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THE MAGNETITE GABBRO AND RELATED
MUSTAVAARA VANADIUM ORE DEPOSIT IN THE
PORTTIVAARA LAYERED INTRUSION,
NORTH-EASTERN FINLAND

by

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with 33 figures and 12 tables in the text and two appendixes

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The Porttivaara intrusion is a basic layered intrusion including a magnetite gabbro layer in the upper part. The primary minerals of this layer are plagioclase, augite and magnetite. Secondary changes have particularly effected augite, which now has mostly altered to uralite. The only idiomorphic mineral is plagioclase, which occurs as elongated laths. Augite and magnetite are aliothiomorphic between the grains of plagioclase. The last mineral to crystallize was magnetite. At Mustavaara the magnetite gabbro is of economic value because of vanadium incorporated in the magnetite.

The chemical composition of augite changes from $\text{Ca}_{43}\text{Mg}_{45}\text{Fe}_{12}$ in olivine gabbro I, which is the lowermost exposed horizon of the layered series to $\text{Ca}_{44}\text{Mg}_{34}\text{Fe}_{22}$ in the upper part of the magnetite gabbro. The differentiation has thus gone toward iron enrichment but has not proceeded to an iron rich residual liquid. The chemical composition of augite in the magnetite gabbro is not in equilibrium with the chemical composition of the rock, being poorer in iron. This indicates that the oxide phase must also be of cumulus origin. The crystal form of the magnetite does not indicate a concentration of magnetite by accumulation of separate magnetite crystals. Instead, the textural features give evidence for the existence of a separate oxide liquid. As indicated by its genesis, the Mustavaara vanadium ore deposit is assignable to those early magmatic ore deposits formed by liquid immiscibility.

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PREFACE

In 1971 at the University of Oulu was initiated a project called the Koillismaa Research Project, a joint effort of the departments of Geology and Geophysics. Because of the massive accumulation of data, the Institute of Data Processing, University of Oulu, became later affiliated with the project, to process the material.

The main purpose of the Project was to study the metallogensis involved in the basic igneous activity on the southern edge of the Kuusamo schist area. One segment of this undertaking was to determine the crystallization history of the basic intrusions so typical to the area and to evaluate those factors which were important for the disseminations of oxides and sulfides which are present in the intrusion. This task was divided into three part: 1) the general crystallization of the intrusion, 2) the sulphide phase, and 3) the oxide phase. The work presented in this paper treats the oxide phase in the Porttivaara intrusion which, at the present time, is the most completely investigated of the Koillismaa intrusions. As a whole the studies of the Koillismaa Research Project were completed by the end of 1976.

The material for this study of the magnetite gabbro was put at the author's disposal by Rautaruukki company, which has drilled several holes in the east and west ends of the intrusion during prospecting operations. The samples from the upper and lower horizons of the intrusion were collected by the Koillismaa project. Chemical analyses were carried out in part by the chemical laboratory of the Rautaruukki company and, in part, by the chemical laboratory of the Department of Geology at Oulu University.

INTRODUCTION

Location of the area

The basic intrusive considered here is located in northern Finland, mostly in the commune of Taivalkoski. Only the most NE part is situated in the commune of Posio. Taivalkoski, the hamlet where the parish church is located, lies 25 km SSE from the area. The town Oulu is at the distance of 180 km to SWW along the road (Fig. 1).

The basic intrusive includes several hills, the highest of which are Haukivaara, Porttivaara, Raiskiovaara and Mustavaara. The summits of the latter three are 390 m

above sea level, Haukiavaara is 20 meters lower. In reference to Porttivaara, which stands in the middle of the intrusion, this igneous body has been named the Porttivaara intrusion. Its dimensions on the earth's surface are 3 km by 20 km.

General geological setting

According to the general geological map of Finland (Fig. 1) and the maps compiled by the Koillismaa project (Fig. 2, Appendix II,) the Porttivaara intrusion lies between the old presvecokarelidic basement complex and the younger Svecokarelian sediments and volcanics. Both the upper and lower contacts are strongly tectonized. Between the basement and the intrusion there has been found in most places a quartz-albite rich rock (albite rock in Fig. 2 and Appendix II) which also cuts the lower marginal zone of the intrusion and partly forms a hybride with it. According to the interpretation of the Koillismaa Research Project this quartz-albite rich rock is derived from the basement by partly mobilization. The mobilization has been caused by the heat of the intrusion. The Svecokarelian rocks just above the intrusion are tholeiitic and keratophyric lavas and above them lie sediments characterized by quartzites, mica schists and dolomites.

In addition to the Porttivaara intrusion there are half a dozen other basic intrusions in the area of Koillismaa. The stratigraphic position and mineralogical composition of these are similar to that of the Porttivaara intrusion. The biggest of these other intrusions are those of Syöte and Kuusijärvi—Lipeävaara (Fig. 2). It is possible that all intrusions in the area initially formed a single coherent sheet, and that this was broken into pieces at a later stage during svecokarelidic orogeny.

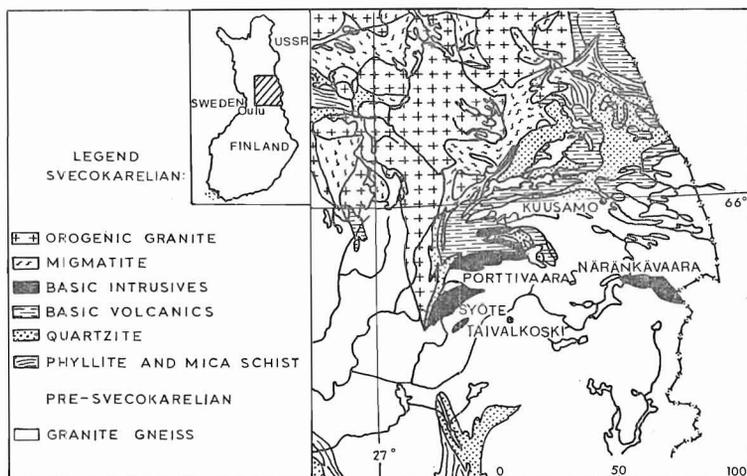


Fig. 1. Location and geology of the Porttivaara intrusion (Geology after Simonen 1960, 1971).

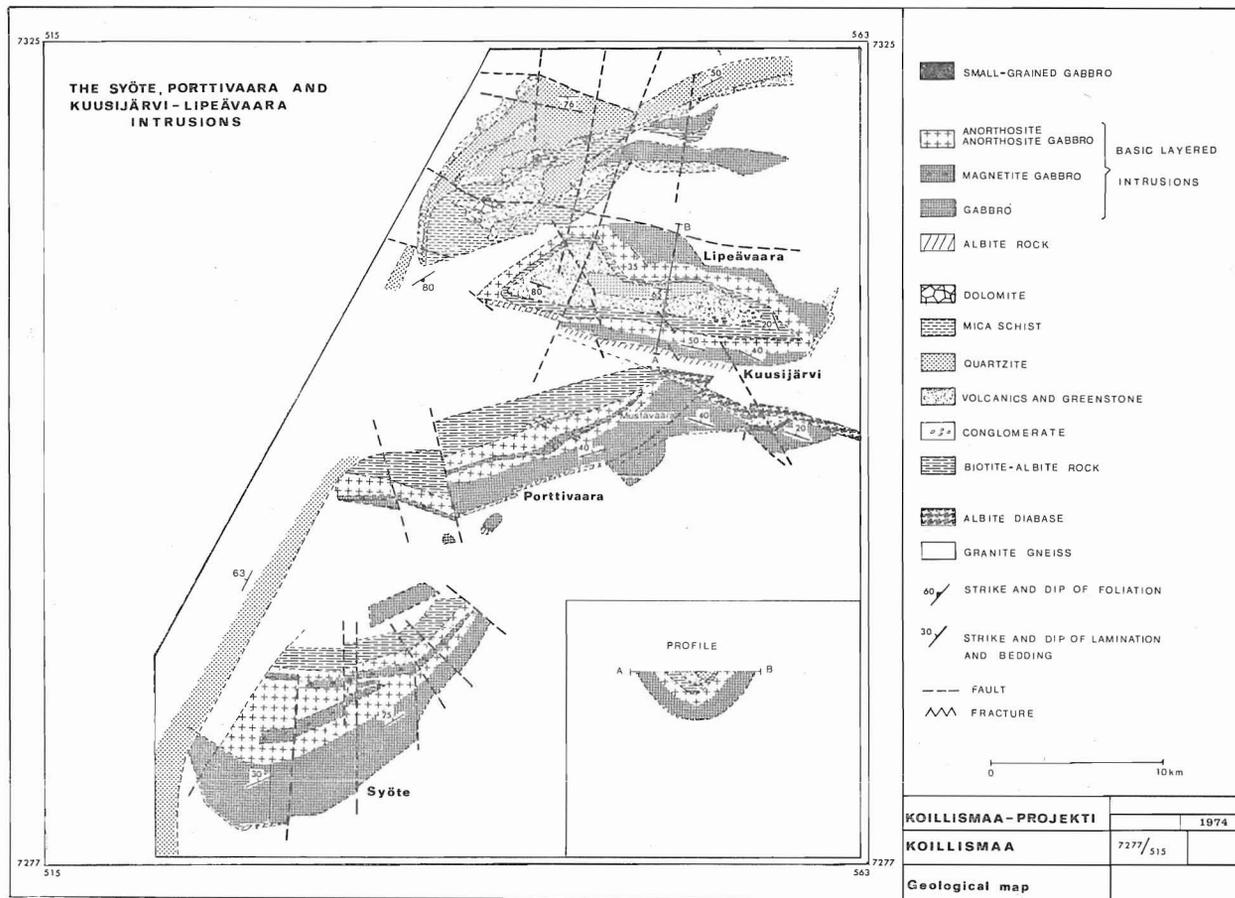


Fig. 2. Geological map of the Koillismaa layered intrusions.

As regards the geological evolution of the area, the basic volcanics and intrusives belong to the initial magmatic stage of the Svecokarelidic magmatism (Piirainen *et al.* 1974). The magmatism started with basic subaerial volcanism. The basic intrusions were then emplaced between the volcanics and the old basement.

Previous works

The first published geological information from the area studied by the Koillismaa Research Project are the general geological maps of Finland, sheets C5—B5 Oulu—Tornio (Enkovaara, Härme and Väyrynen 1952) and D5 Suomussalmi (Matisto 1954) and the explanations for these maps by the same authors for Oulu—Tornio in 1952 and Suomussalmi in 1958. Field work for these maps had been initiated already at the beginning of this century, but not was published until the 1950's.

Because of samples received from the public, prospecting companies became interested in the area in the 1950's. Some samples contained chalcopyrite and pyrrhotite, and some vanadium-bearing ilmenomagnetite. Outokumpu company undertook field work and drilling for sulphides in 1962—1968. On basis of this material Vilho Ohenoja, one of the students working in the area at that time, completed his M. Sc. thesis »Porttivaaran—Kuusijärven alueen kallioperä» in 1968. Otanmäki company (amalgamated with Rautaruukki company in 1968) began prospecting for vanadium-bearing ilmenomagnetite in 1957—1958 and continued work in 1967—1968. This led to the discovery of a coherent magnetite gabbro horizon in the upper part of the intrusion. The material, together with that of Ohenoja, initiated study concerning the genesis of the magnetite gabbro and of the crystallization of spinels in basic intrusives. This theme is incorporated in the works of Piirainen and Juopperi (1968) and in the unpublished M. Sc. and licentiate theses of Juopperi (1970, 1972). The present study is a continuation of these efforts.

Photogeology has been applied to the area by Talvitie and Luoma-aho (1972) and Talvitie and Paarma (1973).

The most recent studies are incorporated in reports from the Koillismaa Research Project. These are the works of Hugg *et al.* (1974), Piirainen *et al.* (1974) and the unpublished M. Sc. thesis of Mäkelä (1975).

The goal of the study

The goal on this study is to determine those conditions which dominated during the crystallization of spinels and to evaluate those factors which have most effected the formation of the magnetite gabbro. The method employed is to examine the changes in compositions of rocks and minerals across the intrusion as well as taking into consideration the general texture of the rocks. The results are then compared with the results of experimental petrology.

THE PORTTIVAARA INTRUSION

The following description of the structure, mineralogy and petrography of the Porttivaara intrusion, excluding magnetitegabbro, is a summary from the M. Sc. thesis of Mäkelä (1975).

Structure

The Porttivaara intrusion is a layered igneous body which is characterized by both rhythmic and cryptic layering. Because of changes occurring in mineral combina-

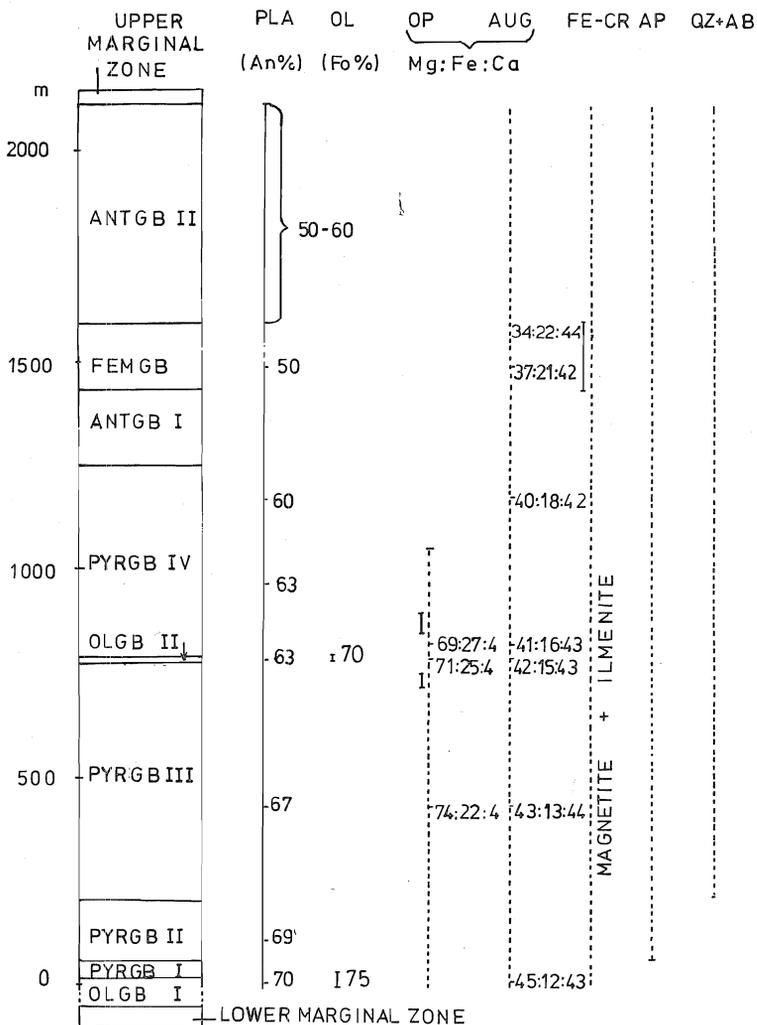


Fig. 3. Cryptic layering in the Porttivaara intrusion according to Mäkelä (1975). OLGB = olivine gabbro, PYRGB = pyroxene gabbro, FEMGB = magnetite gabbro, ANTGB = anorthosite gabbro, PLA = plagioclase, OL = olivine, OP = orthopyroxene, AUG = augite, Fe—Cr = Fe—Cr—Ti-oxide, AP = apatite, QZ+AB = quartz + albite. Line = cumulus mineral; dotted line = intercumulus mineral.

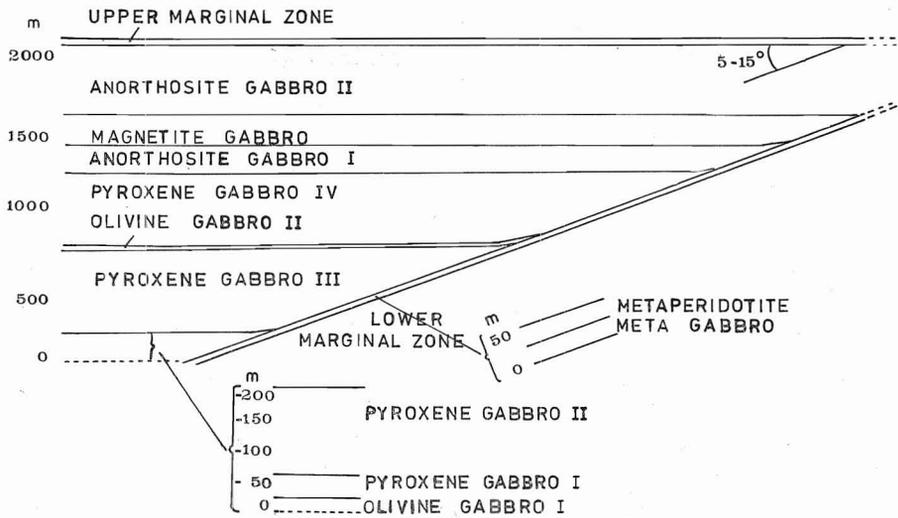


Fig. 4. The structure of the Porttivaara intrusion according to Mäkelä (1975). The angle between lower and upper marginal zones is exaggerated.

tions and in the intensity of rhythmic layering the intrusion has been divided into various rock horizons. These are presented, with cryptic layering, in Fig. 3 and with a model of the structure in Fig. 4. The marginal zone is found everywhere around the layered series so that it forms an envelope surrounding the intrusion. The outer contacts of this zone are strongly tectonized so that if there has primarily been any fine-grained chill zone, this has been destroyed. The dip of the lower marginal zone, which is equivalent to the dip of the bottom contact, has been calculated from results of gravimetric and magnetic measurements. There is an angle of discordance 5—15° between this dip and the dip of layering for layered series measured from outcrops. In its present position the layered series dips 30—40° NNW.

Mineralogy

The most important primary minerals are plagioclase, augite, orthopyroxene, olivine and ilmenomagnetite. Secondary changes have been especially effective in altering mafic silicates. Pyroxenes have been mostly uralitized and olivine has been altered to a mass of serpentine, talc and magnetite. Plagioclase has also been variably altered to epidote. The marginal zones, the magnetite gabbro and the layers lying immediately above it have been most altered. The following description is restricted to the primary features of the minerals. Only these have meaning as regards the crystallization history of the intrusion.

Plagioclase is the most common mineral found in both the layered series and in the marginal zones. Usually it exists as a cumulus mineral. The crystals are laths the borders of which are somewhat sinuous because of growth after accumulation. Zoning is a common feature the difference in An-content between the middle and the margins being 10—15 % or, in extreme cases, 20—30 %. Oscillatory zoning is common in the lower layers of the intrusion. In intercumulus plagioclase zoning is very weak as well as being normal in character. The changes in composition with structural height are presented in Fig. 3. The compositions were determined by U-stage from the middle of the grain. A general feature is that the nucleus becomes more sodic upward through the layered series. The higher An-content of plagioclase in rocks above the magnetite gabbro is due to a cumulate origin of those anorthosites.

Olivine is limited in the layered series to two narrow horizons called olivine gabbros. The grains are equidimensional, ellipsoidal or, partly because of adcumulus growth, even allotriomorphic. The compositions presented in Fig. 3 are from microprobe analyses. Compositional zoning in grains has not been found.

Orthopyroxene is found as an intercumulus phase in all the rocks from pyroxene gabbro IV downwards. As cumulus crystals it occurs only as an accessory in gabbros near olivine gabbro II. The mineral is »Bushveld type» (Hess and Phillips 1938) containing narrow augite lamellae in the (100) direction. The compositions presented in Fig. 3 were determined by microprobe between the lamellae. According to its composition it is bronzite (Deer *et al.* 1963).

Augite, like plagioclase, is found throughout the intrusion. It usually exists as poikilitic grains and is the last silicate mineral crystallized. Because of the absence of visible zoning it is difficult to determine at which stage it is of cumulus, adcumulus or intercumulus origin. Allotriomorphicity gives yet evidence for intercumulus origin. Exsolution lamellae in directions (100) and (001) are typical. Because of the narrowness of the lamellae it was not possible to determine their compositions. The compositions presented in Fig. 3 and Table 8 are from areas between the lamellae. The enrichment of iron at expense of magnesium is clear upwards in the layered series.

Magnetite is an essential constituent only in the horizon called magnetite gabbro. Grains which lie between the silicate grains are allotriomorphic. A more detailed description is given on p. 21. As an accessory, magnetite is found throughout the intrusion. Because of strong alteration it was not possible to determine changes in composition across the intrusion.

Ilmenite, apatite and quartz are primary accessories. The latter occurs as a granophyric intergrowth with albite. Sulphides, most of which are in the metagabbro of the marginal zone, also occur as accessories. Ilmenite is found in layers below the magnetite gabbro, both as lamellae in the magnetite and as separate grains surrounded by silicates. In the magnetite gabbro it is found only as lamellae or in intimate contact with magnetite (p. 24).

Petrography of the rocks

Marginal zones

Marginal zones have been divided into the upper, lying conformably above the layered series, and the lower, comprising the floor of the intrusion (Fig. 4). The latter has been further divided into metaperidotite and metagabbro.

Metagabbro lies at the foot wall contact of the intrusion. Its breadth varies from 10 to 50 meters. The zone is very unhomogeneous containing gabbros of different grain sizes and different amounts of essential minerals. Metaperidotitic areas are not uncommon. In some places weak layering is visible. The chief primary minerals were plagioclase and augite. The present association is due to strong alteration of plagioclase (mostly albite), clinozoisite, carbonate, chlorite and amphibole. Weak dissemination of sulphides is common.

Metaperidotite, lying above metagabbro, is very strongly altered. The primary minerals may have been olivine, augite and orthopyroxene. Now tremolite, magnetite and serpentine form pseudomorphs after olivine and the matrix is composed of a mass of chlorite, talc and carbonate. Small round spots richer in talc are also found in matrix. These may be pseudomorphs after orthopyroxene. The thickness of metaperidotite is 10—30 m.

The upper marginal zone is very unhomogeneous and strongly altered. The zone is composed of light, coarse-grained meta-anorthosite and darker anorthosite gabbro. The mafic mineral is a poikilitic mass of chlorite, probably a pseudomorph after augite. Primary augite has not been found. The grain size of this poikilitic mass is up to 50 mm in diameter. The length of plagioclase laths is half this value. Plagioclase has been so strongly altered to epidote that it was not possible to determine its composition. The breadth of the upper marginal zone is 10—50 meters.

Olivine gabbros

Olivine gabbro is encountered in two horizons. The lower of them is called olivine gabbro I and the upper olivine gabbro II. The lower is visible only in the deeper section of the intrusion. The chief minerals in both are olivine, plagioclase, orthopyroxene and augite. The amount of the latter is rather small in olivine gabbro I. A rhythmic layering, due to changes in amount of olivine, is especially characteristic of olivine gabbro I. In olivine gabbro II the changes are regular. The amount of olivine is greatest in the lower part of each layer and becomes smaller when traced upwards. The changes in amount of plagioclase are the reverse. The most idiomorphic of the chief minerals is olivine. Plagioclase is allotriomorphic in olivine gabbro I. In olivine gabbro II it also exists as idiomorphic laths, especially in the upper, plagioclase-rich part. Orthopyroxene and augite are poikilitic.

Pyroxene gabbros

The division of pyroxene gabbros into horizons I—III is based upon the presence or absence of rhythmic layering. Pyroxene gabbro IV is separated from pyroxene gabbro III by olivine gabbro II. Essential minerals in all pyroxene gabbros are plagioclase, orthopyroxene and augite with magnetite, apatite, quartz and sulphides as accessories. From pyroxene gabbro III upwards there is also a symplectitic intergrowth of albite and quartz between the grains of plagioclase.

Pyroxene gabbro I is characterized by rhythmic layering due to changes in the amounts of plagioclase and pyroxenes. Light layers have 70—90 % plagioclase and those which are dark, 20—60 %. The remainder is 50/50 orthopyroxene and augite. The thickness of the layers is: dark, 0.5—3 cm; light, 1—10 cm. No very good idiomorphs are present in minerals.

Pyroxene gabbro II is homogeneous. No rhythmic layering is present. The rock is composed of 60 % elongated laths of plagioclase and 35 % poikilitic augite. The remaining 5 % consists of orthopyroxene and other accessories.

Pyroxene gabbro III has rhythmic layering in the lower and upper parts of the layer. This is expressed as changes in the amount of plagioclase and pyroxenes as well as in variation in the grain size of the plagioclase. The amount of plagioclase is 30—65 % and that of pyroxenes 35—70 %. The amount of orthopyroxene and augite is equal. The thickness of the layers is 5—15 cm. The grain size of plagioclase is 0.6—1 × 2—3 mm in the lower 2/3 and 1.5—2 × 4—6 mm in the upper 1/3. Local exceptions exist. The grains are good laths. The normal grain size of pyroxenes is 2—4 cm, the biggest being up to 5 cm. The grains are clearly poikilitic in relation to plagioclase.

Pyroxene gabbro IV has rhythmic layering. The layers have typically differentiated so that the upper parts are richer in plagioclase than the lower ones. Some homogeneous layers exist. The exposed thickness of the layers varies from 1 to 10 meters but may be somewhat thicker because only one contact is visible in most outcrops. The amount of plagioclase is 50—60 %, orthopyroxene 15—35 % and augite 15—35 %, despite the fact that the pyroxene is entirely augite in the upper parts of the horizon. The grain size of idiomorphic plagioclase laths is 1—1.5 × 3—5 mm. In the lower part of the intrusion orthopyroxene can occur as roundish grains. In other parts it is poikilitic. Augite is poikilitic throughout. The grain size of poikilitic pyroxene grains is 1—2 mm. The roundish orthopyroxenes are smaller, about 0.1—1 mm.

Anorthosite gabbros

Anorthosite gabbro appears in the upper part of the layered series where it is divided into two parts by the magnetite gabbro. The rock is light in colour, coarse-grained and strongly altered. Lamination which is typical of pyroxene gabbros is weak in anorthosite gabbro I and rare in anorthosite gabbro II. Layering has been found only just below the magnetite gabbro. Plagioclase is altered mostly to epidote

and augite is completely altered to uralite or even to chlorite in anorthosite gabbro II. As far as can be deduced from alteration products, orthopyroxene has not crystallized in the horizon.

Anorthosite gabbro I is usually unhomogeneous being composed of lighter and darker areas. The borders of these are gradual and randomly oriented so that they do not follow the layering of the intrusion. The lighter areas are richer in plagioclase than are the darker. The amount of plagioclase may rise as high as 95 %, in which case the rock is anorthosite. In dark areas the amount of plagioclase is 65 %. In anorthositic areas the grain size of plagioclase is 5×10 –20 mm and in anorthosite gabbro it is clearly smaller, about 1 – 2×4 –5 mm. The uppermost 10–50 m below magnetite gabbro is mostly anorthositic.

Anorthosite gabbro II is more homogeneous than anorthosite gabbro I. The amount of plagioclase is 70–80 % and the altered remains of augite 15–25 %. The grain size of idiomorphic plagioclase is 3 – 5×10 –20 mm. The original augite was poikilitic and several centimeters in size. The amount of interstitial ilmenomagnetite is greater than in anorthosite gabbro I or in lower layers. Crystals appear as large poikilitic grains several centimeters in length.

The chemical composition of the primary magma

No fine-grained chill zone, from which the composition of the primary magma might have been determined was found around the intrusion of Porttivaara. Thus

Table 1.

The mean value of the analyses of rocks of the Porttivaara intrusion (Mäkelä 1975).

SiO ₂	51.35	ILM =	0.90
TiO ₂	0.64	OR =	3.89
Al ₂ O ₃	16.14	AB =	25.28
Fe ₂ O ₃	1.59	AN =	30.04
FeO	7.13	MAG =	1.68
MnO	0.14	FS =	6.33
MgO	8.09	EN =	15.26
CaO	9.48	DIOPS =	14.08
Na ₂ O	2.78	FO =	1.79
K ₂ O	0.65	FA =	0.74
H ₂ O+	1.50		
H ₂ O-			
	SUM		99.49
Mg			
Fe	0.73		
Co	0.007		
Cu	0.030		
Cr	0.030		
Ni	0.033		
V	0.025		
Zn	0.010		

the composition of the magma must be estimated from the compositions of the rocks. In layered intrusions estimations of this kind can yield inaccurate results because most rocks are cumulates, the compositions of which can differ significantly from those of neighbouring rocks. However, if the sampling is at regular, widely spaced and at not too long intervals, then the mean values should produce reasonably good results. This presupposes, that all differentiates are cut in the available section. Mäkelä (1975) has calculated a mean value from 165 samples gathered by this manner in 5 profiles across the intrusion. The results are in Table 1. The composition of the primary magma in the classification of Kuno (1960) is one between tholeiitic and high-alumina basalt. In the classification of Yoder and Tilley (1962) it is somewhere between tholeiite and olivine tholeiite.

THE MAGNETITE GABBRO AND THE VANADIUM ORE OF MUSTAVAARA

Case history

The existence of a coherent magnetite gabbro horizon in the Porttivaara intrusion was discovered from aeromagnetic measurements made by the Otanmäki company in 1959 for prospecting. This prospecting was prompted by vanadium-bearing magnetite gabbro samples sent in by the public during the years 1957 and 1958. Preliminary research showed that some of these samples could be from Haukivaara or from Porttivaara, from where similar rock was found outcropping. The aeromagnetic measurements made the following year showed that these outcrops belong to the same aeromagnetic anomaly which also passes through Mustavaara. The magnetite and vanadium content of the Porttivaara and Haukivaara samples were however low, and thus they did not encourage further prospecting.

Later the Otanmäki company made a special investigation of the vanadium-bearing samples collected from the Taivalkoski area. When all the material was reanalysed, higher vanadium contents were found than previously, and more detailed investigation of the aeromagnetic anomaly was begun. Magnetic measurements were undertaken on ground and the area was mapped geologically. A magnetite gabbro, which contains enough vanadium to justify drillings, was found at Mustavaara. During the years 1967 and 1968 the magnetite anomaly was pierced at Mustavaara at a distance of 1 800 m in 9 profiles. In 1971 and 1972, the distance of the profiles was shortened to 100 m. In addition, 8 holes were drilled at the western end of the intrusion. The drillings at Mustavaara brought to light enough vanadium-bearing magnetite to show that the deposit could be exploited economically. The decision to establish a mine was taken in 1973; production began in 1976.

Position in the intrusion

The magnetite gabbro forms a coherent sheet within anorthosite gabbro in the upper part of the intrusion. The sheet together with the intrusion is cut by a fault into two pieces. The length of the eastern body is 13 km and the western one 6 km (Appendix I and II). The western end of the western body is also tectonic. At the eastern end the horizon, according to magnetic measurements, becomes narrower until on the eastern side of Mustavaara it dies out completely. Before this narrowing the horizontal breadth is c. 300 m. In most parts the dip is 30—40° to the North, only in the easternmost part does it become steeper. In the final drilled profile (includes borehole 35 B) it is c. 70°.

The contact between the magnetite gabbro and the anorthosite gabbro above it is gradual so that upwards in the layered series the amount of coarse-grained anorthosite gabbro blocks in magnetite gabbro increases. This happens until the rock is an unhomogeneous anorthosite gabbro containing specks of magnetite gabbro. Further upwards the magnetite gabbro diminishes and the rock becomes anorthosite gabbro II which is described on p. 14. The breadth of this transition zone is c. 50 m. The foot wall contact of the magnetite gabbro is marked by a sharp boundary beneath which is altered anorthosite/anorthosite gabbro (Fig. 5). During preparation work for mining this contact was uncovered at Mustavaara. The first three metres of the foot wall rock are layered (Fig. 6). The light layers are anorthosite, and the dark layers anorthosite gabbro. In the latter the amount of ilmenomagnetite is greater

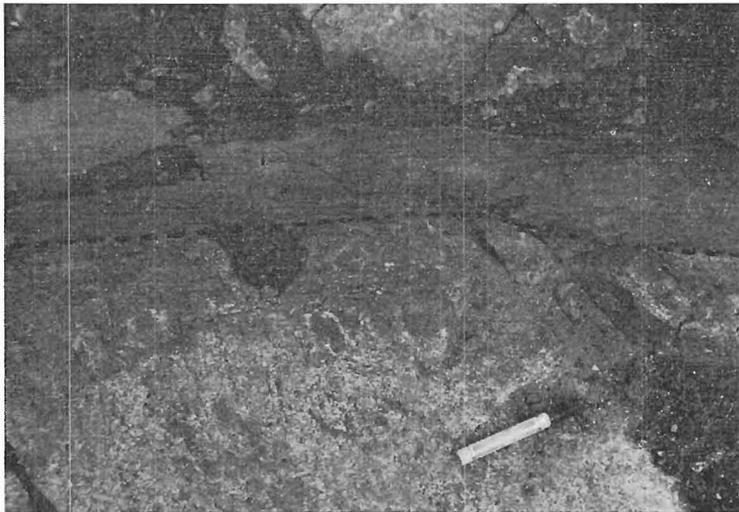


Fig. 5. The lower contact of the magnetite gabbro. Dark magnetite gabbro, light meta-anorthosite. Mustavaara.

than in the rocks below, by about 5 %. In the remaining 13 metres exposed the dark minerals appear as specks giving a spotted habit. A strong altering of plagioclase into epidote in part causes the anorthosite to appear pink. In this variety the layering or spotted habit is no longer visible. Mostly the amount of dark minerals is so small that the rock is anorthositic.

Structure

The drillings at Mustavaara made it clear that the amount of magnetite in magnetite gabbro changes in such a regular way that the horizon can be divided into four thicker layers which are bounded by sharp contacts with each other. The three lower layers comprise the Mustavaara ore deposit and they are called: ore lower layer (OLL), ore middle layer (OML) and ore upper layer (OUL). The fourth layer consists of a weak dissemination above the upper layer of the ore and it is called the disseminated rock (DR). The richest of the layers of the ore is the lowest layer with 25–35 w % magnetite, and the poorest is the middle layer containing c. 15 w % magnetite. Clearly, the different layers can be identified using the susceptibility measurements from the boreholes (Fig. 7).

The most unhomogeneous of the layers is the disseminated rock, which contains scattered anorthosite, and anorthosite gabbro fragments and compact magnetite dykelets. Anorthosites are also found as inclusions in the ore. Their longitudinal directions do not follow the general layering, but they are randomly oriented. Most are rounded. The contact between the fragments and the surrounding magnetite gabbro is sharp (Fig. 8). On a small scale the direction of plagioclase laths of magnetite gabbro follows the contacts of the fragments. At a distance of a few centimetres from the contact the magnetite has altered to silicates (see p. 27). The same situation also occurs at the contact of the lowest layer of the ore and the anorthosite below. In the susceptibility measurements the anorthosite fragments as well as the zones of metamagnetite gabbro appear as zero gaps.

The narrowing of the magnetite gabbro eastward from Mustavaara is also to be seen in the narrowing of the different layers. In the lower layer of the ore, which at its maximum is only 5 metres thick, the narrowing is not as clear as in the middle and upper layers. The width of the middle layer is in normal section c. 50 metres on the western side of Mustavaara. However, at its easternmost known occurrence it is only 15 metres thick. The corresponding numbers for the upper layer of the ore are 40 and 10 metres. According to the susceptibility and magnetic measurements the disseminated rock does not occur at the eastern end of the intrusion. Instead the uppermost layer of the magnetite gabbro is the upper layer of the ore. The lack of anomaly results from the fact that the magnetite component of the ilmenomagnetite grains (see p. 27) has been completely displaced by silicates. All that remains from the primary grains are ilmenite lamellae which occur as crossed skeletons (Fig. 20).

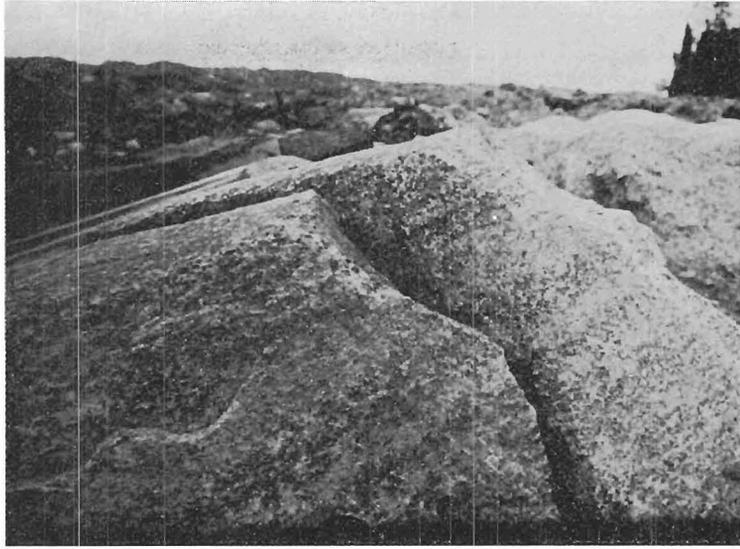


Fig. 6. Layered anorthosite/anorthosite gabbro below magnetite gabbro. Mustavaara.

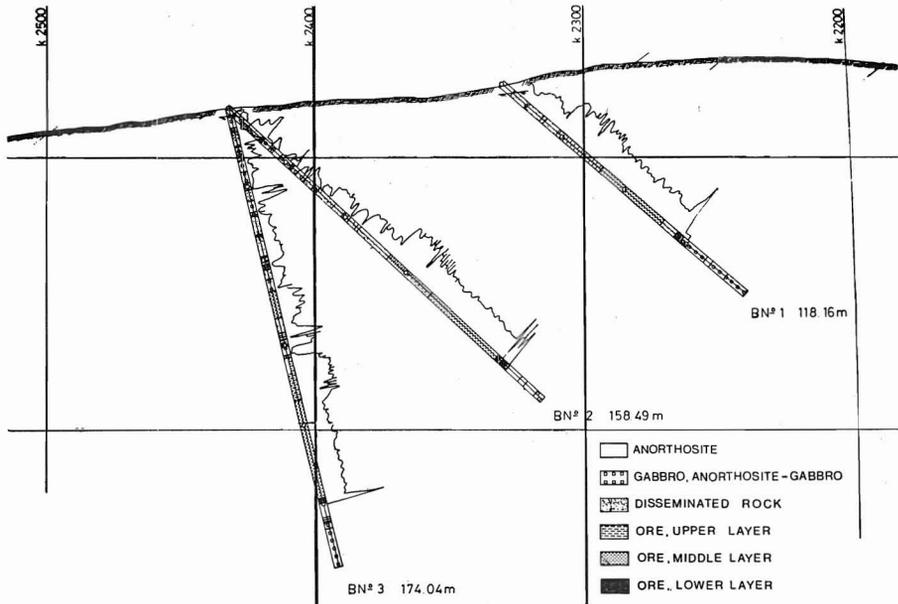


Fig. 7. The results of the susceptibility measurements from boreholes 1, 2 and 3 at Mustavaara. The interval between reading points was 10 cm.



Fig. 8. Anorthosite blocks in magnetite gabbro.



Fig. 9. Layering in the upper layer of the ore. Dark layers are richer in magnetite. Mustavaara.

In addition to the fourth division of magnetite gabbro there is also layering which varies from a few centimetres to a few tens of centimetres. In the upper layer of the ore this is visible with the naked eye (Fig. 9). The difference in amount of magnetite between adjoining layers could be 10 vol %. The contacts between different layers are sharp. The amount of magnetite in each layer is equally distributed throughout so that no gravity stratification could be found. Moreover at the contacts no change in lamination could be seen. The contacts between the lower, middle and upper layers of the ore are compatible with the contacts of this small-scale layering, so that without the magnetic or susceptibility measurements it was difficult to determine the boundaries.

In the area of Haukivaara, where drillings were also done, the layered structure of the magnetite gabbro was not as clear as at Mustavaara. The corresponding layers were still to be found (Fig. 10), despite bore-hole HB 4 where the dissemination was very equal. In these holes the susceptibility anomaly appears abruptly as if there were no disseminated rock horizon. The reason is the same as in easternmost part of Mustavaara, the magnetite in the disseminated rock has been mostly displaced by silicates. In order to facilitate comparison of the corresponding layers of the magnetite gabbro from Haukivaara and Mustavaara, the different layers at Haukivaara are also called in the tables ore lower layer, ore middle layer and ore upper layer, although they are of no economic value.

Mineralogy

The number of primary minerals in the magnetite gabbro is very small. The principal minerals were originally plagioclase, augite and magnetite. Orthopyroxene has not been found. Augite has for the most part altered to uralite. The other sec-

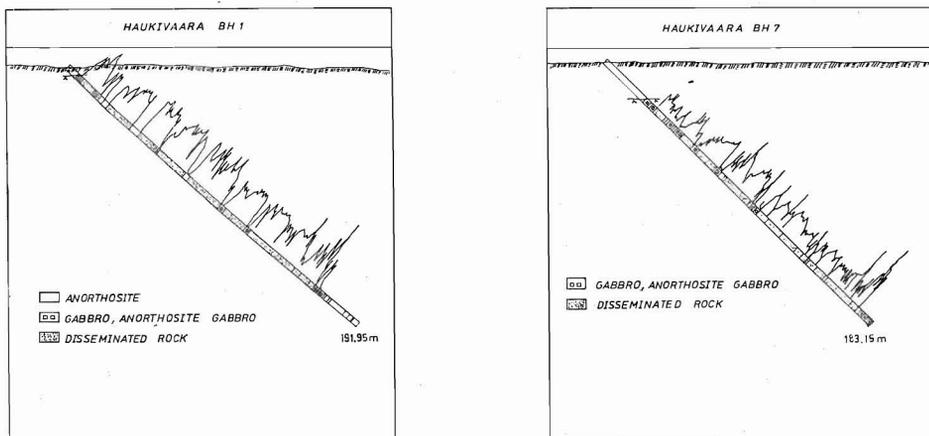


Fig. 10. The results of the susceptibility measurements from the boreholes 1 and 7 at Haukivaara. The interval between reading points was 10 cm.

ondary minerals are epidote, chlorite, biotite, titanite and leucoxene. As accessories quartz, apatite and sulphides are found. The most common of the sulphides are chalcopyrite and pyrite. The number of principal minerals in different layers of magnetite gabbro is presented in Table 3 (p. 31).

Plagioclase

Plagioclase occurs in the same manner as in the other gabbros of the intrusion. The grains are idiomorphic laths (Figs. 11—14) the length of which are 2—4 mm and width 0.5—1 mm. The mineral is very dark to the naked eye. Under the microscope characteristic brownish streaks and flecks are seen especially in the samples from Haukivaara. Zoning is weak, composition varies between An_{51} — An_{49} (U-stage, max. symm. ex. 27° — 28°). Reversal zoning was found only in one sample from the disseminated rock. Alteration is variable; replacing products include epidote, chlorite and to a lesser extent sericite. Fissures filled with epidote, chlorite and amphiboles indicate that mechanical deformation has taken place.

Augite

Unaltered or even relict augite is found only very rarely, for the most part it is altered completely to uralite. The primary features are still visible. The crystals are allotriomorphic against plagioclase. Against ilmenomagnetite they display idiomorphic features as well as in grains which occur as inclusions in ilmenomagnetite. Exsolution lamellae in (100) and (001) are typical. The grain size is 0.5—1 mm. The uralite consists of small flakes and pins so that the area of the primary augite crystal goes to extinction position very unevenly. The colour and pleochroism of this uralite is weak except at the borders of the grains, where there is a reaction rim especially against the plagioclase. Here the pleochroism is X green, Z blue-green. The same pleochroism is also found in the grains altered so thoroughly that the entire area of the primary augite is homogeneous. The chemical compositions of augites from different layers of the intrusion is presented in Table 7 and the Ca:Mg:Fe ratios with cryptic layering in Fig. 3.

Magnetite

According to the terminology of Buddington *et al.* (1963 p. 140) the »magnetite» of magnetite gabbro is ilmenomagnetite, which means magnetite with micro-intergrowths of ilmenite. In this text the names magnetite and ilmenomagnetite have been used as synonyms as far as composite grains and not their components are in question. Throughout most of the magnetite gabbro ilmenomagnetite occurs as anhedral grains, which intrude between the spaces of silicates (Figs. 11—14). The grains are elongated parallel to the layering of the intrusion. In the lower layer of

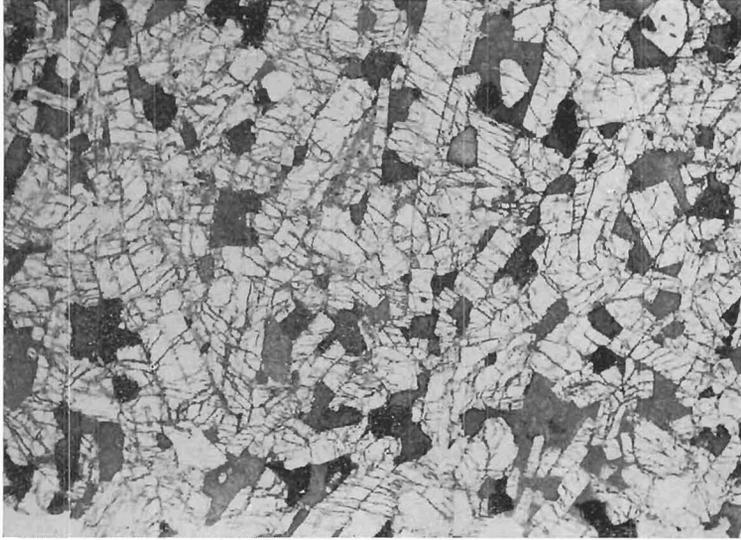


Fig. 11. Disseminated rock. Light plagioclase, grey uralite, black ilmenomagnetite. One nicol, 5.5 x. MB 3/27.25 m.

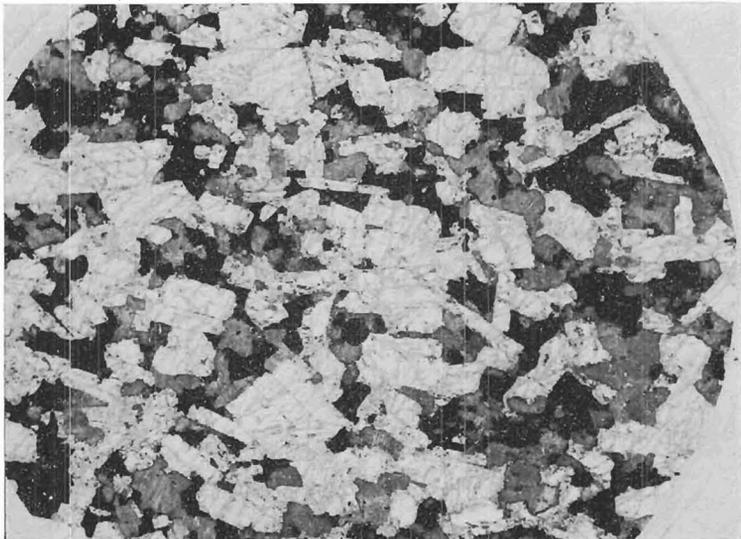


Fig. 12. Ore upper layer. Light plagioclase, altered partly to epidote and chlorite (light grey). Dark grey uralite, black ilmenomagnetite. One nicol, 7 x. MB 56/46.7 m.

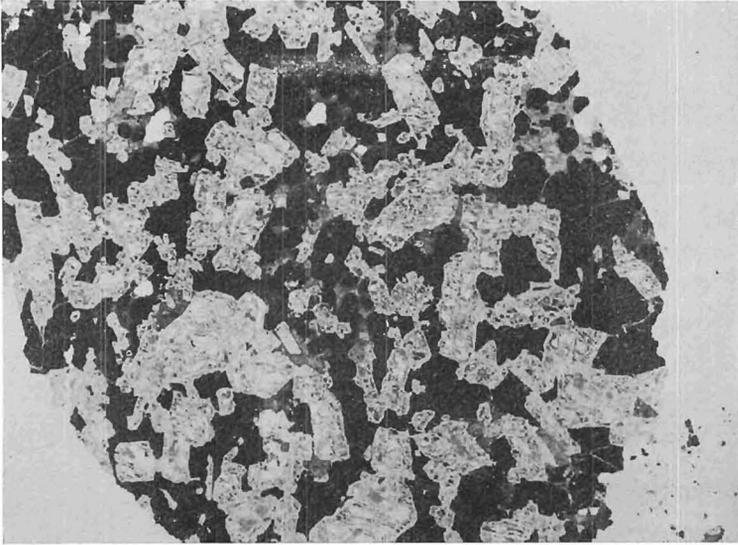


Fig. 13. Ore lower layer. Light plagioclase, altered mostly to epidote and chlorite (light grey). Dark grey uralite, black ilmenomagnetite. One nicol, 5 x. MB 1/85.3 m.

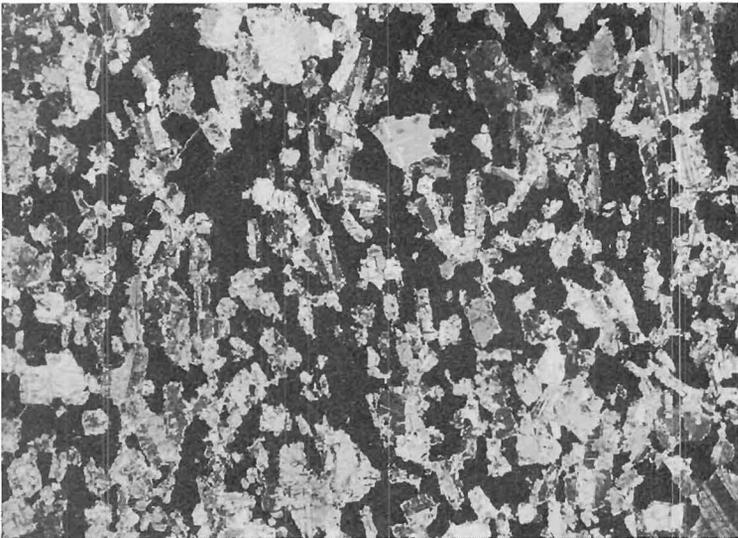


Fig. 14. Ore lower layer. Light and grey plagioclase, altered partly to epidote and chlorite. Black ilmenomagnetite. Nicols crossed, 5 x. MB 40/92.6 m.

the ore, which is richest, the grains touch each other, so that they constitute curved chains of several grains, which separate the silicates. The grain size of the ilmenomagnetite in magnetite gabbro is 0.3—2 mm. However, in the upper part of the disseminated rock, according to the observations from Mustavaara, the grains are smaller, c. 0.3—1 mm.

In the easternmost part of the intrusion, besides the anhedral grains there are also euhedral grains even in majority. In the easternmost boring the upper and middle layer of the ore have idiomorphic grains only (Fig. 16). In addition, the lower layer also has allotriomorphic grains. The grain size of these idiomorphic grains is smaller than normal, c. 0.3—1 mm. Taking into consideration all the magnetite gabbro, the idiomorphicity is quite an exceptional feature.

The ilmenite in the ilmenomagnetite occurs in three different ways:

1. As lamellae continuing through the ilmenomagnetite grains in a direction which conform to (111) in magnetite. These can be subdivided on the basis of their width into two groups: a) Broad lamellae, ca 0.1 mm broad, few in number and only in one set of (111). b) Narrower lamellae width 60 — 1 micron, and which can be abundant. The whole size range from 1 to 60 microns was not found in single samples, but only a variation of less than 20 microns occurs (Figs. 17 and 18).
2. As small splinter-like lamellae between the longer lamellae but following the same direction. The width of these is less than one micron and the maximum length is a few microns (Fig. 18). In some samples where these lamellae are very common, they are not distributed evenly, but form patches. The (111) direction is still clearly to be seen (Fig. 19).
3. As granular grains inside the ilmenomagnetite or on its external border. The grain size of these granules is usually less than 0.5 mm. The optic orientation might follow that of some of the lamellae. In some places the granule can continue as a lamella through the grain (Fig. 17).

In the Mustavaara area the lower layer of the ore is characterized by long but narrow, 1—5 micron wide lamellae and between them abundant small lamellae (Fig. 18). In the upper and middle layers of the ore and in the disseminated rock the lamellae are broader 10—60 micron, and the number of the small lamellae between them is variable. They are absent on occasions (Fig. 17). The compact magnetite vein (p. 17) in the disseminated rock is compared with the lower layer of the ore because of its textural relationship. The amount of granular ilmenite is also different in different layers. It is very rare in the lower layer, in the middle and upper layers it is more common whilst in the disseminated rock it is most frequent.

In the area of Haukivaara, where the layered structure of the magnetite gabbro is weak, the exsolution textures are similar in every layer. Long ilmenite lamellae are narrow, below 5 microns, and between them are very many small lamellae. The texture

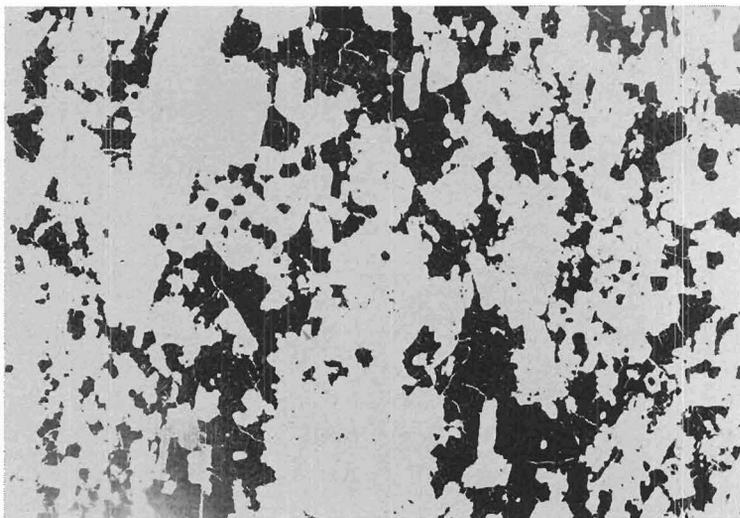


Fig. 15. The crystal form of ilmenomagnetite. Black ilmenomagnetite, white silicates. 4 x. MB 46/56.0 m.

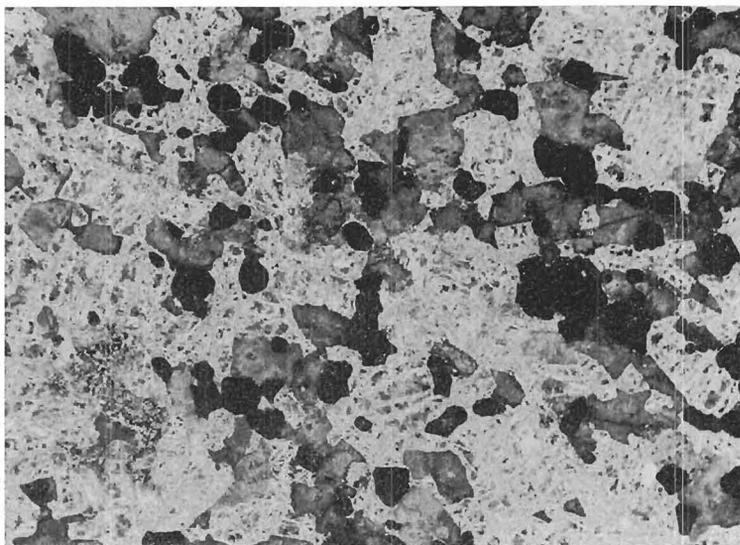


Fig. 16. Idiomorphic ilmenomagnetite in the eastern part of the Mustavaara ore deposit. Black ilmenomagnetite, dark grey uralite, light grey altered plagioclase, now a mass of albite, epidote and quartz. 7 x. MB 35/103.7 m.

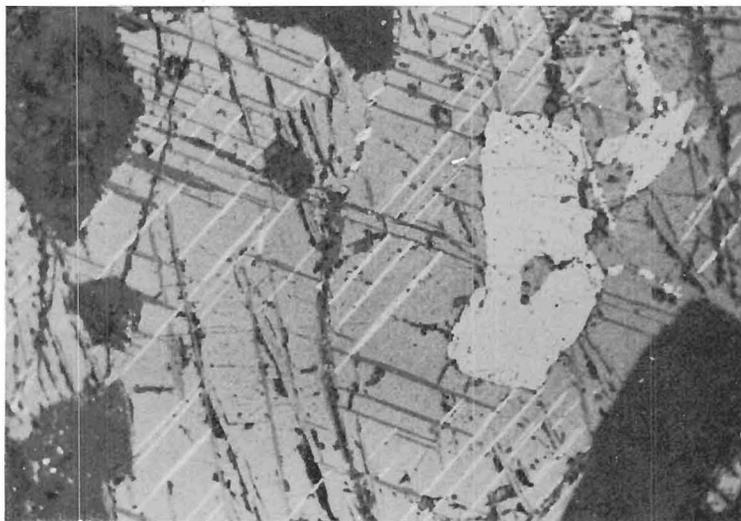


Fig. 17. Ilmenite lamellae (light and dark grey) and granules (light grey) in magnetite (grey). Black silicates. Typical texture for the upper and middle layers of the ore (OUL, OML) and for the disseminated rock (DR). 57 x. MB 56/91.25 m.

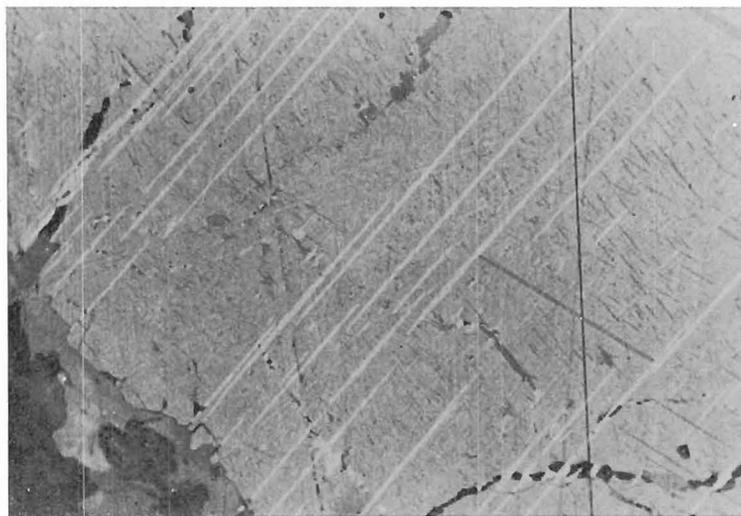


Fig. 18. Long ilmenite lamellae and between them plenty of smaller splinter-like lamellae (light and dark grey), all in magnetite (grey). Darkest grey consists of silicates. Typical texture for ore lower layer (OLL). 290 x. MB 40/93.05 m.

thus resembles that of the lower layer of the ore at Mustavaara. The difference lies in the amount of granular ilmenite which is in contact with magnetite. At Mustavaara they are very few; at Haukivaara they are more common than in the disseminated rock at Mustavaara.

In addition to the ilmenite lamellae, very weakly reflecting (100) oriented rods were accidentally found in the ilmenomagnetite. The size class of the rods was in the order of microns. In the samples from which they were found, they do not cover every grain, and not even all the area of one grain, but are randomly distributed between the ilmenite lamellae. The mineral may be spinel *sensu stricto*.

The most usual alteration on ilmenomagnetite is such that the magnetite component of the grain has been replaced by silicates and the ilmenite lamellae have survived. The first results of the alteration are weakly reflecting spots. They are usual in the ore. The identification of these spots is difficult because of their small size. As the alteration continues, all the magnetite becomes replaced (Fig. 20). The replacing silicates have been found to be chlorite, biotite, amphibole, and epidote; also carbonate occurs. Alteration of this type is common at the contacts of anorthosites, both as fragments and at the footwall contact of the ore. In addition, it is also found in the ore itself not associated with the anorthosites. Most common it is yet in the disseminated rock. The replacement of the magnetite by silicates is not caused by shearing, because the plagioclase and the uralite can be very sound. Most probably an autometasomatic process is in question. After the crystallization of the magnetite the conditions changed so that magnetite became unstable and was replaced by silicates. Because the phenomenon is prevalent in the upper part of the magnetite gabbro, it could be caused by volatiles concentrated in the remaining liquids.

Although usually it is the magnetite component which has been replaced and the ilmenite lamellae which have survived, the reverse is also to be found. In these the ilmenite lamellae have changed to titanite.

In the alteration related to shear zones, both the ilmenite and magnetite have altered, the first to titanite and leucoxene and the second to chlorite. In these zones the rocks' silicates have altered also; plagioclase to albite, quartz and epidote and uralite to chlorite. In a very few samples stringy martite replaces magnetite.

Ilmenite

Ilmenite grains, which are not in contact with magnetite at any point and which surely represent primary grains, are not found in the samples of the magnetite gabbro. Also the amount of granular ilmenite existing as inclusions or at the edges of the magnetite is small. In the lower layer of the ore they are very few and in the middle and upper layers only in approximately every tenth grain. The area of these grains in polished section is only 5—10 % from the area of magnetite. In the disseminated rock at Mustavaara and in the area of Haukivaara their amount is a little greater and

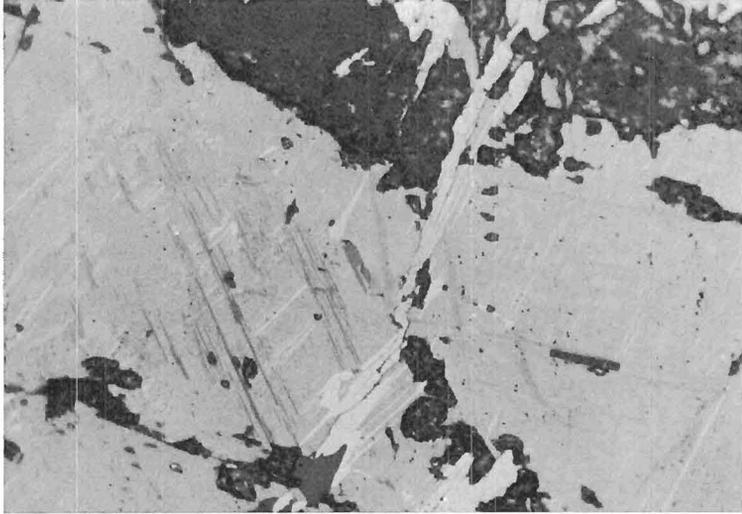


Fig. 19. Splinter-like ilmenite lamellae (light and dark grey) as patches in magnetite (grey). Black silicates. 290 x. HB 7/170 m.

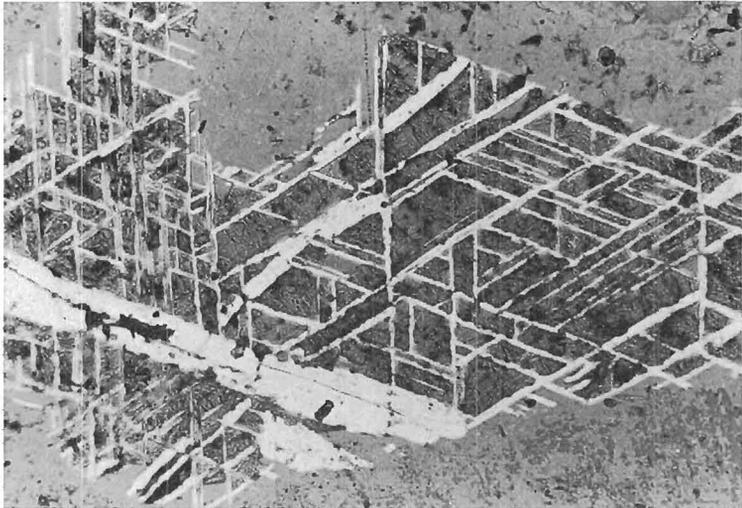


Fig. 20. Ilmenomagnetite, the magnetite component of which has been displaced by silicates (dark grey). The surviving lamellae (white) are ilmenite. The surrounding grey area consists of silicates. 57 x. MB 16/59.1 m.

there are also cases when the area of granular ilmenite is greater than the area of magnetite. These granules are still joined to magnetite without any seam.

The origin of the granular ilmenite associated with the magnetite has been shown to result from a similar oxidation-exsolution process from a homogeneous single phase mineral as do the ilmenite lamellae (Vincent and Phillips 1954, Wright 1961, Buddington and Lindsley 1964, Haapala and Ojanperä 1972). This explanation holds good also for the granules described above. Thus independent ilmenite has not crystallized in the magnetite gabbro.

Exsolution rods of less than 1μ breadth are typical in granular ilmenite and in the broader lamellae (Fig. 21). Usually they are composed of magnetite, but in the grains where surrounding magnetite is altered to martite they are also composed of hematite. Thus magnetite was the primary exsolution mineral and the hematite is its oxidation product. According to this, ilmenite can take a small amount of magnetite into solid solution at high temperatures.

Other ore minerals

A prevailing feature of the samples of magnetite gabbro is an even but very weak chalcopyrite dissemination. It is present usually as inclusions in the uralite. The grain size varies from parts of micron to tens of microns. Sometimes it forms a circle that surrounds uralite grains. Its crystallization is associated with the uralitization of augite. Most of it occurred in the lower layer of the ore. The amount is of no economic consequence.

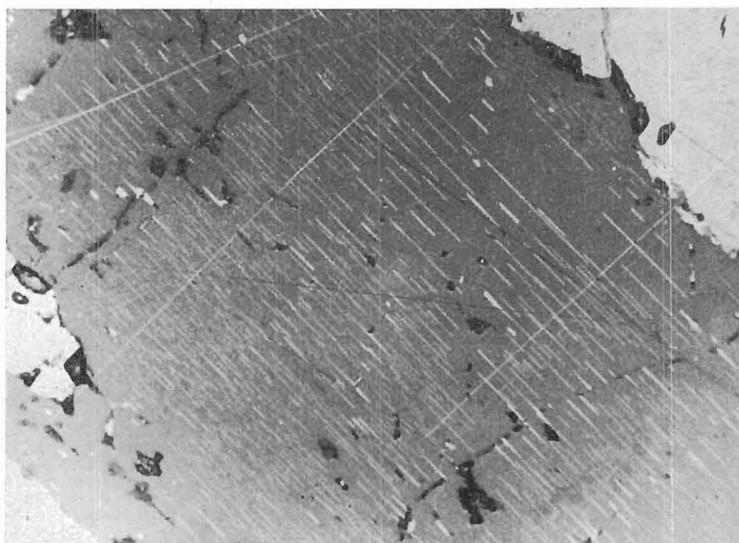


Fig. 21. Magnetite lamellae (light grey) in ilmenite (dark grey). The light grey around ilmenite consists of silicates. 290 x. MB 52/83 m.

Also present and occurring in a similar way to chalcopyrite are small amounts of pyrite, covellite, valleriite, marcasite, sphalerite, millerite, mackinawite, nickelpentlandite, polydymite, chalcosite and bravoite, all identified under an ore microscope by Y. Vuorelainen.

The chemical composition of the magnetite gabbro

The chemical compositions of the different layers of the magnetite gabbro are presented in Table 2. The modal analyses from the same rocks are given in Table 3 and in plagioclase-augite-ilmenomagnetite triangle in Fig. 22.

The changes in amounts of SiO_2 , TiO_2 , Al_2O_3 , FeO , Fe_2O_3 , MgO , CaO and Na_2O are associated with changes in the number of the principal minerals. The advance of iron, titanium and vanadium are related to the abundance of magnetite. The amount of silicon, aluminium, magnesium, calcium and sodium are dependent upon the abundance of silicates.

Cr and Ni are connected with stratigraphical height. Cr-content is greatest in OLL and smaller but equal in the upper layers. Independent chromite crystals were not found. Therefore, the change must be due to changes in the Cr-content of the chief minerals. The Cr-content of magnetite is greatest in OLL (Table 5). The amount of magnetite, which is the Cr-richest phase, is greatest in this layer too.

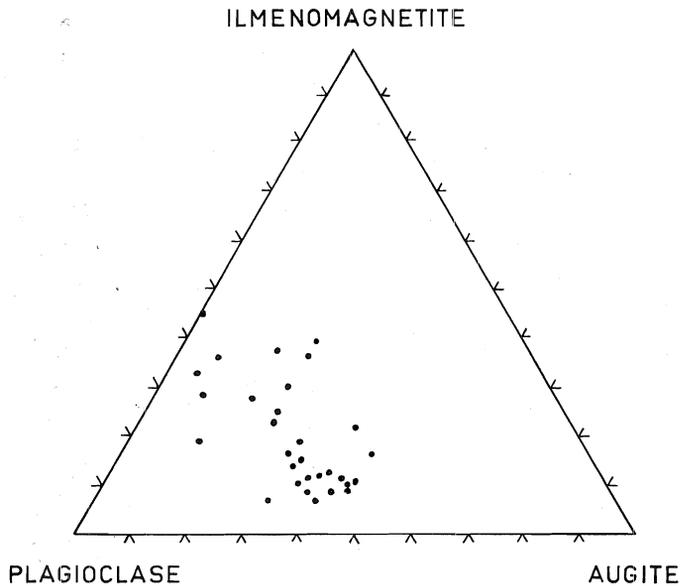


Fig. 22. Modal analyses of the samples of the magnetite gabbro (vol. %).

Table 2.

The chemical composition of the different layers of the magnetite gabbro at Mustavaara and at Haukivaara. The samples from Mustavaara are from drill holes 35 B, 38, 40 and 56. The samples from Haukivaara are from drill holes 2 and 7. Numbers in parentheses show the number of analyses

	MUSTAVAARA				HAUKIVAARA			
	DR (5)	OUL (4)	OML (4)	OLL (4)	DR (3)	OUL (2)	OML (2)	OLL (2)
SiO ₂	44.76	38.99	42.72	34.99	44.72	42.17	43.84	39.06
TiO ₂	2.06	2.11	2.00	2.79	1.63	2.02	1.53	2.71
Al ₂ O ₃	14.69	12.49	12.27	10.44	12.10	13.34	11.42	12.77
Fe ₂ O ₃	8.73	16.49	11.63	19.81	7.57	11.08	9.66	12.34
FeO	9.56	12.85	11.08	15.61	11.05	11.41	11.00	13.65
MnO	0.21	0.17	0.17	0.21	0.23	0.21	0.20	0.22
MgO	5.90	4.28	5.18	3.17	6.67	7.39	5.67	5.84
CaO	10.88	8.61	9.21	7.31	10.39	10.27	9.86	8.83
Na ₂ O	2.53	2.47	2.48	2.32	2.09	2.05	2.64	2.12
K ₂ O	0.3	0.34	0.35	0.89	1.19	0.43	0.80	0.52
V	0.15	0.26	0.22	0.38	0.18	0.23	0.22	0.23
Cr	0.002	0.002	0.003	0.013	0.003	0.003	0.003	0.008
Co	0.008	0.013	0.010	0.013	0.009	0.009	0.009	0.012
Ni	0.009	0.011	0.014	0.029	0.008	0.010	0.015	0.021
Cu	0.032	0.078	0.076	0.061	0.051	0.057	0.065	0.080
Zn	0.01	0.015	0.012	0.017	0.008	0.011	0.010	0.013
	99.90	99.17	97.42	98.05	97.89	100.69	96.94	98.42

Analysed in the Department of Geology, University of Oulu by AAS except SiO₂, which was analyzed gravimetrically.

DR = disseminated rock, OUL = ore upper layer, OML = ore middle layer, OLL = ore lower layer.

Table 3.

Mean values of the modal analyses (vol. %) of the different layers of magnetite gabbro at Mustavaara and at Haukivaara. Samples are the same as in Table 2. 1 000 points counted in every sample. Secondary changes and accessories, which were less than 1 %, were ignored.

	MUSTAVAARA				HAUKIVAARA			
	Pl	Aug	Ox	Sum	Pl	Aug	Ox	Sum
DR	50.2	39.4	10.4	100.0	48.9	42.4	8.7	100.0
OUL	50.4	24.2	25.4	100.0	50.1	38.8	11.1	100.0
OML	55.3	30.8	13.9	100.0	51.7	37.7	10.6	100.0
OLL	49.5	17.6	32.9	100.0	46.9	34.4	18.7	100.0

Pl = plagioclase, Aug = augite, Ox = ilmenomagnetite, DR = disseminated rock, OUL = ore upper layer, OML = ore middle layer, OLL = ore lower layer.

Also the Ni-content is greatest in OLL, but it diminishes gradually upwards. A corresponding change in Ni-content of augite was not found (see p. 43). Consequently, the change must be due to an independent Ni-mineral. Polydymite, millerite and nickel-pentlandite were identified under the microscope. Changes in their con-

centration must cause the differences in Ni contents. Zn behaves similar to Ni. It is most concentrated in OLL. This is caused by a few grains of sphalerite. These are most abundant in OLL.

Copper content at Haukivaara is greatest in OLL. This is in agreement with microscope observations which indicate that the small chalcopyrite dissemination in uralite is most abundant in this layer. The different arrangement at Mustavaara is difficult to understand. Silicate copper does not seem to be the reason but a copper mineral must certainly be involved.

Co also shows tendency to be concentrated in OLL. The appearance of polydymite explains this phenomenon.

Manganese is most abundant in the ilmenite component of ilmenomagnetite. Therefore, rocks which are richest in titanium should be richest in Mn. This holds good for ore but not for disseminated rock. Although the latter is poorer in TiO_2 than OML and OLL it is richer in MnO. A common feature of augites is that they become richer in Mn upward through the layered series (Table 8). This feature has also been preserved in uralites replacing augite (Table 9), and as regards ilmenites in ilmenomagnetite. These enrichments, when considered together, are sufficient to eliminate and even overcome the reducing which is caused by the diminished quantity of ilmenomagnetite.

The chemical composition of the ilmenomagnetite

From drill cores nos. 22—54 from Mustavaara, Rautaruukki company has made magnetic concentrates. Fe, Ti and V of this concentrate have been analysed in the company's laboratory. The results for iron and titanium are in the Fe/Ti coordination in Fig. 23. Mean values for different layers are shown in Table 4. That the sum of oxides stays well below 100 % is due to impurity of the concentrate. The results are, however, compatible with each other. OLL contains most titanium and DR least. As seen from analysis points in Fe/Ti coordination (Fig. 23) there is a great discrepancy in results: Fe is between 59—68 and Ti 1—6 %. In Fe/Ti-coordination a line showing Fe/Ti for different mixtures of magnetite/ilmenite is also included. The scattering follows this line, indicating that there are differences in magnetite/ilmenite proportions in different samples. Independent ilmenite grains are lacking and the proportion of granular ilmenite was also very small. Differences in Fe/Ti are due to different amounts of ilmenite lamellae in magnetite. This, in turn, indicates differences in composition of the primary solid solution. These differences must be due to a lack of titanium in the liquid. The conditions of crystallization favoured magnetite incorporating even greater amounts of titanium in solid solution. Thus when trying to determine f_{O_2}/T during crystallization (p. 56) analyses with the largest amounts of titanium must be utilized.

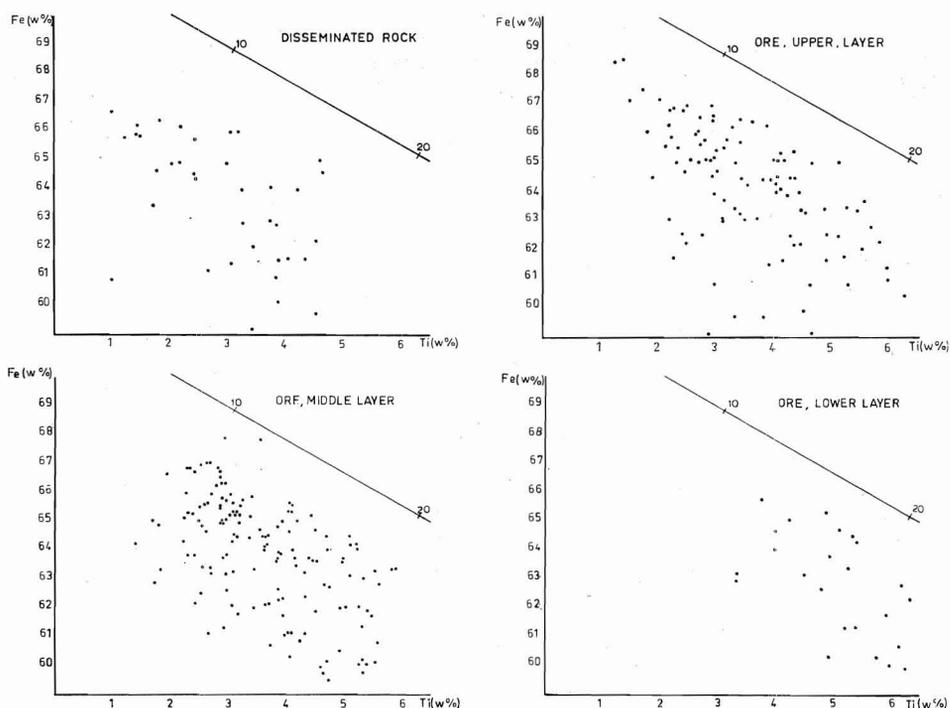


Fig. 23. Fe- and Ti-contents of the magnetic concentrate of the different layers of the magnetite gabbro at Mustavaara. The line in upper right corner of each diagram shows Fe/Ti for different mixtures of magnetite-ilmenite (vol. %).

Table 4.

Mean values of Fe, Ti and V in the magnetic concentrate of the different layers of the magnetite gabbro at Mustavaara. Sum as oxide is $\text{FeO} + \text{Fe}_2\text{O}_3 + \text{TiO}_2 + \text{V}_2\text{O}_5$. Fe calculated first for ilmenite and the remainder for magnetite.

	DR	OUL	OML	OLL
Fe	62.31	63.47	63.71	63.12
Ti	2.76	3.53	3.56	5.16
V	0.87	0.94	0.89	0.93
sum as oxide	90.77	93.42	93.72	94.93
W % Ilm	9.5	11.8	11.9	16.9

A systematic lateral variation in Ti-content of the magnetic concentrate was not found. However, there were differences on order of 2 % in adjoining profiles. An exception was the easternmost drilled profile, where OUL and OML contain less titanium than the average, only 2 %. In these layers ilmenomagnetite is exceptionally idiomorphic and ilmenite lamellae are missing. Only small pins were found under the microscope.

The small differences in mean values of vanadium in different layers of magnetite gabbro do not vary systematically in the profiles. Thus, differences associated with layering do not exist. Nor was systematic lateral variation found at Mustavaara, although there are small differences in different drilled profiles.

The samples from Haukivaara were not analysed systematically. Analyses which were undertaken were from the richest places. There the titanium content is of the same magnitude as at Mustavaara but the vanadium content is clearly smaller, about 0.7–0.8 % V. This is also evident from microprobe analyses (Table 5).

In addition to the analyses of the magnetic concentrate, microprobe analyses were done on ilmenomagnetite grains. The analytical techniques was following: Two ilmenomagnetite grains from each sample were chosen for analysis. The analyses were accomplished on granular ilmenite, referred to as the rhomboedral phase, and on the area between ilmenite lamellae, which is called the spinel phase. The point for analysis was first selected by microscope. For the spinel phase efforts to locate an area where the distance between ilmenite lamellae was in excess of 10 microns were undertaken. Before analysis the homogeneity of the selected point was checked by analyzing a line through the point. In the samples from Haukivaara and of OLL from Mustavaara the inter-lamellar area is so small that it was not possible to carry out analyses between the lamellae. In these cases a line analysis was done over such an area where the occurrence of the lamellae is regular. The length of the line was 20 microns. In some cases, where the arrangement of ilmenite lamellae is very irregular, it was not possible to obtain a reliable analysis.

The analyses were done in the institute of Electron Optics, University of Oulu, by utilizing a JEOL JXA — 3SM microprobe with accelerating voltage of 15kV for the essential components and 25kV for elements found in minute quantities and currents of 0.01–0.1 μ A. Standards were: hematite for Fe, metals for Mn, Cr and V, synthetic TiO₂ for Ti, wollastonite for Ca, synthetic Al₂O₃ for Al and periclase for Mg. The separation of TiK β from VK α was clearly distinct utilizing the present instrumentation. Results were processed for corrections by computer program MK2 (Mason *et al.* 1969). The results are shown in Table 5.

Recalculations for ilmenite basis of spinel phase and FeO and Fe₂O₃ of rhomboedral phase has been done as presented by Carmichael (1967). The principle is that TiO₂ is first recalculated for ilmenite and the excess iron in spinel phase as FeO · Fe₂O₃ and in rhomboedral phase as Fe₂O₃.

Spinel phase

TiO₂-content of the spinel analyses depends upon the abundance of ilmenite lamellae. In cases where the analyses could be done between ilmenite lamellae the amount of TiO₂ was small, below 1 %. This indicates that there is only very minute solid solution between magnetite and a Ti-spinel. Thus the purification of the spinel phase from Ti by exsolution of ilmenite has been very nearly perfect and the remaining

Table 5.

 Microprobe analyses of ilmenomagnetite. MB = Mustavaara borehole, HB = Haukivaara borehole. $V_2O_3^*$ = corrected value for V_2O_3 .

SPINEL PHASE								
SAMPLE	MB 26/ 131.8 m	MB 35 B/ 103.7 m	MB 35 B/ 119.5 m	MB 35 B/ 120.3 m	MB 38/ 13.9 m	MB 38/ 57.5 m	MB 38/ 126.0 m	MB 38/ 148.1 m
LAYER	OLL	OUL	OML	OLL	DR	OUL	OML	OLL
FeO	84.7	90.9	95.0	85.8	—	86.1	90.1	86.1
MnO	0.24	0.03	0.03	0.28	—	0.25	0.05	0.16
Cr ₂ O ₃	0.05	0.02	0.04	0.11	—	0.02	0.03	0.05
V ₂ O ₃	1.34	1.44	1.70	1.52	—	1.40	1.75	1.68
V ₂ O ₃ *	1.51	1.44	1.71	1.68	—	1.53	1.78	1.81
TiO ₂	8.41	0.00	0.29	7.46	—	5.14	1.15	4.67
CaO	0.04	0.05	0.27	0.03	—	0.03	0.04	0.03
Al ₂ O ₃	0.31	0.04	0.17	0.10	—	0.15	0.21	0.19
MgO	0.19	0.04	0.15	0.08	—	0.19	0.14	0.14
Sum	95.3	92.5	97.7	95.4	—	93.3	93.5	93.0
Ilmenite basis								
FeO	33.4	30.7	32.0	32.3	—	31.9	31.1	31.8
Fe ₂ O ₃	57.0	66.9	70.0	58.3	—	60.2	65.5	60.3
total	100.9	99.2	104.4	101.2	—	99.0	100.0	99.0
RHOMBOEDRAL PHASE								
FeO	46.7	—	—	48.0	46.0	47.8	48.0	47.3
MnO	1.38	—	—	1.63	2.30	1.60	1.38	1.15
Cr ₂ O ₃	0.02	—	—	0.02	0.01	0.01	0.01	0.02
V ₂ O ₃	0.48	—	—	0.54	0.30	0.28	0.39	0.43
TiO ₂	50.2	—	—	49.0	51.6	48.8	50.6	48.7
CaO	0.03	—	—	0.04	0.11	0.04	0.05	0.02
Al ₂ O ₃	0.03	—	—	0.06	0.10	0.07	0.14	0.11
MgO	0.03	—	—	0.03	0.30	0.13	0.17	0.18
Sum	98.9	—	—	99.3	100.7	98.7	100.7	97.9
FeO	43.7	—	—	42.3	43.4	42.0	43.8	42.3
Fe ₂ O ₃	3.39	—	—	6.33	2.89	6.47	4.70	5.54
total	99.2	—	—	100.0	101.0	99.5	101.2	98.6
mol % R ₂ O ₃	3.8	—	—	6.8	3.17	6.6	5.0	6.1

Table 5 (continued)

SPINEL PHASE									
SAMPLE	MB 40/ 9.2 m	MB 40/ 9.8 m	MB 40/ 13.0 m	MB 40/ 65.6 m	MB 40/ 76.7 m	MB 40/ 93.05 m	MB 56/ 46.7 m	MB 56/ 91.25 m	MB 56/ 122.6 m
LAYER	DR	DR	DR	OUL	OML	OLL	OUL	OML	OLL
FeO	87.4	84.1	88.2	89.8	—	87.9	—	—	90.9
MnO	0.07	0.31	0.03	0.04	—	0.13	—	—	0.03
Cr ₂ O ₃	0.04	3.00	0.02	0.01	—	0.05	—	—	0.07
V ₂ O ₃	1.47	0.45	1.25	1.71	—	1.50	—	—	1.34
V ₂ O ₃ *	1.48	0.49	1.25	1.72	—	1.57	—	—	1.34
TiO ₂	0.60	4.53	0.10	0.28	—	3.46	—	—	0.16
CaO	0.03	0.02	0.06	0.05	—	0.04	—	—	0.05
Al ₂ O ₃	0.43	0.14	0.11	0.56	—	0.33	—	—	0.39
MgO	0.23	0.13	0.05	0.31	—	0.13	—	—	0.31
Sum	90.3	92.7	89.8	92.8	—	93.5	—	—	93.3
Ilmenite basis									
FeO	29.8	31.5	29.8	30.8	—	31.7	—	—	30.6
Fe ₂ O ₃	64.0	58.5	67.9	65.6	—	62.4	—	—	67.0
total	96.6	98.5	96.2	99.7	—	99.8	—	—	99.9
RHOMBOEDRAL PHASE									
FeO	47.3	44.4	44.8	45.9	46.1	48.1	48.7	45.5	45.7
MnO	1.83	2.36	2.51	1.50	1.95	1.17	1.63	2.00	1.37
Cr ₂ O ₃	0.02	1.06	0.01	0.01	0.01	0.01	0.01	0.02	0.02
V ₂ O ₃	0.28	0.20	0.27	0.54	0.44	0.54	0.34	0.40	0.44
TiO ₂	50.2	51.3	52.0	49.5	50.6	50.2	48.9	51.6	48.8
CaO	0.03	0.05	0.32	0.02	0.24	0.05	0.03	0.13	0.04
Al ₂ O ₃	0.07	0.12	0.07	0.15	0.25	0.13	0.20	0.12	0.12
MgO	0.14	0.15	0.05	0.16	0.12	0.15	0.00	0.24	0.10
Sum	99.9	99.6	100.0	97.8	99.7	100.4	99.8	100.0	96.6
FeO	43.0	43.5	43.7	42.7	43.0	43.6	42.2	43.8	42.3
Fe ₂ O ₃	4.75	1.15	1.15	3.53	3.44	4.97	7.13	1.91	3.80
total	100.3	100.1	100.1	98.2	100.0	100.8	100.4	100.2	97.0
mol % R ₂ O ₃	4.9	1.3	1.5	4.2	3.9	5.3	7.3	2.41	4.2

Table 5 (continued).

SPINEL PHASE								
SAMPLE	HB 2/ 48.0 m	HB 2/ 70.0 m	HB 2/ 110.0 m	HB 2/ 150.0 m	HB 7/ 37.0 m	HB 7/ 87.0 m	HB 7/ 125.0 m	HB 7/ 170.0 m
LAYER	DR	OUL	OML	OLL	DR	OUL	OML	OLL
FeO	—	83.2	93.3	86.3	87.9	—	—	83.7
MnO	—	0.24	0.14	0.35	0.10	—	—	0.29
Cr ₂ O ₃	—	0.01	0.04	0.10	0.02	—	—	0.04
V ₂ O ₃	—	0.97	0.79	0.60	0.97	—	—	0.76
V ₂ O ₃ *	—	1.09	0.81	0.67	1.05	—	—	0.92
TiO ₂	—	9.01	2.62	9.59	4.95	—	—	10.5
CaO	—	0.06	0.06	0.02	0.03	—	—	0.01
Al ₂ O ₃	—	0.13	0.27	0.13	0.12	—	—	0.12
MgO	—	0.19	0.17	0.07	0.04	—	—	0.10
Sum	—	93.8	97.4	97.2	94.1	—	—	95.5
Ilmenite basis								
FeO	—	33.1	32.71	34.46	32.5	—	—	34.2
Fe ₂ O ₃	—	55.7	67.33	57.62	61.6	—	—	55.0
total	—	99.3	104.38	102.91	100.3	—	—	101.0
RHOMBOEDRAL PHASE								
FeO	45.2	47.4	49.0	49.9	46.4	49.3	47.6	48.5
MnO	2.40	1.68	1.73	1.64	1.20	1.71	2.34	1.32
Cr ₂ O ₃	0.05	0.01	0.06	0.03	0.03	0.01	0.04	0.01
V ₂ O ₃	0.30	0.40	0.44	0.27	0.19	0.38	0.24	0.14
TiO ₂	52.9	49.1	50.6	50.2	50.7	50.0	49.1	48.9
CaO	0.02	0.08	0.08	0.02	0.02	0.05	0.02	0.02
Al ₂ O ₃	0.18	0.06	0.22	0.10	0.04	0.14	0.10	0.07
MgO	0.12	0.28	0.14	0.11	0.11	0.36	0.15	0.12
Sum	101.2	99.0	102.3	102.3	98.7	102.0	99.6	99.1
FeO	44.9	41.8	43.40	42.52	44.2	42.52	41.49	42.4
Fe ₂ O ₃	0.33	6.17	6.22	7.53	2.38	7.53	6.79	6.78
total	101.2	99.6	102.89	102.70	98.8	102.71	100.27	99.8
mol % R ₂ O ₃	0.93	7.6	6.56	7.55	2.4	7.55	6.87	6.6

Table 6.
A correlation matrix of microprobe analyses presented in Table 5.

	SPINEL PHASE							
	FeO	MnO	Cr ₂ O ₃	V ₂ O ₃	TiO ₂	CaO	Al ₂ O ₃	MgO
FeO	1.00							
MnO	-0.75	1.00						
Cr ₂ O ₃	-0.30	0.39	1.00					
V ₂ O ₃	0.43	-0.70	-0.50	1.00				
TiO ₂	-0.61	0.76	0.11	-0.45	1.00			
CaO	0.64	-0.41	-0.15	0.36	-0.28	1.00		
Al ₂ O ₃	0.21	-0.32	-0.15	-0.41	-0.25	-0.04	1.00	
MgO	0.12	-0.18	-0.07	0.34	-0.14	0.06	0.83	1.00

	RHOMBOEDRAL PHASE									
	FeO	MnO	Cr ₂ O ₃	V ₂ O ₃	TiO ₂	CaO	Al ₂ O ₃	MgO	FeO	Fe ₂ O ₃
FeO	1.00									
MnO	-0.48	1.00								
Cr ₂ O ₃	-0.39	0.34	1.00							
V ₂ O ₃	0.15	-0.46	-0.26	1.00						
TiO ₂	-0.52	0.62	0.23	-0.34	1.00					
CaO	-0.40	0.49	-0.06	0.11	0.44	1.00				
Al ₂ O ₃	0.08	0.17	0.02	0.21	0.15	0.18	1.00			
MgO	0.09	0.11	-0.01	0.12	0.07	-0.03	-0.02	1.00		
FeO	-0.46	0.19	0.14	-0.20	0.86	0.21	0.09	-0.12	1.00	
Fe ₂ O ₃	0.92	-0.44	-0.34	0.21	-0.76	-0.39	0.02	0.13	-0.76	1.00

phase is »pure» magnetite. The cell edge of this magnetite is 8.397–8.396 Å (Co target, Ni filter, 26 kV, 12 mA, CaF₂ as internal standard, (333,511) reflection), which indicates, according to the diagram of Lindsley (1962, p. 103), of 1–2 % ulvöspinel in solid solution. The same cell edge was also measured for samples with higher TiO₂. Consequently, all of this titanium is due to ilmenite. Differences in the TiO₂ of the spinel phase associated with layering or lateral variation do not exist.

The manganese concentration is many times richer in ilmenite than in magnetite. This causes analyses which are high in Ti to be high in Mn as well. The correlation coefficient between Mn and Ti was 0.76 (Table 6) indicating a significant correlation.

Samples poorest in titanium contain 0.03 % MnO. Corrections, similar to those made in calculating the vanadium concentration, could have been made for manganese. However, the quantities of the latter are so small that the results of such corrections would be questionable.

The amount of Cr₂O₃ is clearly connected with layering. It is most abundant in OLL and diminishes gradually to OUL, at which level it also is present in DR. Thus the first oxide has taken most chromium. Altogether the percentages are small, below 0.1 %. An exception was sample DH 40/9.9 m, which had 3 % Cr₂O₃. The grains from which this analysis was made was strongly altered. Only a relict piece of unaltered ilmenomagnetite was present.

The concentration of vanadium is many times greater in magnetite than in ilmenite. This causes analyses of samples containing ilmenite to yield lower percentages than those from which ilmenite lamellae are absent. This situation is the opposite to that for manganese. To eliminate the effect of ilmenite, a correction calculation was accomplished as follows: All vanadium was supposed to be in ilmenite and magnetite so that the resulting analyses are a mean value of their percentages. In an equation this can be expressed as follows:

$$\frac{w \% \text{ Fem} \times \text{V}_2\text{O}_3 (\text{Fem}) + w \% \text{ Ilm} \times \text{V}_2\text{O}_3 (\text{Ilm})}{w \% \text{ Fem} + w \% \text{ Ilm}} = \text{V}_2\text{O}_3 \text{ analysed}$$

$w \% \text{ Fem} = 1.45 \times \text{Fe}_2\text{O}_3$ of ilmenite basis, $w \% \text{ Ilm} = 1.90 \times \text{TiO}_2$ and V_2O_3 (Ilm) supposed to be the same as in the granular ilmenite of the analysed sample.

V_2O_3 (Fem) can now be calculated. Results calculated by this technique are shown in Table 5 as V_2O_3 * and in the variation diagram in Fig. 24. There is a clear difference in both the amounts and the trend of V_2O_3 between samples from Haukivaara and from Mustavaara.

The samples from Mustavaara are much richer in vanadium. They have between 1.6—1.7 % V_2O_3 as compared to the samples from Haukivaara which have only 0.8—1 % V_2O_3 . In the Mustavaara samples the V_2O_3 content is nearly constant in ore but becomes lower in disseminated rock. In the Haukivaara samples the trend rises from OLL upwards. These same differences are also present in the vanadium contents of ilmenite. Consequently, the differences must have been present in the primary titanomagnetites. These differences are due to either, (1) differences in content of vanadium in the liquids or, (2) differences in the partition coefficient between the silicate and oxide phases.

The rising trend of vanadium of Haukivaara samples upward through the layered series, despite the crystallization of the magnetite-rich spinel phase, is surprising because there is much more vanadium in the oxide than in the silicate phase. The crystallization should impoverish the remainder of the liquid as regards vanadium and this should be reflected in the vanadium content of the magnetite. The rising tendency must be indicated by a rise in the distribution coefficient. Despite differences in the original concentration of vanadium in titanomagnetites exsolution resulted in a situation in which magnetite has 3—5 times the vanadium concentration of ilmenite. From an economic point of view it is interesting to find that those conditions which have induced an abundant oxide phase have also favoured the introduction of vanadium into titanomagnetite.

The CaO content is small, being below 0.1 % with one exception, and there is no systematic variation either laterally or with layering. Between MgO and Al_2O_3 there is a very significant correlation. This must be due to submicroscopic exsolutions of spinel *sensu stricto* which cause dispersions in the analytical results.

SPINEL PHASE RHOMBOEDRAL PHASE

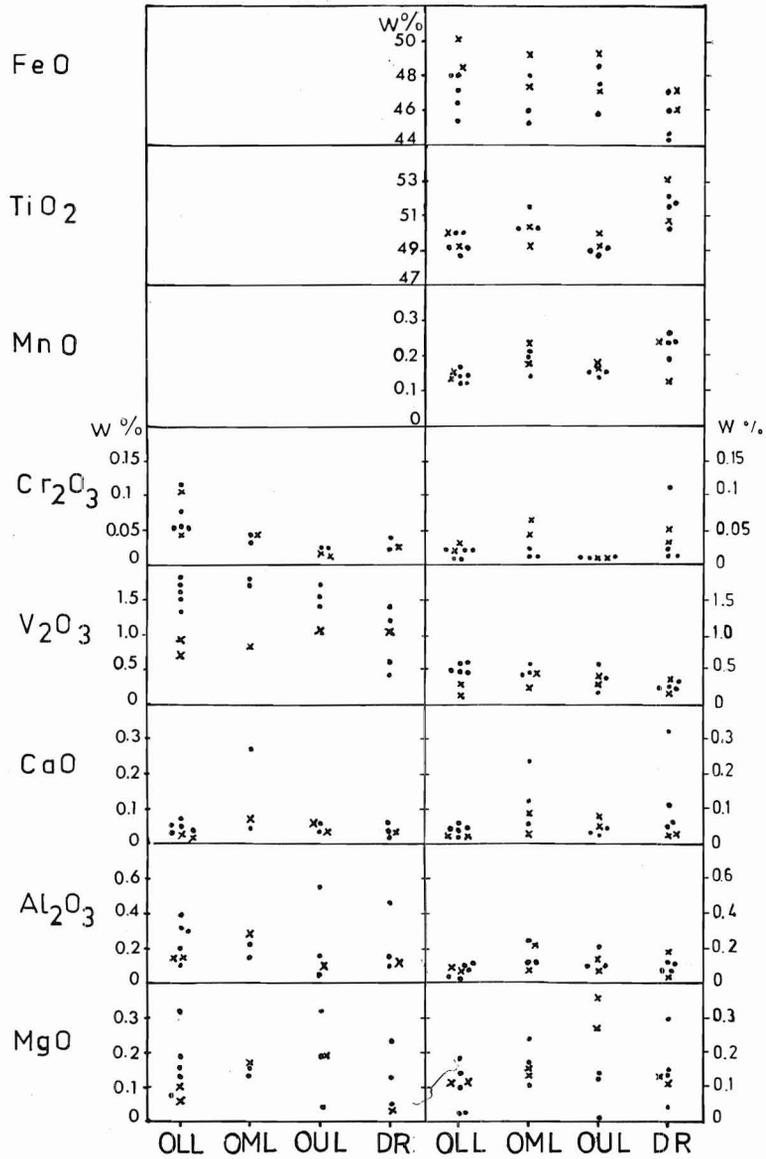


Fig. 24. Variation in the compositions of spinel and rhomboedral phases of ilmenomagnetite with layering in magnetite gabbros at Mustavaara and at Haukivaara. X = samples from Haukivaara; . = samples from Mustavaara. OLL = ore lower layer, OML = ore middle layer, OUL = ore upper layer, DR = disseminated rock.

Rhomboedral phase

There is a tendency toward an increase in TiO_2 upwards through the layered series. However, this does not indicate that TiO_2 increases at the expense of FeO in the ilmenite. The reason for the increase must lie in the magnetite lamellae or in the solid solution of hematite. This is confirmed by a significant negative correlation between TiO_2 and Fe_2O_3 . Microscopic examination did not reveal magnetite lamellae in the analysed points, not even in those samples which are richest in titanium. Also the lines over the analysed point are even, indicating solid solution of hematite with ilmenite. Mol.% Fe_2O_3 in OLL is 5 % and in DR about 2 %.

The trend of Mn follows that of TiO_2 the correlation coefficient between them being 0.62. Because Mn is more closely related to ilmenite than to hematite or magnetite, the increase in the ilmenite component of the rhomboedral phase causes an increase in Mn. This is not, however, an adequate explanation for the rise of more than 0.5 % which occurs upward through the layered series. The Mn-content of pure ilmenite is c. 3 % (interpolated from analytical results). A rise of 5 % in the ilmenite component of the rhomboedral phase would increase Mn no more than 0.15 %. This accounts for no more than half of the real increase. Consequently, there must also be a rise in the Mn content of ilmenite upward through the magnetite gabbro.

The Mn content in pure magnetite is 0.03 % and in theoretically pure ilmenite c. 3 %. Thus, the concentration of Mn in exsolution is 100 times greater in ilmenite. This is a very high ratio. A general feature in the distribution of Mn between ilmenite and magnetite is an increase in the ratio $\text{MnO (II)}/\text{MnO (Fem)}$ as temperature decreases (Buddington and Lindsley 1964, p. 352). On the other hand, this ratio has been said to be random (Anderson 1968; Czamanske and Mihalik 1972, p. 502—508). The distribution of Mn as a function of T/fo_2 has also been studied. No correlation was reported by Dasgupta (1970).

The differences in trend and amount for vanadium in the rhomboedral phase, between samples from Mustavaara and Haukivaara, are the same as for the spinel phase. CaO , Al_2O_3 , Cr_2O_3 and MgO show no clear trend, nor do correlations with other analysed elements exist.

The chemical composition of the augite

Augites from different horizons of the magnetite gabbro were analyzed by microprobe to discover if there are changes in iron ratios associated with changes in the total compositions of the rocks. The analytical technique is in principle the same as described for ilmenomagnetite. Because of the strong alteration fresh augite was found only in a few samples. The number of analyses therefore remained small. The results of each analysis are shown in Table 7 and mean values for the different layers

in Table 8 together with the other augite analyses from the Porttivaara intrusion. In Fig. 25 the results are presented in the CaSiO_3 — MgSiO_3 — FeSiO_3 -triangle. For comparison, the corresponding relationships for the augites from the Skaergaard intrusion are also presented in Fig. 26.

Changes associated with total composition are not found, but the iron/magnesium relationship follows the general differentiation trend of the intrusion. Thus in the lowest horizon of the magnetite gabbro, i.e. in the ore lower layer, although its total iron content is highest, the augite is relatively poor in iron compared to the upper horizons. The differentiation trend is similar to the beginning of that for the Skaergaard intrusion. The higher CaSiO_3 content in the augites from Porttivaara intrusion is due to differences in analytical method. The analyses of augites from the

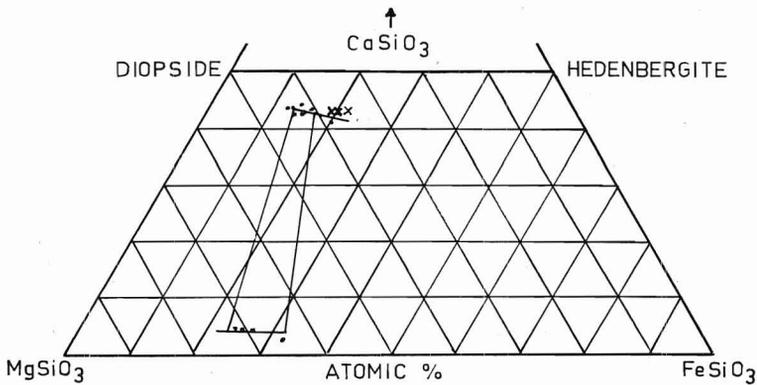


Fig. 25. Trend of crystallization of pyroxenes in the Porttivaara intrusion. Tie lines connect grains from the same samples. \times = augite from magnetite gabbro (from this study), \cdot = augites and orthopyroxenes from lower layers (from Mäkelä 1975).

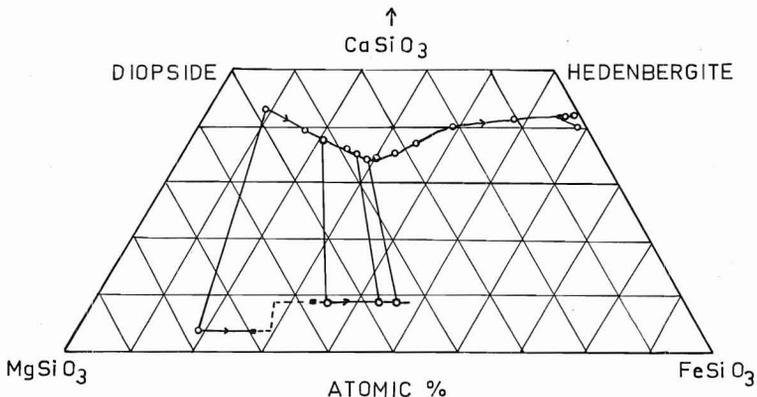


Fig. 26. Trend of crystallization of pyroxenes in the Skaergaard intrusion according to Wager and Brown 1968, Fig. 19, p. 39. Reproduced by the permission of C. M. Brown.

Table 7.

The chemical compositions of augites in different layers of the magnetite gabbro at Mustavaara. DR = disseminated rock; OML = ore middle layer; OLL = ore lower layer.

Layer	DR	OML						OLL				
Sample	718	MD 1/ 64.65 m	MD 1/ 64.65 m	MD 1/ 64.65 m	MD 52/ 83 m	MD 52/ 83 m	MD 56/ 91.25 m	MD 38/ 148.10 m	MD 46/ 56 m	MD 46/ 56 m	MD 52/ 125 m	
FeO	13.3	12.4	13.5	14.0	12.7	14.0	12.8	10.6	12.0	12.0	12.4	
MnO	0.27	0.32	0.31	0.34	0.32	0.30	0.26	0.26	0.27	0.14	n.d.	
Cr ₂ O ₃	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n.d.	
V ₂ O ₃	0.07	0.02	0.05	0.10	0.07	0.06	0.07	0.12	0.07	0.06	n.d.	
TiO ₂	0.46	n.d.	0.35	0.35	0.42	0.46	0.38	0.37	0.48	0.44	0.34	
CaO	21.2	20.3	20.0	21.2	20.6	21.1	22.5	21.1	22.3	20.6	20.1	
Al ₂ O ₃	2.12	1.93	1.47	2.04	1.37	1.94	1.99	1.88	2.00	2.20	2.19	
MgO	11.8	12.3	13.0	12.5	13.1	11.8	12.6	14.5	12.7	13.3	12.9	
NiO	0.02	0.03	0.01	0.02	0.07	0.00	0.02	0.01	0.12	0.02	n.d.	
SiO ₂	47.2	51.8	50.8	52.1	48.6	48.7	51.9	53.1	50.1	50.1	48.1	
	96.5	99.1	99.5	102.7	97.3	98.4	102.5	101.9	100.0	98.9	96.0	
Ca	44	43	41	43	42	44	45	43	45	43	42	
Mg	34	36	37	35	37	34	35	40	36	38	38	
Fe	22	21	22	22	20	22	20	17	19	19	20	
$\frac{\text{Mg} \times 100}{\text{Mg} + \text{Fe} + \text{Mn}}$	61	63	63	61	64	60	63	70	65	66	65	

Table 8.

The chemical composition of augites of the Porttivaara intrusion.

	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	V ₂ O ₃	MgO	FeO	CaO	MnO	NiO	Yht.	A	xMg	xFe	xCa	$\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe} + \text{Mn}}$
12	47.2	0.46	2.12	0.05	0.07	11.8	13.3	21.2	0.27	0.02	96.5	2.06	34	22	44	61
11	50.3	0.38	1.84	0.00	0.06	12.6	13.1	20.8	0.30	0.03	99.4	2.02	36	21	43	62
10	50.3	0.40	2.06	0.00	0.08	13.3	11.7	21.0	0.22	0.02	99.2	2.02	38	19	43	66
9	52.4	0.52	2.25	n.d.	n.d.	13.6	12.3	19.8	0.21	0.00	101.2	1.99	39.2	19.9	41.0	66.0
8	52.6	0.54	1.72	n.d.	n.d.	14.4	11.2	21.0	0.26	n.d.	101.7	2.01	40.2	17.6	42.2	69.1
7	51.6	0.65	1.98	0.08	0.06	14.3	10.2	20.7	0.20	0.10	99.9	2.00	41.0	16.4	42.6	71.0
6	50.8	0.84	2.36	0.07	n.d.	14.2	9.80	21.1	0.23	0.03	99.5	2.01	40.7	15.8	43.5	71.6
5	51.5	0.72	2.46	0.13	n.d.	14.6	9.13	20.5	0.18	0.02	101.3	1.99	42.4	14.9	42.8	73.6
4	51.8	0.72	2.46	0.03	0.08	14.6	8.78	21.3	0.20	0.05	100.1	1.98	41.9	14.1	44.0	74.3
3	51.7	0.73	2.10	n.d.	n.d.	15.1	8.53	20.6	0.18	0.03	99.0	2.00	43.5	13.8	42.7	75.5
2	51.7	0.90	2.65	0.11	n.d.	15.0	8.08	21.0	0.15	0.03	99.5	1.99	43.3	13.1	43.6	76.5
1	51.7	0.49	2.11	0.09	0.04	15.6	7.37	21.3	0.08	0.04	98.8	2.00	44.5	11.8	43.7	78.9

1 = olivine gabbro I, 2 = pyroxene gabbro III, 3–5 = olivine gabbro II, 6–9 = pyroxene gabbro IV, 10 = ore lower layer, 11 = ore middle layer, 12 = disseminated rock. 1–9 from Mäkelä (1975).

x_{Mg} = mol % of MgSiO₃ in augite; x_{Fe} = mol % of FeSiO₃ in augite; x_{Ca} = mol % of CaSiO₃ in augite.

Table 9.
The chemical composition of augites and replacing uralites.

Sample	MD 1/64.65		154/MI/71					MD 52/83	
	Aug	Ural	Aug	Ural	Aug	Ural	Ural	Aug	Ural
FeO	13.5	15.3	11.8	14.5	11.3	13.8	16.1	14.0	16.6
MnO	0.31	0.23	0.58	0.22	0.29	0.29	0.14	0.30	0.22
Cr ₂ O ₃	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
V ₂ O ₃	0.05	0.05	0.04	0.06	0.08	0.07	0.13	0.06	0.05
TiO ₂	0.35	0.22	0.44	0.14	0.41	0.56	0.14	0.46	0.23
CaO	20.0	14.7	19.4	12.1	21.6	16.7	9.92	21.1	12.7
Al ₂ O ₃	1.47	1.63	2.05	1.90	1.94	1.96	2.12	1.94	1.97
MgO	13.0	14.1	14.5	14.7	13.6	14.2	15.2	11.8	12.9
NiO	0.01	0.01	0.02	0.01	0.00	0.01	0.02	0.00	0.02
SiO ₂	50.8	53.1	54.8	55.5	53.3	49.7	51.8	48.7	54.6
	99.5	99.3	103.6	99.1	102.5	97.3	95.5	98.3	99.3

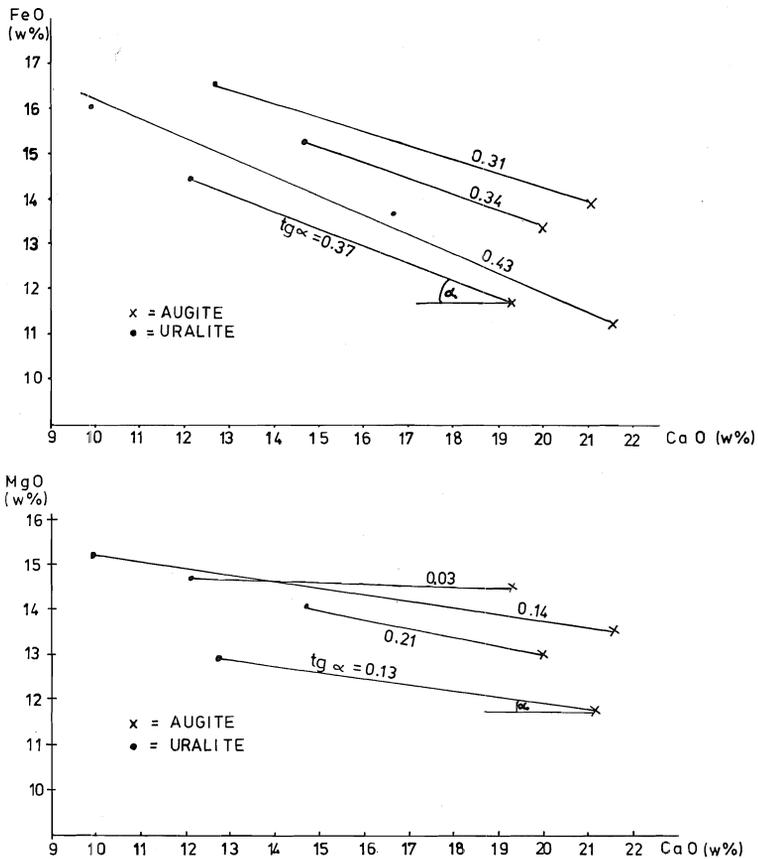


Fig. 27. The changes in FeO, MgO and CaO when augite has altered to uralite. The lines connect the same grains.

Table 10.

The chemical compositions of uralites in different layers of the magnetite gabbro at Mstavaara.

Layer	DR			OUL			OML					OLL
	MD 1/ 16.5 m	MD 40/ 9.80 m	MD 40/ 18 m	MD 38/ 57.5 m	MD 38/ 57.5 m	MD 56/ 46.7 m	MD 1/ 64.65 m	MD 1/ 64.65 m	MD 38/ 126 m	MD 40/ 76.7 m	MD 52/ 83 m	MD 40/ 93.05 m
FeO	16.1	11.6	13.6	13.9	16.2	14.3	13.2	15.3	15.2	14.9	16.6	12.9
MnO	0.29	0.28	0.17	0.23	0.20	0.20	0.22	0.23	0.28	0.24	0.22	0.14
Cr ₂ O ₃	0.00	0.02	0.01	—	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
V ₂ O ₃	0.10	0.04	0.09	0.07	0.21	0.08	0.02	0.05	0.06	0.14	0.05	0.10
TiO ₂	0.38	0.04	0.36	0.34	0.27	0.31	0.06	0.22	0.27	0.73	0.23	1.43
CaO	13.2	11.4	13.5	12.2	11.2	13.3	11.8	14.7	12.9	12.5	12.7	15.0
Al ₂ O ₃	1.80	1.67	2.51	2.25	4.89	2.43	2.78	1.63	2.36	3.72	1.97	2.44
MgO	13.7	14.1	15.0	14.2	11.3	12.5	14.7	14.1	14.6	13.6	12.9	18.7
NiO	0.01	0.02	0.01	0.02	0.01	0.00	0.03	0.01	0.02	0.03	0.00	0.02
SiO ₂	52.7	58.4	52.2	55.2	51.9	57.5	51.8	53.1	53.0	50.7	54.6	51.2
	98.3	97.6	97.5	98.4	96.2	100.6	94.6	99.3	98.7	96.6	99.3	101.9
$\frac{\text{Mg} \times 100}{\text{Mg} + \text{Fe} + \text{Mn}}$	59.8	67.9	66.0	64.2	55.1	60.6	66.1	61.8	62.7	61.5	57.7	71.9

Table 11.

The chemical compositions of uralites in different layers of the magnetite gabbro at Haukivaara.

Layer	DR			OUL		OML		OLL	
	HD 2/ 48 m	HD 2/ 70 m	HD 3/ 37 m	HD 2/ 70 m	HD 7/ 87 m	HD 2/ 110 m	HD 7/ 125 m	HD 2/ 150 m	HD 7/ 170 m
FeO	16.1	13.7	14.5	13.7	14.2	14.5	16.0	14.8	13.5
MnO	0.10	0.13	0.22	0.13	0.22	0.24	0.20	0.10	0.14
Cr ₂ O ₃	—	—	—	—	—	—	—	—	—
V ₂ O ₃	0.17	0.09	0.07	0.09	0.17	0.12	0.07	0.10	0.06
TiO ₂	1.10	0.68	0.24	0.68	0.34	0.38	0.24	0.36	0.24
CaO	12.5	13.0	13.0	13.0	12.6	12.5	12.5	12.3	11.5
Al ₂ O ₃	4.40	2.44	2.90	2.44	2.52	3.10	3.44	2.82	2.24
MgO	11.2	15.6	14.6	15.6	13.9	14.4	14.5	14.8	14.0
NiO	0.01	0.03	0.01	0.03	0.02	0.04	0.02	0.03	0.03
SiO ₂	52.6	53.1	53.7	53.1	54.9	52.7	54.0	55.1	57.5
	98.2	98.8	99.3	98.8	98.9	98.0	101.0	100.4	99.2
$\frac{\text{Mg} \times 100}{\text{Mg} + \text{Fe} + \text{Mn}}$	55.2	66.8	63.9	66.8	63.2	63.5	61.5	63.9	64.7

Skaergaard intrusion are total analyses including Ca-poor lamellae. The Porttivaara augites were analysed by microprobe between the Ca-poor lamellae and thus results give higher Ca-contents than the total analyses.

Because of the scarcity of augites the possibility to calculate the composition of augite from the composition of replacing uralite was studied. Four grains of augite and uralite were analysed for this purpose. The results are shown in Table 9. In the major components a general feature is a small rise in the amounts of iron and mag-

Table 12.

The chemical composition of augites of the magnetite gabbro as calculated from the compositions of replacing uralites presented in Tables 10 and 11.

	MUSTAVAAARA						HAUKIVAARA					
	MgO	FeO	xMg	xFe	xCa	$\frac{100 \text{ Mg}}{\text{Mg}+\text{Fe}}$	MgO	FeO	xMg	xFe	xCa	$\frac{100 \text{ Mg}}{\text{Mg}+\text{Fe}}$
DR	13.2	10.8	39	17	44	69	12.8	11.8	37	19	44	66
OUL	11.5	11.6	35	20	45	64	13.7	11.0	39	18	43	69
OML	12.9	12.1	37	19	44	66	13.3	12.2	38	19	43	66
OLL	12.1	10.7	36	18	45	67	13.3	10.9	38.5	17.5	44	68.5

x_{Mg} = mol % of MgSiO_3 in augite; x_{Fe} = mol % of FeSiO_3 in augite; x_{Ca} = mol % of CaSiO_3 in augite.

nesium and an abrupt decrease in the amount of calcium. The changes in CaO seem to be very sensitive to alteration. In Fig. 27, FeO and MgO are presented in coordination with CaO. The changes especially in FeO but also in MgO are inversely proportional with changes in CaO. The mean value for $\Delta\text{MgO}:\Delta\text{CaO} = \text{tg } \alpha$ is 0.13 and for $\Delta\text{FeO}:\Delta\text{CaO}$ 0.36. If ΔCaO is known, changes in FeO and MgO and further the iron ratio of the original augite can be calculated. A value 21 % CaO forms a constant mean value for augites of the magnetite gabbro. By subtracting from this value the CaO content of uralite ΔCaO is obtained and calculations for iron and magnesium contents of the primary augite can be made. The results calculated using this method from uralite analyses presented in Tables 10 and 11 are shown in Table 12. The iron ratios are of the same magnitude as in augite analyses. The greatest difference is in disseminated rock, where the scatter in analyses was also greatest. The results confirm that the augites of the magnetite gabbro were not especially rich in iron.

THE CRYSTALLIZATION OF THE PORTTIVAARA INTRUSION

Differentiation

The Porttivaara intrusion has been divided structurally into lower and upper marginal zones which surround the intrusion like an envelope, and into a layered series inside these marginal zones (see Fig. 4). The lower marginal zone has been further divided, on the basis of petrography, into metagabbro, which is the lowermost rock of the intrusion, and the overlying metaperidotite. The contacts of the intrusion are very strongly tectonized and the lower contact hybridized by albite-quartz rock. Any fine-grained chill zone, which may have existed previously, has been destroyed.

The existence of pyroxene gabbro, indicated by the presence of metagabbro at the contacts of the intrusion, must be accounted for by the rapid conduction of heat from the intrusion into the colder country rock. This caused rather rapid congealing of the magma at the margins of the intrusion. There was insufficient time for any sort of differentiation. The absence of homogeneity in this layer may be the result of several injections, the intervals of which were such that the partially congealed margins of early injections were brecciated by newly intruded magma. The fact that this horizon is not observed at the upper contact of the intrusion is due to the absence of good outcrops as well as because this layer must be rather thin.

The peridotitic layer above the metagabbro must be a cumulate. Primary essential minerals were olivine, orthopyroxene and augite, all of which indicate a possible cumulus origin. The texture is so destroyed by alteration that primary features can no longer be seen.

The occurrence of metaperidotite is best explained by gravitational differentiation. After filling, the magma chamber achieved a stationary condition during which the crystallizing minerals underwent differential density sorting. The heaviest settled to the bottom of the intrusion. Because the margins of the chamber sloped gently, the minerals settled evenly and no slumping occurred. Such a stationary state following filling was also present in the Skaergaard intrusion during formation of the tranquil division (Wager and Brown 1968, p. 206). Crystallization took place at this time in both the upper part and at the margins of the intrusion.

Initially only olivine and pyroxene crystallized on the margins and plagioclase at the roof. The reason for this is partial contamination of the marginal magma, which is indicated by the hybrid of the lower marginal zone with albite-quartz rock. In the upper marginal zone such hybrid is missing. The contamination increased the Na/Ca ratio and the water pressure of the magma. Both of these changes reduce the field of crystallization of plagioclase (Bowen 1915, Yoder 1955). The magma nearest contact (= metagabbro) was also contaminated by silica. This moved the composition of the liquid into the crystallization field of pyroxene, and the crystallization of olivine was prevented. Somewhat further from the contact the amount of silica was small but alkalis were abundant. The crystallization field of olivine was enlarged at expense of pyroxene (Kushiro 1976) and, as a result, olivine was the first mineral to crystallize.

If plagioclase was crystallizing near the roof of the intrusion during the stationary stage, and if its density was less than that of the liquid, it would have risen and formed a layer to the roof of the intrusion. This is exactly what is found in the upper marginal zone. The thickening of this upper cumulate may have continued throughout crystallization despite currents, since between currents there were quiet intervals during which plagioclase had time to rise the short way from its place of nucleation to the roof of the magma chamber.

Wager and Brown (1968) do not consider the density of plagioclase to be less than that of the liquid in the Skaergaard intrusion. However, they explain the forma-

tion of the plagioclase-rich Upper Border Group by the mechanism of upward currents (Wager and Brown 1968, pp. 209, 231). Laboratory measurements have shown that plagioclase can be lighter than magmatic liquid although the difference is small, especially during the first stage of differentiation (Bottinga and Weill 1970, Martignole 1974).

The layered series is characterized by rhythmic layering. Usually the layers are uniform. Only olivine gabbro II and pyroxene gabbro IV show gravity stratification. The formation of rhythmic layering can be explained by two main hypothesis: (1) sorting of cumulus crystals by a mechanical agent or (2) changes in the order of nucleation due to changes in the physicochemical stage of the magma. The first hypothesis is favoured in the case of Skaergaard. The mechanical agent was currents. Steady currents produced uniform layering and intermittent currents yielded gravity-stratified layers (Wager and Brown 1968, p. 210—221). Jackson (1961) postulates that changes in the order of nucleation have resulted in the formation of rhythmic layering in the ultramafic zone of the Stillwater intrusion. The changes are believed to have been caused by latent heat of crystallization. Changes in the order of crystallization have also been suggested as a reason for the layering of the ultramafic intrusion of Rhum. In this case the change has been caused by the injections of new magma (Brown 1956).

In the Porttivaara intrusion the rhythmic layering is considered to be due to magmatic currents. That currents exist and are necessary to move energy in reasonably thick intrusions has been demonstrated by the theoretical calculations of Bartlett (1969) and Irvine (1970). The primocrysts involved in the mechanical sorting of olivine gabbros were olivine and plagioclase. In pyroxene gabbros the primocrysts were plagioclase and smaller amounts of pyroxenes. The interstitial form of the latter indicates that they crystallized largely between the laths of plagioclase. Because the pyroxenes crystallized only at the floor of the otherwise uncrystallized chamber during all stages, they were not very effectively withdrawn from the melt in which their crystallization was initiated. Consequently, a better equilibrium was reached and iron enrichment was less than in those cases in which pyroxenes are primocrysts and are withdrawn by currents from the surrounding melt. This latter situation has been reported for the intrusions of Skaergaard and Bushveld. This difference in the development of pyroxenes is surely involved in explaining variations in the amount of iron enrichment between the Porttivaara and other intrusions considered here.

Despite rhythmic layering, layered intrusions are characterized by cryptic layering. The latter reflects gradual changes in the composition of solid solution mineral series and the abrupt appearance or disappearance of cumulus minerals across the intrusion (Wager and Brown 1968, p. 29). Gradual changes of solid solution series in the Porttivaara intrusion have been demonstrated for the pyroxenes and plagioclase. The pyroxenes become richer in iron and plagioclase becomes more albitic upward through the layered series (see Fig. 3). These changes are due to changes in compositions of the liquid from which the minerals crystallized. The changes in

compositions of the liquid, in turn, are associated with fractional crystallization. This process was confirmed experimentally by Bowen *et al.* (1935).

The sporadic appearance of olivine and the introduction of ilmenomagnetite in the magnetite gabbro layer is also assignable to cryptic layering in the Porttivaara intrusion. In the Skaergaard and Bushveld intrusions olivine is present in the lower part of the intrusion, is missing in the middle part, and reappears in the upper part where it is enriched in iron. This is satisfactorily explained by fractional crystallization, as was pointed out by Bowen *et al.* (1935) in studies related to FeO—MgO—SiO_2 . The principle, in multicomponent systems, is that in fractional crystallization a liquid can move over the boundary surface from the field of olivine into the field of pyroxene through the crystallization of olivine. Because of the instability of iron-rich orthopyroxene, olivine reappears when the composition of the liquid has become rich in iron.

In the area considered here the disappearance of olivine after olivine gabbro I might be the result of fractional crystallization of olivine. However, its appearance in olivine gabbro II does not indicate that the liquid has become iron rich. This is so because orthopyroxene is present during all periods of olivine crystallization and the olivine is chrysolite in composition. On the other hand, the olivine of olivine gabbro I may be a cumulus crystal of that olivine which crystallized at the margins of the intrusion.

When comparing the existing order of crystallization of cumulus silicates in the »system» Ol—Cpx—Pl—Q (Fig. 28), the formation of the lowest cumulate (= metaperidotite) indicates that the liquid was on the phase boundary between olivine and orthopyroxene. It may even have been on the boundary curve of Ol—Opx—Cpx . The formation of olivine gabbros presupposes that the liquid was on the boundary plane of olivine and plagioclase. During the accumulation of pyroxene gabbro it must have been in the plagioclase field. Changes of this sort cannot be explained by simple crystallization differentiation. They require changes in the physico-chemical state of the magma.

The unusual order of nucleation in the lower marginal zone in the intrusion studied is explained by partial contamination. Olivine gabbro I lying above this zone, may have formed by mixing of plagioclase, crystallizing near the roof, and olivine and orthopyroxene, crystallizing near the margins. The mixing is caused by currents. Similar features are shown by pyroxene gabbro I, the grains of which are lacking in good idiomorphicity. During the accumulation of pyroxene gabbro II crystallization had ceased at the margins and the only cumulus crystal was plagioclase, crystallizing in the upper part of the intrusion. This also applies to overlying layers. The reappearance of cumulus olivine in olivine gabbro II shows that some changes in the system had occurred. There is no indication of changes in the chemical composition of the system as indicated by the composition of the silicates. Movement from the plagioclase field on the olivine-plagioclase boundary surface has been via the olivine-orthopyroxene boundary surface, and must be due to changes involving

the boundary surfaces themselves. The reason for these changes may have been changes in the partial pressures of volatiles. That these can modify boundaries is well documented by experimental petrology (Muan and Osborn 1956, Roeder and Osborn 1966).

The appearance of ilmenomagnetite as a primary precipitate as fractional crystallization proceeds toward iron enrichment seems very natural, particularly so if iron enrichment is associated with a small rise in the fugacity of oxygen. This is the simplest way to explain the occurrence of magnetite gabbro in the Porttivaara intrusion. However, textural features do not favour this hypothesis. The matter is treated in the chapter »The genesis of the Mustavaara vanadium ore deposit».

The Fe/Mg ratio in the liquid increases continuously during fractional crystallization. The appearance of magnetite does not alter the situation which is indicated by the compositions of pyroxenes (Fig. 3; Wager and Brown 1968, Fig. 14). Such an increase does not necessarily lead to differentiates which are rich in iron because changes in the amount of SiO_2 are also involved. According to the differentiation

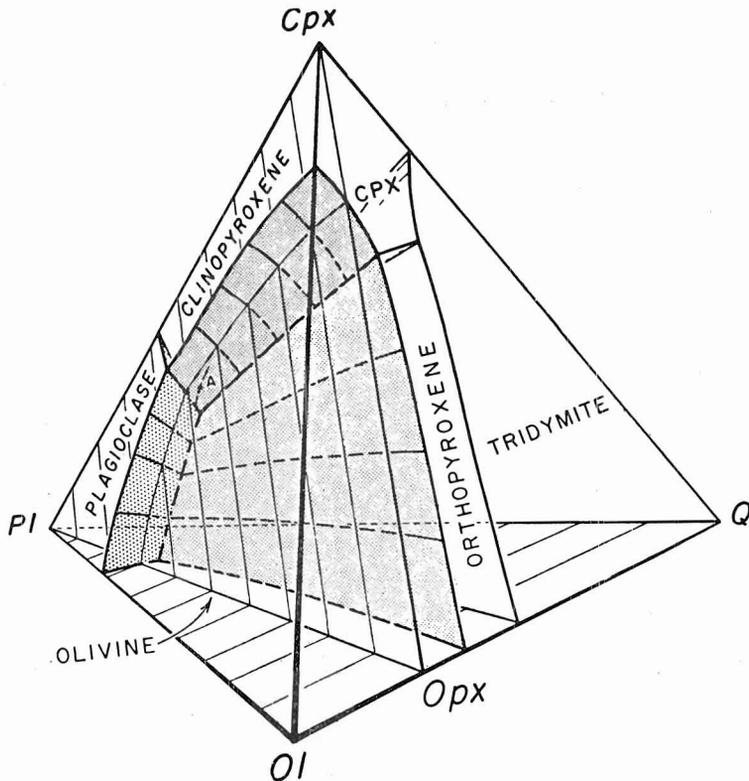


Fig. 28. Phase diagram model of the »system» olivine (Ol)-clinopyroxene (Cpx)-plagioclase (Pl)-silica (Q). Reproduced from Irvine (1970) by the permission of the Geological Society of South Africa.

model suggested by Bowen (1922), the composition of the liquid becomes more salic as crystallization proceeds. The resulting rock association is referred to as calc-alkalic. This theory is based on the reaction series of feldspars and iron-magnesium silicates. However, observations made from dikes and intrusions which were differentiated in situ indicated that the remaining liquids had become enriched only in iron and possibly in alkalis. They were not enriched in SiO_2 , as indicated by the fact that salic components were represented only by a few granophyres which may have been contaminants (Fenner 1929, Wager and Deer 1939). This model of differentiation is known as Fenner's trend. Thus there appear to be two kinds of differentiation models leading to completely different rock associations. Factors involved in magmatic differentiation include the mixing of magmas (Fenner 1948), the contamination of basaltic magma with salic sediments (Waters 1955), and the value of the primary oxidation state (Kennedy 1955).

Studies in experimental petrology during the 1950's have shown that an additional important factor which controls the crystallization and differentiation of basaltic magma is the fugacity of oxygen (Muan 1955, 1958, Muan and Osborn 1956, Osborn 1959, 1962). According to Osborn four types of crystallization paths can be distinguished (Osborn 1959, p. 617):

1. Equilibrium crystallization at constant total composition
2. Fractional crystallization at constant total composition
3. Equilibrium crystallization at constant P_{O_2}
4. Fractional crystallization at constant P_{O_2}

Fractional crystallization at constant total composition of any mixture produces a high iron differentiate, while fractional crystallization at constant P_{O_2} leads to differentiates rich in SiO_2 . The total composition is constant when the gas component is small or the melts are dry. In wet melts P_{O_2} remains constant. The theoretical differences between these two kinds of differentiation are illustrated in Fig. 29. This figure indicates phase relationships in the system $\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$. When fractional crystallization occurs at constant total composition the liquid moves along the boundary surface and subsequently along a quaternary univariant line within the tetrahedron. At maximum differentiation it reaches the fayalite-magnetite-tridymite eutectic point. When crystallization proceeds at constant P_{O_2} , the liquid must remain on the same isobaric surface. The $\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$ triangle in Fig. 29 illustrates such a surface. During differentiation the composition of the liquid moves on this surface along univariant lines in the direction of lower temperature until it reaches pyroxene-magnetite-silica univariant line, where crystallization is completed. As seen from the tetrahedron, the composition of the remaining liquid is quite different in each case. In the first situation the remaining liquid had moved in the direction of the FeO apex but, in the latter case, it had moved toward the SiO_2 apex. In the Porttivaara intrusion the differentiation took place according to Fenner's trend,

involving fractional crystallization under constant total composition. This means that the liquid was dry. However, as concluded from the composition of the augites, the iron-enrichment did not proceed very far.

Temperature of crystallization and fugacity of oxygen

Information concerning the temperatures of crystallization and fugacities of oxygen which prevail during crystallization of basic magmas has been derived from measurements in lavas, melting experiments of minerals and rocks, theoretical calculations and mineral thermometers and barometers. Melting experiments on basaltic rocks under 1 atm. total pressure have yielded liquidus temperatures between 1 150—1 250°C. Furthermore, between these limits the liquidus can be interpolated from measurements made in lavas.

The experiments by Tilley *et al.* (1963, 1964) showed that there is a correlation between the liquidus temperature and the iron enrichment in basic rocks. Iron enrichment results in a reduced liquidus temperature as shown in Fig. 30.

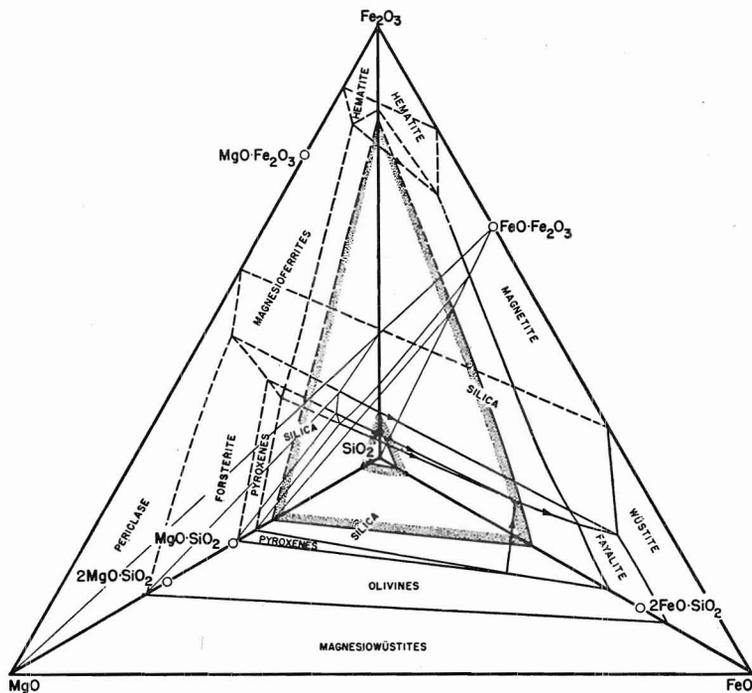


Fig. 29. Phase relationships in the system $\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$. Reproduced from Muan and Osborn (1956) by the permission of the American Ceramic Society.

From this diagram a liquidus temperature of 1 230°C has been determined for the primary magma of the Porttivaara intrusion with $\text{FeO} + \text{Fe}_2\text{O}_3 / \text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}$ 0.52 (p. 14). This is almost the same as that of the fine grained chill zone sample of the Skaergaard intrusion. The responsible ratio for the liquid, from which magnetite gabbro crystallized, is 0.72 (calculated from the compositions presented in Table 2; for anorthosite gabbro II is FeO 5.20, Fe_2O_3 2.67 and MgO 4.23 (Juopperi 1972, p. 19). The thicknesses of different layers are presented on p. 61). This ratio gives liquidus temperature 1140°C.

In the experiment concerning the fine-grained chill zone sample of the Skaergaard intrusion the first mineral to crystallize was plagioclase. This was followed by olivine at a temperature reduction of 30°C, and by clinopyroxene at a further deduction of 10°C. The temperature difference between the initiation of crystallization and its virtual completion was at least 260°C (Tilley *et al.* 1963). From these differences one may conclude that the interstitial crystallization of clinopyroxene in the lower part of the Porttivaara intrusion was initiated, and continued for some time, prior to initial crystallization of plagioclase in the magnetite gabbro. However, the former crystallization had not gone to completion at this time.

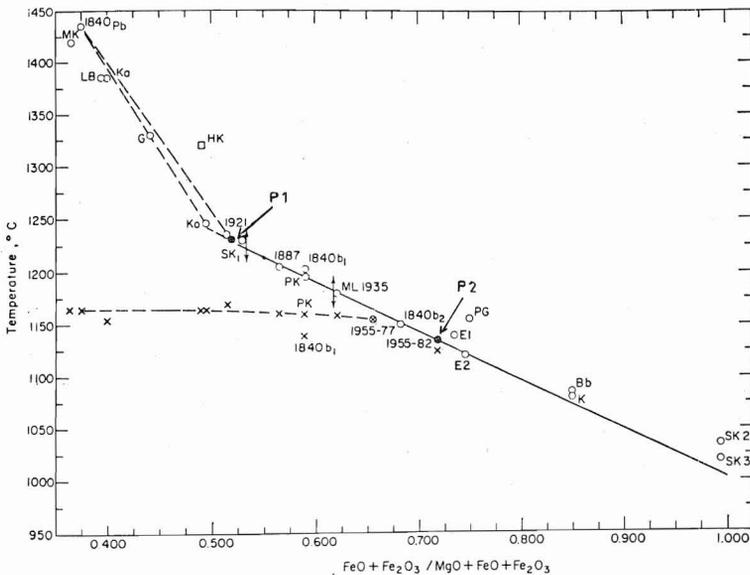


Fig. 30. Diagram correlating liquidus temperatures with iron enrichment. The calculated iron ratios for the primary magma of the Porttivaara intrusion and for the magma from which magnetite gabbro crystallized are marked by P1 and P2 respectively. SK 1 is a sample from the fine grain chill zone of Skaergaard intrusion. Crosses indicate the temperatures of attainment of the four phase boundaries (olivine, plagioclase, clinopyroxene, liquid). Other markings refer to samples mentioned in the original paper, Tilley *et al.* 1964, Fig. 23, p. 95.

The experiments reported for in the foregoing were carried out under dry conditions and, consequently, they yield excessively high values. The addition of water into such a system lowers the crystallization temperatures. The experiments of Yoder and Tilley (1956, 1962) showed, that 1 000 bars P_{H_2O} lowered the liquidus temperature of an olivine tholeiite c. 70°C, and the solidus temperature c. 120°C. At 5 000 bars P_{H_2O} the corresponding numbers were 110°C and 300°C. For high-alumina basalt the lowering of the liquidus temperature at 1 000 bars P_{H_2O} was c. 90°C and in solidus temperature c. 110°C (Fig. 31). At water pressures higher than 1 000 bars for high-alumina basalt, and higher than 1 500 bars for olivine-tholeiite basalt, amphibole became a primary mineral at the end of crystallization. This mineral replaced olivine and pyroxenes.

Because primary hornblende is missing from the last differentiates of the layered series of the Porttivaara intrusion, water pressure must have been below 1 500 bars. A value of 1 150—1 200°C can, thus, be accepted as a rather accurate estimate of the liquidus temperature of the primary magma in the Porttivaara intrusion. The liquidus temperature of the magma from which plagioclase of the magnetite gabbro crystallized was c. 100° lower, or 1 050—1 100°C. The completion of crystallization occurred at temperatures 200—300°C below liquidus temperatures. The highest and lowest temperature reported for the Parikkala gabbro massif are 1 180°C and 875°C, respectively (Häkli 1971). Hornblende accumulated in the final differentiate. Ni^{Ol}/Ni^{Aug} was used as a thermometer. This method cannot be applied to the Porttivaara intrusion because of the absence of olivine and augite, both of which were either cumulus or intercumulus in origin.

Experiments involving the fugacity of oxygen in natural rock samples have yielded values of 10^{-8} — $10^{-8.5}$ bars at 1 200°C for basalts (Fudali 1965), and of 10^{-8} — 10^{-9} b at 1 210°C for an ultrabasic dyke (Gibb *et al.* 1971). Thermodynamic calculations of the equilibrium oxygen fugacities of volcanic and fumarolic gases have resulted in values of 10^{-8} b at 1 500°K under 1 atm. total pressure; all the water was suggested to be juvenile (Heald *et al.* 1963). Direct measurements in lavas gave values of 10^{-9} — 10^{-20} b at temperatures between 1 069—505°C. The fugacities fell within the stability field of magnetite and the changes occurred as a function of temperature. They also conformed with the changes which were calculated for the degree of disassociation of water (Sato and Wright 1966).

Additional information concerning f_{O_2} can also be obtained from the order of crystallization of minerals. According to the experiments of Hill and Roeder (1974) chromite does not crystallize as an early phase in basalts with 200 ppm Cr, if the f_{O_2} is below 10^{-8} b. If the Cr content is 300 ppm, which is the mean value for the Porttivaara intrusion as calculated by Mäkelä (1975), the corresponding limiting value is 10^{-9} b. The nucleation order of pyroxenes and plagioclase is effected by f_{O_2} as well as by other factors. In normal basalts plagioclase crystallizes before pyroxenes if the f_{O_2} is below 10^{-9} b. The order of nucleation is reversed in higher fugacities of oxygen

(Roeder and Osborn 1966). The similar change in high-alumina basalts associated with changes in P_{H_2O} is seen in Fig. 31. The critical value of P_{H_2O} there is 1 500 bars.

All the results mentioned above are in good agreement with each other and they show that at liquidus temperatures the fugacity of oxygen in basaltic magma is normally 10^{-8} b or slightly lower. The absence of early spinel, and the crystallization of plagioclase before pyroxenes in the intrusion of Porttivaara proves that f_{O_2} was below 10^{-9} b during initial crystallization. As crystallization proceeded the numerical value of f_{O_2} became smaller despite the fact that conditions became more oxidizing.

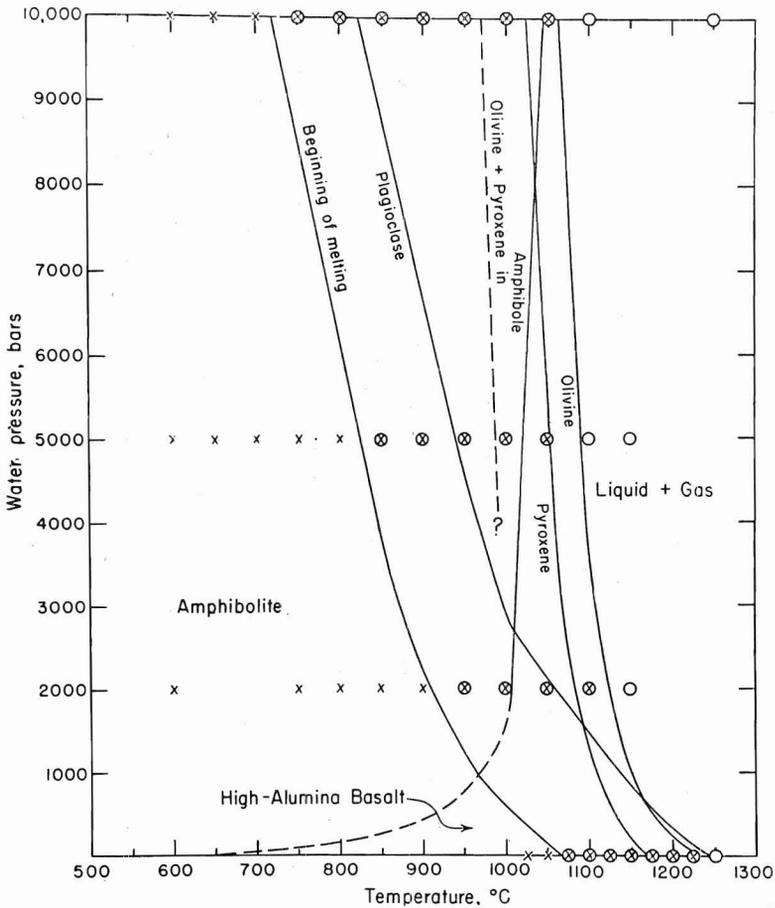


Fig. 31. Changes in liquidus and solidus temperatures and in stability areas of olivine, plagioclase, pyroxene and amphibole in a high-alumina basalt under different water pressures. Reproduced from Yoder and Tilley, 1962, Fig. 28, p. 451. by the permission of Oxford University Press.

As regards the $\text{FeO}-\text{Fe}_2\text{O}_3-\text{TiO}_2$ system, Lindsley (1963) prepared the diagram presented in Fig. 32. From compositions of coexisting magnetite—ulvöspinel_{ss} and ilmenite—hematite_{ss} and with reference to the diagram it is possible to determine the fugacity of oxygen and the temperature of minerals crystallization or equilibration. During crystallization of magnetite—ulvöspinel_{ss} there should be a surplus of titanium in order that original ilmenite might crystallize (Buddington and Lindsley 1964).

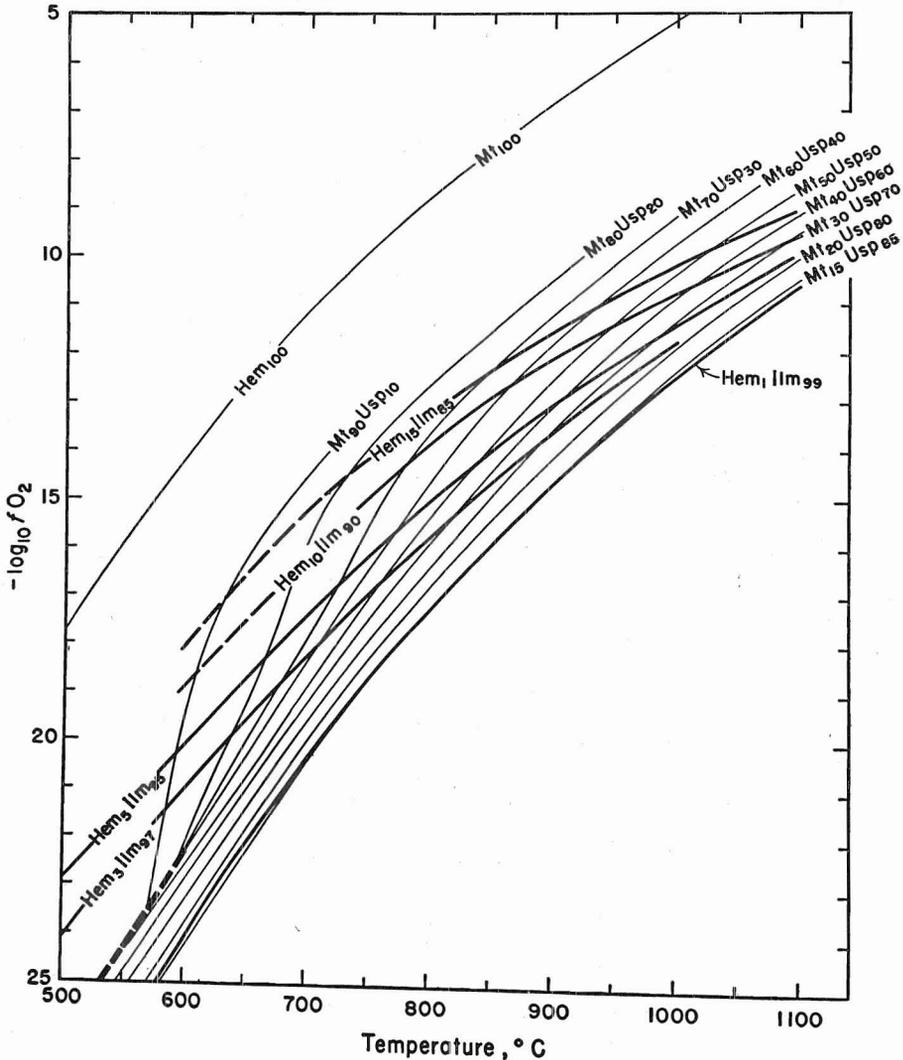


Fig. 32. The compositions of coexisting magnetite-ulvöspinel and hematite-ilmenite in f_{O_2}/T coordination according to Lindsley (1963).

Because of the absence of primary ilmenite in the ore of Mustavaara it is not possible to obtain exact values for f_{O_2} and T , but some limiting values can be determined. From the diagram in Fig. 23 p. 33 it can be seen that the magnetic concentrate richest in titanium has c. 6 % Ti and 64 % Fe. By calculating all titanium for ulvöspinel and the remaining iron for magnetite a composition for the primary single phase spinel of $Mt_{70}Usp_{30}$ can be estimated. This is the highest possible solid solution for magnetite under the prevailing crystallization conditions. Probably there would have been more Usp if there had been enough titanium. By using an approximated crystallization temperature of 1 050°C for magnetite an upper limit for f_{O_2} during crystallization of 10^{-10} bars can be determined. The lower limit is the magnetite/wüstite boundary curve. As indicated by the $Fe_8O_4-Fe_{1-x}O$ assemblage it is at 1 050°C and under a total pressure 2 000 bars $10^{-11.5}$ b (Lindsley 1963, p. 61).

In the easternmost part of the Mustavaara ore, where the magnetite was idiomorphic, the fugacity of oxygen must have been higher than average during crystallization. The absence of primary ilmenite grains made the determination of numerical values impossible.

In the Skaergaard intrusion fugacities of oxygen have been determined from Lindsley's diagram to have been $10^{-13.2}-10^{-16.4}$ b, and temperatures to have been 890°—760°C (Buddington and Lindsley 1964). According to the writers such fugacity and temperature values involve exsolution. This also applies to the values for the Otanmäki ore of Finland, where $T = 590^\circ\text{C}$ and $f_{O_2} = 10^{-18.7}$ b (Buddington and Lindsley 1964, p. 338).

THE GENESIS OF THE MUSTAVAARA VANADIUM ORE DEPOSIT

Common to most theories concerning the origin of titanium-iron ores, of which the Mustavaara vanadium ore deposit is one example, is the magmatic character of the ore, the close association with surrounding rocks which are commonly gabbros, anorthosites or anorthosite gabbros, and the formation of ore as a result of segregation of an iron-rich liquid. Differences in the opinions concern the process through which the iron-rich liquid develops.

Titanium-iron ores, such as that at Ulvö, Sweden, where titaniferous magnetite lies as idiomorphic grains at the bottom of a sheet or an intrusion have the simplest genesis. The ore has formed by the gravitational settling of titanomagnetite which crystallized early (Mogensen 1946). However, this situation is uncommon. In most cases titaniferous magnetite is allotriomorphic between the grains of silicates and, when the concentrates consolidate, they lie in the upper part of the intrusion. Discordant features are also common. These features have been interpreted to indicate the existence of an iron-rich liquid. Vogt (1924), who believed that spinel always crystallizes early, explained the occurrence of iron-rich liquid as the result of remelting

of titaniferous magnetite which had sunk to the bottom of a magma chamber with early silicates.

More recently, the opinion that the iron-rich liquid is of a residual type which is removed from the basic magma by differentiation of the Fenner type has become popular. This iron-rich liquid has then either filtered into the spaces of silicates which crystallized earlier or been pressed out of the crystal porridge. This latter situation would result in the discordant character of the ores. This model has been utilized to explain the titanium-iron ores of Canada and of the U.S. East Coast (Balsley 1943, Faessler *et al.* 1941, Bateman 1951), those of Taberg in Sweden (Hjelmqvist 1950), the ilmenite ore of Abu Ghalga in Egypt (Amin 1954), and the magnetite gabbro of the Bushveld intrusion (Bateman 1951). Later theories suggest that the magnetite gabbro of Bushveld intrusion may be a cumulate and that the allotriomorphicity of the magnetite is due to adcumulus growth (Wager and Brown 1968, Willemse 1969). The intrusive character of the Otanmäki ore also favours existence of ore liquid (Paarma 1954), which was associated with differentiation of a basic magma (Saksela 1964). On the other hand, the Otanmäki ore has also been explained by metamorphic differentiation (Pääkkönen 1956).

Schneiderhöhn (1958), in his textbook, includes titanomagnetite ores in liquid-magmatic ores. At the time they formed, most of the magma from which they separated was in a liquid state. The separation can occur in different stages of crystallization.

A different origin for the iron-rich liquid suggests liquid immiscibility. Such an origin has been favoured by Fischer (1950), Buddington *et al.* (1955), Ramdohr (1956), Gjelsvik (1957), Lister (1966) and Philpotts (1967). In addition to structures favouring liquation, supporting evidence is derived from experimental petrology by Fischer and Philpotts, from microscopic textures by Buddington and Ramdohr and from partitioning of the minor elements between the ore and the country rock by Lister.

A metamorphic origin has been suggested for the titanium-iron ores associated with charnockitic affinity by Ramberg (1948) and, as mentioned earlier, a metamorphic origin was also proposed for the ore of Otanmäki by Pääkkönen (1956).

This summary of opinions concerning the genesis of titanium-iron ores leads to one clear conclusion. It appears unlikely that additional hypotheses are required. What is necessary here is the critical evaluation of facts concerning the Mustavaara ore as they relate to the conflicting theories of ore genesis.

When considering the genesis of the Mustavaara ore, and thus the genesis of magnetite gabbro of the Porttivaara intrusion in general, the following facts must be kept in mind:

- magnetite gabbro lies in the upper part of the Porttivaara intrusion where it forms a coherent layer following the general layering of the intrusion
- the lower contact of the ore is sharp, upwards the border is gradational
- the magnetite gabbro itself has layering due to changes in the amount of magnetite, which is inversely correlated with the amount of augite

— the primary silicates were plagioclase, An_{49-51} , and augite, $Ca_{43}Mg_{38}Fe_{19}Ca_{41}Mg_{34}Fe_{22}$.

The conformable position of the magnetite gabbro, in association with the compositions of plagioclase and augite which are gradational with those of the lower layers, shows that the magnetite gabbro is only a single horizon in the layered series. Thus, its formation is associated with the general differentiation of the entire intrusion.

When the differentiation trend of a basic magma follows that suggested by Fenner, the result is an enrichment in iron during differentiation. In extreme cases this can lead to a residual liquid rich in iron from which large quantities of magnetite may crystallize as an intercumulus mineral. The position and texture of the Porttivaara magnetite gabbro suggests this possibility. However, the composition of augites indicates that, although the direction of differentiation has been toward iron enrichment, the process has not proceeded very far (Fig. 25).

In Fig. 33 the tie lines connecting the Fe/Fe+Mg+Mn of a liquid, and of an augite crystallizing from that liquid, are indicated. The compositions of augites of the magnetite gabbro are also shown. Following these tie lines it is found that the iron ratio of the liquid from which these augites crystallized was about 55 for OLL, 63 for OML and 65 for disseminated rock. In Fig. 33 also the iron ratios of different layers of the magnetite gabbro (connected by broken lines with corresponding augites) are shown. In the crystallization of liquidus with iron ratios such as those mentioned above, it is not possible to produce the iron ratios which occur in the ore without some kind of a concentration process. In other words, the layers of the ore must be »cumulates» in which oxide and plagioclase have each been a cumulus phase. The layered structure itself also confirms the cumulate character.

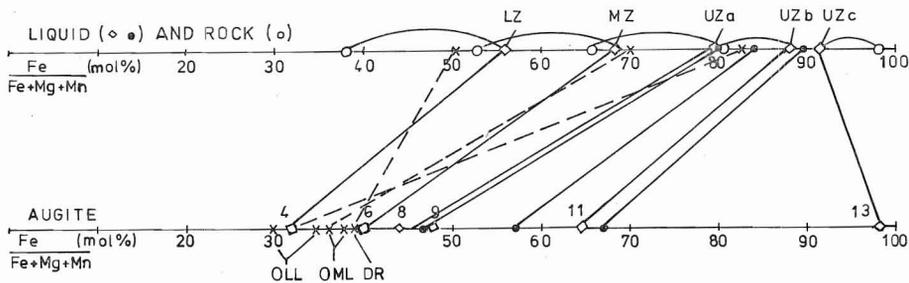


Fig. 33. The iron ratios of liquids, and of augites crystallized from them (connected by tie lines) in the Skaergaard intrusion (\diamond) and in some volcanics (\cdot). The iron ratios of rocks crystallized from the liquids of Skaergaard intrusion are indicated by circles (connected by curved lines). Iron ratios of augites of the magnetite gabbro of the Porttivaara intrusion and of corresponding rocks are indicated by crosses (connected by broken lines). The analyses from the Skaergaard intrusion are for rocks from Wager and Brown 1968, p. 158, for liquids from Wager 1960, p. 386, for augites 4, 6, 8 and 9 from Brown 1957, p. 516, for augites 11 and 13 from Brown 1963, p. 177. Analyses of volcanics are from Carmichael 1960 p. 314 and 327.

LZ = lower zone, Skaergaard intrusion, MZ = middle zone, Skaergaard intrusion, UZ = upper zone, Skaergaard intrusion, OLL = ore lower layer, OML = ore middle layer, DR = disseminated rock.

The term cumulate indicates a rock which is formed by accumulation of discrete crystals (Wager, Brown and Wadsworth 1960). The idiomorphicity of the cumulus crystals is still visible although it could be partly modified by growth after accumulation. In the layers of the magnetite gabbro the cumulus origin of plagioclase is well documented by good idiomorphicity. However, the crystal form of magnetite does not favour a cumulus origin because it is usually interstitial between the grains of silicates. The presence of a few idiomorphic grains suggests that the bulk of the allotriomorphic grains could have been formed by adcumulus growth from such cores. However, the adcumulus growth in such a situation would normally have resulted in crystals many times larger than the primocrysts. This does not appear to be the case. Furthermore the exsolution textures do not favour adcumulus growth.

The liquation hypothesis suggests a model for the formation of the magnetite gabbro which explains the texture and the composition of augite and seems compatible with most other aspects of the Porttivaara intrusion. According to this model a separate oxide liquid formed at some later stage of differentiation. The solidus temperature of this liquid was lower than that of the coexisting silicate liquid. The oxide globules were incorporated in currents and became concentrated in varying amounts in different currents. This resulted in the layered structure. As well as separate plagioclase crystals and oxide globules, the currents transported anorthosite blocks from near the roof of the magma chamber. These now occur as inclusions which result in a brecciated appearance. Similarly, anorthosite inclusions are also encountered in the lower horizons. Because the blocks and the transporting liquid possessed different current velocities, the long axes of the plagioclase prisms have achieved an orientation parallel to the block surfaces.

By the liquid immiscibility hypothesis it is also relatively easy to explain the increase in the amount of ilmenomagnetite at the expense of augite. Such an explanation requires only the presence of different amounts of oxide and silicate liquids in association with the plagioclase crystals. Had augite and ilmenomagnetite crystallized from a single interstitial liquid, the greater amount of ilmenomagnetite should result in a residual liquid richer in Mg, which, in turn, should be reflected in the compositions of the augites. Such differences were not found. It is also very difficult to explain the rocks which are composed only of plagioclase and ilmenomagnetite by the hypothesis of a single liquid. In such rocks, one would visualize a very large adcumulus growth. This should result in a liquid rich in Mg. At least a portion of such a liquid would remain as pore material, but no indication on this is present in the rocks.

According to the experiments made by Fischer (1950) liquation of an oxide liquid can occur under the following conditions:

1. Silicate liquid must have alkalis in excess to calcium
2. Heavy metals must be in a higher state of oxidation
3. Magma must contain phosphorus
4. Magma must contain volatiles.

All but one of these conditions are fulfilled in the present situation. Volatiles are documented by the alteration of augite to uralite and plagioclase to epidote. Phosphorus is evidenced by the occurrence of a few grains of apatite. The ore itself indicates higher oxidation state of the metals. Concerning this last point, however, alkali-rich rocks are not found in association with the intrusion.

Much of experimental petrology deals with demonstrating that a given process is possible under fixed and experimentally controlled conditions. In more complex field situations, in which it is impossible to evaluate the multiplicity of variables, a process may often be considered as a very real possibility if the data conform with the general framework of experimental work. This is the case in the present situation.

As mentioned previously, magnetite occurs in that upper part of the intrusion which includes the magnetite gabbro and the lowest 300 m of anorthosite gabbro II. From the compositions of these rocks the composition of the liquid from which they crystallized can be calculated. The following values were utilized for Mustavaara:

layer	thick- ness m	Fe %	Mg %
OLL	3	26.0	1.90
OML	40	16.7	3.11
OUL	20	21.5	2.57
DR	100	13.5	3.54
ANTGB II	300	5.9	2.55

(values for Fe and Mg of the magnetite gabbro are from Table 2, for the anorthosite gabbro II from Juopperi 1972, p. 19).

Fe in the liquid was 9.3 w % and Mg was 2.8 w % and the iron ratio was 58.7. It is a little higher than the one obtained from the composition of augite of the lower layer of the ore (Fig. 33) which means that a part of iron was separated from the liquid by liquid immiscibility before crystallization of the augite.

One may postulate a liquid, which has 9.3 % Fe and 2.8 % Mg and from which an augite with a composition like that of the disseminated rock (i.e. 13.3 w % FeO 11.8 w % MgO and Fe/Mg 1.45) is precipitated. When all magnesium has been exhausted, there would remain 5.2 w % Fe. If this remainder crystallizes as magnetite it results in 7.2 w % magnetite. The mean mass value of magnetite for ore is 16 %, for disseminated rock 10 % and for anorthosite gabbro II 3 %. When using the same thicknesses for different layers as before a mean mass value for magnetite 6.3 % is obtained. Ilmenite is included in this calculation. The calculation shows clearly that the mass of magnetite found in magnetite gabbro and in the overlying anorthosite gabbro II could derive from the liquid prevailing in that space before crystallization despite the fact that the liquid was not especially rich in iron.

SUMMARY

The magnetite gabbro of the Porttivaara intrusion, including as somewhat richer concentrate Mustavaara vanadium ore deposit, is a single layer of the layered series of the intrusion. Thus its formation is only one event in the unified differential crystallization of the intrusion, which can be summarized as follows:

A primary basic magma intruded between the old basement and the younger Svecokarelian sediments. The emplacement of the magma occurred so rapidly that only the margins had congealed prior to intrusion of the next magmatic pulse. Consequently, marginal blocks of the earlier pulse became incorporated in the later pulse. This resulted in a lack of homogeneity along the margins. As a result of this rapid intrusion, the principal crystallization of the entire magma took place as a continuous process and the situation may be regarded as a closed system in relation to the main components of the essential minerals.

Following intrusion, crystallization initially occurred at the margins and at the roof of the intrusion. The temperature of crystallization was 1150—1200°. The partial mobilization of the country rock at the margins caused contamination and resulted in a different order of nucleation at the margins and at the roof. Contamination near the contact was high in silica. This precluded the crystallization of olivine and resulted in the appearance of pyroxenes and plagioclase. Somewhat further from the contact the contamination was higher in alkalis and water than in silica. Consequently, crystallization was initiated by olivine and followed by pyroxenes. By gravitational settling these minerals accumulated on the congealed margin and formed a peridotite layer. At that time the magma was in a stationary state. In the uncontaminated upper part of the intrusion plagioclase crystallized and rose to the roof of the intrusion forming the upper cumulate. This thickened throughout crystallization by the continual accumulation of plagioclase.

As the cooling continued, nucleation ceased at the margin. It proceeded only near the roof where plagioclase was the only mineral to crystallize. The rising temperature gradient between the upper and lower parts of the magma initiated currents which carried plagioclase to the bottom of the intrusion and produced the layered series in sequence from the bottom to top. As a result of changes in the phase boundary surfaces, plagioclase, olivine, and orthopyroxene appeared sporadically as cumulus crystals. However, olivine is usually missing and pyroxenes have crystallized from intercumulus liquid. The trend of differentiation was toward iron enrichment

but iron ratios higher than 2 times that of original liquid, were never attained as concluded from composition of augites, which change from $\text{Ca}_{43} \text{Mg}_{45} \text{Fe}_{12}$ in olivine gabbro I to $\text{Ca}_{44} \text{Mg}_{34} \text{Fe}_{22}$ in magnetite gabbro. After three quarters of the intrusion had crystallized, possibly as a result of the concentration of volatiles and a rise in the fugacity of oxygen, the liquation of oxide phase occurred. The oxide globules were incorporated with the plagioclase phase in currents and became concentrated in layers. These form the magnetite gabbro. The temperature of crystallization at this stage was 1050–1100°C and f_{O_2} 10^{-9} – $10^{-11.5}$ b. The remaining liquid crystallized last above the magnetite gabbro as anorthosite gabbro.

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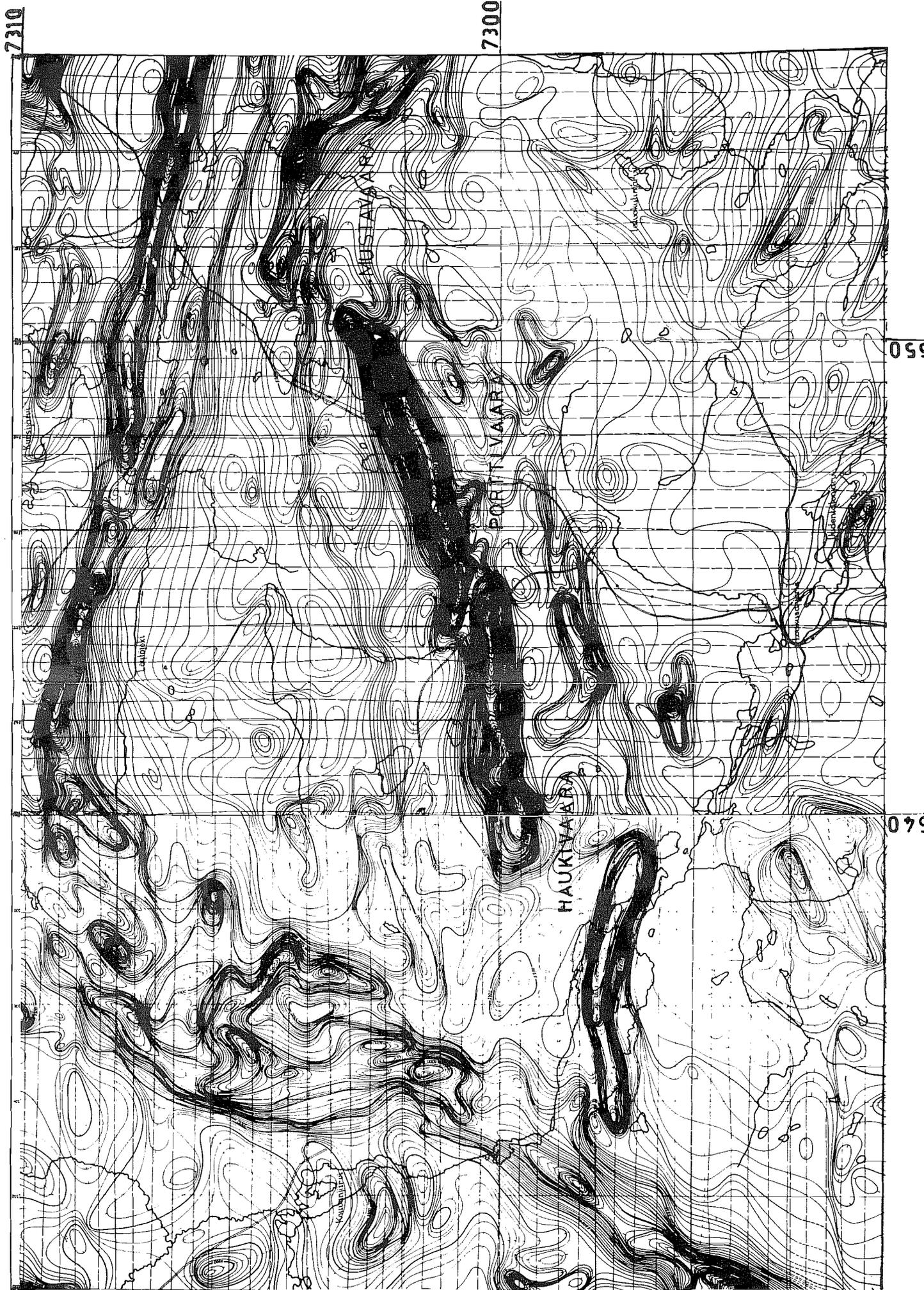
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Aeromagnetic map from the area of the Porttivaara intrusion. Part from sheets 3541 and 3543.

THE PORTTIVAARA INTRUSION

LEGEND

INTRUSION ROCKS

SURROUNDING ROCKS

 ANORTHOSITE GABBRO

 ALBITE ROCK

 MAGNETITE GABBRO

 GRANITE GNEISS

 PYROXENE GABBRO

 50°
STRIKE AND DIP OF LAMINATION
AND BEDDING

 OLIVINE GABBRO

 FAULT

 MARGINAL ZONE

 BORE HOLES

