MICROTEXTURES AND MICROINTERGROWTHS OF IRON-TITANIUM-ALUMINIUM OXIDE MINERALS IN A MAGMATIC TITANIFEROUS IRON ORE FROM ATTU ISLAND, SOUTH-WESTERN FINLAND

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Microtextures of coexisting magnetite, ilmenite and aluminous spinel and their chemical composition have been studied in a magmatic titaniferous iron ore from Attu Island in south-western Finland.

Primary ilmenite contains exsolution lamellae of magnetite and aluminous spinel, oriented along the basal plane (0001). The microtextures of magnetite have been formed by exsolution of aluminous spinel and by oxidation-exsolution of ilmenite along $\{100\}$ and $\{111\}$ — planes respectively.

To some extent the exsolutions have been formed preferentially along planar structures like grain interfaces and intragranular high angle boundaries. Primary magnetite forms intergrowths with secondary ilmenite and aluminous spinel in border zones adjacent to primary ilmenite. These intergrowths partly show a similarity with exsolution textures of primary magnetite.

The available data suggest that they have been formed by privileged growth of exsolved ilmenite and aluminous spinel in the magnetite border zones adjacent to ilmenite. Corrosion of magnetite by the adjacent ilmenite is considered to be less probable for the genesis of these intergrowths.

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Introduction

Iron-titanium oxide minerals have become the subject of a strongly increasing number of petrological and geochemical studies. Vincent (1960) stressed the fundamental importance of intergrowths of magnetite and ilmenite for a full understanding of the petrological role of the opaques. New interest in iron-titanium oxide minerals was especially stimulated by the introduction of coexisting magnetite and ilmenite as a geothermometer and oxygen geobarometer (Buddington and Lindsley 1964).

The present paper concerns the investigation of iron-titanium-aluminium oxide minerals of a magmatic titaniferous iron ore from Attu Island in south-western Finland.[1] The

[1] »This investigation forms a part of a current petrological project carried out in the Kemiö-area since 1974 by staff members and students of the Free University of Amsterdam under the direction of Dr. László Westra».

island is situated in the Gullkrona Region, about 30 kilometers south of the town of Turku. It forms a part of the Sveco-Karelidic orogene that strikes in west-east direction through southern Finland. Notes on the geology of the island have been presented by Pehrman (1927) and Edelman (1949, 1960).

The rocksuite consists of a supracrustal series of pelitic sediments and basic volcanics, intercalated with sheets of synkinematic gabbroic to granitic intrusives, all metamorphosed in amphibolite to lower granulite facies. These rocks are cut by numerous pods and veins of latekinematic granite and pegmatite. The ore bodies occur within hornblende metagabbros.

The ore minerals have been studied in polished thin sections with reflected light. Different types of oxide microtextures and microintergrowths are synoptically described. Their origin and petrological significance are discussed, also on the base of microprobe analyses of the oxide compositions.

The term 'oxide minerals' as used in this text, refers to all iron-titanium-aluminium oxides present in the investigated ore specimens. In the descriptions the oxide mineral classification of Buddington *et al.* (1963) is applied.

Mineral Composition of the Ore

The ore specimens essentially consist of ilmeno-magnetite and magneto-ilmenite. Green hercynitic spinel is a minor constituent that makes up between 0.5 and 6 Vol % of the rock. Ilmeno-magnetite is usually slightly dominant to ilmenite. Pehrman (1927) has calculated mean values of 53 and 47 Vol % respectively for these minerals in ore concentrates. Gradual transitions exist among the rocks between massive oxide ore and metagabbros with an average oxide content of 1—2 Vol %. The coexisting minerals form an equigranular polygonal microtexture. Ilmeno-magnetite and magneto-ilmenite both show an average grain size of about 2 mm. The spinel grains rarely exceed a size of 1 mm.

Microtextures of Ilmenite

The primary ilmenite contains exsolution lamellae of magnetite and aluminous spinel which are oriented along the basal plane (0001) (Fig. 1). For brevity the term 'ilmenite' is used in the descriptions to refer to this spinel-bearing magneto-ilmenite.

The lamellae may consist only of magnetite or of spinel, but a single lamella frequently contains both phases in alternating parts along its lenght. Magnetite is always highly dominant to spinel, which is consistent with the low content of Al relative to excess iron typical of natural ilmenite solid solutions (Haggerty 1976).

The following twofold classification of 'ilmenite' textures is based on observed differences between the lamellar exsolution intergrowths (Fig. 1).

Ilmenite I. Microintergrowths of ilmenite I may contain three textural types of lamellae which will be referred to as (a), (b) and (c) respectively. Type (b) lamellae always predominate and frequently are the only type present in the intergrowth. Their width is uniform between 1—3 microns. The length varies between a few tens and several hundreds of microns, giving the lamellae a distinct needle shape. They form regular dense sets that cover the entire grain, except a narrow zone along the grain boundary (Pl. I—1). Type (c) lamellae are rare and exclusively occur in such border zones free of lamellae of type (b) (Pl. I—2). They ar locally present between type (b) lamellae, where these show relative wide spacings adjacent to the border zone. Their size is very small,
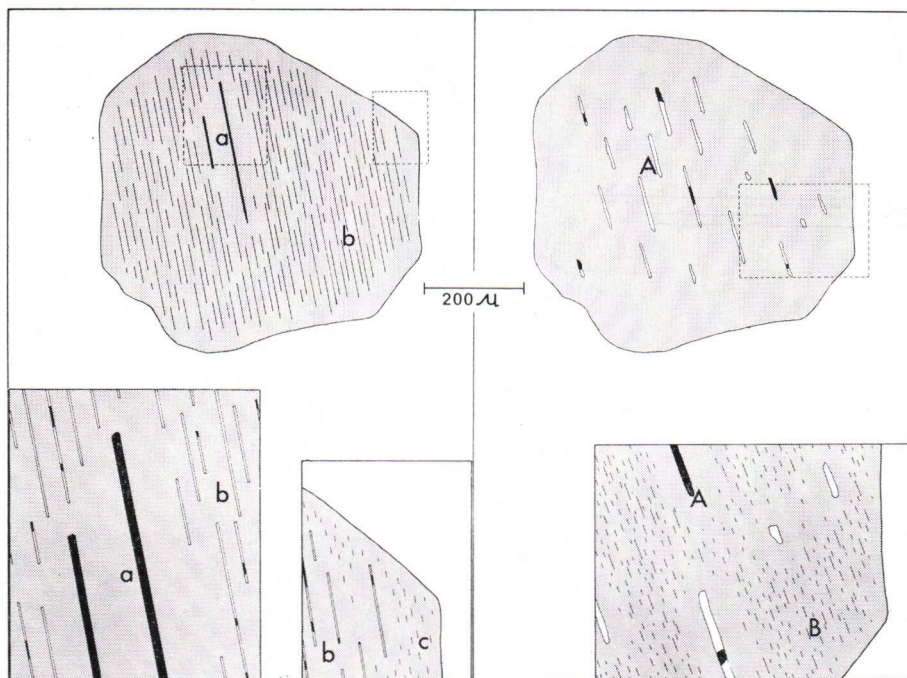
Fig. 1. Diagram of the microtextures of primary ilmenite (gray). Ilmenite contains exsolution lamellae of magnetite (white) and aluminous spinel (black) which are oriented along the basal plane (0001). (For explanation of the diagram, see text).

showing a length of only a few microns and a width that is far less than 1 micron. The type (c) lamellae decrease in number and finally disappear in directions towards ilmenite grain boundaries and type (b) lamellae.

Lamellae of type (a) were rarely found only in a few grains. They are distinctly coarser than type (b) and mainly consist of hercynitic spinel instead of magnetite. They are surrounded by narrow zones which are free of type (b) lamellae (Pl. I—3).

Ilmenite II. Microintergrowths of ilmenite II always contain two types of lamellae, which will be referred to as (A) and (B) respectively (Fig. 1).

Type (A) lamellae are distinctly coarser and less regular shaped than type (b) lamellae in ilmenite I. They occur in the inner grain parts as more irregular sets with a lower number of lamellae and wider spacings between the lamellae. They sometimes show a preferential location along intragranular high angle boundaries.

Type (B) lamellae are extremely fine, similar to those of type (c) in ilmenite I. They are numerous and occur between type (a) lamellae, also in the inner parts of the grains. They have a zonal distribution which is similar to that observed for lamellae of type (b) and type (c) in ilmenite I. Type (B) lamellae decrease in number and finally disappear in directions towards grain boundaries and type (A) lamellae (Pl. I—4).

Exsolution-zoning in 'Ilmenite'. Zonal arrangement of exsolution lamellae occurs in both types of 'ilmenite' microtextures described above. This will be called exsolution-zoning, a term used by Mukherjee *et al.* (1972) to describe similar exsolution textures in spinel-bearing hemo-ilmenites.

The coarser lamellae are always surrounded by narrow zones which are free of

finer lamellae, as illustrated by Fig. 1. Similar zones, which are apparently free of exsolutions, occur along the grain boundary. This is shown most clearly by lamellae of type (b) in 'ilmenite' I. Such zones usually measure some 50—150 microns in the direction normal to the grain boundary. Lamellae of type (c) are locally present in these zones but they also disappear at a distance of a few tens of microns from the grain boundary.

The zonality occurs irrespective of the nature of the neighbouring mineral. It is found in 'ilmenite' adjacent to silicates, sulfides, spinel, and also along mutual 'ilmenite' boundaries. The textures found along the contacts with the different minerals, however, may be somewhat different. The zonality is always distinct where 'ilmenite' is in juxtaposition with primary magnetite. Along mutual 'ilmenite' boundaries on the contrary, the lamellae may be continuous up to the grain interface, showing a wedge shape in the border zone (Pl. II—1). This texture is most frequently found in border zones of 'ilmenite' I and is formed by type (b) lamel-

lae. It rarely occurs in 'ilmenite' II, where the lamellae of type (A) generally end at a greater distance from the grain boundary. Microcrystals of magnetite and spinel are locally present along the contacts of adjacent clear 'ilmenite' border zones.

These more complicated textures of 'ilmenite' mutual boundaries are only rarely found in 'ilmenite' border zones adjacent to silicates or sulfides and never occur adjacent to primary magnetite.

Microtextures of Magnetite

The primary magnetite contains exsolution lamellae of ilmenite and aluminous spinel along planes of $\{111\}$ and $\{100\}$ respectively (Pl. II—2). The microtextures of 'magnetite' are complicate since different types of exsolutions of both ilmenite and spinel are always associated in a single host crystal. Three types of ilmenite — and two types of spinel exsolutions are distinguished on the basis of their textural relationships, which are illustrated by Fig. 2. They will be referred to
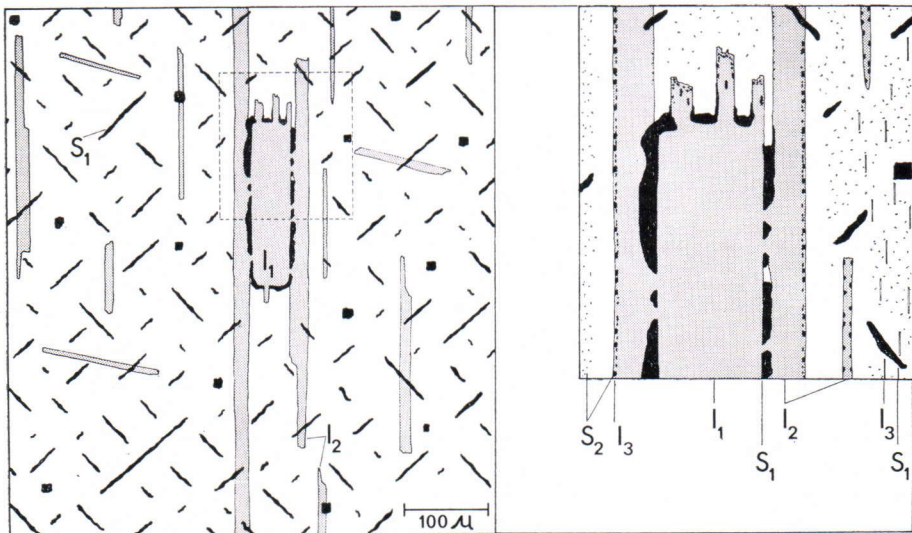

Fig. 2. Diagram of exsolution intergrowths in primary magnetite (white). Exsolution lamallae of aluminous spinel (black) and ilmenite (gray) are oriented along planes of $\{100\}$ and $\{111\}$ respectively. (For explanation of the diagram, see text).

as ilmenite I_1, I_2, I_3 and spinel S_1, S_2 respectively. These exsolutions are all abundant in the studied 'magnetites', except those of type I_1 which are only found occasionally in a few grains.

'Magnetite' is also intergrown with ilmenite and aluminous spinel in its border zones adjacent to 'ilmenite'. These phases will be described separately from the exsolved ilmenite and spinel mentioned above.

Ilmenite I_1. Ilmenite I_1 forms irregular lamellar bodies which are oriented along $\{111\}$ (Pl. II—3). The lamellae have a length of about 100—500 microns and a width of a few tens of microns. They are always surrounded by a rim of spinel (S_1) that usually is 10—20 microns wide. Lamellae of I_2, described below, are often aligned parallel to the I_1-lamellae and are oriented along the same direction of $\{111\}$. Both types of ilmenite are locally connected, where the spinel rim is only fragmentary.

Ilmenite I_2. Ilmenite I_2 forms lamellae which are oriented along one or several $\{111\}$ directions. The related intergrowths are generally known as the sandwich — and the trellis type (Haggerty 1976). The exsolutions of I_2 range from tiny laths to coarse lamellae that have a length of several hundreds of microns and a width of a few tens of microns. The lamellae are often rimmed by and/or dotted with microcrystals of spinel. In most cases the latter probably consist of S_2 but frequently, both S_1 and S_2 seem to be present. The microcrystals are often arranged in thin strings and rims that run parallel to the $\{111\}$ lamellae sides (Pl. III—1, 2). High concentrations of I_2 lamellae are locally found along intragranular high angle boundaries (Pl. II—4). Such I_2 concentrations, however, often are irregular granular aggregates rather than lamellar intergrowths.

Ilmenite I_3. Ilmenite I_3 forms very fine lamellae, usually in all $\{111\}$ directions. They

have a length of only a few microns and their width is far below one micron. They are distributed evenly in the 'magnetite' but they also show exsolution-zoning which is essentially similar to that, shown by the exsolution lamellae in 'ilmenite'. I_3 lamellae gradually decrease in number and finally disappear in the directions of both lamellae of I_1 and I_2 and to 'magnetite' grain boundaries adjacent to 'ilmenite'.

Spinel S_1. Spinel S_1 exsolutions form numerous spots, discs, and lamellae along cube planes $\{100\}$ of the magnetite host (Pl. II—2). Their various shapes are related to different crystal orientations in the thin sections. For the greater part, they are similar to those described by Faessler and Schwartz (1941). An exceptional dendritic intergrowth of S_1 occurs where the spinel is oriented along planes of $\{111\}$ instead of $\{100\}$ (Pl. III—3). S_1 exsolutions, showing unchanged $\{100\}$ orientations, are locally included by lamellae of I_2. Moreover, they are concentrated along the 'magnetite' grain boundaries, inclusions of other minerals, and along intragranular high angle boundaries. Rims of S_1 that surround lamellae of I_1 were already mentioned.

Spinel S_2. Spinel S_2 forms extremely fine exsolutions which are visible as scattered dust-like particles, only at high magnifications. Their $\{100\}$ orientations are hard to establish in most places, owing to their small size and granular shape. S_2 exsolutions are frequently concentrated in the borders of I_2 lamellae. They are always absent in narrow zones that surround the exsolutions of S_1.

Microtextures of Spinel

Primary hercynitic spinel locally occurs as individual grains within aggregates of primary ilmenite and magnetite. In thin section these grains are clearly transparent and have

a dark green colour. In few ore specimens the spinel is partly dotted or clouded with extremely fine opaque particles of unknown composition, which are oriented along {100}. Microprobe analyses did not show compositional differences between transparent and clouded parts of a single spinel grain. Microprobe analyses, however, showed minor compositional differences between the spinel of individual grains (Mg 8.1, Zn 1.7 Wt %) and exsolved spinel in the 'magnetite' (Mg 7.0, Zn 2.2 Wt %). Anderson (1968) has determined the refractive indices of both types of spinel in magnetite ore from the La Blanche Lake deposit in Quebec. In his opinion the lower value for exsolved spinel (1.75) results from a higher content of Mg compared to the spinel of individual grains (1.77). The clouding is probaly due to dissiminated magnetite that could have been formed either by exsolution or by oxidation of the spinel according to the following reaction:

$$6 \ FeAl_2O_4 + O_2 \rightleftharpoons 2 \ Fe_3O_4 + 6 \ Al_2O_3$$

(Turnock and Eugster 1962).
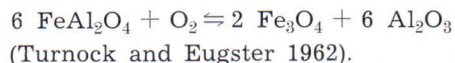
Microtextures at the Contacts between 'Magnetite' and 'Ilmenite'

The oxide minerals in the studied ore specimens usually show regular straight crystal interfaces. The contacts between 'magnetite' and 'ilmenite', however, are characterized by ilmenite intergrowths of aluminous spinel and secondary ilmenite in the 'magnetite' border zones. The secondary ilmenite will be referred to as ilmenite I_s in the following text.

The intergrowths may show various textures, which range from rather simple (Pl. III—4) to highly complex (Pl. IV—1, 2).
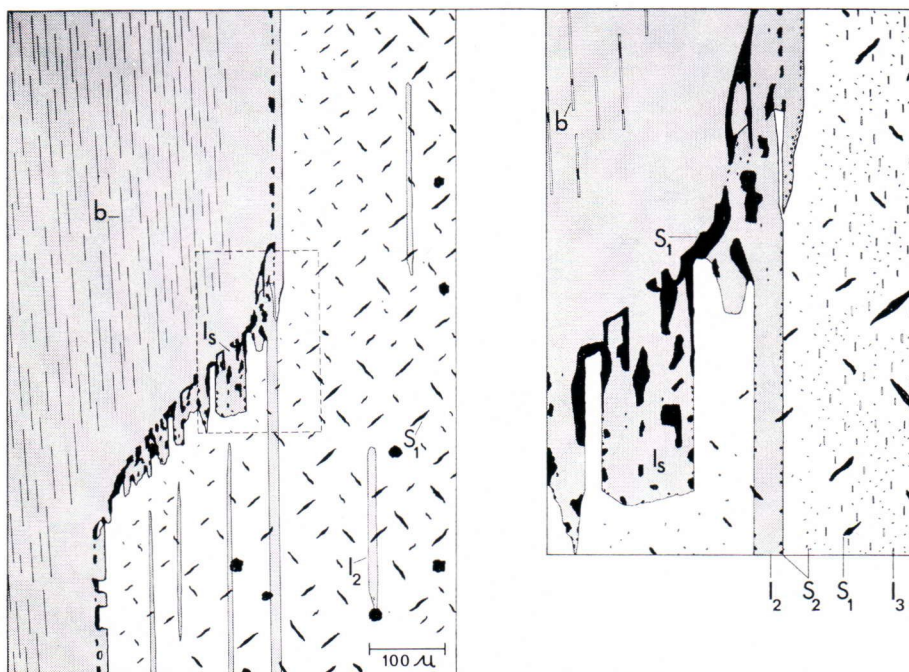
The spinel is concentrated along the

Fig. 3. Diagram of a contact intergrowth between adjacent grains of primary ilmenite (left) and primary magnetite (right). The exsolution intergrowths in both grains are similar to those shown in Figs. 1 and 2, respectively. (For explanation of the diagram see text).

'magnetite'-'ilmenite' contact as fine irregular grains which often form a rim between both phases. Such spinel rims may be connected with concentrations of spinel S_1 (Pl. V—3). As was described before, the latter occur along the 'magnetite' grain boundaries adjacent to silicates, sulfides, primary spinel and also along mutual 'magnetite' boundaries.

The ilmenite I_s generally forms the main constituent of the contact intergrowths. It is intergrown with the 'magnetite' adjacent to the spinel rim, in a manner that is apparently controlled by the 'magnetite' crystal structure. In most intergrowths ilmenite I_s is optically continuous with the adjacent primary ilmenite. Both phases can then only be distinguished by their position on opposite sides of the spinel rim. Occasionally, however, ilmenite I_s is oriented along a {111} direction of the 'magnetite' host and forms a distinctly lamellar type of contact intergrowth (Pl. IV—3, 4). The lamellae always project from the spinel rim into the 'magnetite'. They are separated by bars of 'magnetite' which are typically connected with grains of the spinel rim, causing a mushroom-like texture (Pl. III—4; V—1). Lamellae of I_s locally change into exsolution lamellae of ilmenite I_2, that are oriented along the same {111} direction. (Pl. IV—3; V—2). Ilmenite I_s may be abundantly dotted with spinel (Pl. IV—2). This spinel is distinctly finer grained than the spinel of the rims and it is usually concentrated in thin fringes of I_s around 'magnetite' (Pl. V—1). Ilmenite I_s moreover locally includes {100} exsolutions of spinel S_1. The intergrowths of of I_s are always bordered by narrow zones of 'magnetite' that is free of exsolutions of ilmenite I_3 and spinel S_2.

Genesis of the 'Ilmenite' Microtextures

As mentioned before, the lamellar micro-

intergrowths of 'ilmenite' have been formed by exsolution. It is apparent that the initially homogeneous ilmenite contained excess iron and some aluminium in solid solution at supersolvus temperatures. Upon cooling this solid solution was impoverished in excess iron and aluminium by exsolution of magnetite and aluminous spinel. The exsolution-zoning textures indicate that the coarser lamellae have formed prior to the surrounding finer ones. The lamellae of types (a), (b), and (c) in ilmenite I and also those of types (A) and (B) in ilmenite II are accordingly considered as exsolutions of successively younger generations. The exsolution-zoning textures were also investigated with the electron microprobe. Continuous scanning profiles for Fe, Ti, Al, and Mg did not show compositional gradients in the host-ilmenite between the lamellae or in the zones which are apparently free of exsolutions.

The exsolutions thus occur in homogeneous host-ilmenites which have nearly stoichiometric compositions. These findings agree with those of Kretschmar & McNutt (1969) concerning exsolution textures in some hemo-ilmenites. With the electron microprobe they also showed the absence of compositional gradients across ilmenite border zones free of hematite exsolutions. Mukherjee et al. (1972) have described hematite — free zones surrounding older exsolutions of aluminous spinel in hemo-ilmenites. In their opinion the earlier exsolution of spinel has caused privileged consumption of Fe and Al in the immediate vicinity of the exsolution centre. This should have lowered the concentration of these elements sufficiently to prevent later exsolution of hematite in narrow zones surrounding the exsolutions of spinel. The exsolution free zones surrounding the lamellae of types (a), (b) and (A) could well be explained by a similar mechanism.

The zonal textures of the 'ilmenite' border

zones probably also have been formed by exsolution. Excess iron and aluminium have migrated out of these zones, probably towards the adjacent grain boundary. They could have been removed by a mobile intergranular fluid. The role of such an iron-rich fluid is indicated by the local occurences of magnetite and pyrite as fillings of fine cracks. Fine grains of magnetite and spinel, which are locally present along 'ilmenite' grain boundaries, could have been formed when outward diffusion was accompanied by exsolution along the contact.

A gradual increase of cation diffusion rates towards grain boundaries has been demonstrated experimentally by Stanton (1972). This could well explain the wedge-shape of the lamellae in 'ilmenite' border zones (Pl. II—1). Inwards diffusion of iron as proposed by Mukherjee et al. (1972) to explain hematite-free zones along hemo-ilmenite grain is considered unlikely for the origin of the zonal texture of the 'ilmenite' border zones.

Genesis of the 'Magnetite' Microtextures

Magnetite forms a complete solid solution series with ulvöspinel (Fe_2TiO_4) at temperatures above $600°$ C (Vincent et al. 1957). Complete solid solution also exists in the magnetite-hercynite series at temperatures higher than $860°$ C (Turnock and Eugster 1962).

The primary magnetite apperently had an initial composition, intermediate between these solid solution series. The lamellae of the ilmenites I_1, I_2, and I_3 probably all have been formed by exsolution due to oxidation of ulvöspinel according to the reaction;
$$6 \ Fe_2TiO_4 + O_2 \leftrightharpoons 6 \ FeTiO_3 + 2 \ Fe_3O_4 \ (Haggerty, 1976).$$

The ilmenite thus produced has arranged itself along $\{111\}$ in the magnetite host, forming trellis and sandwich-types of micro-

intergrowths. Spinel S_1 and S_2 have been formed by exsolution along the cube planes $\{100\}$ of the magnetite.

The observed textures indicate that the lamellae of ilmenite I_1, I_2, and I_3 represent three successively younger exsolution generations. The spinel exsolutions similary belong to an older (S_1) and a younger generation (S_2). Ilmenite I_1 probably is the first phase exsolved from the primary magnetite solid solution. Spinel S_1 exsolved later as indicated by its occurence also as rims which surround lamellae of I_1. These I_1-lamellae and planar structures like magnetite grain boundaries and intragranular high angle boundaries have served as centres of privileged exsolution of S_1. Consequently little or no exsolution of S_1 did take place in the immediate vicinity of these centres.

Lamellae of ilmenite I_2 have overgrown intergrowths of S_1 which indicates that they are younger than the spinel. The spinel bearing lamellae of I_2, however, probably have been formed by simultaneous exsolution of I_2 and S_1. The spinel cannot be exsolved from the ilmenite in the observed quantaties because of Al_2O_3-deficiencies in the latter mineral (Haggerty 1976).

Exsolutions of I_3 and S_2 are even younger. Their small size and dense distribution moreover suggest that they have been formed under conditions of more restricted cation diffusion. Privileged exsolution of I_3 and S_2 has taken place on contacts of the I_2-lamellae and, as discussed below, also on ilmenite I_s in the contact intergrowths.

Genesis of the Contact Intergrowths between 'Magnetite' and 'Ilmenite'

The contact intergrowths in 'magnetite' border zones adjacent to 'ilmenite' partly resemble certain exsolution intergrowths in 'magnetite'. A lamellar texture similar to that

of some contact intergrowths has been formed by privileged exsolution of spinel S_1 and ilmenite I_2 along I_1-lamellae, as illustrated by Fig. 2.

The lamellar types of contact intergrowths only seem to have been formed in places where the basal plane (0001) of the 'ilmenite' and a favored {111} exsolution plane in the adjacent magnetite have parallel or nearly parallel orientations. In this case ilmenite I_s has formed lamellae along this {111} direction. More irregular intergrowths of I_s, that is optically continuous with the adjacent 'ilmenite', have been formed in places where a greater divergence exists between these crystal plane orientations. A special type of lamellar intergrowths has been formed where the contact between 'magnetite' and 'ilmenite' is parallel to the favored {111} plane of I_2-sandwich exsolutions, as illustrated by Fig. 3. Here ilmenite I_s has grown as a thin lamella-shaped rim parallel to the rim of spinel. If the contact, however, cuts this {111} direction at some angle, the contact intergrowth shows the lamellar mushroom-like texture.

Similar textures have been formed by exsolution in primary magnetite when spinel S_1 and ilmenite I_2 have grown preferentially on I_1-lamellae. A lamellar mushroom-like texture has been formed along those contacts of I_1, cutting a privileged {111} plane of I_2-lamellae. When the contact is parallel to this {111} direction, however, I_2 has grown as a thin lamella-shaped rim along the rim of spinel (S_1) that surrounds I_1 (Fig. 2).

All presented data suggest that the contact intergrowths between 'magnetite' and 'ilmenite' have been formed by exsolution of spinel and ilmenite in the 'magnetite' border zone. The spinel rim seems to be equivalent with S_1 concentrations of other 'magnetite' grain boundaries. The secondary ilmenite I_s probably is equivalent with ilmenite I_2 since both phases are locally connected and both have overgrown S_1 exsolutions.

Both I_s and I_2 have formed prior to the exsolutions of I_3 and S_2 as indicated by the related exsolution-zoning textures. The outermost rims of I_s, some microns wide, which are dotted with fine grained spinel, probably have been formed by simultaneous exsolution of I_3 and S_2, analogous to similar rims along I_2-lamellae.

Replacement of 'magnetite' by the adjacent 'ilmenite' is considered to be less probable for the origin of the contact intergrowths. This mechanism was proposed by some authors (Gierth and Krause 1973; Krause and Pape 1975) to explain rims of spinel-bearing ilmenite on contacts between primary magnetite and hemo-ilmenite.

Conclusions

The present investigation shows the importance of microtextures and microintergrowths of oxide minerals for a proper understanding of the cooling history of the host rock.

The stability of the coexisting magnetite and ilmenite solid solutions was maintained by complex processes of diffusion and exsolution during the subsolidus stage. The initial magnetite solid solution was impoverished in Al and Ti by exsolution of aluminous spinel and oxidation exsolution of ilmenite. The latter process was caused by oxidation of the ulvöspinel molecule.

The ilmenite solid solution was impoverished in Al and Fe by exsolution of aluminous spinel and exsolution of magnetite. The adjustment of these oxide compositions upon cooling has taken place periodically rather than continuously as indicated by the occurrence of different exsolution generations.

Electron microprobe analyses showed that the compositional adjustment almost ran to completion, resulting in homogeneous exsolved phases in host crystals which are nearly stoichiometric in composition. It was moreover shown that for all mineral phases concerned, the exsolutions of different generations have identical compositions. The microtextures stress the importance of preexisting planar structures like grain boundaries and intragranular high angle boundaries as centres of privileged exsolution.

It is tentatively concluded that the intergrowths at the contacts between adjacent grains of primary magnetite and ilmenite have been formed by privileged exsolution of ilmenite and spinel in the magnetite border zone. This mechanism is as yet poorly understood and further study is needed to unravel the complexity of the involved diffusion and exsolution processes. Corrosion of magnetite by the adjacent ilmenite, due to cation exchange, is considered to be less probable for the genesis of the contact intergrowths. Accordingly it is assumed that the coexisting magnetite and ilmenite have remained a stable oxide pair during the subsolidus stage.

This assumption is important with respect to the possible use of associated spinel-bearing ilmeno-magnetite and magneto-ilmenite as a geothermometer and oxygen geobarometer.

Limits may be set to the compositions of the initial magnetite and ilmenite solid solutions by measuring the magnetite-ilmenite-spinel ratios of the combined intergrowths. Herewith it must be realized that, according to the proposed model, the spinel and the secondary ilmenite of the contact intergrowths initially have been incorporated in the magnetite solid solutions, as the hercynite and ulvöspinel molecules respectively. Results of such measurements should be treated cautiously and will only provide rough estimations of crystallisation temperatures and oxygen fugacities. Corrections have to be made for additional elements, especially Al and Mg. The measurements nevertheless may provide valuable data about the genesis of the coexisting oxide minerals and their microtextures and intergrowths.

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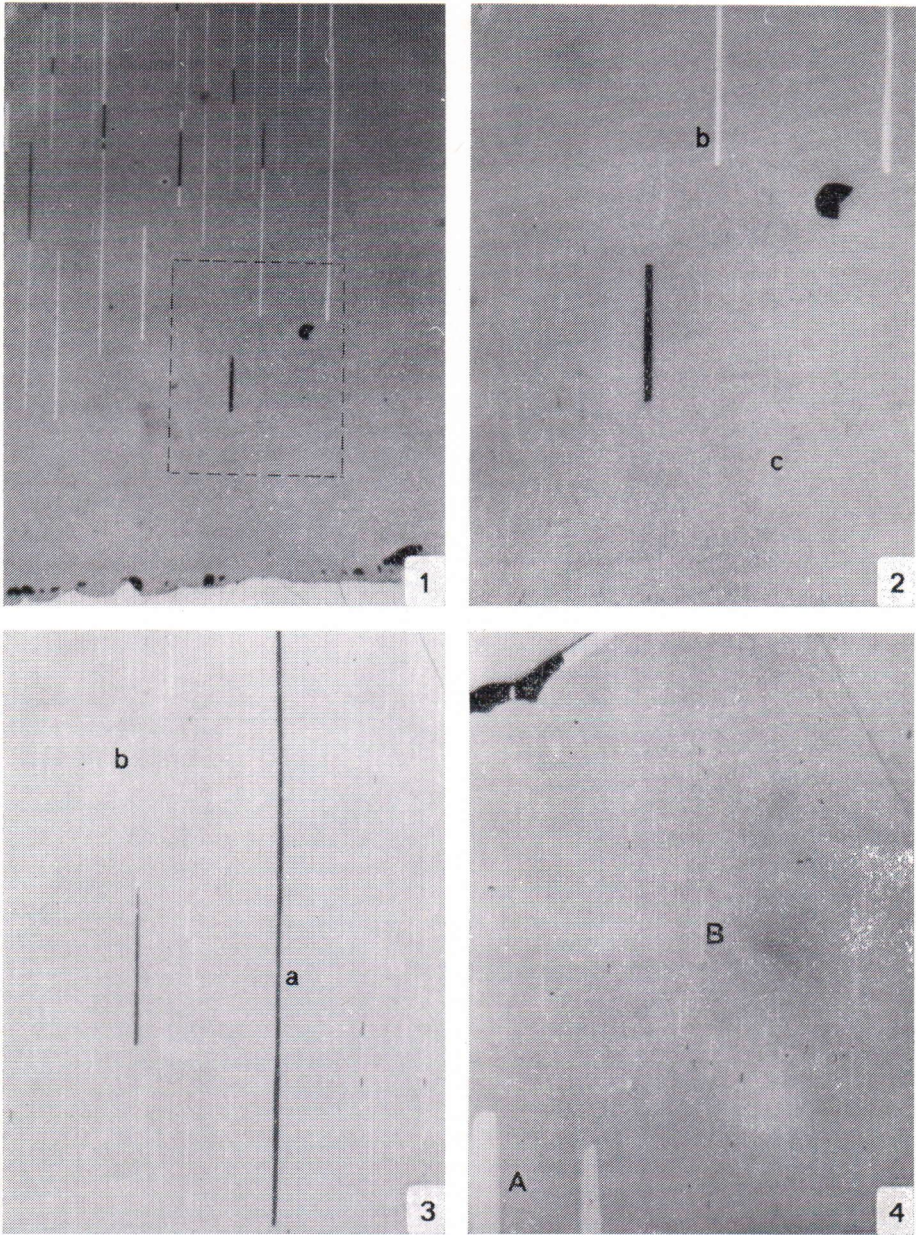
PLATE I

1. Primary ilmenite (gray) adjacent to primary magnetite (white). Exsolution lamellae of magnetite and hercynite spinel are oriented along (0001) in the host ilmenite (X 240).

2. Inset of Pl I—1, enlarged. Exsolution lamellae of magnetite and spinel belong to an older (b) and a younger generation (c). The c-type lamellae only occur in the 'ilmenite' border zone free of lamellae of type (b) (X 600).

3. Exsolution lamellae in primary ilmenite oriented along (0001). The coarser lamellae of spinel (black) belong to an older exsolution generation (a). Younger exsolutions (b) of magnetite and spinel are absent in narrow zones surrounding the lamellae of type (a) (X 240).

4. Primary ilmenite with exsolution lamellae of magnetite (white) and spinel (black) along (0001). The lamellae belong to an older (A) and a younger generation (B). A-type exsolutions have partly been formed preferentially along the grain boundary (upper left corner). B-type lamellae are absent in zones surrounding the exsolutions of type (A). (X 600).
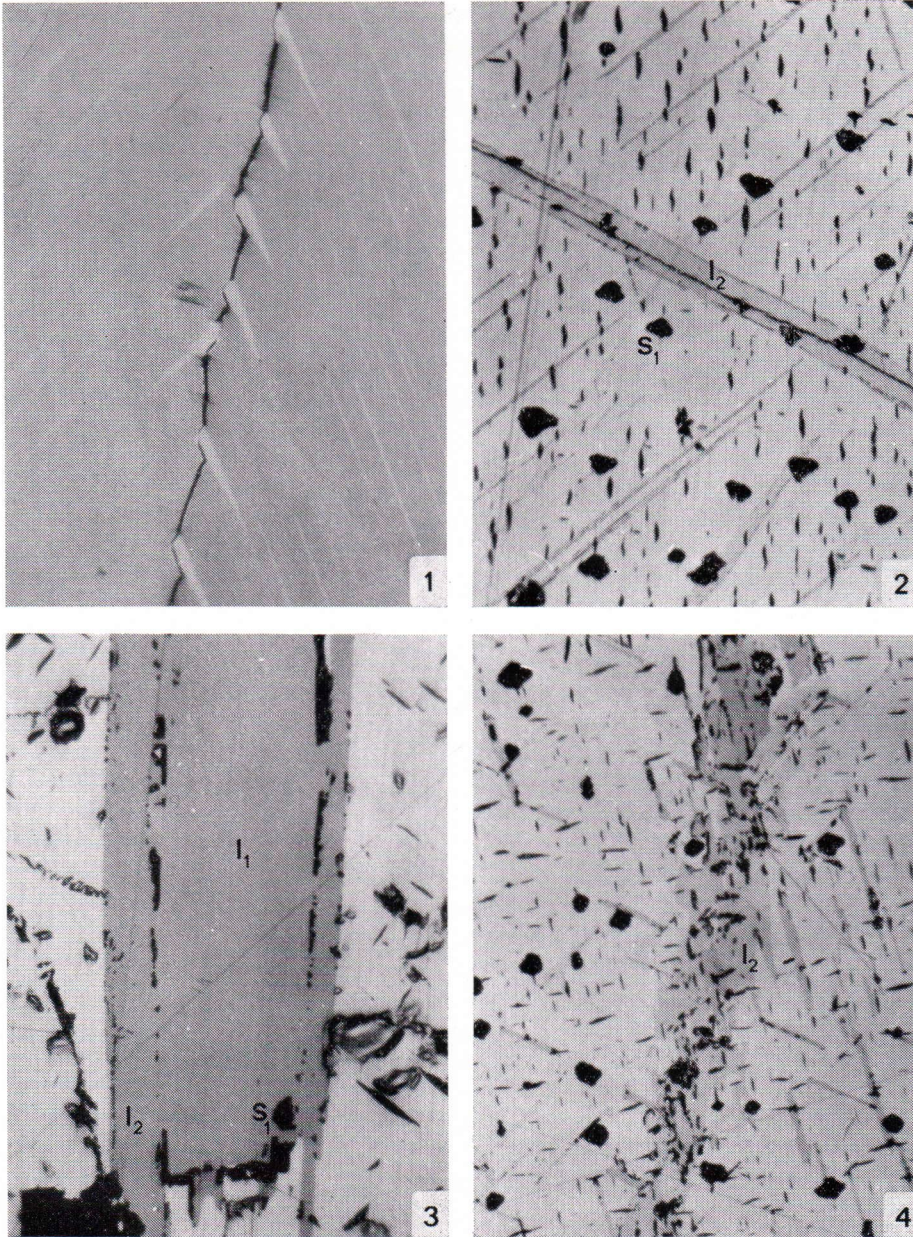
PLATE II

1. Primary ilmenite interface. (0001) exsolution lamellae of magnetite (white) are wedge-shaped close to the grain boundary (X 240).
2. Primary magnetite with {111} exsolution lamellae of ilmenite I_2 (dark gray) and {100} exsolutions of spinel S_1 (black) (X 240).
3. Primary magnetite with an {111} exsolution lamella of ilmenite I_1. The lamella is surrounded by a fragmentary rim of younger spinel S_1. Still younger {111} lamellae of ilmenite I_2 have grown preferentially along the rim of spinel (X 600).
4. Exsolution texture in magnetite, similar to Fig. 2. Exsolution of ilmenite I_2 has preferentially taken place along an intragranular boundary (X 240).
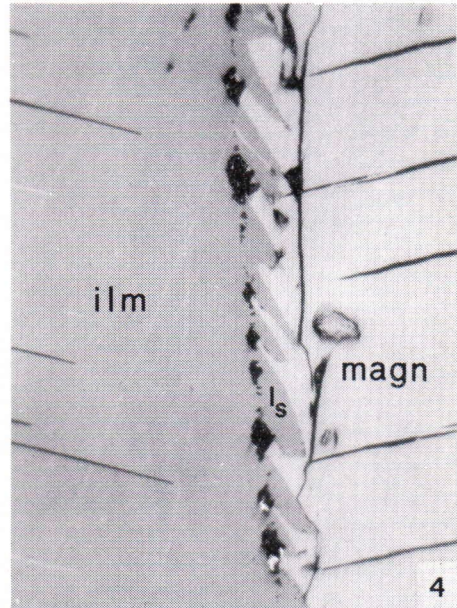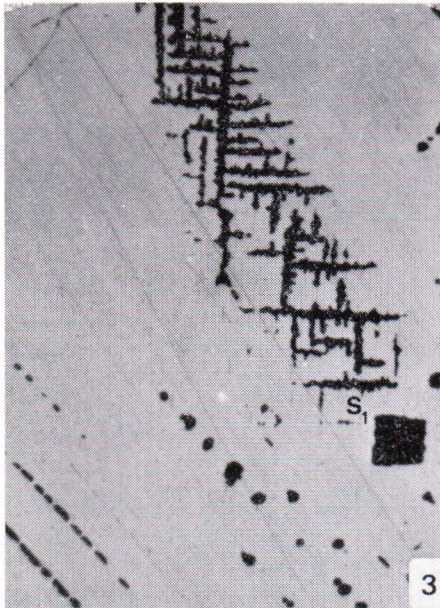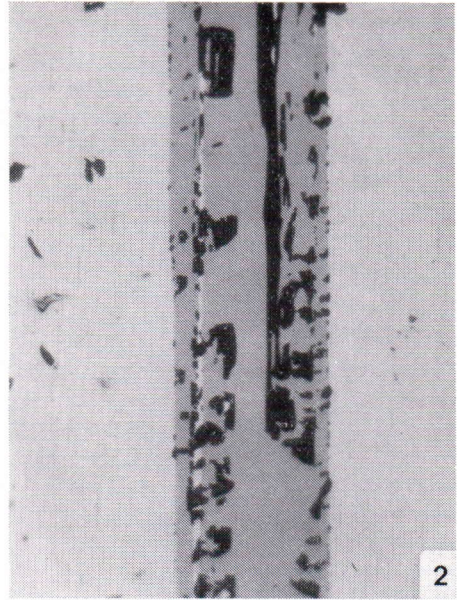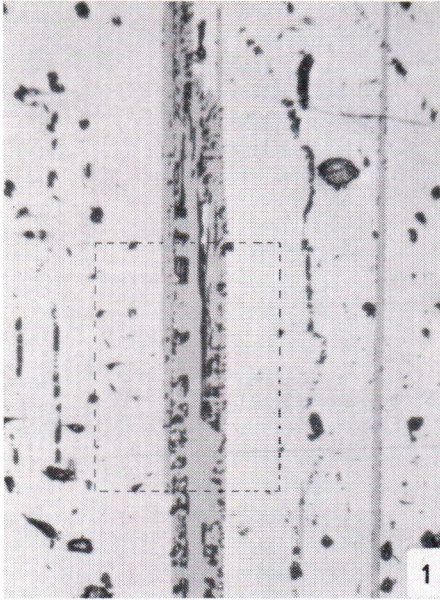
PLATE III

1. Spinel-bearing exsolution lamella of ilmenite (gray) oriented along {111} in primary magnetite (X 240).
2. Inset of 1. enlarged. Spinel is oriented in a symmetric pattern parallel to the {111} sides of the lamella. This pattern probably has been formed by repeated growth of the lamella during successive stages of ilmenite and spinel exsolution (X 600).
3. Primary magnetite with an exceptional dendritic intergrowth of exsolved spinel S_1 along {111}. Normal {100} exsolutions are also present (lower half) (X 240).
4. Contact intergrowth between adjacent grains of primary ilmenite (gray) and magnetite (white). Spinel has been exsolved from the magnetite as lamellae along {100} and as grains along the contact. Secondary ilmenite (I_s) has been exsolved later, preferentially in the magnetite border zone adjacent to the primary ilmenite. Ilmenite I_s has grown along the contact where it is free of spinel, leaving bars of magnetite connected with spinel grains. The growth of ilmenite I_s has proceeded along a {111} direction into the magnetite (X 600).
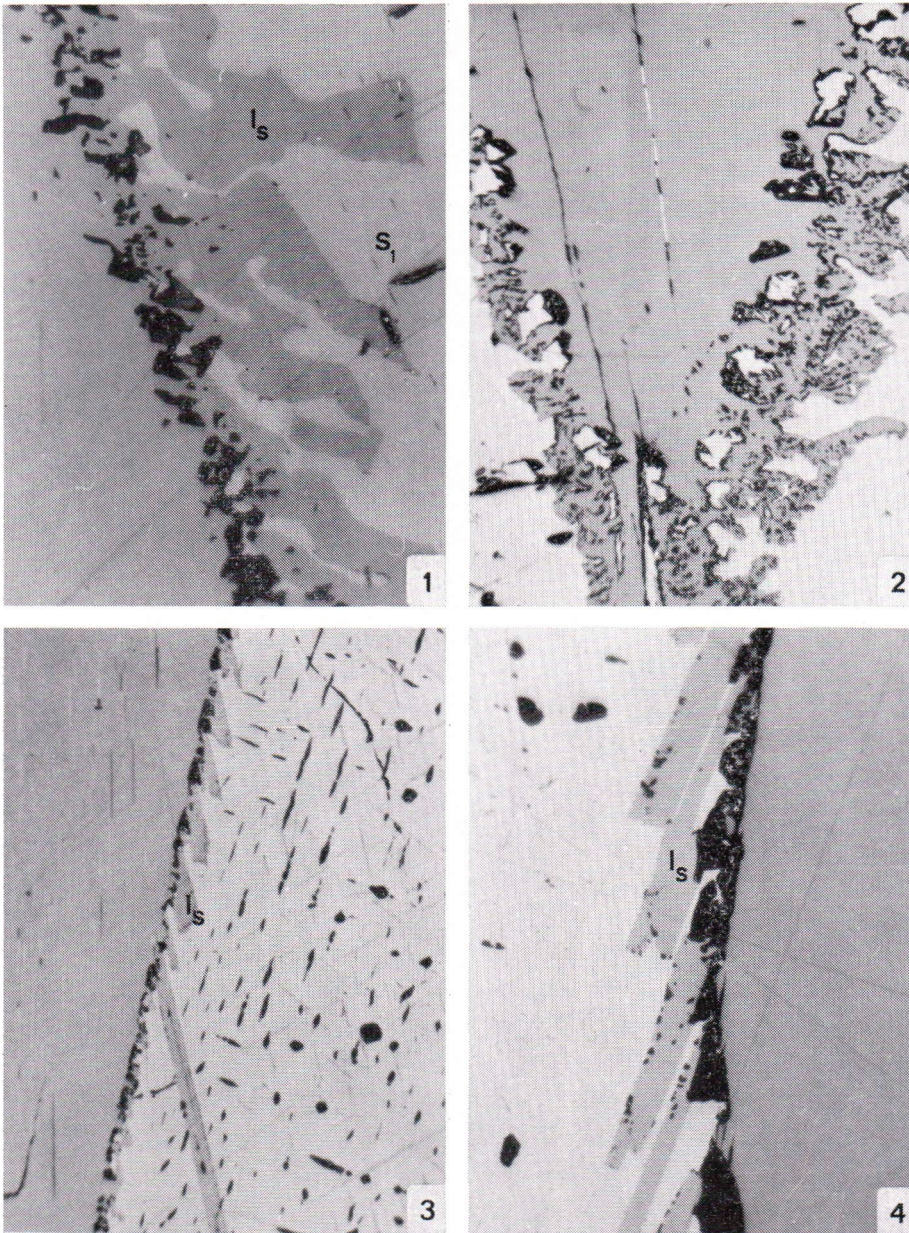
PLATE IV

1. Similar to Plate III—3. The contact intergrowth shows a more complex texture. Ilmenite I_s is optically continuous with the adjacent primary ilmenite and has locally overgrown {100} exsolutions of spinel S_1 (X 600).

2. Contact intergrowth with an intricate texture. For explanation, see text to Plate III—3. Spinel is concentrated on the contacts of ilmenite I_s and magnetite, forming an atoll-like texture (X 240).

3. Lamellar type of contact intergrowth. Ilmenite I_s is oriented along a {111} direction and is optically discontinuous with the adjacent primary ilmenite. The lower I_s-lamella deeply penetrates the magnetite (X 240).

4. Lamellar contact intergrowth with a highly regular texture. The individual lamellae of ilmenite I_s are separated by very thin magnetite bars. Fine grained spinel is concentrated in ilmenite I_s, especially along the contacts with magnetite (X 600).
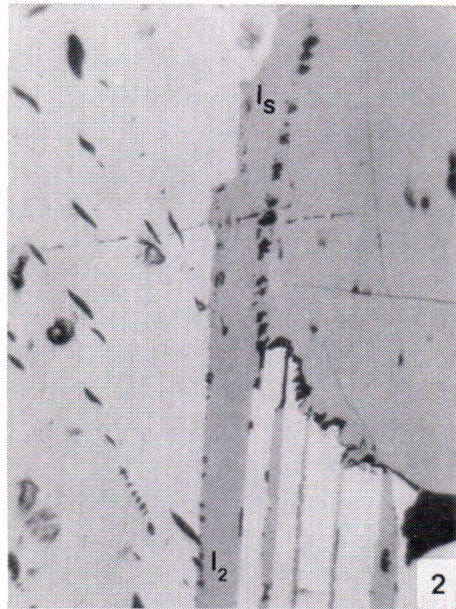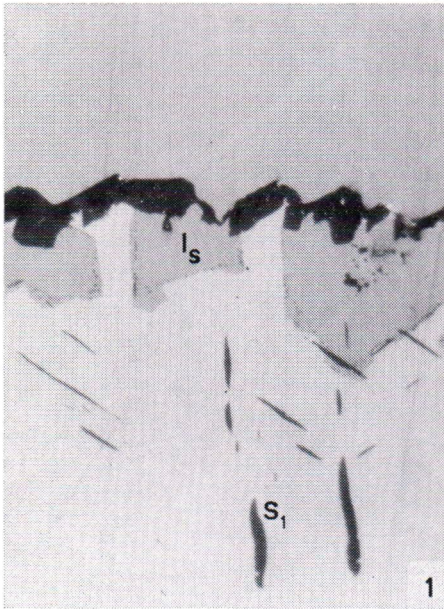
PLATE V

1. The shape of ilmenite I_s is controlled by {100} and {111}-planes of the host magnetite. {100} exsolutions of spinel S_1 locally have been overgrown by ilmenite I_s. Fine grained spinel is concentrated in ilmenite I_s adjacent to the contacts with magnetite (X 600).

2. An exsolution lamella of ilmenite I_2 passes into a rim of ilmenite I_s. Ilmenite I_s is almost absent along the contact that cuts the favored {111} exsolution plane of ilmenite I_2 (X 600).

3. Spinel concentrations of adjacent contact inter-growths pass into a string of spinel S_1 exso-lutions that has been formed along the mutual magnetite boundary (X 600).

4. Irregular intergrowth of ilmenite and spinel in primary magnetite. Ilmenite shows the same optical orientation all over the inter-growth. Spinel is concentrated along the con-tacts between magnetite and ilmenite, causing an atoll-like texture. The ilmenite probably has been formed by early oxidation-exsolution, causing dump of spinel along the borders of magnetite remnants (X 240).