gangen er omdannelsen af ilmenit til rutil ikke særlig udpræget.

Lokalt i Kås gangen, blandt andet i tilknytning til nogle af kalkspatårerne, træffes endnu en form for ilmenitomdannelse. Denne omdannelsesform er interessant derved, at den hidtil kun er beskrevet fra tungsandsforekomster i tropiske og subtropiske områder. Omdannelsesproduktet er mere gennemskinneligt og har en større refleksionsevne end ilmenit. Dets gitter ligner imidlertid ilmenitgitteret meget.

For alle de beskrevne omdannelsesformer gælder det, at omdannelsesproduktet er fattigere på jern end udgangsmaterialet. Omdannelserne har derfor formentlig medført en borttransport af jern, men bortset fra talrige, ganske tynde, delvis limonitfyldte slirer der forekommer ved kontakten af begge gangene, er der ikke fundet noget, der kan vise, hvor det borttransporterede jern er endt.

Det er forfatterens opfattelse, at de forskellige her omtalte omdannelsesformer alle skyldes hypogene opløsninger. DESBOROUGH (1963) har undersøgt omdannelse af titanomagnetit til grumset titanit i basiske bjergarter fra Missouri, U.S.A. og anfører, at omdannelsen sandsynligvis skyldes hydrotermale opløsninger af høj temperatur.

Selv om der fra Bornholm kendes forskellige tegn på hydrotermal aktivitet yngre end diabasgangene, antages alle de beskrevne omdannelser at skyldes opløsninger stammende fra diabaserne selv. Forfatteren formoder, at opløsninger dannede i de dybere endnu flydende dele af magmaet er presset op gennem allerede størknede dele af gangene på højere niveau, hvor de har forårsaget omdannelserne.

De mineralogiske forskelle mellem de to undersøgte gange beror i høj grad på forskellene i vanddamptryk og i ilttryk, idet disse to faktorer har stor indflydelse på udviklingen af magmabjergarter. Da plagioklasens anorthitindhold er afhængig af vanddamptrykket, vil dette således i visse tilfælde kunne være afgørende for, om et magma krystalliserer som en basalt eller som en andesit. Selv om forskelle i ilttryk næppe vil kunne resultere i fremkomsten af bjergarter, der ligefrem må betegnes med forskellige navne, kan ilttrykkets indflydelse på magmabjergarternes udvikling ingenlunde siges at være mindre påfaldende end vanddamptrykkets indflydelse. Ilttrykket gør sig først og fremmest gældende ved udviklingen af Fe-Ti-oxiderne, der er almindeligt forekommende bestanddele af magmabjergarter, og som udviser meget iøjnefaldende forskelligheder i udvikling. Tidligere har man anset udviklingen af Fe-Ti-oxiderne for kun at afhænge af dannelsestemperaturen og afkølingshastigheden. Det er imidlertid nu hævet over enhver tvivl, at ilttrykket i mindst lige så høj grad som dannelsestemperatur og afkølingshastighed er bestemmende for udviklingen af Fe-Ti-oxiderne.

Den udvikling Fe-Ti-oxiderne har gennemgået i de undersøgte diabasgange fra Bornholm, er antagelig ret typisk for diabaser, men det finmaskede netværk efter ulvöspinelafblandingen forekommer ikke i alle diabaser. Selvom der således er nogle forskelligheder i Fe-Ti-oxidernes udvikling i forskellige diabasgange, er der imidlertid meget slående forskelle mellem diabaser og basalter som grupper. Disse forskelle skyldes i høj grad, at ilttrykket almindeligvis er højere i basalter, hvilket blandt andet medfører fremkomsten af pseudobrookit, en fast opløsning mellem Fe_2TiO_5 og $FeTi_2O_5$ der dannes under høj temperatur og højt ilttryk. Udviklingen af Fe-Ti-oxider i basalter kan imidlertid yderligere kompliceres af den omstændighed, at basalter ofte udsættes for mere end én afkølingscyklus, idet hvert lavalag genopvarmes af det næste lavalag, der flyder ud over det.

Da det må antages, at såvel vanddamptryk som ilttryk stiger med stigende højde i en gang, når først størkningen i gangens øvre dele er så vidt fremskredet, at gasser ikke længere kan undslippe, kan de mineralogiske forskelle mellem Kås gangen og Listed gangen tænkes fremkommet ved, at det undersøgte tværsnit af Listed gangen repræsenterer et relativt højere niveau end det undersøgte tværsnit af Kås gangen. Denne mulighed bestyrkes i nogen grad af, at de rent kemiske forskelle mellem de to gange er ret små. De undersøgte tværsnits relative højde kan desværre ikke fastslås, og ingen af gangene giver mulighed for snit i mere end ét niveau. Det vil derfor være af stor betydning fremtidigt at få undersøgt de mineralogiske variationer på forskellige niveauer af én og samme gang.

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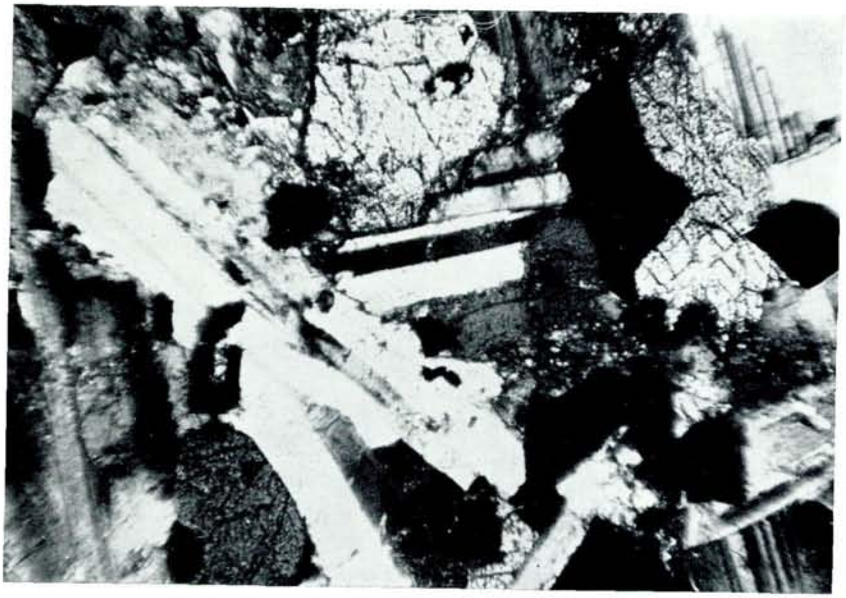

Fig. 1. Transmitted light, crossed polars. ×50. K8.
Plagioclase, pyroxene, and Fe-Ti-oxides.

Fig. 2. Transmitted light, crossed polars. ×50. L6.
Plagioclase, pyroxene, Fe-Ti-oxides, and olivine (in centre).

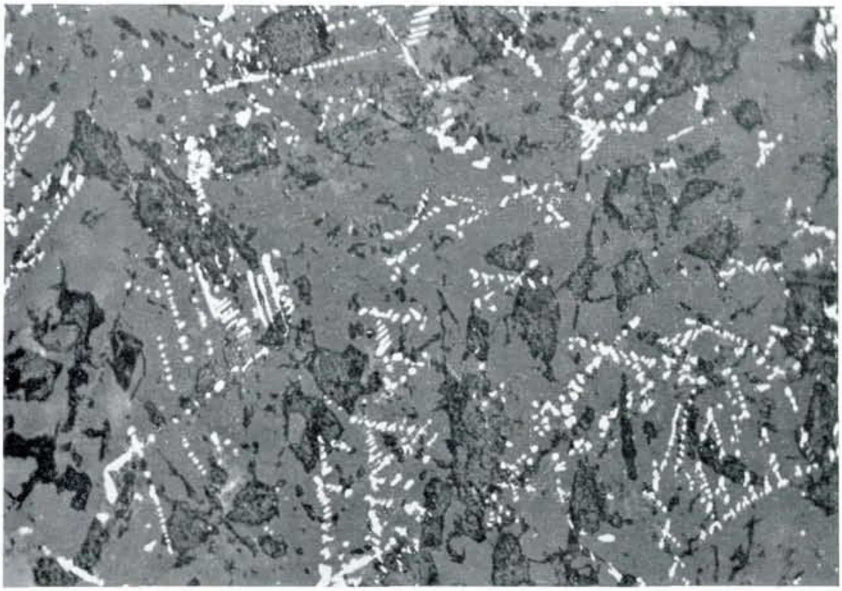

Fig. 1. Reflected light, polariser only. ×220. K2.
Skeleton crystals of ilmenite.

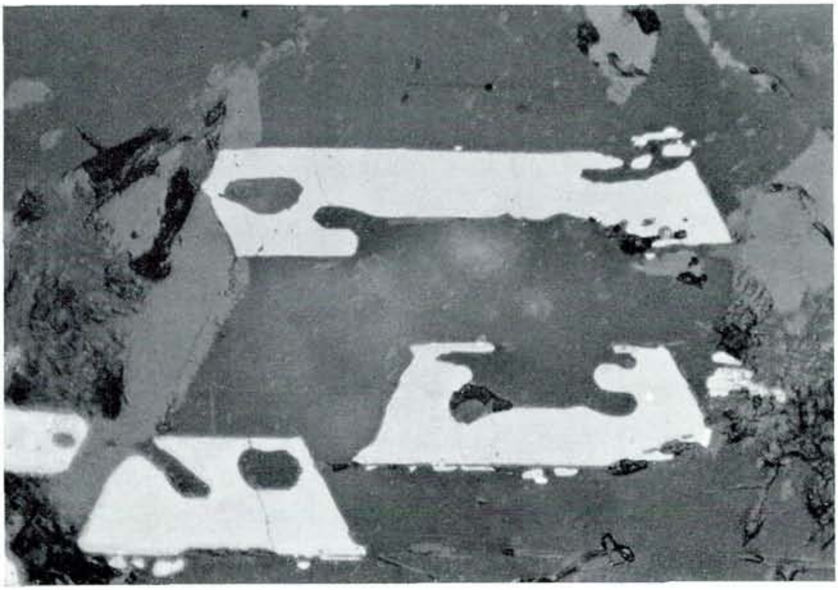

Fig. 2. Reflected light, polariser only. ×600. K3.
Ilmenite plates parallel to {0001}. Note the characteristic protuberances, and the smaller plates below two of the main plates.

Fig. 1. Reflected light, polariser only. ×220. K3
Ilmenite. The row of grains in the middle of the picture shows the development from skeleton crystals to plates parallel to {0001} with protuberances step by step from left to right.

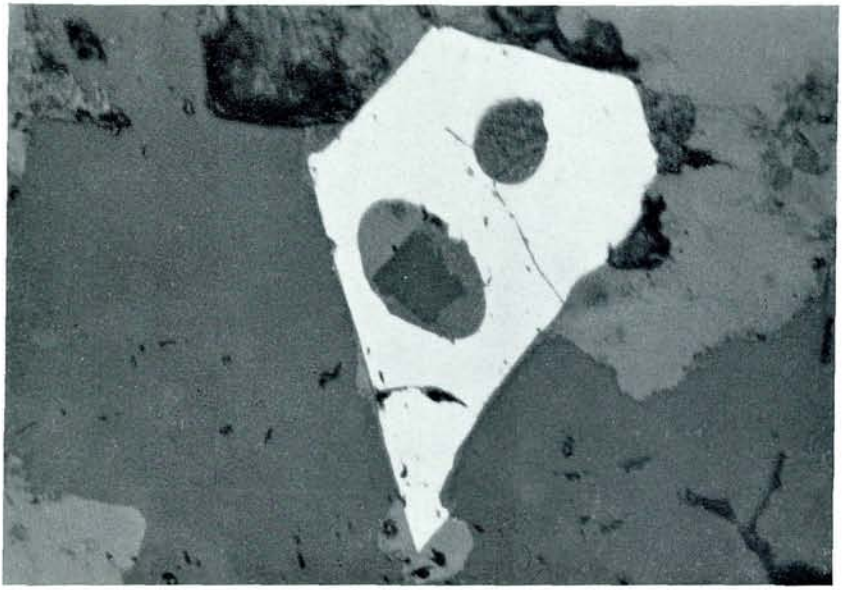

Fig. 2. Reflected light, polariser only. ×300. K8.
Idiomorphic ilmenite with two globules. The one to the left contains at least three different silicates.

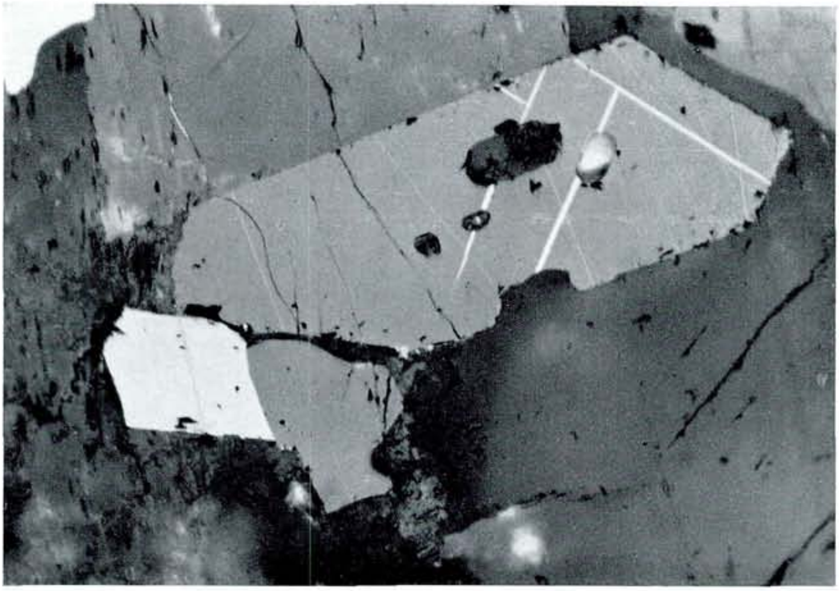

Fig. 1. Reflected light, polars 6° from crossed position. ×220. K8.
Idiomorphic ilmenite. The one grain with elongated globules and thin lamellar twins on the rhombohedron. The other grain with single twins.

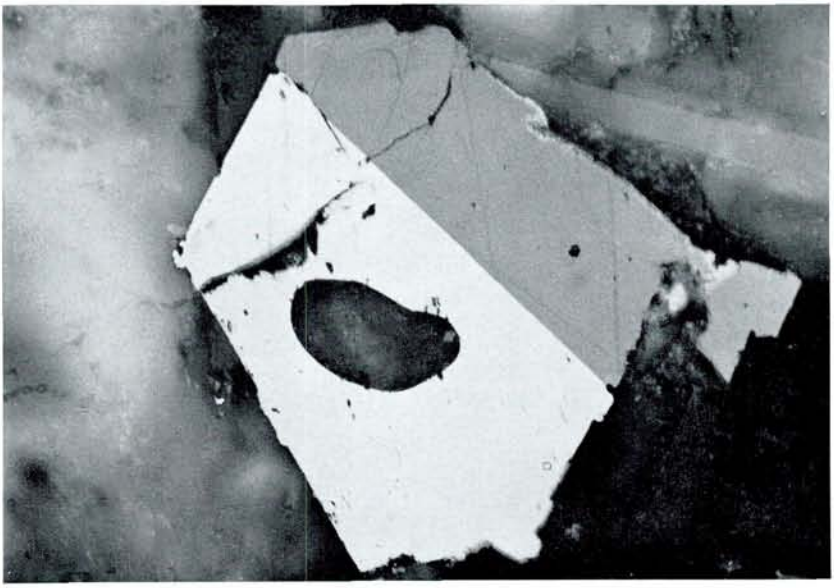

Fig. 2. Reflected light, polars 4° from crossed position. ×220. K8.
Idiomorphic ilmenite with single twins,
one of which contains an elongated globule.

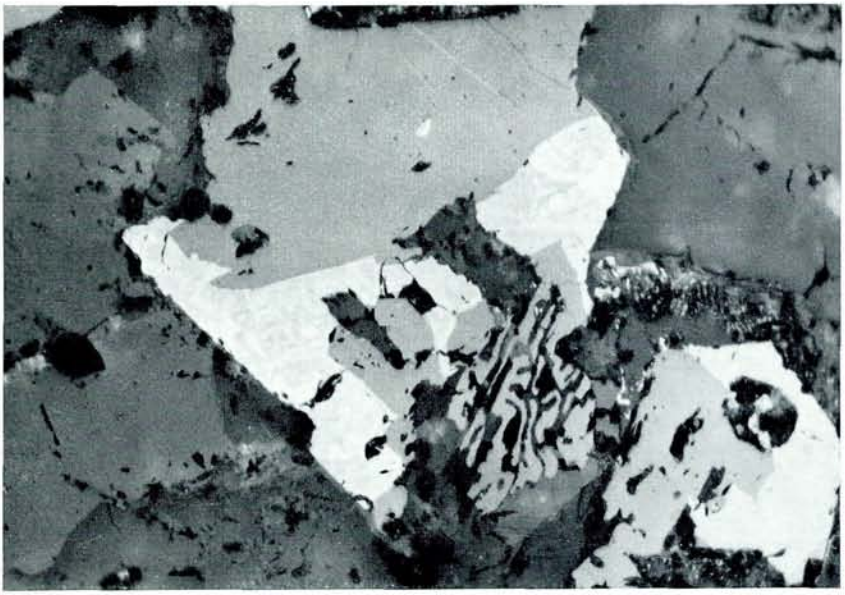

Fig. 1. Reflected light, polars 6° from crossed position. ×220. K8.
Composite grain with ratio of ilmenite area to magnetite area somewhat larger than 4/1. This grain therefore could not have developed from one original solid solution, but was probably formed by titanomagnetite filling out part of the area intervening between two already formed ilmenite grains, one of which is developed as a myrmekite.

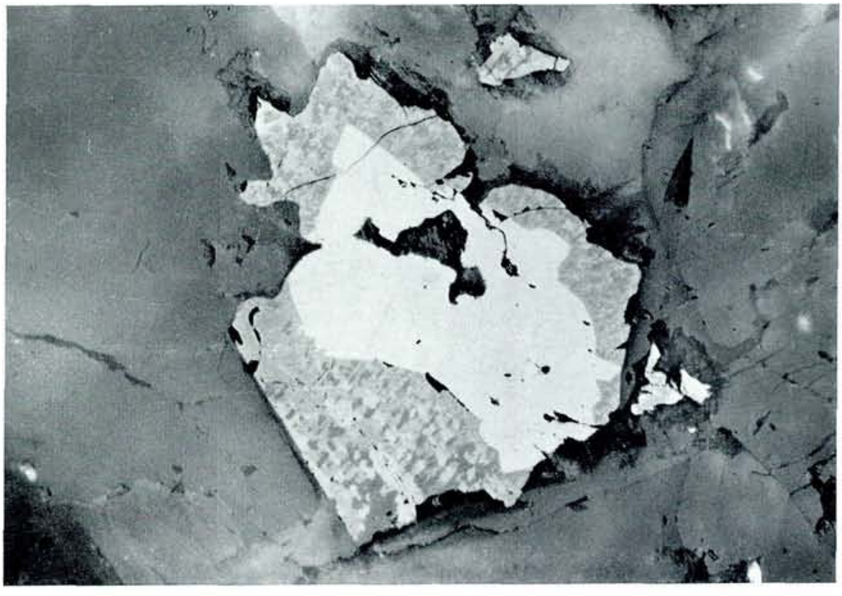

Fig. 2. Reflected light, polars 4° from crossed position. ×220. K8.
Composite grain with ilmenite as a core.

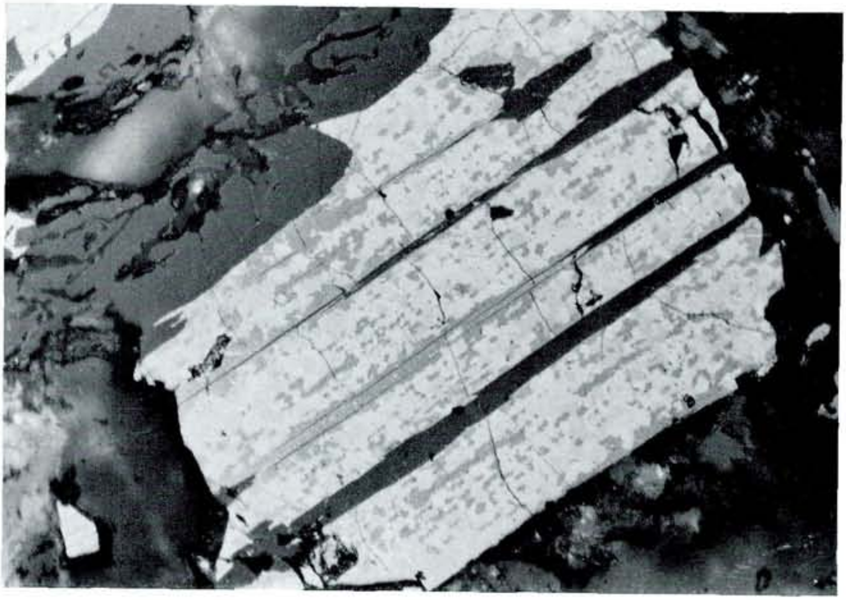

Fig. 1. Reflected light, polars 4° from crossed position. ×220. K7.
Ilmenite lamellae of Group 1 and Group 3. One of the Group 1 lamellae continues as two thin lamellae of Group 3. It is clearly seen that only Group 3 lamellae have influenced the orientation of the ilmenite part of the neighbouring titanomagnetite. Note cracks arranged as "ladder veins" between ilmenite lamellae.

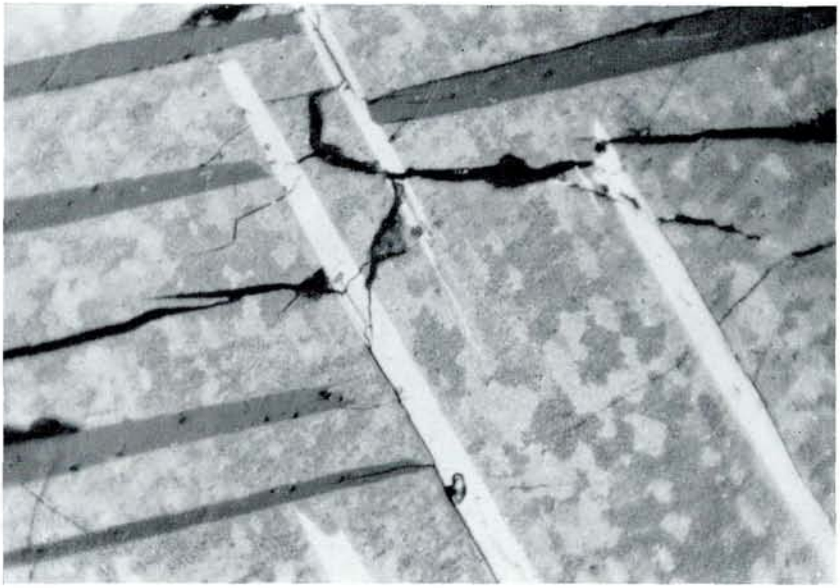

Fig. 2. Reflected light, polars 6° from crossed position. ×800. Oil immersion. K7.
Regularly distributed ilmenite lamellae of Group 2 without influence on the orientation of the ilmenite part of the neighbouring titanomagnetite. Curving cracks as well as straight cracks following ilmenite lamellae can be seen. None of the cracks influences the orientation of the titanomagnetite, the lobal pattern of which is clearly seen throughout the picture.

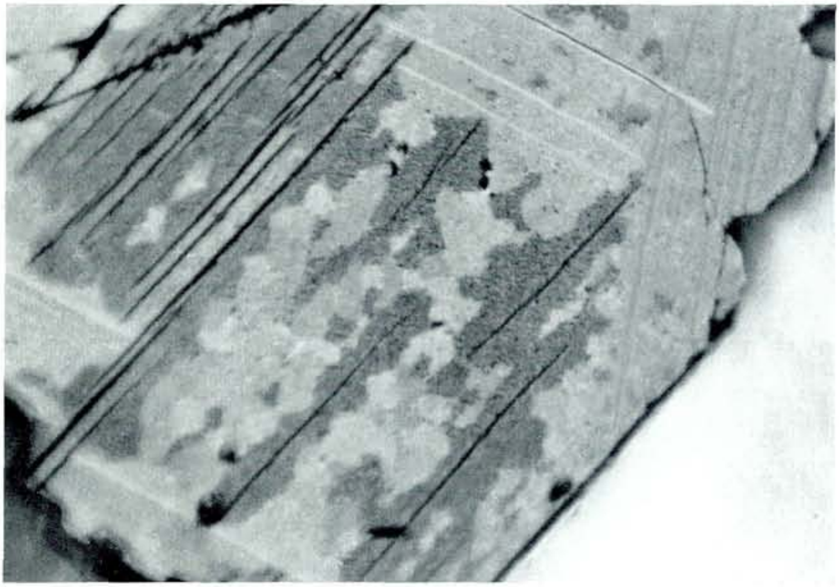

Fig. 1. Reflected light, polars 6° from crossed position. ×800.
Oil immersion. K7.
Regularly distributed thin tapering ilmenite lamellae of Group 3, the influence of which on the orientation of the ilmenite part of the neighbouring titanomagnetite is clearly seen.

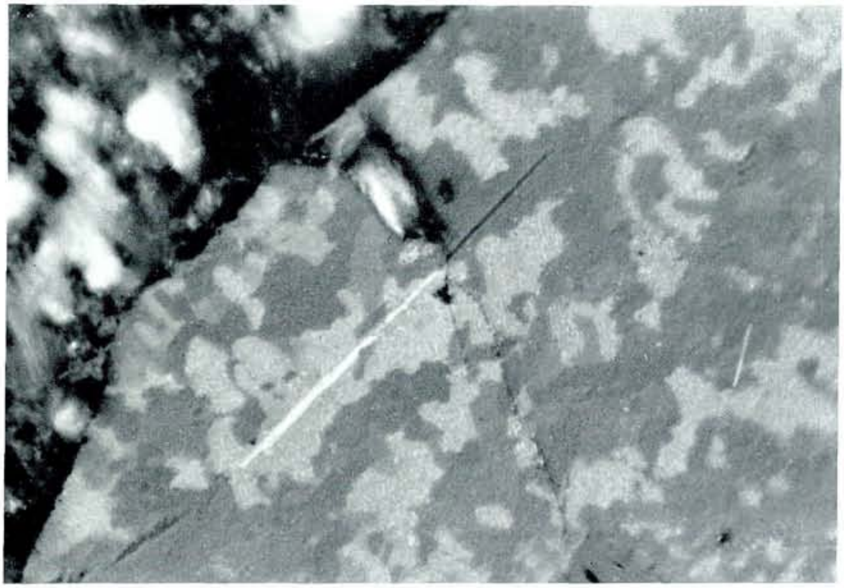

Fig. 2. Reflected light, polars 2° from crossed position. ×800.
Oil immersion. K8.
NE–SW across the picture is an ilmenite lamella, the north-eastern third of which has the right orientation i. e. the ordinary ray is parallel to the length direction, whereas the south-western two thirds of the lamella has the extraordinary ray parallel to the length direction which therefore could not possibly lie in {0001}. The wrongly orientated part is more irregular than the part with the right orientation. Both parts influence the orientation of the ilmenite in the neighbouring titanomagnetite.

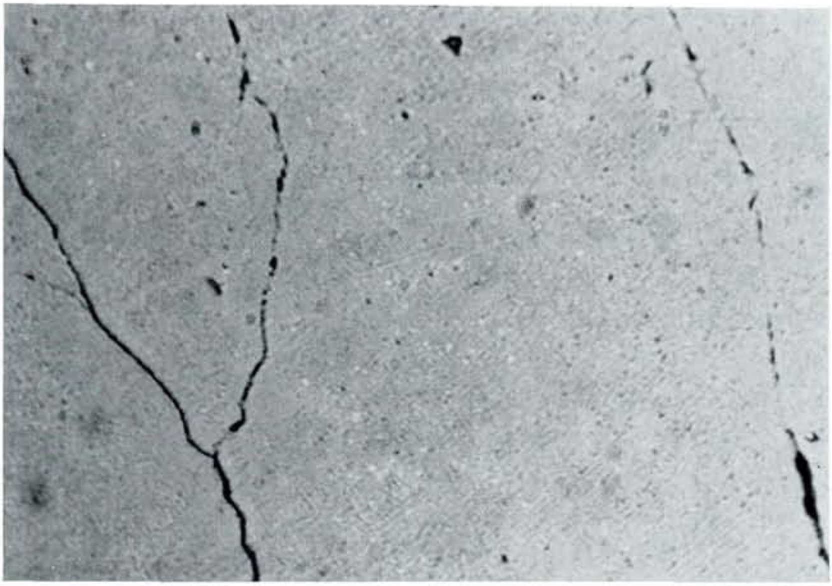

Fig. 1. Reflected light, polariser only. ×1450. Oil immersion. K8.
The ulvöspinel exsolution pattern as seen in the titanomagnetite groundmass.

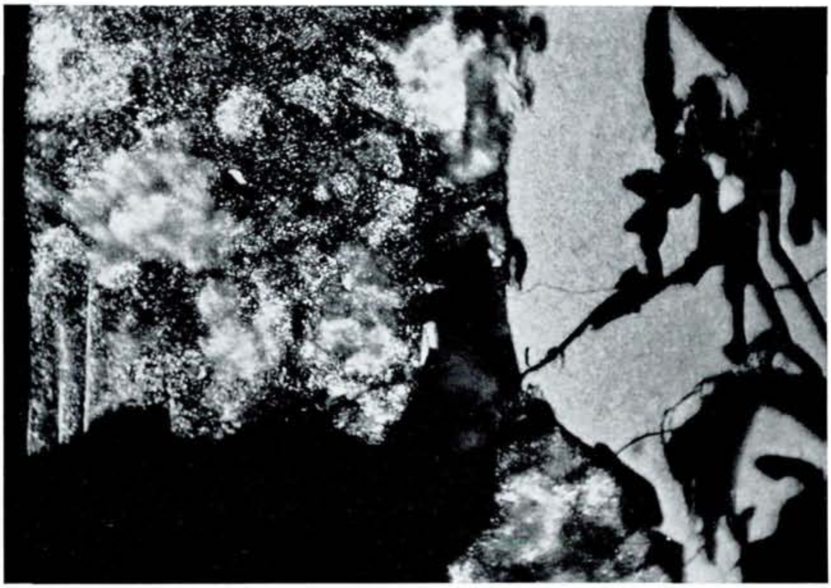

Fig. 2. Reflected light, polariser only. ×800. Oil immersion. K13.
To the left is seen former titanomagnetite which is now altered to turbid sphene. In spite of the alteration the ulvöspinel exsolution pattern can still be seen. To the right is seen ilmenite with alteration of beach sand type.

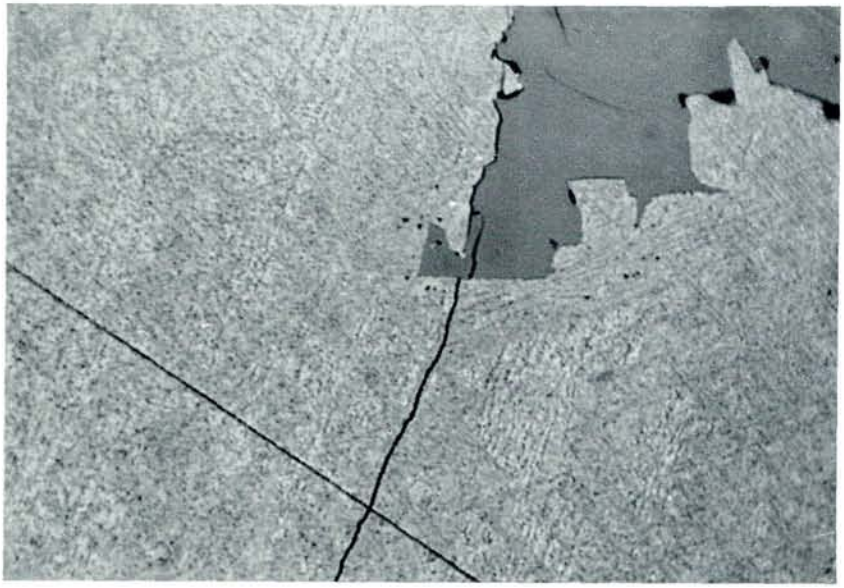

Fig. 1. Reflected light, polariser only. ×1100. *Oil immersion.* K*8*.
Titanomagnetite groundmass in which the ilmenite formed from already exsolved ulvöspinel is reorganised from {100} to {111}.

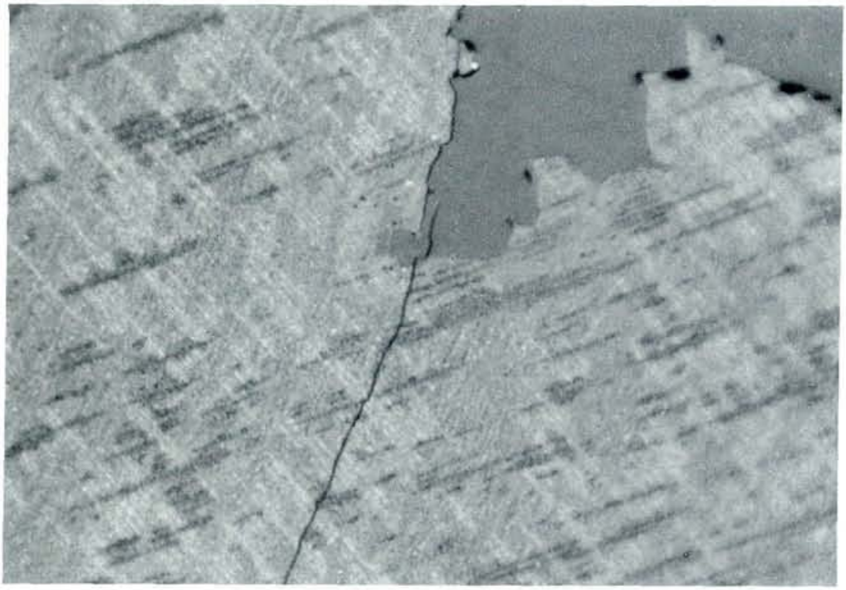

Fig. 2. Reflected light, polars 6° from crossed position. ×1100.
Oil immersion. K8.
Titanomagnetite groundmass in which the ilmenite formed from already exsolved ulvöspinel is reorganised from {100} to {111}.

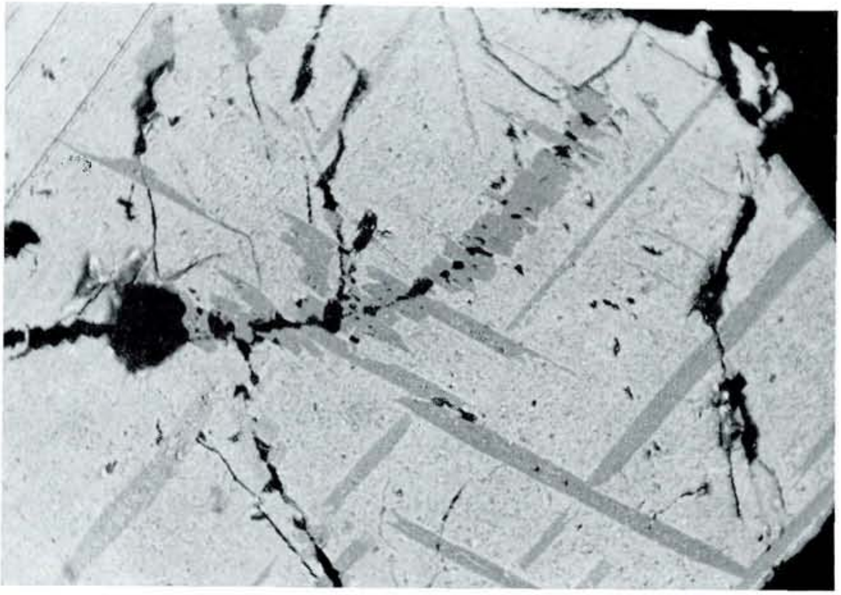

Fig. 1. Reflected light, polariser only. ×800. Oil immersion. K7.
Short and broad ilmenite lamellae originating from a curving crack. In addition there are regularly spaced ilmenite lamellae.

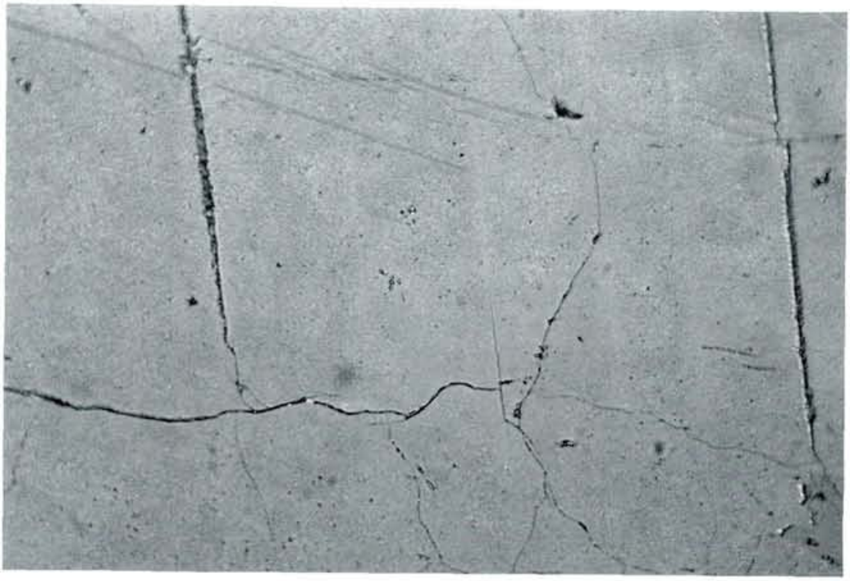

Fig. 2. Reflected light, polariser only. ×800. Oil immersion.
KB (10 m from west contact).
In the upper part of the picture thin tapering ilmenite lamellae can be seen originating from a tiny crack. Regularly spaced thin tapering ilmenite lamellae are faintly seen as light streaks running almost N–S.

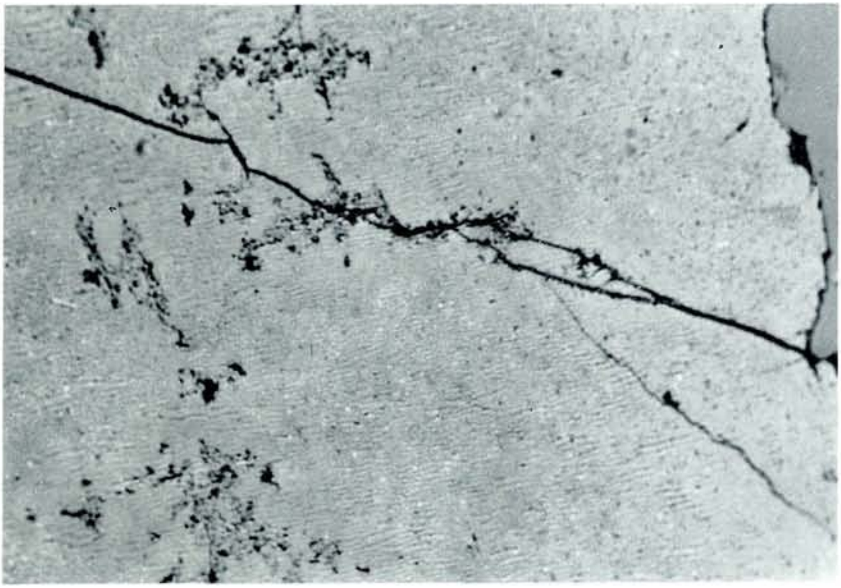

Fig. 1. Reflected light, polariser only. × 1450. Oil immersion. K8. Titanomagnetite groundmass with incipient alteration to turbid sphene along cracks. A faint worm-like texture (see p. 400 in the text) can be seen in the unaltered groundmass.

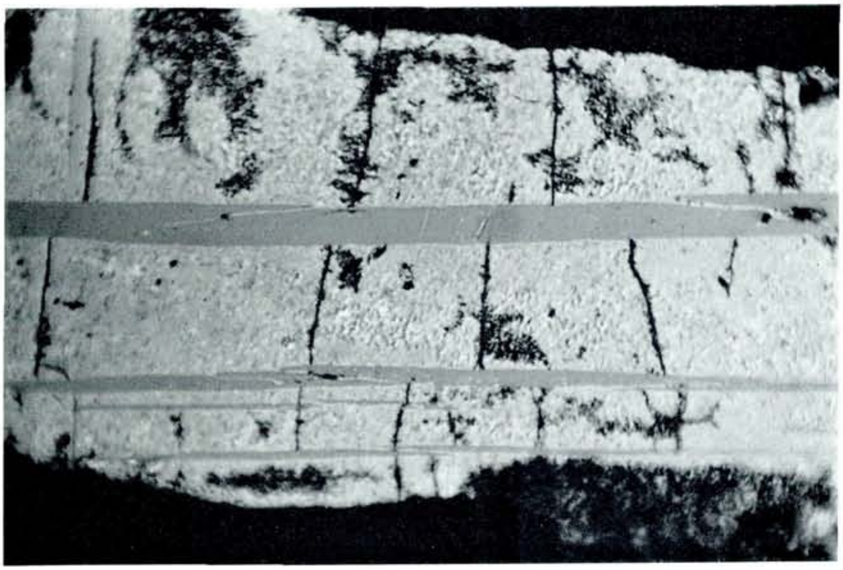

Fig. 2. Reflected light, polariser only. × 750. Oil immersion. K8. Titanomagnetite with incipient alteration to turbid sphene along cracks which are arranged as "ladder veins" between ilmenite lamellae.

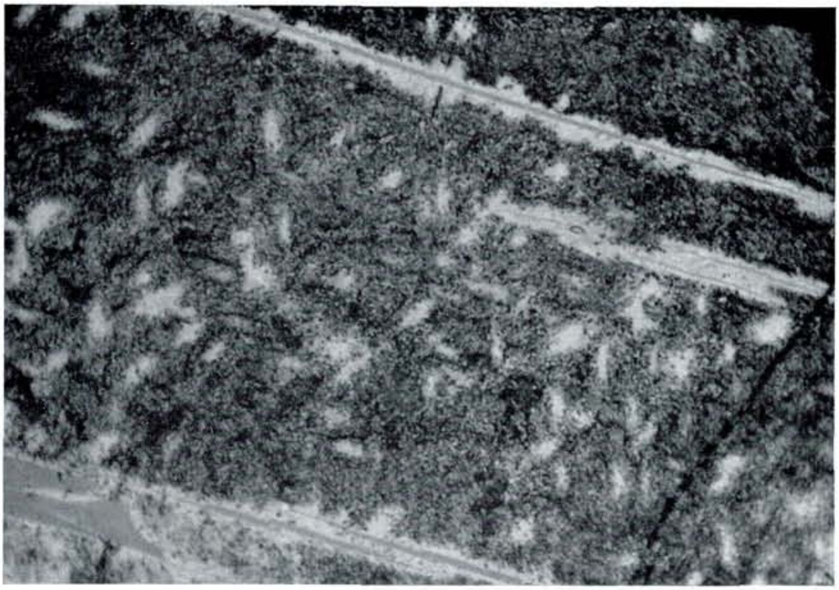

Fig. 1. Reflected light, polariser only. ×800. Oil immersion. K8.
Titanomagnetite strongly altered to turbid sphene. The ilmenite lamellae parallel to {111} in the titanomagnetite are unaltered and have also protected the titanomagnetite groundmass in their immediate vicinity against the alteration. It is to be noted that broad lamellae as well as very tiny lamellae have had this protective effect.

Fig. 2. Reflected light, polariser only. ×800. Oil immersion. K13.
Titanomagnetite, the groundmass of which is strongly altered to turbid sphene, while the ilmenite lamellae parallel to {111} have been altered by beach sand type of alteration. The white grain in the lower right corner is ilmenite likewise altered by beach sand type of alteration.

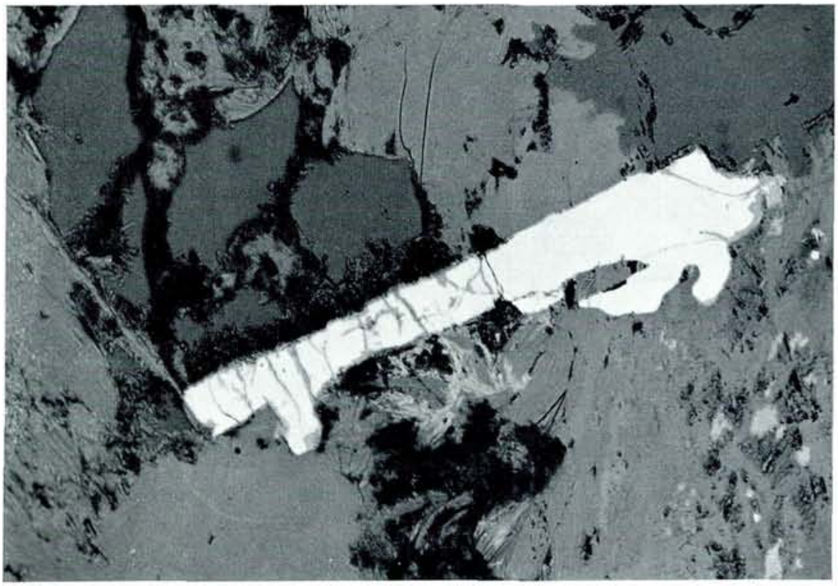

Fig. 1. Reflected light, polariser only. ×220.
LA (7 m from east contact).
Irregular plate of ilmenite with alteration to sphene along thin cracks across the plate and along part of the grain boundary.

Fig. 2. Reflected light, polariser only. ×750. Oil immersion.
LA (7 m from east contact).
Ilmenite grain with alteration to sphene advancing partly from the grain boundary and partly along cracks. Remnants of unaltered ilmenite with serrated boundaries are left as islands in the sphene. The outline of the original ilmenite grain can still be seen.

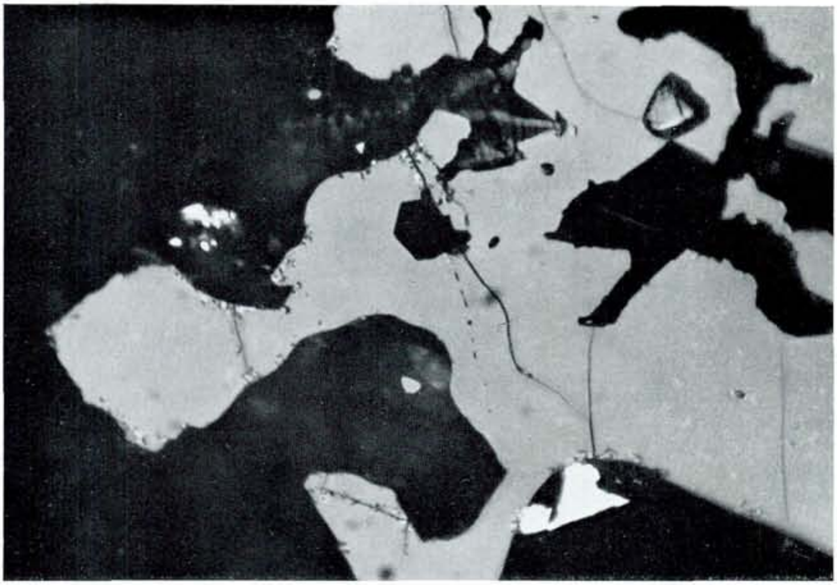

Fig. 1. Reflected light, polariser only. ×800. Oil immersion. K8.
Ilmenite with incipient alteration to rutile along grain boundaries and small cracks. Note the basal section of idiomorphic apatite included in ilmenite near the centre of the picture.

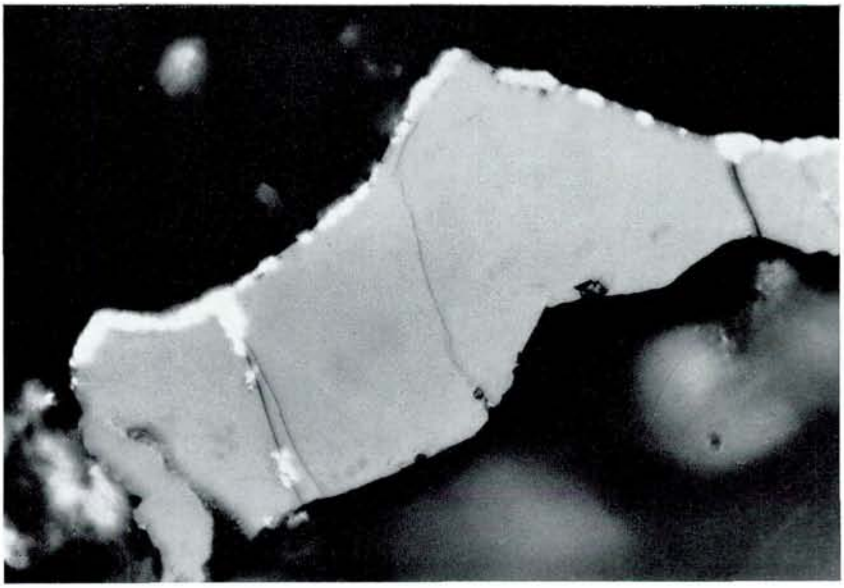

Fig. 2. Reflected light, polars 6° from crossed position. ×800.
Oil immersion. K8.
Ilmenite with incipient alteration to rutile, mainly along the grain boundary, but to some extent also along cracks.

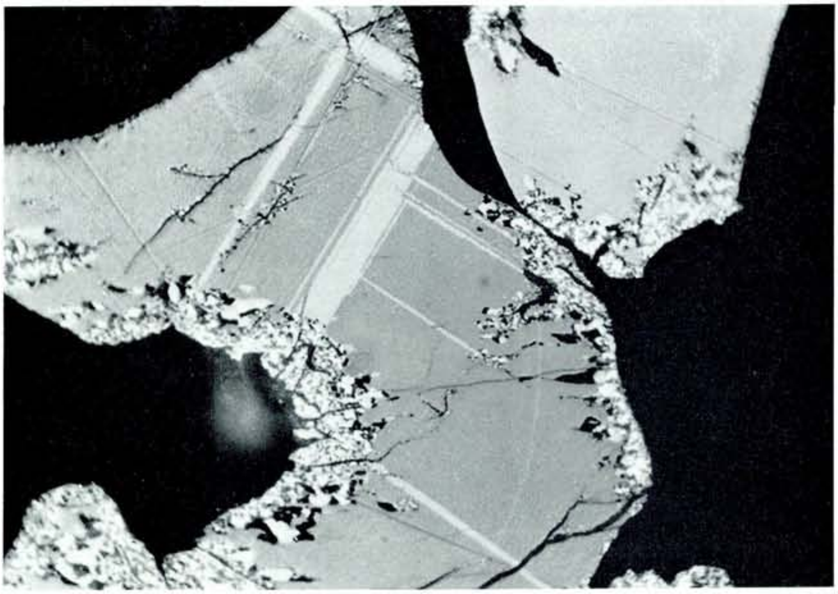

Fig. 1. Reflected light, polariser only. × 800. Oil immersion. K5.
Ilmenite with progressed alteration to rutile along grain boundaries. Note the diminishing in grain size and the strengthening of internal reflections in the rutile, with proximity to the grain boundaries. The large ilmenite grain has lamellar twins on the rhombohedron varying in width from $\frac{1}{2}$ to 5 μ, and also shows incipient alteration to rutile along cracks.

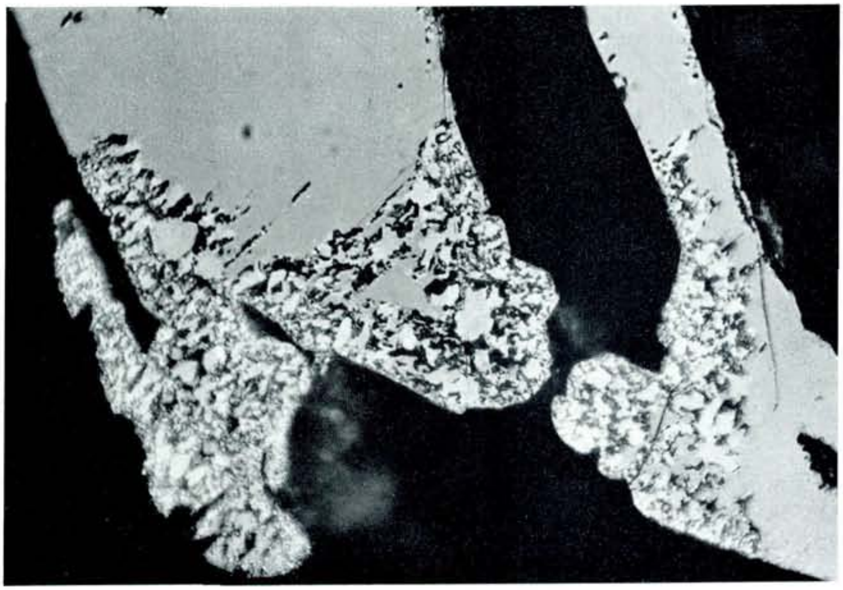

Fig. 2. Reflected light, polariser only. × 800. Oil immersion. K5.
Ilmenite showing progressed alteration to rutile. The rutile shows diminishing in grain size and strengthening of internal reflections with proximity to the grain boundaries, and it can also be seen that holes are more pronounced farther into the grains than at the grain boundaries.

Fig. 1. Reflected light, polariser only. × 800. Oil immersion. K13. Grain of ilmenite with incipient alteration of beach sand type clearly related to grain boundaries and cracks.

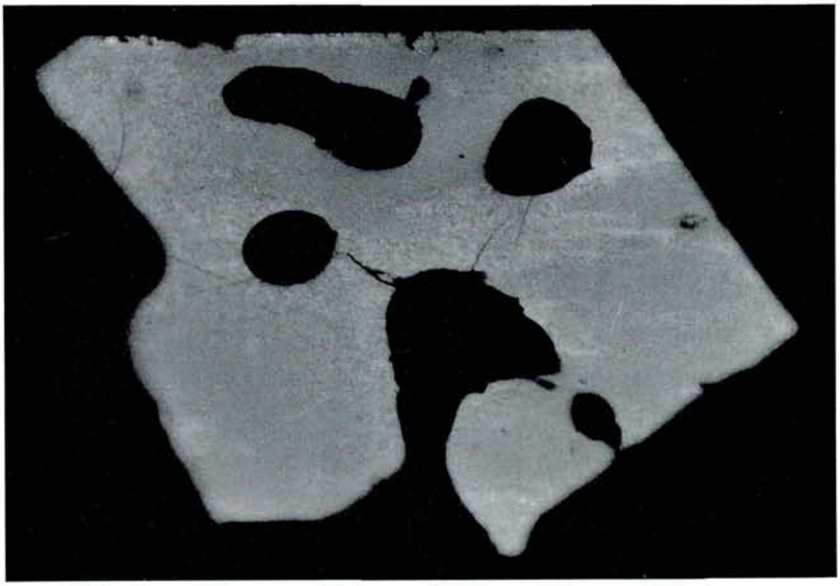

Fig. 2. Reflected light, polariser only. × 800. Oil immersion. K13. Grain of ilmenite with globules, and alteration of beach sand type, partly arranged in parallel layers, probably parallel to {0001}.

Fig. 1. Reflected light, polariser only. ×750. Oil immersion. K13.
Ilmenite with alteration of beach sand type spreading out from cracks and grain boundaries.

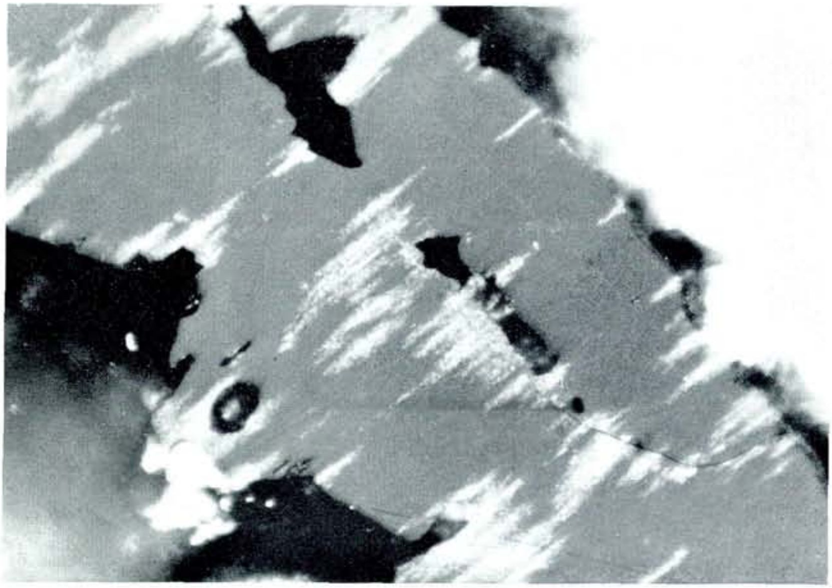

Fig. 2. Reflected light, polars 6° from crossed position. ×750.
Oil immersion. K13.
Ilmenite with alteration of beach sand type spreading out from cracks and grain boundaries.

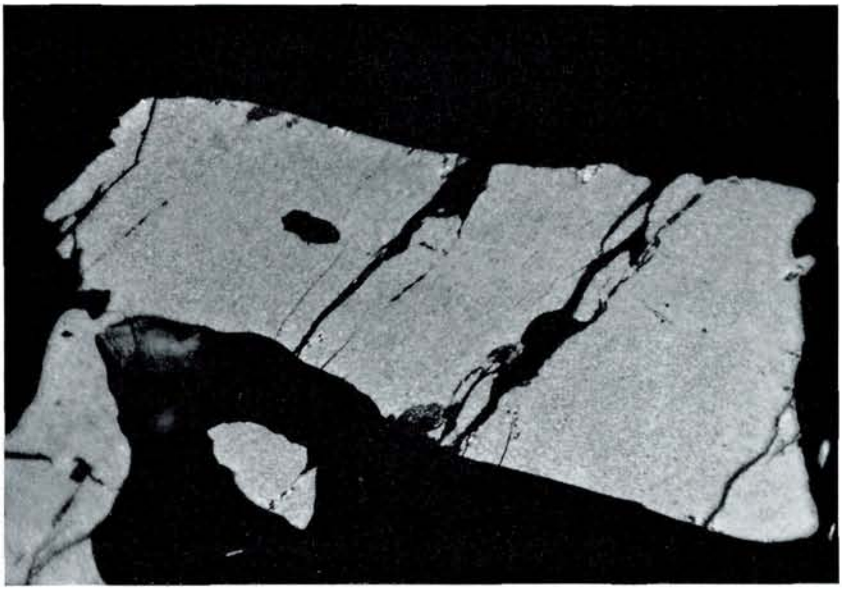

Fig. 1. Reflected light, polariser only. ×750. Oil immersion. K13.
Ilmenite, all of which is altered by beach sand type of alteration. The alteration product appears homogeneous except that along the upper border of the ilmenite some small groups of strongly luminous internal reflections mark the spotwise development of small rutile grains.

Fig. 2. Reflected light, crossed polars. ×750. Oil immersion. K13.
Ilmenite, all of which is altered by beach sand type of alteration. Various substages in the alteration can be recognised, and lamellar twins on the rhombohedron are still observable. Along the upper border of the ilmenite some small groups of strongly luminous internal reflections mark the spotwise development of small rutile grains.

Fig. 1. Reflected light, crossed polars. ×800. Oil immersion.
KG (about ½ m from east contact).
Grain of ilmenite attacked by beach sand type of alteration in which numerous small rounded opaque and isotropic spots occur. (See text p. 439).

Fig. 2. Reflected light, polariser only. ×800. Oil immersion. K5.
Ilmenite with rather strong alteration to rutile, and with rims of beach sand type of alteration along parts of the borders of the grains. (See text p. 439).