GEOLOGINEN TUTKIMUSLAITOS

BULLETIN

DE LA

COMMISSION GÉOLOGIQUE

DE FINLANDE

N:o 171

OTANMÄKI
THE ILMENITE-MAGNETITE ORE FIELD IN FINLAND

BY

VEIKKO PÄÄKKÖNEN

WITH 41 FIGURES AND 19 TABLES IN TEXT, 2 PLATES AND 3 MAPS

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Helsinki 1957. Valtioneuvoston kirjapaino

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Fig. 1. Otanmäki Mine Region.

PREFACE

The field studies for this paper were begun in the summer of 1938. The mapping was mainly carried out in the summer of 1940 and partly revised in the following summers.

To the Director of the Geological Survey of Finland, Professor Aarne Laitakari, I am greatly indebted for his kindness in allowing me the opportunity to take part in the investigations of the Otanmäki region and in agreeing to have this work published by the Geological Survey.

Professor Heikki Väyrynen and Professor Martti Saksela have been kind enough to read the manuscript and to offer many useful suggestions. For all this I owe them a debt of gratitude.

Dr. H. B. Wiik, Mr. E. Savolainen, M. A., and Mr. V. Leppänen, M. A., have carried out the chemical analyses of this research. Mrs. Toini Mikkola, M. A., has performed some optical determinations. Miss. Karin Dahl and Mrs. Lyyli Orasmaa have drawn the maps and some pictures. Mr. Erkki Halme has made some photographic prints. Mrs. Joyce Preston, M. A., and Mr. Johnny Ask have given me valuable help in preparing the manuscript. Mr. Paul Sjöblom, M. A., has corrected the manuscript. To all these persons I offer my best thanks.

Geological Survey of Finland, Helsinki, 1956.

Veikko Pääkkönen

INTRODUCTION

The ore field of Otanmäki is situated in the parish of Vuolijoki and about 5 km south of Oulujärvi, a large lake in Central Finland. The small church village of Vuolijoki is located 9 km west of the center of the main ore field; and the nearest town, Kajaani, is 32 km to the northeast. At the time of the discovery of the field the nearest railway, running between the towns of Kajaani and Iisalmi, was 25 km away. The vicinity of Otanmäki is mainly wooded, hilly and marshy terrain.

Fig. 2. A map of Finland, showing the situation of Otanmäki.

The investigations leading to the discovery of the ore field were made by the Geological Survey of Finland. In 1937 two small ilmenite-magnetite ore boulders were found at Sukeva, which is 30 km southeast of Otanmäki. During the following summer a search for the source of these ore blocks was carried out systematically. The starting point for the investigations was the Sukeva district. From there the search proceeded northwestwards, because it was proved that the glacial transport of erratic boulders had been from that direction. The prospecting was considerably helped by the observations of two geologist of the Geological Survey of Finland, who discovered a magnetic anomaly on the hill of Otanmäki. In the subsequent magnetic investigations a strong disturbance was noticed over a rather large area surrounding the hill. When the moss and peat layer had been removed from the place of the strongest magnetic anomaly, the rock was found to contain ilmenite-magnetite ore like that of the blocks found at Sukeva.

In the summer of 1939 the Geological Survey continued to investigate the region, searching at the same time for other possible ore formations in the Vuolijoki district. Accordingly the Vuorokas ore field was discovered about 4 kilometers east of Otanmäki. During geological mapping of the region in the summer of 1940, a third magnetic anomaly area was found at Pentinpuro, which is situated about 3 kilometers west of the Vuolijoki church; and during the same summer a fourth occurrence of ilmenite-magnetite ore, the Itäranta field, was also discovered a little east of Vuottolahti bay.

The first microscopic examination of the ore specimens showed at once that the structure of the rock would make possible dressing of the ore minerals; and as the area of magnetic anomaly at Otanmäki first discovered was about 500 000 square meters, the ore formation seemed to be of economic importance.

Since the primary country rock in the ore district is almost everywhere covered by glacial deposits from 1 to 3 meters in thickness, a necessary investigation by diamond drilling was started on the ore field in the spring of 1939. After 10 borings carried out by the Geological Survey, it became clear that the ore bodies had in places a considerable thickness, varying from 10 to 30 meters, and ore-bearing rocks were found even at depths of more then 200 meters. Nevertheless the ilmenite-magnetite concentrations occurred so very irregularly that these investigations did not give a definite idea of the economic importance of the ore field.

The following year the ore field was taken over by the Suomen Malmi Co., a prospecting company belonging to the State. They also started to investigate the ore by diamond drilling and concentrated their prospectings wholly on the 400 meters-long western part. It was ascertained that there were about 10 million metric tons of dressable ore in this area when the estimation was limited to a depth of only 200 meters. As the more detailed investigation covers only a fifth of the whole ore zone and as the drill has met ore at a depth of more than 300 meters, it may be assumed that the actual mangetic anomaly area of Otanmäki contains several dozen million tons of economic ore.

The question of profitable mining could not be solved by the investigations of Suomen Malmi Co. In order to gain additional information regarding the amount of ore, a State Commission was appointed, which continued the diamond drillings. These investigations did not lead to a final solution either. After a long interval the Finnish Government in 1946 appointed a new consulting committee for Otanmäki to cooperate with the Otanmäki Office concerning the exploitation of the ore. More investigations by deep drilling have been carried out and in the mine proper a vertical shaft 103 meters deep has been sunk on the north side of the ore zone. From the shaft, at a depth of about 66 meters, examination workings were run in the ore as well as in the country rock between the various veins of ore.

This work could be seen already as a preliminary step to future mining activity. In addition the equipment was made for trial concentration of the ore.

In 1950 a company named Otanmäki Oy. was formed by the State for the mining of the ore. A branch railway line to Otanmäki was constructed and all the production equipment installed in 1951—1953. The productive mining and dressing operations began in August of the latter year. The annual quarrying capacity is planned to reach 600 000 metric tons of ore.

THE MAIN GEOLOGICAL FEATURES OF THE VUOLIJOKI REGION

EARLIER STUDIES

The first geological observations concerning in part the Vuolijoki district were made by Isac Castrén (1880). In 1906 Benjamin Frosterus and V. R. Svensson, geologists of the Geological Survey of Finland, made geological investigations in the parish of Vuolijoki. In the next year J. N. Soikero, a member of the staff at the same institution, also carried out research in the same parish, mainly in the remaining, western part. The map sheet of Kajaani of the General Geological Map of Finland compiled by W. W. Wilkman (1931), State geologist employed by the Geological Survey of Finland, also, gives the general geological picture of the area of Vuolijoki parish. In the explanation appended to the map sheet, Wilkman (1931) gives a short description of the rocks in this region. The different rocks are presented in chronological sequence, as first published by himself in the preceding year (Wilkman 1930). Vaasjoki (1947) has published some analyses and microscopical descriptions of some ore samples of Otanmäki. The preliminary opinions of the author on the Otanmäki ore were published in 1952 (Pääkkönen 1952). Paarma (1954) gave a short account on the geology of the ore deposit of Otanmäki in 1954.

According to Wilkman the area of Vuolijoki parish consists of three different kinds of granitic rocks. He called the oldest complex of rocks Katarchaean »granitic gneiss», which name was generally used for gneisses of granitic or granodioritic composition exhibiting very varied features.

The red granite occurring between the church village of Vuolijoki and Vuottolahti is called striped granite aplite and combined chronologically with the post-Bothnian formations.

The coarse-grained or partially pegmatitic granite massifs and veins in the E part of the Vuolijoki district was regarded as post-Kalevian.

The several large amphibolitic inclusions occurring within the formation of the granitic gneiss and in the post-Bothnian granite are designated in the map sheet as post-Bothnian intrusives.

The rock of the outcrops in the Pikku-Otanmäki hill and west of Humpinmäki is called gabbro in the explanation but in the map sheet it is drawn as belonging to the Kalevian metabasite.

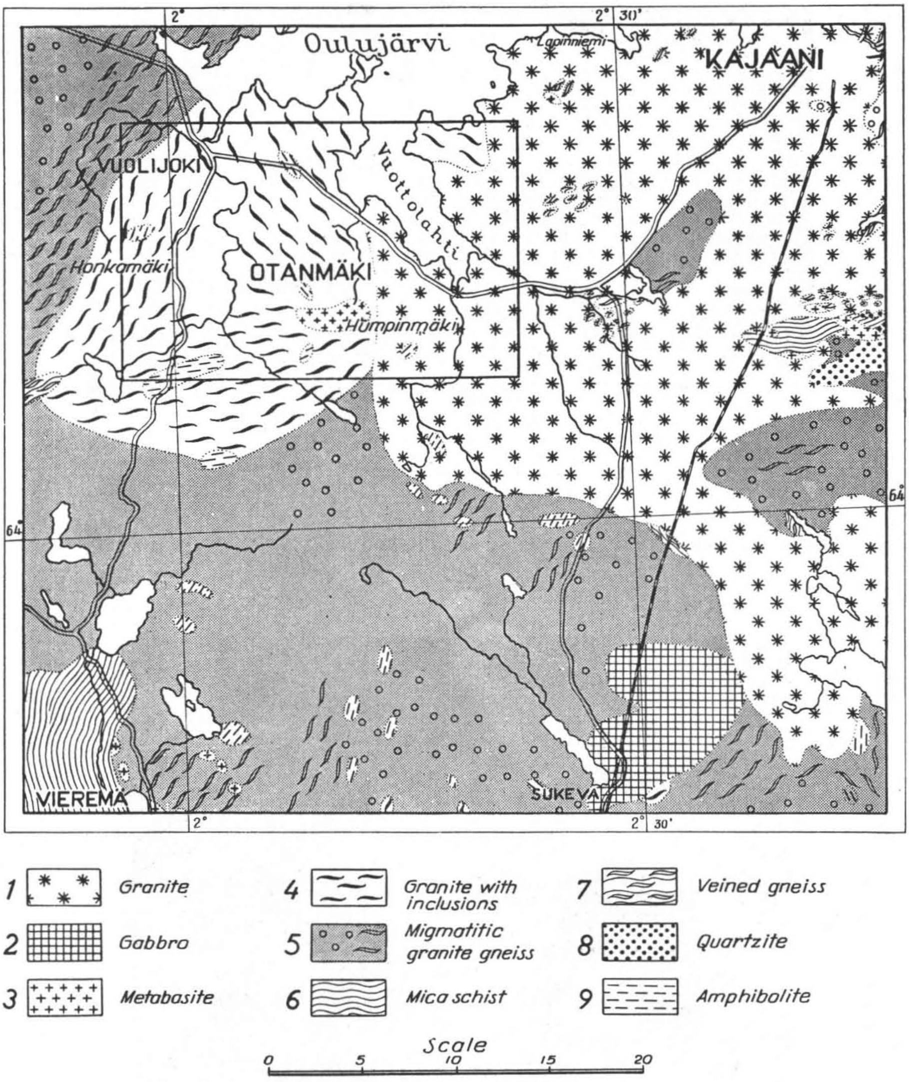


Fig. 3. A part of the map sheet of Kajaani from the General Geological Map of Finland compiled by W. W. Wilkman. 1. Post-Kalevian; 2. 4. 9. Post-Bothnian; 3. 6. 8. Kalevian; 7. Bothnian; 5. (without marks) granite gneiss in general.

THE ROCKS OF THE REGION

THE STRIPED GNEISS

As noted in the geological map of the area investigated (Map II), the rocks of the striped gneiss formation occur in zones of various widths. Because of the scarcity of outcrops the zones are constructed with the aid

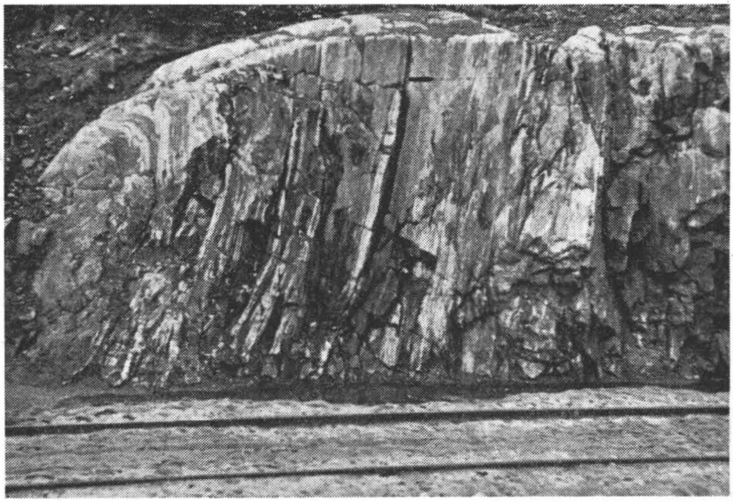


Fig. 4. Veined and banded gneiss. Railway SW of Pikku-Otanmäki. 1/100 natural size.

Fig. 5. The folded structure of the striped and banded gneiss. The light bands are mostly composed of plagioclase and the dark stripes have a rich content of biotite. Railway SW of Pikku-Otanmäki. 1/6 natural size.

of magnetic observations. The main characteristic of this complex of rocks is its very complicated heterogeneity. Even megascopically the colour, structure and texture are quite variable in the same outcrop. In some places the striped gneiss has only a slightly developed schistosity, is pink in colour with a small- or medium-grained gneissose granitic structure. In other places it occurs as a greyish, strongly compressed, contorted and veined gneiss (Fig. 4 and 5). The veins of pegmatite granite, amphibolitic bands and zones or fragments of the micagneiss rich in quartz all increases its heterogeneity (Fig. 6).

In the outcrops on the bend of the road 2 km from Otanmäki to the E the rock is for the most part light gneiss containing chiefly quartz and feldspar. Here and there dark grey fragments and reddish spots occur. In places of the same outcrop the typical structure of veined gneiss is seen when the greyish granitic material is banded by dark stripes rich in biotite and fine-grained zones alternate with the mainly medium-grained rock. Microscopic examination shows that in the light part of the rock the essential mineral, quartz, has a strong undulatory extinction. Its grains are partly crushed and elongated in the direction of the schistosity. The other chief mineral, plagioclase (An_{22}), is partly altered to sericite. Cross-hatched microcline is also present. The dark stripes and fragments are formed by parallel flakes of biotite. Zircon, sphene and apatite occur as accessories and epidote as well as chlorite as alteration products. The general impression is that the rock has a distinct orientation caused by stress, and that it is

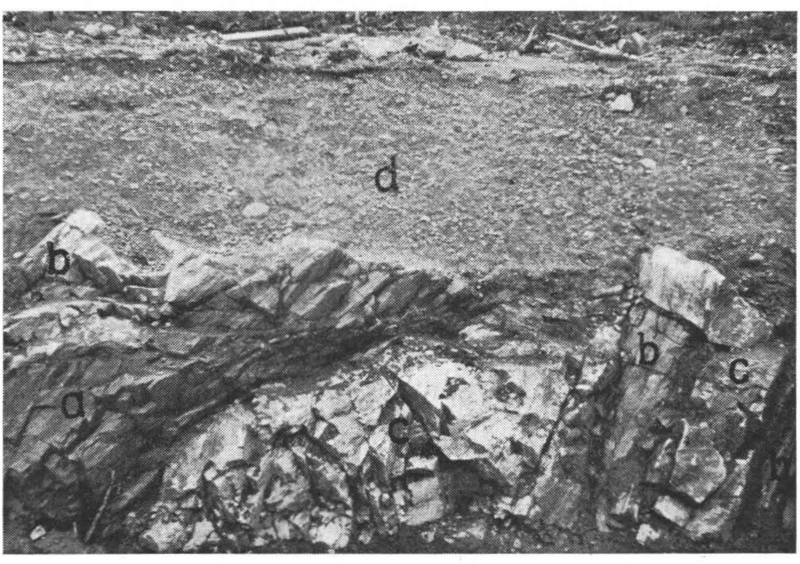


Fig. 6. Complex of rocks in the area of the striped gneiss. Railway SW of Pikku-Otanmäki hill. 1/100 natural size. a = amphibolite, b = mica gneiss, c = granite, d = glacial deposits.

strongly metamorphosed and migmatized under orogenic circumstances. The rock has suffered such strong regional metamorphism that it is impossible to draw definite conclusions concerning its origin.

In the outcrops at Pirttimäki the rock has a slightly different character than in the previous place. The schistosity is more definite and the light and dark zones occur more regularly. The grains of the chief mineral, quartz, are strongly elongated parallel to the schistosity and have a strong undulatory extinction. Plagioclase (An_{25}), the other predominant mineral, the grains occurring as lines, forms with the quartz the light zones of the rock. The dark stripes are caused by an abundance of biotite. Partly perthitic and cross-hatched microcline appears to a smaller extent. Epidote, sericite and chlorite are present as alteration products. A few grains of magnetite and apatite are met with.

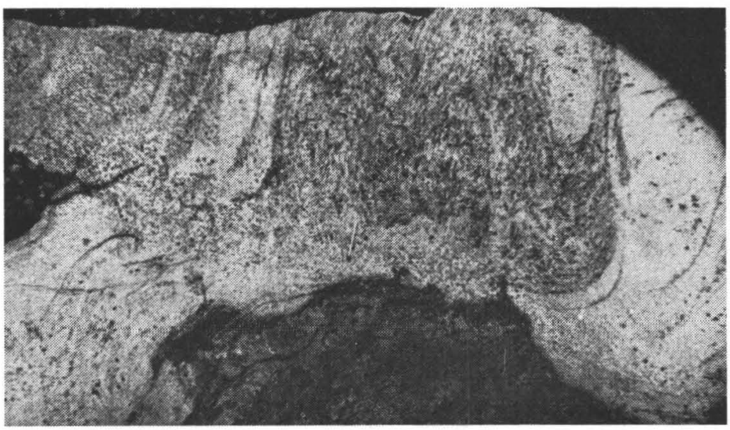


Fig. 7. Nebulous folds of the striped gneiss. Railway N of Humpinmäki. 1/6 natural size.

At the outcrops N of Humpinmäki the grey gneiss is very slightly foliated but has a parallel banded structure. Its essential mineral, plagioclase (An_{27}) is turbid, because of very small inclusions. The quartz grains have an undulatory extinction and include streaks of pigment. The grains of biotite are small and have the habit of idioblastic flakes with simultaneous pleochroism for the most part. Microcline is only seen as small inclusions in plagioclase. Apatite is an accessory.

Grey gneiss with dark amphibolitic bands occurs at the railway SW of Pikku-Otanmäki (Fig. 8). The rock has generally a very strongly folded structure. The light parts contain an abundance of plagioclase (An_{26}) and quartz but a small amount of hornblende and epidote only. In the amphibolitic bands hornblende predominates, but plagioclase (An_{25}), biotite,

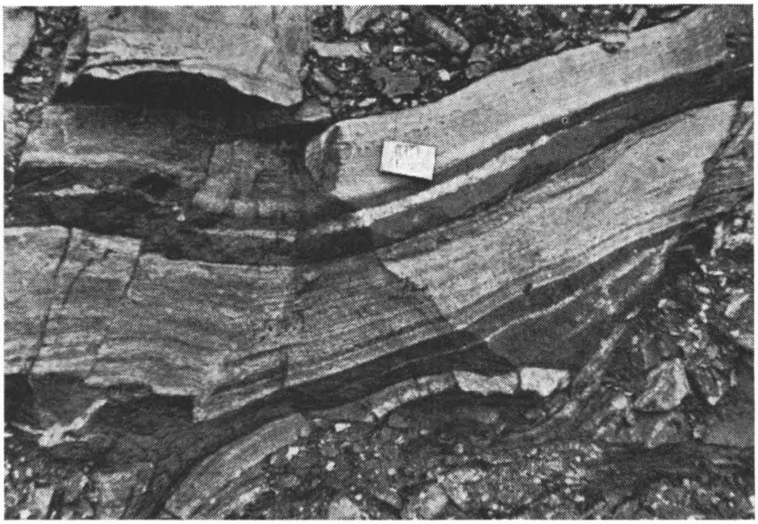


Fig. 8. Dark amphibolite veins in the striped gneiss. Railway SW of Pikku-Otanmäki. 1/9 natural size.

epidote and chlorite are present in minor amounts. The larger amphibolitic bands have intruded into the gneiss, but the small veins of the granitic material are injected into the dark parts.

A more distinctly gneissose granitic variety of the striped gneiss occurs as bands in the amphibolite of the outcrops at the railway on the N slope of Otanmäki (Fig. 9). The greyish rock contains predominantly quartz with a strongly undulatory extinction and forms with the plagioclase (An_{24}) the light lines, but the biotite occurs as dark stripes.

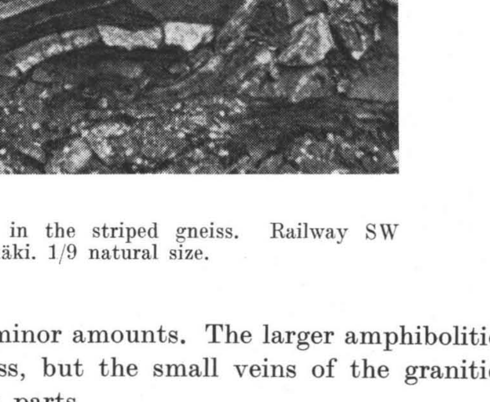


Fig. 9. Light grey bands of the striped gneiss in the amphibolite zone. NW slope of Otanmäki hill. 1/12 natural size.

The crystalloblastic texture of gneiss is seen in the pale red granitic veins situated as minor occurrences on the NW slope of Otanmäki. The same distinct crystalloblastic or blastoporphyric texture of gneiss is seen also in the pale red fine-grained zone of

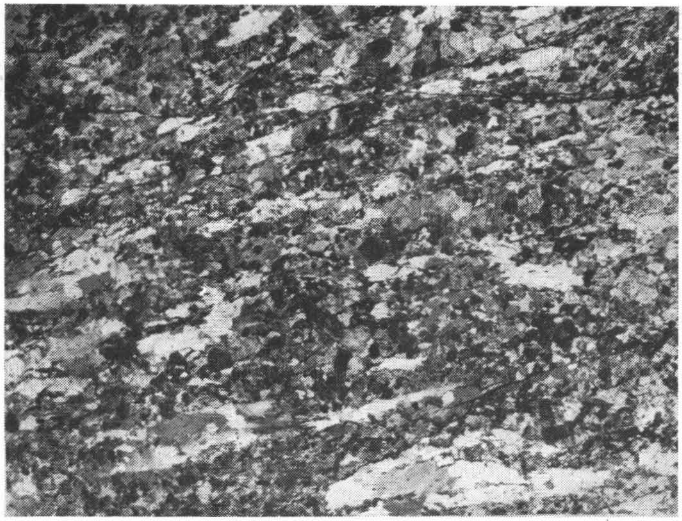


Fig. 10. The striped gneiss. Kinetically metamorphic crystalloblastic texture. Otanmäki. Drill hole 24. Nic. +, magn. 6 x. Photo E. Halme.

drill hole 24 (Fig. 10). Its chemical analysis and mineral content are presented in Table I. This rock contains more microcline than is usual in gneiss, but owing to its structure and heterogeneous habit it is regarded as adjoining the striped gneiss formation.

Table I. A variety of the striped gneiss at Otanmäki.
Drill hole No. 24. Depth: 55.48—56.60 m.
Analysed by H. B. Wiik.

	%	Mol. prop.	Niggli numbers		Norm		Mineral composition [1]	%
SiO_2	71.88	11968	si	358.3	Q	25.86	Quartz	25.8
TiO_2	0.17	21	ti	0.6	Il	0.32	Plagioclase (An_{10})	42.5
Al_2O_3	15.35	1506	al	45.1	C	0.80	Microcline	23.3
Fe_2O_3	0.60	38	fm	11.3	Mt	0.88	Epidote	7.0
FeO	0.83	115	c	9.5	Hy	0.77	Chlorite	0.6
MnO	0.02	3	alk	34.2			Ore	0.6
MgO	0.75	186	qz	121.7	En	1.87	Apatite	0.2
CaO	1.77	316	k	0.27	An	7.95		100.0
Na_2O	5.18	835	mg	0.49	Ab	43.78		
K_2O	2.88	306	c/fm	0.84	Or	17.03		
P_2O_5	0.14	10			Ap	0.31		
H_2O+	0.57	316			H_2O	0.65		
H_2O-	0.08	44						
	100.22					100.22		

Or:Ab:An = 24.77:63.67:11.55

[1]) The determination of this mineral composition and that of the rocks analysed in the following have been made according to Rosiwal's micrometric method.

The microscopic examinations have shown that in all the outcrops investigated the gneiss in general also has almost a uniform texture and mineral composition, although it has so varied a habit observed megascopically. Evidently the variations in chemical composition are considerable but because of the heterogeneous character of the rock it is very difficult and in this case unnecessary to investigate further.

THE AMPHIBOLITIC ROCKS

The amphibolitic rocks occur in the granitic area, as large zones and lens-shaped inclusions but in the gneiss area as concordant as well as discordant veins everywhere in the region investigated. The outcrops are so few that the geological map included in this description has been partly drawn with the aid of the strikes and magnetic observations and cannot give an altogether accurate picture of the formations.

At the outcrops on the SW side of Pikku-Otanmäki the predominant mineral of the small-grained amphibolite is plagioclase (An_{26}), occurring partially sericitized. Hornblende is present abundantly in closely spaced streaks. Biotite and apatite are met with in small amounts. Epidote, zoisite, chlorite and sericite appear as alteration products. The grains of plagioclase sometimes contain small inclusions of microcline. The few grains of ilmenite are surrounded by small grains of sphene and a few grains of pyrite are scattered irregularly. The schistosity is very distinct.

Amphibolites containing quartz are found in the S part of Pirttimäki. The small quartz grains have an undulatory extinction and seem to have been formed secondarily. Hornblende, however, is the chief mineral in this rock. Its small- and medium-sized crystals form lines parallel to the schistosity. The large primary grains of plagioclase (An_{50}) are greatly altered, and new small, clear grains (An_{50}) have crystallized in abundance. The ilmenite grains surrounded by aggregates of small sphene crystals occur also in this amphibolite body. Some sericite and epidote occur as products of alteration. Of special interest are the fissures filled with talc and chlorite and intersecting the schistosity at right angles. This shows that a metasomatic migration of rock material has taken place there after the latest regional metamorphism.

The amphibolitic schist situated by the roadside E of Vuolijoki church seems to have been orientated by a strong stress. The quantity of plagioclase (An_{50}) in this rock is greater than hornblende. The former mineral is fine-grained and turbid, whilst the small hornblende grains, often containing tiny inclusions of plagioclase, form dark green lines parallel to the schistosity of the rock. The quantity of epidote exceeds that of the other accessory minerals, which are sericite, pyrite and sphene. Because of the strong dynamometamorphic habit the origin of the rock cannot be determined.

The amphibolite body at Honkamäki, S of Vuolijoki church, represents a type which is sheared to a smaller extent. The grains of hornblende and plagioclase (An_{31}) are larger (2—4 mm) than in the aforementioned amphibolites. Common accessories are sphene, apatite, epidote and pyrite. The coarse-grained texture and the slight schistosity indicate that in this case the metamorphic recrystallization seems to have taken place during a condition of minor stress, unlike most of the occurrences in the region.

At Otanmäki and in the vicinity of the hill amphibolitic rock is very common. It must be said first of all that the distinctness of the schistosity varies considerably. In most cases hornblende occurs as the chief mineral and often its larger grains are ragged and seem to be of an older generation, whilst the small ones are clear and evidently have crystallized later. The anorthite content of the plagioclase varies from 35 to 55 per cent within the same amphibolite zone and in one exceptional case has been observed to be 70 per cent. The plagioclase also usually occurs in two generations. The large older grains are turbid and richer in the anorthite component, but the younger small and clear grains contain a smaller proportion of anorthite. The rock is formed almost wholly of hornblende and plagioclase though ilmenite and magnetite ore grains are present in varying amounts. Chlorite, epidote and apatite occur generally, but biotite and sericite only occasionally. The two generations of the chief minerals indicate that the rock has recrystallized only partly during the metamorphism and evidently had a coarse-grained habit of gabbro before it.

In some places the strongly schistose amphibolitic rock contains only a few grains of plagioclase or none at all but hornblende in abundance; and therefore it is better to call it a hornblende-schist. In such cases, in addition to the large turbid and small clear hornblende grains, apatite, sphene and epidote are present. Ore minerals are also often met with in various amounts. In some places the amphibolite is light in colour, caused by the abundance of plagioclase. Occasionally the light green colour of the rock is caused by a large amount of epidote as against only disseminated shreds of hornblende. All these types of amphibolite at Otanmäki occur as alternating zones and their contacts are mostly extremely indefinite. The visible schistosity of the darkest variety is strongest; but it is very slight in the lightest. A very homogeneous but small-grained and moderate schistose modification of amphibolite forms zones resembling relics in the other types (Fig. 24 type 7). A more detailed description of the amphibolitic rocks at Otanmäki is appended to the geologic report of the actual ore field (Page 32).

The descriptions in the foregoing show that the variation in the mineral composition of the amphibolitic rocks of the Vuolijoki region is considerable. The intensity of the schistosity also varies considerably, but the crystalloblastic texture is general. The greatest difference with regard to schistosity and mineral composition is between the anorthositic and peridotitic varieties. In the explanation to the map sheet of Kajaani, Wilkman described the amphibolites and maintained that they were varieties of hornblende-gabbro, but that the degree of metamorphism was different. According to him they differ from the younger enstatite-augite- and hornblende-diabase, because, when in contact, veins of the younger granite cut these amphibolite formations.

Usually the larger amphibolite and striped gneiss zones and smaller bands alternate. Then they both have the same strike and degree of metamorphism. Usually the amphibolites in the area are so markedly metamorphosed that it is difficult or impossible to determine their origin. Because of their mineral composition as well as habit, resembling gabbro, and occurrence as veins, resembling diabase, there is reason to conclude that they are either deep or hybabyssal intrusions. The amphibolite occurrences in the SW corner of Vuolijoki parish differ from these since they contain stripes of calcite and their fine-grained structure indicates a volcanic origin. They are also in close contact with other supracrustal formations outside the mapped area. (The mica schist area of Vieremä and the effusive rock of Lautakangas. Wilkman 1931). Indeed, metamorphism has destroyed all distinct indications of the origin of these amphibolites too.

THE GNEISSOSE GRANITE

Several groups of outcrops on the W and N slopes of Otanmäki consist of this granite. In the large marshy area situated farther to the N and NW no outcrops are to be found, but the minima of the magnetic map of the area and several observations of gneissose granite boulders SE of the area show that these tracts for the most part evidently belong to the area of this reddish rock. The same kind of rock is to be found in the outcrops at Honkamäki S of Vuolijoki church.

In the outcrop at Katajakangas on the W side of Otanmäki the chief mineral of the rock, middle-grained microcline, usually has a cross-hatched texture and contains flame-shaped perthitic inclusions. The large quartz grains have an undulatory extinction and ragged borders, and are often elongated in the direction of the lineation. Here and there crush zones occur with very small-grained quartz filling the fissures. These fissures also contain a few ragged amphibole grains, which seem to be of metasomatic origin and have been partly altered into mica.

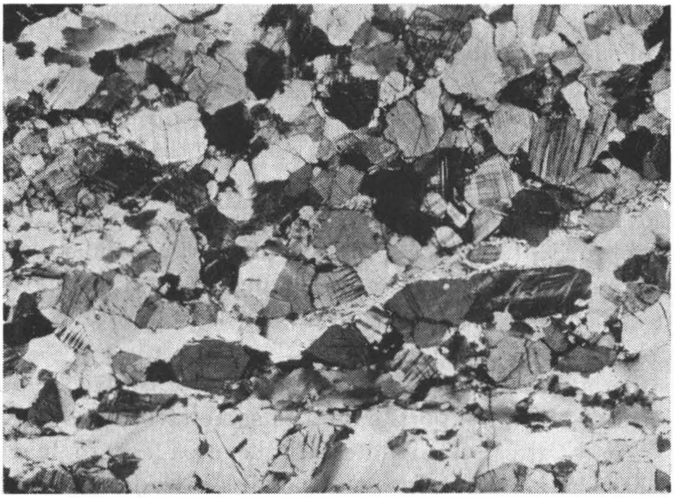


Fig. 11. The gneissose granite, in which the larger quartz grains are mostly in zones and have nearly a contemporaneous extinction. Drill hole 26, Otanmäki. Nic. +, magn. 10 x.

The colour of this amphibole varies from yellow green to dark blue. The pleochroism is as follows:

α dark blue
β yellow green
γ deep blue

The determinations of 2V for different grains have given various positive values:

$$2V\gamma = 78°;\ 80°;\ 84°$$

The extinction angle $\alpha \wedge c$ varies 0°—4°

The indices of refraction: $\alpha = 1.692$ and $\gamma = 1.707$, $\gamma - \alpha = 0.015$

According to these optical properties a riebeckitic composition is most probable. The diversity of the colour may indicate variations in the composition, especially in the content of iron.

The mica is brownish or greenish yellow in colour and has the habit of biotite with ragged borders. The ray vibrating parallel to the cleavage is wholly absorbed. The index 1.735 is nearly that of stilpnomelane rich in Fe[1]).

[1]) C. O. Hutton: Stilpnomelane of Otago. Mineral Mag. XXV. 172 (1938).

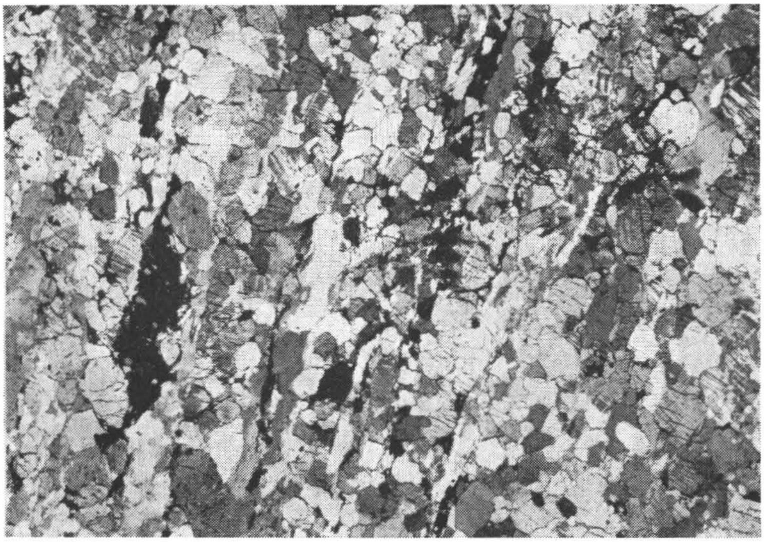


Fig. 12. The gneissose granite of Otanmäki. Texture is generally granoblastic but cataclastic zones are also to be seen. The black grains are amphibole. Drill hole 26, nic. +, magn. 6 x. Photo E. Halme.

Plagioclase (An_{10}) is present to a minor extent. Magnetite occurs much more than is usual in granites but crystallized in the aforementioned fissures. Epidote and apatite grains are few.

On the W border of the actual Otanmäki ore field, in drill hole 26 and at a depth of 55 m, the gneissose granite is nearly the same as on the N slope of Otanmäki, but the quartz has a very strong undulatory extinction and the plagioclase contains antiperthitic inclusions and its twin lamellae are bent and broken. In addition small fibrous blue green grains (plausible of crocidolite) radiate from groups of amphibole crystals and intrude in the grains of quartz. Very small-grained groups of quartz occur on the borders of the zones of the larger quartz grains (mostly white in Fig. 11). The general impression is that the rock has obtained its crushed (cataclastic) habit by stress caused by regional movements after the primary crystallization and in lower temperature conditions.

The chemical analysis (Tab. II) of this rock shows a high content of alkali oxides. The quantity of ferric oxides is greater than is usual in granites rich in microcline. It is evidently due to the magnetite and amphibole content of the rock.

In the outcrop of the gneissose granite on the NW slope of Otanmäki the rock is extraordinarily strongly crushed. The microcline as well as the quartz grains have been broken into small pieces. In the same outcrop

Table II. The gneissose granite of Otanmäki.

Drill hole No. 26. Depth 54.43—58.44 m.
Analysed by H. B. Wiik.

	%	Mol. prop.	Niggli numbers		Norm		Mineral composition	%
SiO_2	71.55	11913	si	380.8	Q	25.49	Quartz	32.1
TiO_2	0.45	56	ti	1.8	Il	0.85	Plagioclase (An_{10})	11.6
Al_2O_3	12.81	1257	al	40.2			Microcline	45.5
Fe_2O_3	2.80	175	fm	16.1	Hm	1.60	Amphibole & mica	9.4
FeO	0.94	131	c	3.6	Mt	1.74	Ore	1.3
MnO	0.06	8	alk	40.1	Wo	1.18	Apatite	0.1
MgO	0.09	22	qz	120.2	En	0.33		100.0
CaO	0.63	122	k	0.29	An	0.03		
Na_2O	4.60	742	mg	0.04	Ab	38.90		
K_2O	4.84	514	c/fm	0.22	Or	28.60		
P_2O_5	0.05	3			Ap	0.10		
H_2O+	0.50	277						
H_2O-	0.35	194			H_2O	0.85		
	99.67					99.67		

Or:Ab:An = 42.35:57.60:0.04

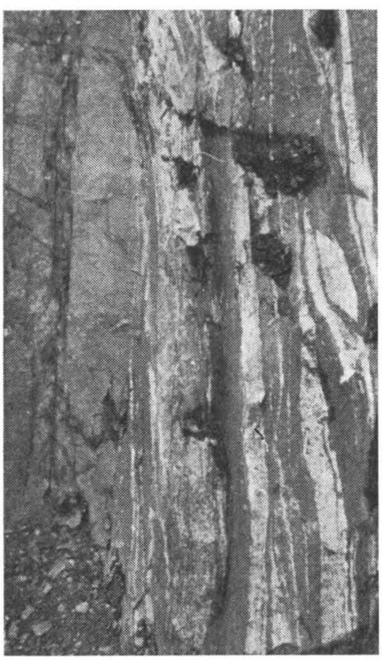


Fig. 13. Granite veins in the amphibolite zone. N slope of Otanmäki hill. 1/12 natural size.

the strike of schistosity varies considerably and differs in this respect from the usual almost constant strike of the gneissose granite at the N side of Otanmäki.

At Honkamäki the gneissose granite is not so strongly sheared, but still has strongly crushed zones, and the gneissose structure is clearly to be seen. An abundance of microcline is evident and an amphibole of the hornblende group forms stripes parallel to the schistosity. According to Wilkman (1931) the presence of amphibole is caused by several inclusions of amphibolite found in the neighbourhood; but which form migmatite by injection of the granitic matter. At Otanmäki also the amphibolite and the gneissose granite are situated close together. Veins of granite occur in amphibolite (Fig. 13) and fragments of amphibolite are observed in the actual area of the gneissose granite.

THE MASSIVE GRANITE

In the surroundings of Vuottolahti the variety of granite is not gneissose. No distinct strike could be seen in it, but the quartz has, however, a strong undulatory extinction. Amphibole is not present, but the rock contains a moderate quantity of biotite. Most of the plagioclase (An_{15}) grains are partly zoned and turbid. Apatite, epidote, muscovite and zircon occur as accessories. The analysis (Tab. III) shows that this variety of the massive granite on the south side of Vuottolahti contains more SiO_2 but less K_2O than the gneissose variety at Otanmäki. Aluminium and calcium oxides are also present in greater amounts in the former than in the latter type.

Table III. The granite of Vuottolahti NE of the Otanmäki region. Analysed by V. Leppänen.

	%	Mol. prop.	Niggli numbers		Norm		Mineral composition	%
SiO_2	73.33	12209	si	399.8	Q	31.91	Quartz	34.0
TiO_2	0.21	26	ti	0.8	Il	0.40	Plagioclase (An_{15})	40.4
Al_2O_3	14.20	1393	al	45.6	C	2.24	Microcline	18.3
Fe_2O_3	0.64	40	fm	11.2	Mt	0.93	Biotite	5.7
FeO	1.15	160	c	7.6	Hy	2.34	Epidote	0.5
MnO	0.04	6	alk	35.6			Muscovite	0.4
MgO	0.41	102	qz	157.4			Ore	0.6
CaO	1.30	232	k	0.31	An	2.39	Apatite	0.1
Na_2O	4.62	745	mg	0.30	Ab	39.06		100.0
K_2O	3.22	342	c/fm	0.68	Or	19.03		
P_2O_5	0.62	44			Ap	1.44		
H_2O+	0.52	289			H_2O	0.61		
H_2O-	0.09	50						
	100.35					100.35		
Or:Ab:An = 31.46:64.58:3.95								

The mineral composition of the massive granite in the outcrop at the east end of Vuottolahti is as follows:

Table IV. Modal composition of the granite at Vuottolahti.

Quartz	Plagioclase	Microcline	Biotite	Epidote	Apatite
22.5 %	42.5 %	26.6 %	7.8 %	0.3 %	0.3 %

Muscovite and chlorite are very scarce. The quartz has a slightly undulatory extinction.

In several outcrops the massive granite of Vuottolahti is coarse-grained and has a pegmatitic character. In some places this type of granite contains more or less nebulitic gneissose inclusions.

Possibly the massive type of granite occurring at Vuottolahti adjoins the large Karelian granite area of Kajaani (Väyrynen 1928), which extends in the West to the NE corner of the mapped part of the Vuolijoki region. According to Wilkman (1931) this granite is medium- or coarse-grained and alternates with aplitic or pegmatitic red granite variations. Wilkman (1931) has described also a massive granite type rich in muscovite and occurring 5 km W of Kajaani.

GABBRO

The field investigations have shown that there are two separate occurrences of gabbro. One is situated on the S slope of Otanmäki and the largest outcrop of the other is on Rinneaho hill 4 km E of Otanmäki. The whole gabbro area extends 4—5 square kilometers.

The gabbro zone of Otanmäki has been determined by the outcrops on the hill known as Pikku-Otanmäki and by diamond drilling on the S slope of Otanmäki. The rock is mainly medium- or coarse-grained. The nearly rectangular greenish or reddish grey plagioclase grains and the dark green fringes of acicular hornblende crystals are characteristic of this rock. The chief mineral, plagioclase, usually has a 45—60 per cent content of

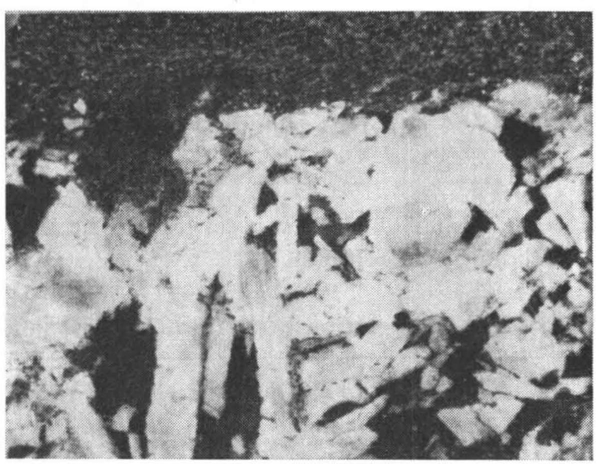


Fig. 14. The coarse-grained anorthositic gabbro in close contact with fragment of small-grained amphibolite. The light grains are plagioclase (An_{30}) and the dark groups of the grains are hornblende. Pikku-Otanmäki. Natural size.

the anorthite component, but in the coarse-grained or leucocratic segregations it may fall to 25—35 per cent. Hornblende is always present but seldom as the predominant mineral. Microscopic investigation shows that the hornblende is partly chloritized. Remnants of colourless monoclinic pyroxene can sometimes be noticed. Ilmenite, magnetite, epidote, apatite, sphene and pyrite are common accessories. Chlorite, calsite, quartz and rutile occur occasionally. In the gabbro of the Otanmäki region the rectangular habit of the plagioclase grains and the fringe-like form of the hornblende prevail. Wilkman had noticed a similar gabbro on Junttila peninsula on the N side of lake Oulujärvi. Therefore he also called the gabbro of Otanmäki »the gabbro type of Junttila peninsula». (Wilkman 1931 p. 218).

The gabbro found in the outcrops on Pikku-Otanmäki presents a normal medium-grained type. The twinning lamellae of the plagioclase laths

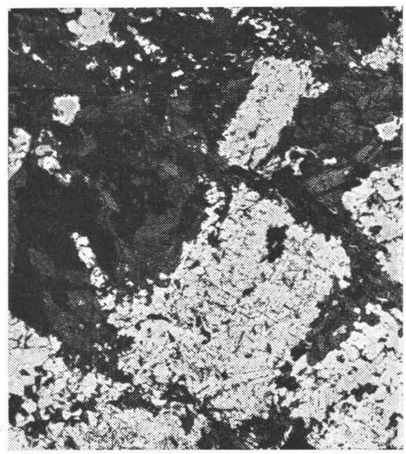


Fig. 15. The type of gabbro occurring to the south of the area marked with »S». The large, mostly rectangular plagioclase (An_{56}) grains containing small epidote inclusions are partially granulated into smaller, rounded and lighter grains. The dark areas are formed by hornblende containing small epidote inclusions and black pigment. The cleavage in the middle of a large hornblende grain resembles partly that of pyroxene. The smaller and less dark hornblende crystals seem to have been formed later. Magn. 7 x.

are often bent and have sometimes an undulatory extinction. In spite of their rectangular form the plagioclase (An_{55}) grains are only slightly idiomorphic. The middle of the greater laths contains a little pigment and small flakes of hornblende. The aggregates of small-grained hornblende have gathered between the plagioclase crystals. In some places the remnants of the monoclinic pyroxene grains are surrounded by grains of uralitic hornblende. In addition to these predominant minerals a small amount of ilmenite is to be noticed. Its grain remnants are surrounded by groups of small crystals of sphene. Sometimes there is no ore mineral at all, but only a small brownish yellow or brownish red rutile grain is seen in the centre of the aggregates of sphene. Some pyrite and epidote are also present.

Another variety of gabbro is found also at Pikku-Otanmäki. Its chief mineral, plagioclase, forms small turbid grains. The zoned extinction and index of refraction show that the centres of some grains contain less anorthite component than the border zone. The hornblende is coarse-grained and very turbid. A small amount of light or slightly greenish amphibole (tremolite) is present. There is an abundance of clinozoisite but only a few grains of sphene, pyrite and sericite.

Table VII. The Gabbro of Pikku-Otanmäki.
The Otanmäki region.
Analysed by V. Leppänen.

	%	Mol. prop.	Niggli numbers		Norm		Mineral composition	%
SiO_2	48.87	8137	si	109.9	Il	1.03	Plagioclase (An_{55})	46.3
TiO_2	0.54	68	ti	0.9	C	5.93	Hornblende	47.4
Al_2O_3	19.47	1910	al	25.8	Mt	1.85	Epidote	3.8
Fe_2O_3	1.28	80	fm	37.9	Hy	13.96	Ore	1.1
FeO	5.18	721	c	30.6	Di	28.12	Sphene	1.4
MnO	0.09	13	alk	5.7	An	25.29		100.0
MgO	7.75	1922	qz	—13.6	Ab	19.61		
CaO	12.71	2266	k	0.11	Or	2.50		
Na_2O	2.32	374	mg	0.68	Ap	0.60		
K_2O	0.42	45	c/fm	0.81				
P_2O_5	0.26	18			H_2O	1.85		
H_2O+	1.82	1010						
$H_2O—$	0.03	16						
	100.74					100.74		

Or:Ab:An = 5.3:41.4:53.3

The same type of gabbro is found in the outcrops of Rinneaho. The colour and size of its plagioclase grains varies considerably. In addition there is a variety of gabbro very similar to uralite diabase. Its large, clear plagioclase (An_{56}) crystals have a nearly rectangular, platey form. The small splinter of hornblende fills the spaces between the plagioclase grains. The fringe-like, more intense green border rims around the larger hornblende crystals give them a zoned structure. The very small magnetite grains seem to have been formed in connection with uralitization. The larger crystals of ore between the silicate minerals are pyrite. The mineral composition determined by Rosiwal's micrometric method is as follows:

Table VIII. Modal composition of the gabbro at Rinneaho.

Hornblende	Plagioclase	Ore	Sericite	Apatite
63.7 %	34.8 %	0.9 %	0.5 %	0.1 %

At the SW end of the Rinneaho zone quite an extraordinary variety of gabbro is found. Here the elongated laths of plagioclase (An_{55}) give an ophitic structure to the rock. The large groups of uralitic amphibole grains are surrounded by small crystals of a new hornblende generation in a fringe-like zone. Of especial interest is an abundance of garnet. Some small quartz grains are connected with the uralite, which also has large ragged inclusions of magnetite evidently formed by the uralitization. There is some apatite and sometimes in the neighbourhood of the ore grains there are small crystals of a brownish red isotropic mineral, which is very difficult to determine.

Fig. 16. Uralite gabbro of Rinneaho. Nic. +. Magn. 10 x.

The more acid and pegmatitic varieties of gabbro occur in several places in the border zones of the gabbroic areas. It has often intruded as veins in the adjacent amphibolite. The plagioclase (An_{25}) of this variety is mainly coarse-grained and turbid and includes many small epidote grains; also small clear plagioclase grains can be observed. The coarse-grained hornblende is always turbid and ragged, but small clear grains are also abundant. A small amount of quartz is often found in this variety of gabbro. When the different minerals show very strong hydrothermal alteration, it is evident that this pegmatitic segregation and the sometimes leucocratic veins have been caused by differentiation in the presence of a high water content in the border zone of the gabbroic mass.

Fig. 17. Aggregations of hornblende in the anorthositic gabbro of Rinneaho. 1/7 natural size.

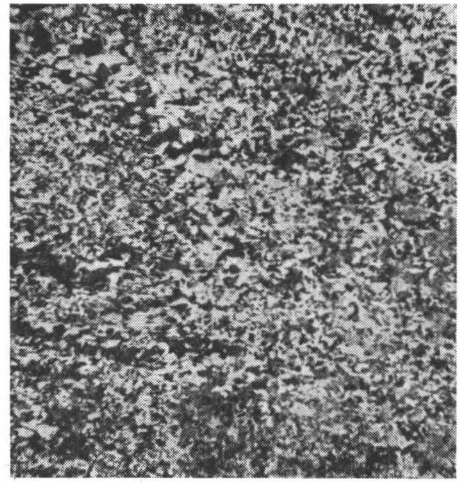


Fig. 18. Medium-grained hornblende gabbro of Rinneaho. 1/7 natural size.

Besides the great differences in the coarseness of the grains and the differences between the dark and white varieties of the gabbro, the heterogeneity is increased by the varying degree of metamorphism. In many cases the lineation is so strong that the rock may be called a metagabbro, and in several places it is difficult to distinguish between the gabbro and a slightly schistose amphibolite. The gabbro, however, has only the parallel arrangement of the mineral grains and no strike of the schistosity plane, whilst the amphibolite has both. In some places the gabbro is crushed and mylonitized so strongly that it is difficult to find a single clear mineral grain. Microscopic observations show that the gabbro, after the main crystallization, has been autometamorphosed by the water content and decrease of temperature, but still more metamorphosed by the regional stress influence.

PERIDOTITE

A minor occurrence of peridotite is noticed at the NE corner of the mapped area. This occurrence may be called the serpentine rock of Haarapuro because antigorite serpentine is its main mineral. In addition anthophyllite and talc are present abundantly. The former mineral makes the rock look like asbestos. Some magnetite grains are also to be seen in it. By microscopic investigation one can observe a minor amount of pyrrhotite and pentlandite.

Evidently this peridotitic rock belongs together with the larger serpentine occurrences of the Paltamo area, which is situated around the eastern end of the large lake Oulujärvi. According to W. Wilkman (1931) these serpentine bodies were intruded during the later part of the time of Karelian folding.

TECTONIC FEATURES

Earlier tectonical studies have drawn only the general outlines of the conditions in the Vuolijoki region and surroundings. According to the general geological map of Finland and the publications of H. Väyrynen (1928 and 1939) the area in question is in close connection with the Karelian folding zone. The parish of Vuolijoki is situated geologically in the SW border of the Kainuu part of the Karelian mountain chain. In the Otanmäki region proper the Karelian sediments cannot be observed. Therefore it is evident that there the ancient roots of the chain have been more deeply exposed or have risen higher than elsewhere in the chain and the majority of the supracrustal formations deposited in the Karelian times have been destroyed by erosion in this area. Indeed Karelian quartzites occur in the neighbourhood of this district on the peninsula of Lapinniemi only a few kilometers from the NE corner of the area on the geological map of the Otanmäki region. Not far from its SW corner is the wide Vieremä mica schist area, which has also been regarded as belonging to the Karelian formations (E. Mäkinen 1916) and especially to the Kalevian time (Wilkman 1931). At a distance of about 25 kilometers to the NE are the formations of the depression area of the Oulujärvi region (Wegmann 1928), which is connected to the actual Karelian folding chain.

The general strike in the western part of the Otanmäki region runs almost N—S and dips steeply to the W or E. In the vicinity of the hill proper the strike of the schistosity varies considerably, forming large folds. The lineation evidently parallel to the last folding axes caused by stress in the rock of the western part of the area plunges gently to the S; but in the middle part of the area it plunges more steeply on the average, and to the SW. As this latter direction of lineation is a characteristic of the younger, evidently later-orogenic rocks, the conclusion may be drawn that the stress system of the mountain chain, which in the early stage of the folding operated in an E—W direction, had at the end or at the later phase of the orogeny changed its direction to NW—SE. Evidently the curving form of the geological formations visible in the map of the area is caused by these later tectonic movements of the Karelian time. Väyrynen (1939) has described the deflecting movements of the neighbouring Iisalmi block during the Karelian folding, and he thinks that the deflection was caused

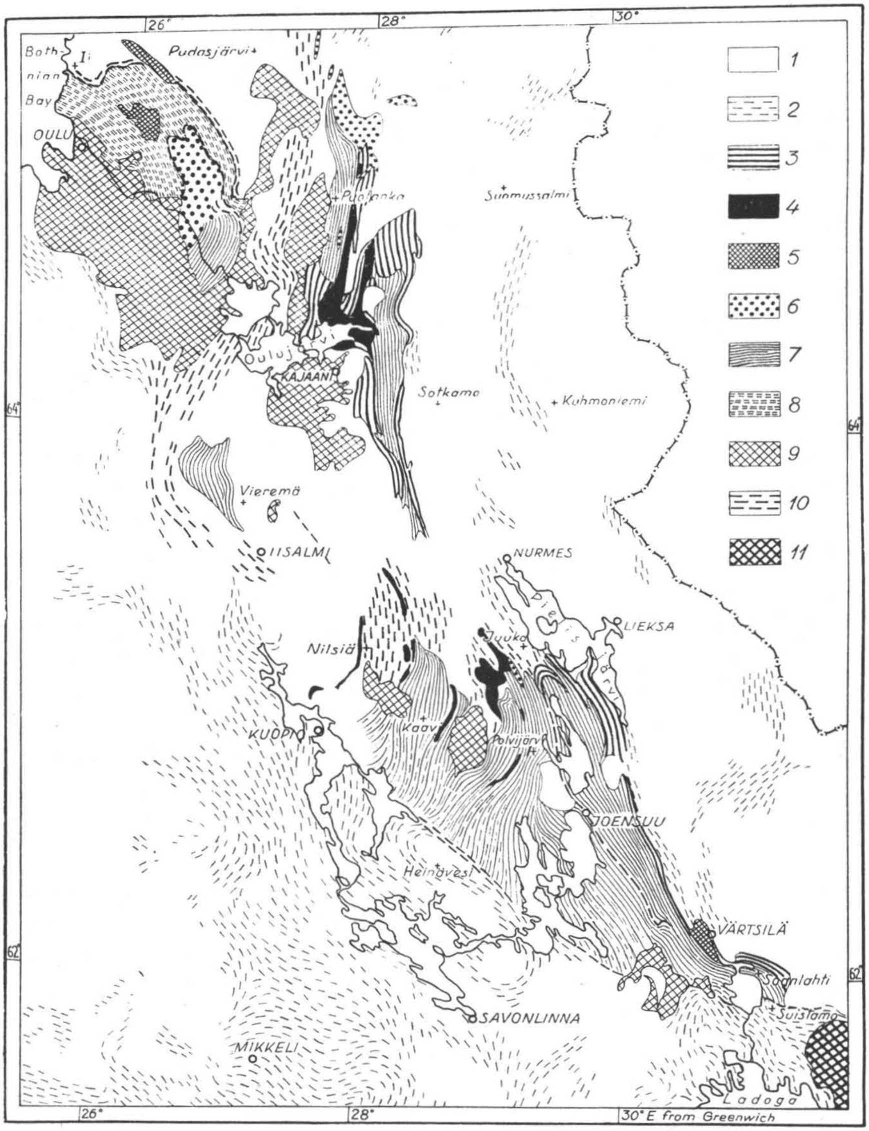


Fig. 19. Karelian rocks in the areas of Karelia and Kainuu. Väyrynen 1939.

1 pre-Jatulian granites
2 pre-Jatulian schists
3 autochtonous Jatulian
4 allochtonous Jatulian
5 post-Jatulian basic rocks
6 Kalevian quartzites and conglomerates
7 Kalevian phyllites
8 schists belonging to Kemides
9 post-Kalevian granites
10 tectonitic gneisses
11 rapakivi

by the western Archean crustal segment acting as a resistance area. Evidently the same phenomenon had extended also to the Otanmäki region.

Several strongly sheared and mylonitic zones are observed in the areas of gneiss, amphibolite and granite in the Vuolijoki district. These observations accord with the description of Väyrynen (1939). According to him a strongly sheared zone of gneiss W of Vieremä runs curving to NE through the Otanmäki region (Fig. 19). The zone of these tectonitic gneisses occurs also in the Heinävesi region farther S on the W border of the Karelian formation.

In spite of the general strikes of the larger folding-curves in the striped gneiss and amphibolite, the fragments have the strikes and the directions of the axis of the small folds varying considerably. Plausibly before the last folding and before the injection of the granitic material the formation of the striped gneiss was exposed to an earlier metamorphism. According to Wegman (1928) the »old crystalline» reacted in the Karelian folding: »Es löst sich meistens in Keile auf, welche in Fische übergehen können. Diejenigen Partien, welche bis zu einem gewissen Grade intim deformiert wurden, können mehr fliessende Formen zeigen».

In addition the granite has a more or less distinct schistosity (much more constant than in the striped gneiss formation) and in places the gabbro also has a more or less distinct lineation. As both have a penetrating character, it is evident that they have received their present form and locations during the latest phase of the orogeny. It is evident also that this later folding readily allows room for intruding magma activated by the folding process. The same process has forced the magma to intrude between the folded layers of the earlier formations and in the core of the large folds. Väyrynen (1939) evidently points to the same phenomenon when he mentions the deflecting movements of the Iisalmi segment and the intrusion of the granitic body S of Kajaani into the opening that was made.

GEOLOGIC DESCRIPTION OF THE OTANMÄKI ORE FIELD

Otanmäki, the main ore-bearing area of the region, is situated geologically in the large amphibolite zone running in a curve across the center of the Vuolijoki district. On the N slope of Otanmäki the amphibolite zone is limited by gneissose granite, which occurs also on the W slope of the hill, as it is to be seen in the small outcrops of Katajakangas and met with in drill hole 26. In the zone of contact the granitic veins have been intruded into the amphibolite, and amphibolite fragments are included in the granite. On the S and E slopes of Otanmäki the rock is very heterogeneous containing variable metamorphosed basic rocks with several ore bodies and is in close association with the gabbro formation of Pikku-Otanmäki. The striped gneissose rock is met with in drill holes 24 and 35, occurring with amphibolite as fragmental inclusions in the gabbro area.

In regard to the general impression of the amphibolite zone, mention should be made of its complicated heterogeneity. The border part of it up to 200 meters in width against the northern granite is strongly sheared, but in the middle of the area the distinctness of schistosity varies greatly and is alternately distinct or indistinct. In its S side the zone has the most various schistosity.

The heterogeneity is increased considerably by the variable mineral composition of the rocks. The rock of the northern outcrops contains more biotite and apatite than in the southern part of the zone, in which they are present very scarcely and also the amounts of plagioclase and hornblende vary considerably, making the rock sometimes dark, sometimes light. In places the rock mainly consists of light green hornblende and in others the plagioclase forms almost the whole of the rock so that in the southern part of the ore-bearing area of Otanmäki the normal amphibolite is seldom seen but the metamorphosed anorthosite is dominant. The variable content of ilmenite and magnetite grains in amphibolite and the ore bodies, especially, also causes the variegation in the South and East sides of the zone.

Both types of the basic rock are sometimes strongly mylonitized when the dark varieties form chloritized fine-grained pieces and the light variety is crushed to a mass in which only in places small plagioclase grains are to be noted.

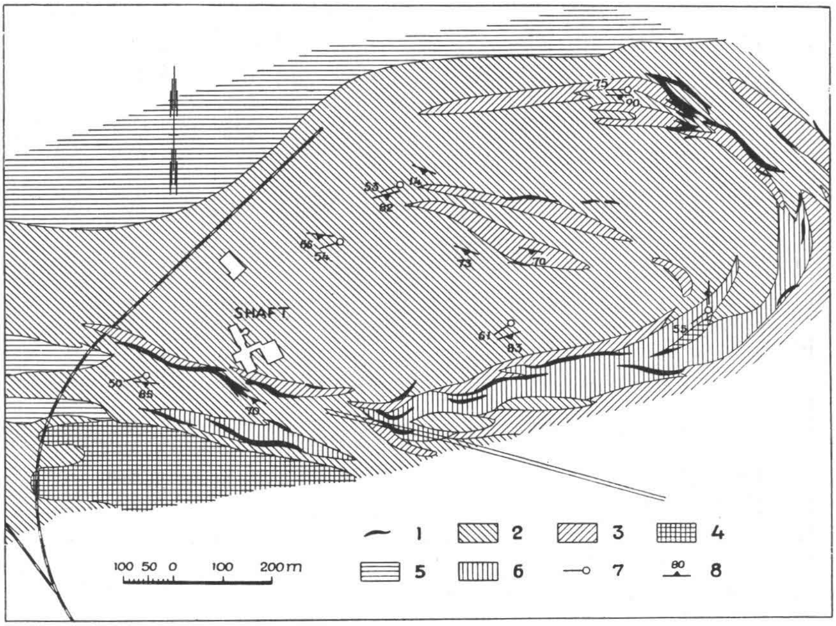


Fig. 20. Geological Map of Otanmäki. By H. Paarma. 1. Ore; 2. Amphibolite; 3. Anorthosite; 4. Gabbro; 5. Granite; 6. Heterogeneous zone; 7. Lineation; 8. Strike and dip of foliation.

During the operations in the mine H. Paarma (1954), the chief geologist of Otanmäki Co., compiled a map of the main ore field at Otanmäki (Fig. 20) and described the formations a little differently from the map made by the author during the surface investigations.

The structure of the western part of the Otanmäki ore-bearing zone and especially the strong intermixing of the rock varieties is best ascertained in the drill core description presented in Fig. 21.

The drill hole No. 1 of Otanmäki begins from the south side of the »M» [1]) area and dips 45° at NE. At the beginning of the hole the rock is of the normal medium-grained Pikku-Otanmäki gabbro type. Then a small heterogeneous zone containing some scattered ore grains, followed again by a gabbroic band, now, however, light and coarse-grained, was penetrated. In the zone between 22 and 52 meters the heterogeneous rock with some stripes of ore grains predominates. At about 52 meters the first chief ore zone begins.

The drill core shows that the ore zone is much more coherent at the depth of 50 meters than at outcrop »M». Nevertheless compact ore bands can be observed at both levels. As an especially interesting phenomenon

[1]) The largest outcrop of the ore zone. The special map of »M» area is to be seen on the page 43.

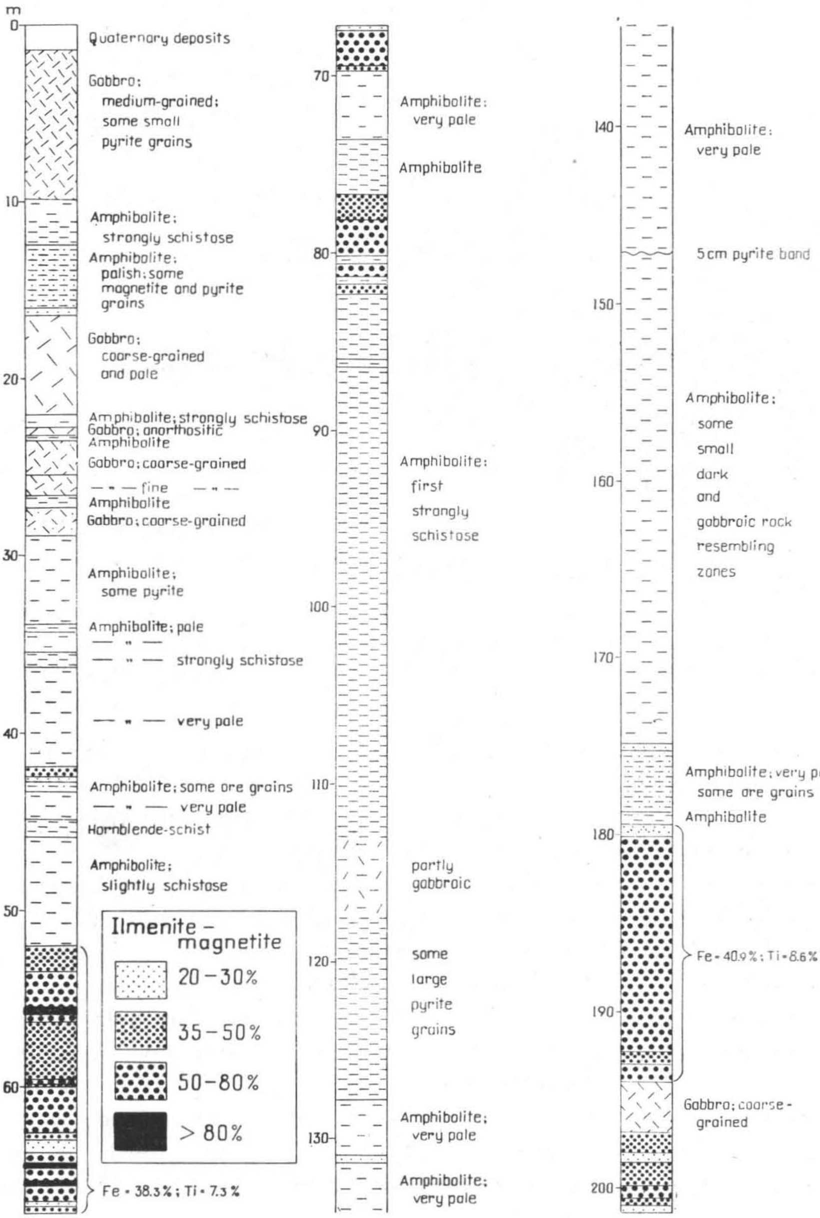


Fig. 21. Drill hole No. 1. at Otanmäki.

it may be noticed that in the neighbourhood of the thicker ore zone the rock, owing to a lesser amount of hornblende in it, is lighter than usual. The following, poorer and smaller ore band, however, is connected to a dark and more schistose amphibolite. At about 110 meters the rock turns again into a slightly schistose and at 126 meters into a very pale variety approaching anorthosite. Between 177 and 192 meters another coherent ore zone occurs and it is separated from the following poorer ore segregation by a pegmatitic gabbro band. At the end of the drill hole the rock containing ore minerals is no longer of the schistose type but having the habit where the plagioclase and hornblende crystals are cemented by small grains of ore minerals.

In close connection with the ore zone in drill hole 18, the dark variety of amphibolite, which is analysed between the depths of 281.34 and 284.44 meters (Tab. IX), is revealed under microscopic examination to be slightly orientated (Fig. 22). The main mineral, hornblende ($c \wedge \gamma = 20°$),

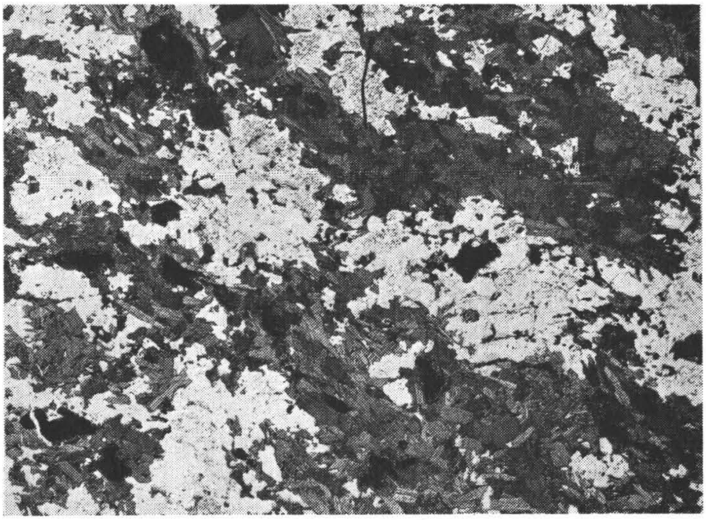


Fig. 22. The dark amphibolite of drill hole 18. The black is ilmenite and magnetite, the dark grey hornblende. The greyish dotted plagioclase grains seem to be of an older generation, but the smaller clear grains evidently are younger. Magn. 6 ½ x.

occurs as medium-grained large groups between groups of plagioclase (An_{45}) crystals also of medium-size. The larger hornblende grains include small ilmenite and sphene crystals. The larger ilmenite grains are likewise surrounded by zones of sphene, as in the poorer ore (Fig. 31). Small epidote inclusions occur in the large plagioclase grains of the older generation. Pyrite and chalcopyrite are seldom to be seen. In places the hornblende grains have ragged borders, which seem to have been formed contemporaneously with the crystallization of the younger generation of

Table IX. The dark amphibolite at Otanmäki.
Drill hole No. 18. Depth 281.34—284.44 m.
Analysed by H. B. Wiik.

	%	Mol. prop.	Niggli numbers		Norm		Mineral composition	%
SiO_2	43.11	7178	si	97.9	Il	11.38	Plagioclase (An_{45})	31.5
TiO_2	6.00	750	ti	10.3	C	4.02	Hornblende	56.4
Al_2O_3	15.48	1519	al	20.7	Mt	5.99	Epidote	0.1
Fe_2O_3	4.13	259	fm	46.7	Hy	7.73	Ore	7.5
FeO	11.30	1573	c	26.6			Sphene	4.4
MnO	0.16	23	alk	6.0	Di	27.93	Apatite	0.1
MgO	5.38	1334	qz	—36.1	An	19.09		100.0
CaO	10.92	1947	k	0.13	Ab	20.13		
Na_2O	2.38	384	mg	0.39	Or	3.05		
K_2O	0.52	55	c/fm	0.57	Ap	0.10		
P_2O_5	0.04	3			H_2O	0.67		
H_2O+	0.62	344						
$H_2O—$	0.05	28						
	100.09					100.09		

Or : Ab : An = 7.24 : 47.61 : 45.15

plagioclase. The texture of the rock gives the impression that the schistosity had been vanishing (metablastesis) or that the regeneration had not been completed during the last metamorphism.

In some outcrops on the W and NW slopes of Otanmäki the most normal (old fashioned or unregenerated) type of amphibolite is found. Because of the abundance of hornblende it must most nearly be classed with the dark variety, but contains a greater quantity of apatite than is usual as well as a small amount of ragged biotite. The clear medium-sized hornblende grains are strongly elongated parallel to the schistosity. Plagioclase is turbid and slightly zoned. Elongated grains of ilmenite and magnetite are moderately present, but sphene, epidote and pyrite are met with scarcely. For instance a sample of this amphibolite contains apatite to such a great extent that the percentage of P_2O_5 reaches 1.22. The mineral composition of the same rock is presented in the analysis (Tab.X), made by the Rosiwal's micrometric method.

Table X. Modal composition of the amphibolite on the NW Slope of Otanmäki.

Hornblende	Plagioclase	Ilmenite Magnetite	Apatite	Biotite	Chlorite Sericite	Pyrite
55.8 %	24.5 %	10.5 %	5.3 %	3.5 %	0.05 % 0.05 %	0.3 %

This unregenerated type of amphibolite is sometimes found as fragments in gabbro (Fig. 14) and as several zones of amphibolite pierced by diamond drill, but in these cases the biotite and apatite content is not notable. It is recognizable because of the even-grained texture and more homogeneous schistosity (Fig. 25; 7) than in the other types of amphibolite in the ore field at Otanmäki.

A very light variety of the basic rock (Fig. 23) was found when the shaft was begun to be sunk on the W slope of Otanmäki not far from the N border of the ore zone. The main mineral is plagioclase (An_{52}) the grains having a diameter of 0.5—3.0 mm. They often have ragged borders and varying amounts of sericite inclusions. Sometimes the twin lamellae are straight, but sometimes they are bent and broken into small pieces. The smaller plagioclase grains, usually without inclusions, form a cement between the larger grains, which are remnants of phenocrysts. The smaller grains often have a zonal structure and are more idiomorphic than the larger ones. The zoning is inverted (compare Fig. 24), so that the anorthite content becomes greater towards the border [1]). The epidote grains are in close contact with the ragged borders of the large plagioclase grains, and

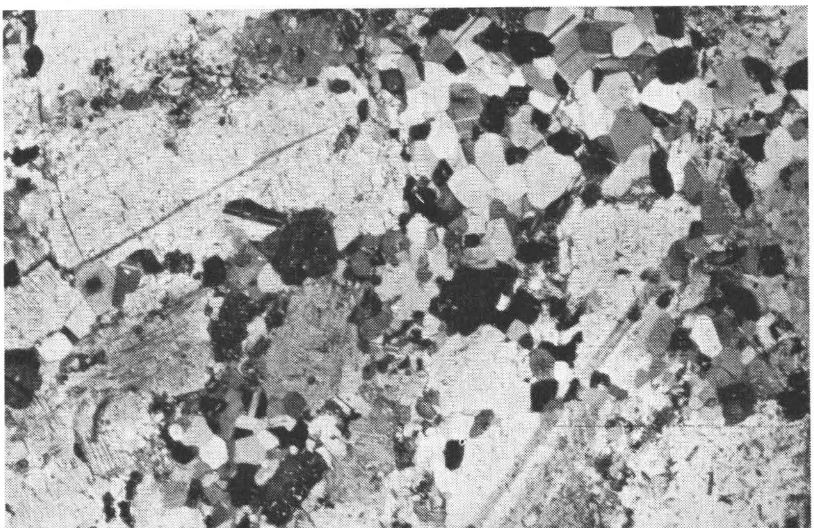


Fig. 23. Anorthositic rock occurring in the shaft at Otanmäki. Nic. +, magn. 12 x. Photo E. Halme.

[1]) This phenomenon is sometimes noticed in regionally metamorphosed rocks (Becke 1897) and Köhler (1948) wrote: »Die Anwesenheit inverser Zonenstruktur zeigt ohne Zweifel mehr oder weniger völlige Umprägung der früheren Mineralvergesellschaftung an».

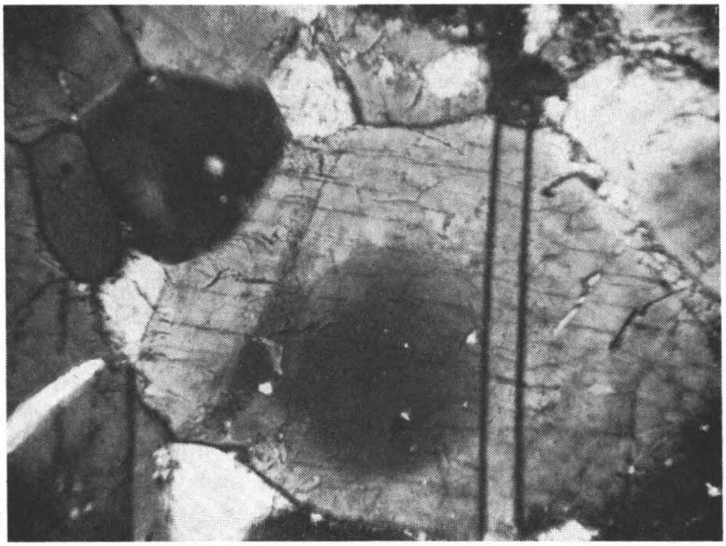


Fig. 24. A plagioclase grain with inverted zoning in the light basic rock. The dark central part of the grain represents a 30 per cent content of the anorthite component. On the lighter border zone it varies from 50 to 55 per cent. The twin lamella (the twin law: Albit-Ala) contains an average of 44 per cent anorthite. Drill hole 18, depth 434.5 metres. Nic. +, magn. 140 x.

also occur in the fractures. Some chlorite and calcite have evidently been formed by hydrothermal alteration. The accessory minerals are sphene, apatite and pyrrhotite. The mineral content determined by Rosiwal's method is as follows:

Table XI. Modal composition of the light rock on the W slope of Otanmäki.

Plagioclase	Epidote	Chlorite	Sericite	Pyrrhotite	Sphene
81.4 %	11.9 %	3.8 %	2.4 %	0.4 %	0.1 %

When sinking the first shaft, a rock was found which contains plagioclase as large porphyroblastic grains (An_{40}) with ragged borders, as well as small rounded grains (An_{45}) often with inverted zoning and forming a granoblastic matrix. The abundance of garnet makes it possible to call this rock a garnet anorthosite.

The usual accessories of the dark amphibolite are also found in the light rock but clinozoisite and pennine are more abundant in the latter.

The analysis of the light variety of the rock (drill hole 18, depth 434.5 meters) shows the scarcity of silica and the great abundance of alumina, which evidently replaces iron in the clinozoisite.

The considerable content of the anorthite component in plagioclase and the scarcity of hornblende as well as the indistinct schistosity give reason to call the light rock variety of anorthosite, but it is very difficult to draw the limits between the two types, because they grade from one to the other by such small degrees or the light variety occurs only as small inclusions and veins in the dark rock.

Table XII. The chlorite epidote plagioclase rock at Otanmäki.
Drill hole No. 18. Depth 434.42 m.
Analysed by H. B. Wiik.

	%	Mol. prop.	Niggli numbers		Norm		Mineral composition	%
SiO_2	51.80	8625	si	148.1			Plagioclase (An_{55})	33.4
TiO_2	0.40	50	ti	0.9	Il	0.76	Epidote	31.2
Al_2O_3	28.32	2778	al	47.7	C	2.45	Sericite	17.3
Fe_2O_3	0.92	58	fm	3.4	Mt	1.34	Chlorite	18.0
FeO	1.48	206	c	29.8	Hy	1.19	Apatite	0.1
MnO	0.01	1	alk	14.1	Di	0.16		
MgO	0.67	166	qz	—8.3	En	1.67		100.0
CaO	9.74	1736	k	0.08	An	47.76		
Na_2O	4.70	758	mg	0.34	Ab	39.74		
K_2O	0.59	63	c/fm	3.56	Or	3.50		
P_2O_5	0.05	3			Ap	0.10		
H_2O+	0.91	505			H_2O	1.06		
H_2O-	0.14	78						
	99.73					99.73		

Or : Ab : An = 3.58 : 43.67 : 52.48

The southern part of the ore-bearing zone is situated in the neighbourhood of the gabbro area. In the actual contact zone the gabbro has been strongly intruded into the amphibolite, of the ore-bearing zone, and therefore the boundary line between the areas of these rocks is very indistinct. In some places the gabbro has pushed aside the amphibolite from its earlier location and in other places the large and small dikes of gabbro have broken it into fragments, which are often found far inside the area of gabbro. Some coarse-grained veins of anorthosite are to be noticed generally penetrating the ore bodies and the adjoining amphibolite. In several places the anorthositic rock forms the fine- and medium-grained stratum veins and bands of various width between the strongly schistose zones containing only darkest minerals of amphibolite. In both these cases the anorthosite (andesinite) contains plagioclase (An_{35}) as nearly its sole component.

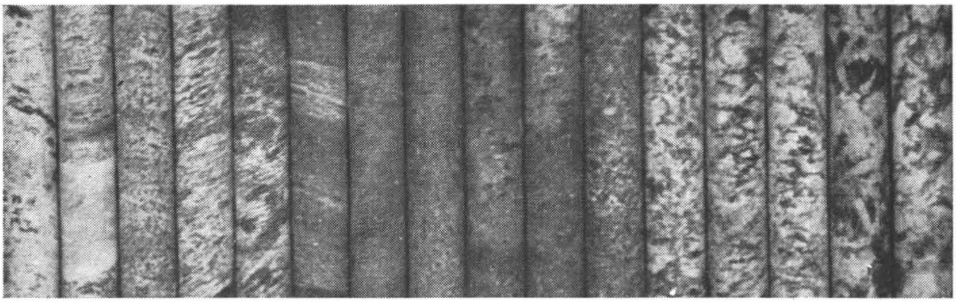


Fig. 25. The varying types of the gabbroic and amphibolitic rocks of the Otanmäki ore zone. ½ natural size.

1. Amphibolite; white and slightly schistose.
2. Amphibolite; strongly epidotized and clearly schistose.
3— 6. Amphibolite; strongly schistose but unequally containing dark and light minerals.
7. Amphibolite; dark and slightly schistose.
8. Gabbro; fine-grained, (homogenized amphibolite).
9—11. Gabbro; fine-grained, dark and light varieties.
12—14. Gabbro; white and medium-grained.
15—16. Gabbro; coarse-grained and partly leucocratic.

Type 7 represents normal amphibolite and occurs as remnant-like fragments included within the others.

Although the amphibolite often has a slightly schistose but only meta-gabbroic habit, it is very difficult to distinguish between gabbro and amphibolite, because nevertheless the veins of gabbro sometimes have such a strongly stressed and crushed texture. Where hornblende is present in sufficient abundance the strike of schistosity plane is more distinct in amphibolite but the gabbro has a slight direction of the lineation only. In regard to anorthositic rock the fine- and middle-grained varieties have a rich content of chlorite and epidote but the coarse-grained dikes are formed by plagioclase (An_{35}) nearly exclusively.

ORE DEPOSITS IN THE OTANMÄKI FIELD

GENERAL DESCRIPTION

The map showing the relative magnetic intensities of the Otanmäki ore field (Fig. 26) reveals that the ore bodies are mainly situated in two parallel zones beginning on the W side of the hill running eastwards and curving northwards on the NE side. By comparison with the geological map, it can be observed that the main zone of the magnetic anomaly almost follows the southern boundary of the amphibolitic area, except in its E and NE parts, where its regularity is disturbed. In addition small areas of magnetic anomaly are found in the middle of this main horse-shoe shaped zone which is 2 km in length. As the ore is visible only in some outcrops and excavations, it is difficult to determine accurately the contacts between the different rocks. The excavations and deep diamond drillings show that ore is to be found in all areas with a high magnetic anomaly. Consequently the geological map of the field shows ore bodies in places where the ore rock is covered and no diamond drilling has been made, but where intense magnetic anomalies occur.

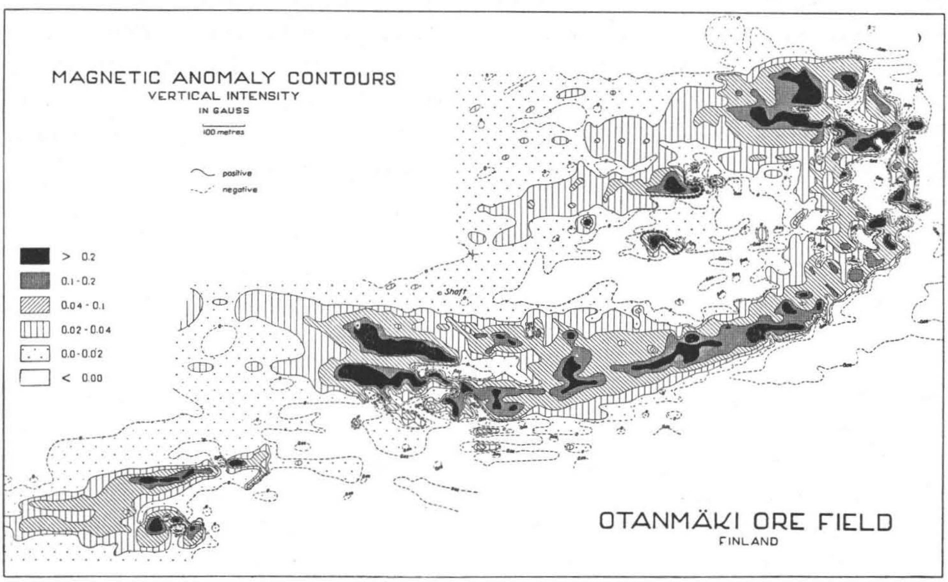


Fig. 26.

The difference as seen in the map between the ore bodies in the W and E parts of the field is caused by the fact that there have been more extensive excavations and diamond drillings in the W part, and is also due to differences in the tectonic forms. In any case, this picture of the ore formation has only a general character, since the superficial deposits and the varying content of the ore minerals in the rock have a disturbing effect on the magnetic anomaly field caused by the actual ore bodies. The sketch maps of the largest outcrops (»M» and »S») give a much truer description of the character of the ore formation.

In the horizontal plane section the ore bodies mostly are elongated parallel to the strike of the schistosity, which runs generally E-W, but in the E part of the ore formation both the strike of the amphibolite as well as the orientation of the ore bodies vary considerably, being quite indefinite in the eastern curve. The schistosity usually dips steeply to the south but the pitch varies in some places. Generally the ore zone has a definite direction of lineation but several separate ore bodies have a very indefinite direction of elongation. The direction of lineation is mostly constant at N 60° E plunging 57° at WSW and has proved to be useful in drawing the geological maps of the outcrops, and therefore it has also been used in drawing the map of the whole ore field of Otanmäki. Every geologically significant point on the outcrops and in the drill holes has been projected along this line of lineation to the plane of the map. Although the ore bodies have lens shapes also in this direction, the method is not useful for long distances. The deep diamond drilling has shown that, on a whole, the ore bodies seen in the horizontal plane have the same direction of elongation as the general strike of the formation but that the ore segregations occur as divided into separate lenses also in the vertical direction. Further some ore veins are situated in vertical position. These irregularities cause great difficulties in calculating the exact quantity of ore.

THE STRUCTURE AND CLASSIFICATION OF THE ORE ROCKS

During the prospecting 50 deep drill holes have been made in the Otanmäki field. The total length of all these holes is 9 133 meters. In the more closely investigated W part, 400 meters in length, there are 32 diamond drill holes, which have a total length of 6 259 meters. Most of them have a dip of 45° to the N. Also, most of the excavated exposures have been made in the same part of the field, so that the geological map of this area gives a fairly accurate picture of the ore formation.

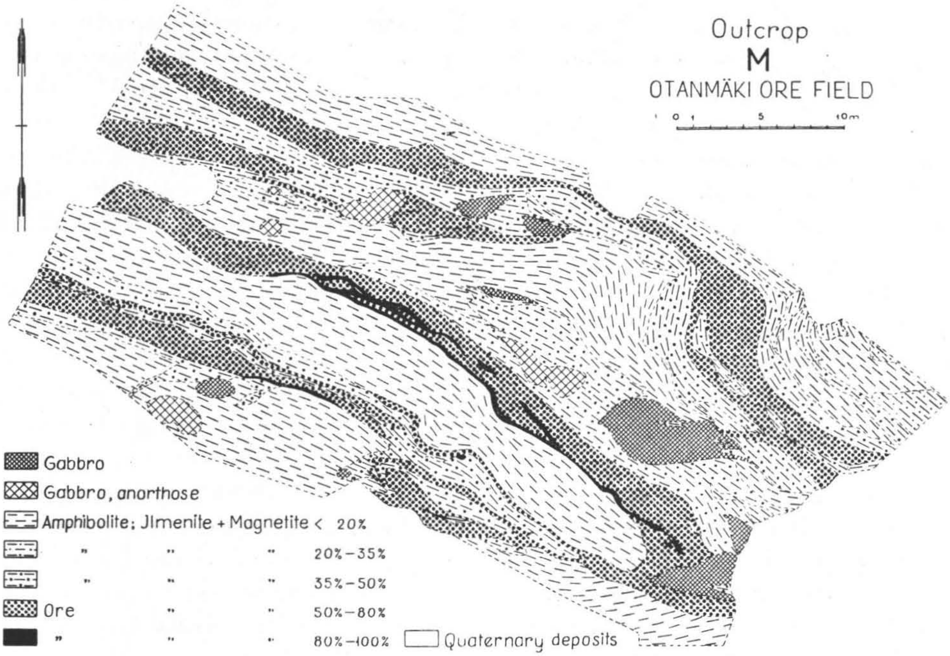


Fig. 27. The petrological map of the »M» area. 1/400 natural size.

The sketch map of the large exposure, called »M» area (1 200 sq. m) (Fig. 27), gives a very distinct idea of the structure and mode of occurrence of the ore, which forms several narrow zones rich in ore grains and elongated parallel to the strike of the amphibolite. In some cases the contacts between the ore rock and amphibolite are distinct, but often the transition of amphibolite into the ore takes place gradually with the increasing quantity of ilmenite and magnetite grains. At last the ore grains form nearly the whole rock. The gradual and irregular variations of richer and poorer ore segregations cannot be seen clearly in the map, because exploitation purposes demand a macroscopic classification of the ore rock into four different kinds of ore.

The rock containing 50—80 per cent ore minerals may be called first class ore. The usually adjoining silicate minerals are colourless chlorite (pennine) or for the most part chloritized hornblende orientated parallel to the tectonic lineation and surrounded by the ore minerals. Further clinozoisite and epidote are mostly present. In addition to the ilmenite and magnetite ore grains there are small amounts of pyrite.

The rock with a 35—50 per cent content of ore minerals may be called second class ore, with coarse- as well as fine-grained hornblende and a few strongly altered plagioclase grains. Microscopically it can be seen that ilmenite and magnetite often replace the hornblende. The ore material usually brecciates the rock into irregular fragments when it intrudes it as veins. This phenomenon shows that the actual ore material has moved after the crystallization of the other minerals of the rock. In this type of ore there is more pyrite than elsewhere.

It is not difficult to distinguish between the first two types of the ore rock, because the absence of hornblende gives to the rock of the first class ore a more compact habit. The difference between the second and third class ore is not so distinct, because the content of the ore minerals decreases from 35 to 20 per cent in the third class, but no other change of the habit can be noticed. The amphibolite rocks are called third class ore when they contain much more ore minerals than normal amphibolite. The ore of this class can only be utilized when it is situated so that it must be exploited with ore of a higher class; but usually where better ore is found, third class ore is only present to a slight extent. It more usually occurs in large separate zones as disseminated ore included in the normal amphibolite, and it causes strong magnetic anomalies, which in a few cases are drawn as ore bodies in the general map of the Otanmäki ore field. The extraordinary »extra prime» class is formed by compact ore bands, which usually occur as cutting veins and do not contain any silicate minerals at all. The amount of »extra prime» ore is so small that it is insignificant for exploitation, but is interesting because of its exceptional appearance in the field. The contacts between the »extra prime» ore and the wall rock are distinct. It often cuts the direction of the formation, but usually follows the strike of the schistosity. Evidently the veins of the »extra prime» ore (Fig. 28) are the last newcomers to the field, and have been

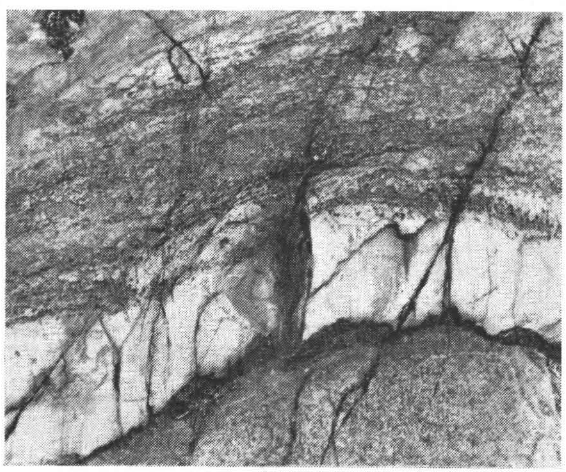


Fig. 28. The compact ore band conforming the crushed zone of the amphibolite rock. »M» area. 1/6 natural size.

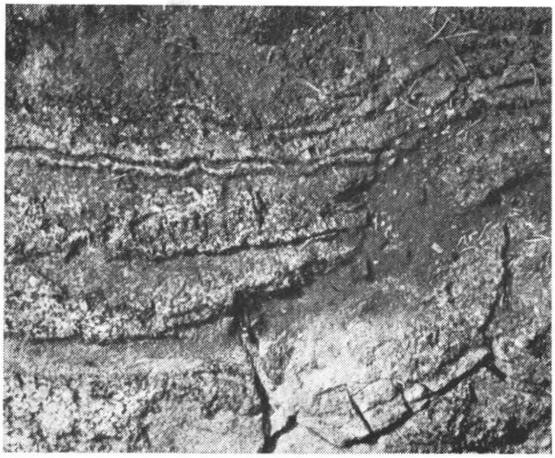


Fig. 29. The small stripes of the light ore mineral grains in the amphibolite rock. »M» area. 1/10 natural size.

intruded after the active stress has decreased. These veins have a thickness of only 10—20 cm, but they can have very great depth.

The classification of the ore rock also offers difficulties because the poorer ore rock has a small veined habit. There are several thin but nearly compact ore veins parallel to the poore ore zones, or to the zones containing no ore grains at all. The classification of this rock is based on the average amount of the ore grains. The small veins could not be marked in the map, but they are to be seen in the picture (Fig. 29). This small veined habit seems to indicate that the material of the ore has migrated in the axial direction which is perpendicular to the direction of stress. The same phenomenon is also evident in the larger ore formations of the Otanmäki field, and has caused elongation of the ore bodies in the axial direction.

The map of the »M» area shows that amphibolite occurs as a wall rock of the ore zones as well as curved fragments between the ore bodies. Some of these amphibolitic rocks can have a considerable content of ore mineral and can be exploited together with the rich ore. The amphibolite of the »M» area is slightly schistose and its chief mineral is small- and clear-grained hornblende. The plagioclase is also small-grained but turbid. The ilmenite and magnetite grains are ragged and usually the ilmenite is surrounded by crystals of sphene. Pyrite and epidote are accessories.

In this connection may be mentioned the white-coloured gabbroic and anorthositic veins, which also in the »M» area adjoin the ore rock. In some places they are pegmatitic or coarse-grained, slightly compressed intrusions, elongated in the axial direction like pipes, but in other places they

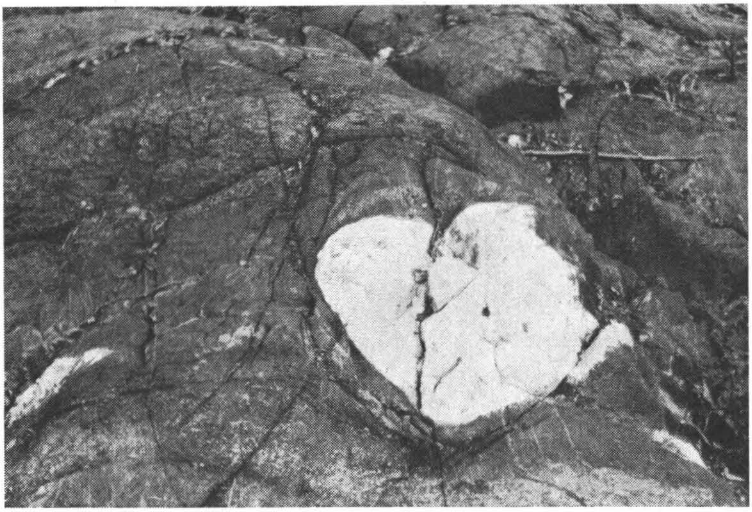


Fig. 30. A white, fine-grained segregation of plagioclase (An_{35}) as an inclusion of amphibolite in the »M» area. 1/10 natural size.

are fine-grained, fragmental inclusions. In the photograph (Fig. 30) the amphibolite can be seen to bend round them, evidently owing to the greater toughness of the amphibolite during the formation of these inclusions or during the metamorphism.

The chief mineral in these light veins and inclusions of the »M» area is plagioclase (An_{52}), which occurs as an older, turbid and coarse-grained generation, and also as a clear and small-grained later generation. The few ragged hornblende grains also seem to have been formed in two generations. Small grains of ore, calcite, epidote, chlorite and apatite are present in slight amounts. In some strongly stressed white inclusions the large plagioclase crystals are completely altered to quartz, sericite and epidote. These altered crystals include small hornblende and ore mineral grains.

The three main ore zones seen in the map of the »M» area are united at a depth of 50 m into one great ore body as is established by drill hole No. 1. Deeper still this ore zone becomes poorer and disconnected, evidently due to the strong disturbing effect of the gabbro, which there intrudes further to the N than at the surface.

The other large outcrop of ore is situated only 50 meters to the SW of »M», and is called the »S» area (Fig. 31). In the special map it is seen that the main rock is amphibolite, which is cut by gabbro and small ore veins. In addition to the disseminated ilmenite and magnetite grains pyrite occurs more than usual. It is very clearly seen that the ore veins penetrate the amphibolite and the veins of gabbro penetrate both. South-

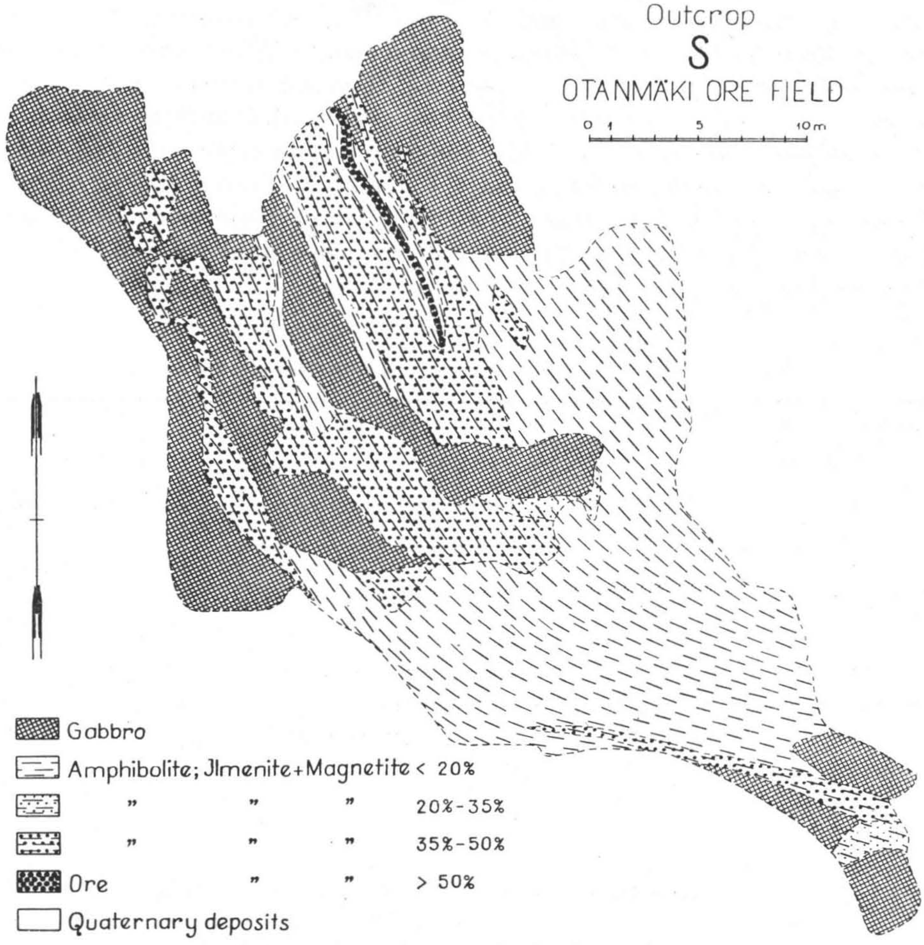


Fig. 31. The petrological map of »S» area. 1/400 natural size.

wards in the actual gabbro area no more ore bodies are to be found and amphibolitic fragments become rare. Similarly further in the amphibolite area gabbro veins are fewer and their disturbing effect is slighter. Therefore the ore bodies of the northern zone are larger and more continuous. Diamond drilling has proved that at a depth of 100—200 m in this southern zone there is more gabbro and less ore, but in the northern zone the amphibolite with ore bodies continues even more deeply and gabbroic veins are few. However, at still greater depths the amphibolite gradually turns into gabbro containing assimilated ore material, which seems to replace the hornblende, but as ore it is not good enough for classification. Generally the diamond drilling investigations show that in the western part of the field the surface ore is poor and discontinuous, but improves with depth, though beneath 150 m it becomes poorer again. When moving E-wards the ore formation at first becomes poorer; then it improves again, forming considerable ore bodies in the NE part, as seen in drill hole 9, which penetrates 90 m of first class ore. However, the neighbouring holes have penetrated mainly disseminated ore, but the quantity of ore grains in the rock varies considerably or in some places small compact ore veins are present. The search of cores shows that the drill has penetrated the wall rock and different kinds of the ore rock as follows:

Table XIII. Ore and rock types in the drill cores.

»Extra prime» ore	First class ore	Second class ore	Third class ore	Amphibolite		Anorthosite	Gabbro
				dark	light		
8	428	332	635	4 104	341	1 072	1 612 meters
0.1 %	5.0 %	3.9 %	7.4 %	48.1 %	4.0 %	12.6 %	18.9 %

The foregoing examples show that the ore field of Otanmäki resembles several other ilmenite-magnetite ore fields in the world, the ore formation consisting of several separate ore veins, lenses and impregnated ore bodies occurring as zones.

MICROSCOPIC FEATURES OF THE ORE ROCK

The first thing that must be mentioned is that the essential ore minerals, ilmenite and magnetite, form separate grains and only small inclusions of other minerals are found in the ore grains. Lamellar intergrowth too is observed to be very scarce.

The ilmenite grains usually have a diameter of 0.2—0.3 mm and form small groups; some, however, have a diameter of 0.02—0.03 mm and are found among the magnetite grains. Coarse-grained types of the ore are rare. Lamellar twinning of ilmenite is very common and in some cases the lamellae are crossed or strongly curved. Very common are the small, shuttle-shaped hematite inclusions evidently segregated during the crystallization of the ilmenite grains and between these larger inclusions there are some very small hematite flecks only noticeable under great magnification. Small silicate inclusions are found as well, but no magnetite is seen in the ilmenite.

The size of the magnetite grains varies, but they are usually smaller than the grains of ilmenite and seem to have crystallized later between them, as a matrix. Lamellar inclusions of ilmenite are very seldom found in magnetite, but small rounded flecks are common. Therefore the separation of magnetite by the magnetic method cannot give quite pure material, but there remains about 2 per cent titanium; it is, however, pure enough for technical purposes. Martite is found at the borders of several magnetite grains in shapes resembling skeletons.

The third ore mineral, pyrite, is present only as a few grains or small groups of grains. Its content in the ore rock is on the average 1 per cent. In some cases the quantity of pyrite

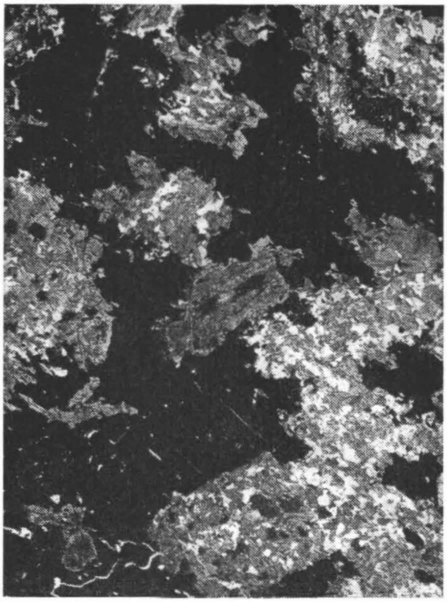


Fig. 32. The structure of the second class ore of »M»-area. Black = ilmenite and magnetite, grey = hornblende, white = andesine. Magn. 6 ½ x.

Fig. 33. A large ilmenite grain surrounded by a zone of small sphene crystals and embedded in a group of hornblende grains. Amphibolite of the ore zone at Otanmäki. Magn. 80 x.

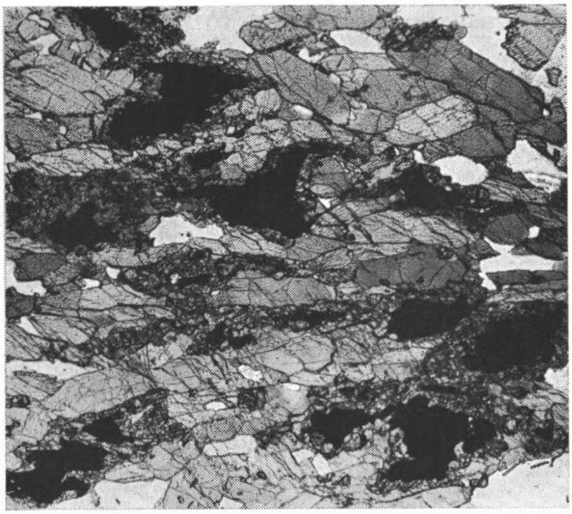


Fig. 34. The ore-bearing amphibolite from Otanmäki. The black ilmenite grains are surrounded by the groups of the small sphene crystals. The grey slightly directed grains are hornblende; white = plagioclase. Magn. 16 x.

can be greater, owing to a few small compact pyrite veins, which, because they penetrate, seem to have been intruded last in the rock.

Fig. 35. A mineral combination in the ore of Otanmäki. The grey is hematite and the white pyrite. The dark blots are silicate inclusions. Magn. 520 x.

Chalcopyrite is very seldom found and pyrrhotite only in the wall rocks.

Adjoining some aggregates of pyrite the ore occasionally contains a few separate grains of hematite (Fig. 35 and 36).

The texture of the first class ore is to be regarded as granoblastic in its small features, but in its macrostructure the directed pennine grains give to the rock a strongly stressed habit. Because of the directed hornblende grains and the ilmenite or magnetite aggregates elongated parallel to the lineation, the poorer qualities of ore have a clear stressed structure. In the poorest ore

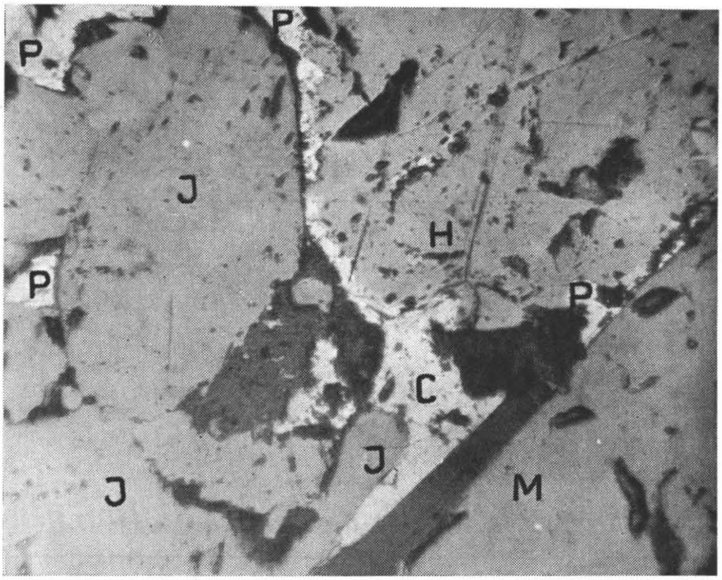


Fig. 36. Ilmenite-magnetite ore of Otanmäki. In this case the hematite forms separate grains. I = ilmenite, M = magnetite, H = hematite surrounded by pyrite (P), C = chalcopyrite. Magn. 210 x.

also the plagioclase grains form aggregates elongated according to the direction of the schistosity.

THE METAL CONTENT OF THE ORE

As seen in the classification of the ore its quality varies considerably. The first two ore boulders found at Sukeva were very rich in ilmenite and magnetite. The analyses made by the Geological Survey of Finland have proved the rich contents of titanium and iron.

Table XIV. The analyses of the ore boulders at Sukeva.

Iron	Titanium	Sulphur
I 53.66 %	9.90 %	0.13 %
II 50.86 %	10.40 %	1.24 %

At the Otanmäki field the greatest amount of iron in the compact ore vein of the »M» area has been noted to be 63.5 per cent, but usually it is between 51—58 per cent. The titanium content of the compact veins varies between 9 and 15 per cent. A sample of the »extra prime» quality of ore was analysed by Landergren (Sweden) and shows the content as follows:

Table XV. »Extra prime» ore.

Titanium	Iron	Chromium	Nickel	Vanadium	Manganese	Cobalt
9.8 %	51.4 %	0.3 %	0.02 %	0.40 %	0.32 %	0.03 %

The first general samples of the »M» area are analysed by H. Raja-Halli and the results are presented below:

Table XVI. The ore types of the »M» area.

Ore types	Fe %	Ti %	V %
Extra prime ore	57.8	8.94	0.47
First class ore			
sample 1	51.3	8.16	0.35
sample 2	49.2	7.32	0.34
Second class ore			
sample 1	34.9	5.17	0.32
sample 2	31.2	6.36	0.21

For the most part, the ore rock is inferior and varies greatly in different bodies. The diagram in fig. 37 shows the variation in the contents of iron, titanium and vanadium as compared with the specific gravity of the analysed rock.

Table XVII. Analyses of the dressing fractions.

Fractions	Weight %	Fe %	TiO_2 %	S %
Magnetite	35.0	68.5	2.5	—
Ilmenite	23.5	36.4	48.1	—
Pyrite	1.5	46.0	—	54.0
Rest (silicate minerals)	40.0	9.0	3.0	—
Ore rock	100.0	36.8	13.4	0.8

During the investigations the ore was considered commercially profitable to work because on the average it contained magnetite iron 26.4 %, ilmenite iron 3.5 %, titanium 7.3 %, sulphur 0.65 %, vanadium 0.24 % and phosphorus only 0.01 %.

According to the dressing investigations made by U. Runolinna (1952) it may be possible to get the fractions according to table XVII.

The chemical laboratory of the Geological Survey of Finland has analysed the content of cobalt in the pyrite fraction and obtained the figure of 0.75 per cent and for copper 1.15 per cent.

The dressing investigations have shown also that the vanadium for the most part goes to the magnetite fraction.

Since the beginning of the exploration, the vanadium was taken as being the most valuable metal of the ore. In 1956 the mining company, Otanmäki Oy., has begun the extraction of this metal from the magnetite fraction using a chemical method.

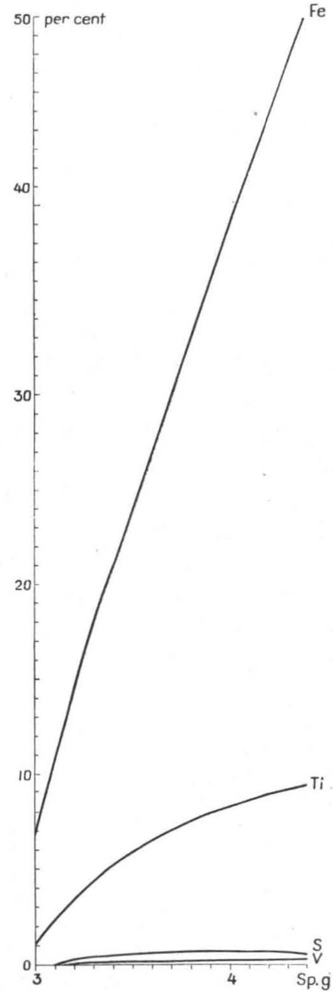


Fig. 37. The variation in the contents of iron, titanium, sulphur and vanadium as compared with the specific gravity of the ore rock (average of 150 analyses).

THE SEPARATE ORE FORMATIONS OF THE REGION

THE ORE BODIES OF OTANNEVA

This area, mainly determined by the magnetic anomalies, is situated only half a kilometer to the SW from the W end of the actual Otanmäki field. The whole anomaly area of Otanneva is considerable, but not especially strong. Diamond drillling has shown that the actual ore bodies are small and poor. Evidently most of the magnetic anomaly is caused by a part of the amphibolitic wall rock, which contains an unusual quantity of ore grains. As seen in the geological and magnetic maps there are two ore zones resembling the main area. Evidently the intrusion of the microcline granite has broken the large ore zone of Otanmäki and moved its western end toward the southwest. The eastern end of the Otanneva ore field is very irregular, apparently owing to the gabbro intrusion on the E side.

Aeromagnetic investigations have shown a minor, isolated but rather strong anomaly area about half a kilometer SW from the actual Otanneva field. For the present it is an unexplored ore occurrence, but evidently it is situated geologically in a minor amphibolite zone.

THE ORE FIELD OF VUOROKAS

This ore field is situated about 4 kilometers E of the center of Otanmäki. The single magnetic anomaly zone runs in a NE direction and its length is slightly more than one kilometer. The anomaly is not so strong and the area not so large as at Otanmäki. The outcrop at the NE end of the field shows that the ore rock found there resembles the Otanmäki type with regard to the ore minerals and their mode of occurrence. The ore bodies are connected with an amphibolitic rock, which again is in contact with the gabbro area of Rinneaho on the E side. The amphibolite, as well as the gabbro, is very similar to that of Otanmäki, but in some cases the gabbro differs, resembling more an uralite diabase. The plagioclase (An_{60}) grains are large and clear, and the hornblende grains are uralitic with reaction rims. Several ilmenite grains are surrounded by small groups of sphene. Pyrite, sericite, and epidote are usual accessories. The light and dark varieties of gabbro alternate.


MAGNETIC ANOMALY FIELD
OF
VUOROKAS
OTANMÄKI REGION
IN FINLAND
100 meters
VERTICAL INTENSITY
> 0.15 gauss
0.11 - 0.15 "
0.07 - 0.11 "
0.04 - 0.07 "
0.02 - 0.04 "
0.00 - 0.02 "
< 0.00 "

Fig. 38.

Plagioclase (An_{55}), the chief mineral of the amphibolite, is turbid and partly altered to epidote and sericite. The hornblende is ragged and often altered to chlorite. The dark variety of this amphibolite is cut by pegmatitic gabbro veins, and the chief mineral is a clear medium-grained hornblende.

The ore field of Vuorokas has been partly investigated by diamond drilling in the last years, but the knowledge of its ore bodies is still very slight. The magnetic anomalies show that in the main zone there are five separate successive maxima, of which one is dual. It is evident that the quantity of profitable ore at Vuorokas is not as great as at Otanmäki. However it may contain several million tons of profitable ore.

The aeromagnetic map shows that also in the surroudings of the Vuorokas field proper there are some strong magnetic disturbances, apparently caused by minor ilmenite-magnetite ore bodies.

THE ORE FIELD OF PENTINPURO

The ore field of Pentinpuro is in a flat marshy country 3 km W of Vuolijoki church and 11 km NW of Otanmäki. There are no outcrops at all, for the quaternary deposits have an average thickness of ten meters. Magnetic investigations show that the length of the anomaly area is half a kilometer. The cores of the two diamond drillings show that there are ore bodies like those of the Otanmäki field and that they are connected with heterogeneous basic rock, which is present as both light and dark varieties. The distinct Pikku-Otanmäki type of gabbro has not been found, but sometimes the rock is slightly schistose and resembles normal gabbro. In drill hole No. P 1 and at a depth of 35.30 m, this rock contains plagioclase (An_{60}) as the main mineral, and ranges from coarse to medium in grain. Often the large plagioclase grains are orientated parallel to the schistosity and its twinning lamellae are often curved. The hornblende is ragged and contains inclusions of plagioclase and sphene. In addition to the usual epidote, chlorite and apatite, a small quantity of biotite is found. Half a meter deeper the rock is more schistose. There are two generations of plagioclase, the older large grains (An_{57}) and younger small grains (An_{35}). The darker variety of the rock contains more hornblende and ore grains, but the darkest variety contains no plagioclase at all, and at the same time the rock is strongly schistose and better named hornblende schist. In addition there are several large sphene grains in this last variety, which often includes small hornblende and ore grains. Some of the sphene grains have lamellar twinning and are slightly pleochroic. In some cases the sphene seems to replace the hornblende and several ore grains give this same impression. Sometimes the ore material is situated between the hornblende grains and forms thin but long veins parallel to the schistosity. Some small rutile crystals adjoin the ore and sphene grains.

Another basic rock variety is very fine-grained and partly mylonitic, which evidently shows that the rock has been strongly sheared at a relatively low temperature. In addition there are small ragged chlorite, epidote, sericite and ore grains in the rock, which also contains some plagioclase remnants.

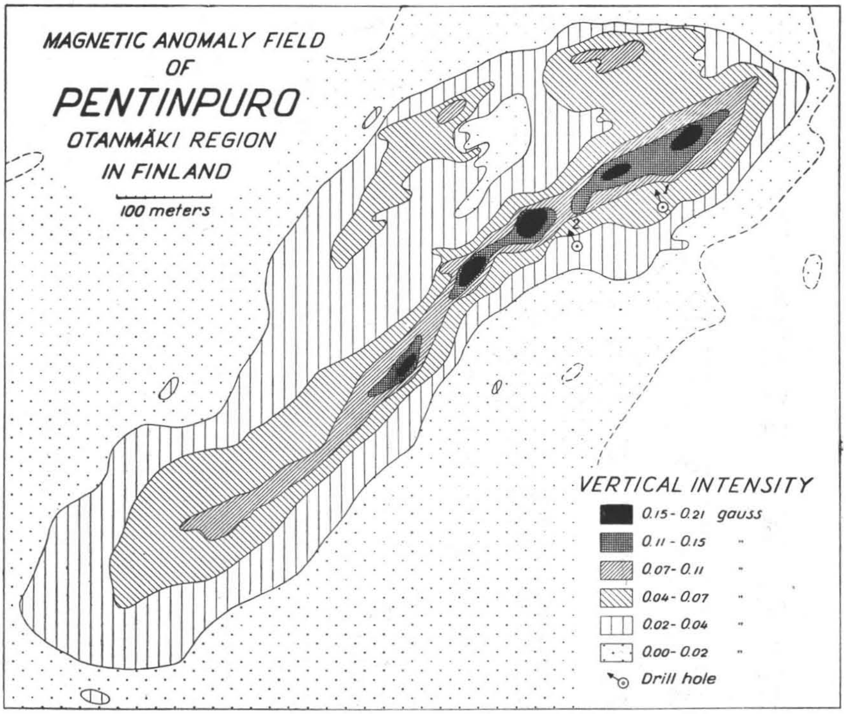


Fig. 39.

Diamond drilling indicates an average thickness of 10 m for the ore bodies. The ore zone is situated in the amphibolite formation and both have the same strike. A very light variety of basic rock closely follows the ore zone. The same phenomenon is also often noticed in the ore of Otanmäki.

The probable quantity of poor ore in the Pentinpuro field can be roughly estimated at some millions of tons, but the amount of first class ore is probably only some hundred thousand tons.

In fig. 40 are seen the variations of the habit in the heterogeneous basic rock of Pentinpuro. The dark bands are strongly schistose but the

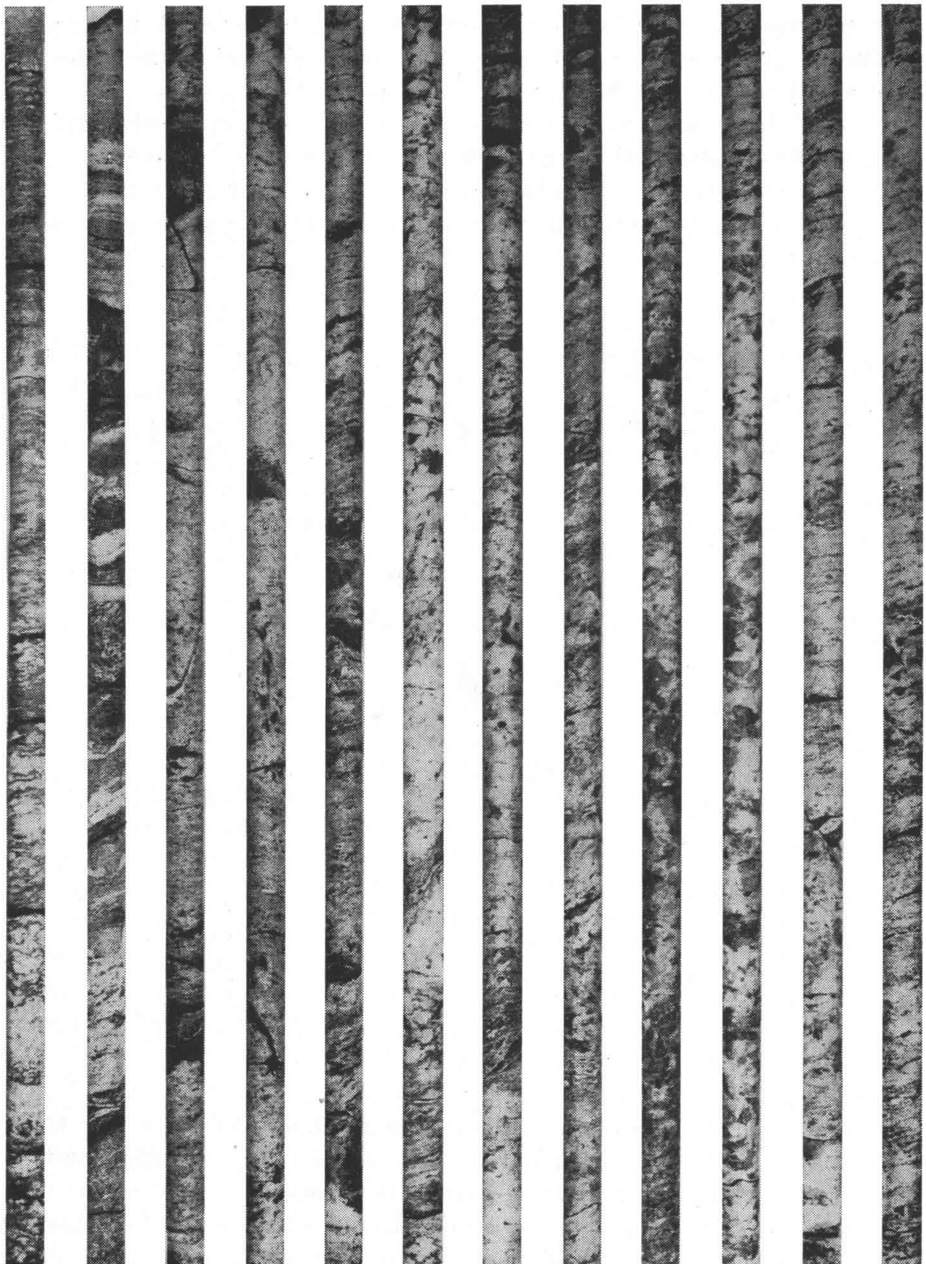


Fig. 40. Variations of the habit in the wall rock of Pentinpuro ore field. Drill hole 1 P between 11.70—21.20 meters. 1/4 natural size. Photo Erkki Halme.

Table XVIII. Analyses of the ore zone of Pentinpuro.
Analysed by E. Savolainen.

Drill hole	Between depths	Fe %	Ti %	V %	S %	P %
P 1	53.87—55.55 m	49.4	10.2	0.32	0.13	0.003
P 2	38.72—41.72 »	37.0	7.6	0.40	0.25	
P 2	41.98—47.74 »	29.0	8.1	0.31	0.27	
P 2	62.41—65.00 »	24.0	7.6	0.20	0.28	

light parts are mostly slightly schistose. In the coarse-grained rock cannot been noticed any schistosity but the contacts between the fine-grained and coarse-grained parts are very indefinite. The same phenomenon is noticeable also in the basic rocks of the Otanmäki ore zone and seems to be due to the process of metablastesis.

THE ORE FIELD OF ITÄRANTA

A small ore formation is situated on the E side of Vuottolahti bay and about 11 km NE of the Otanmäki field. The amphibolite, adjoining the striped gneiss zone, contains abundant plagioclase (An_{40}) and also here constitutes the wall rock. The hornblende grains are clear and medium-sized. Ilmenite, magnetite, pyrite, biotite and apatite all occur in minor amounts. As the amphibolitic bodies of this area are small and ragged owing to the penetrating character of the granites, the ore bodies are of small size and scattered. Even though magnetic anomalies, evidently caused by segregations of ilmenite-magnetite ore, cover an area 2 km long, the quantity of profitable ore is only some hundred thousand tons. Occurrences of gabbro like those of Otanmäki and Vuorokas have not been noticed in the Itäranta field, but the habit of the ore and its appearance are very similar.

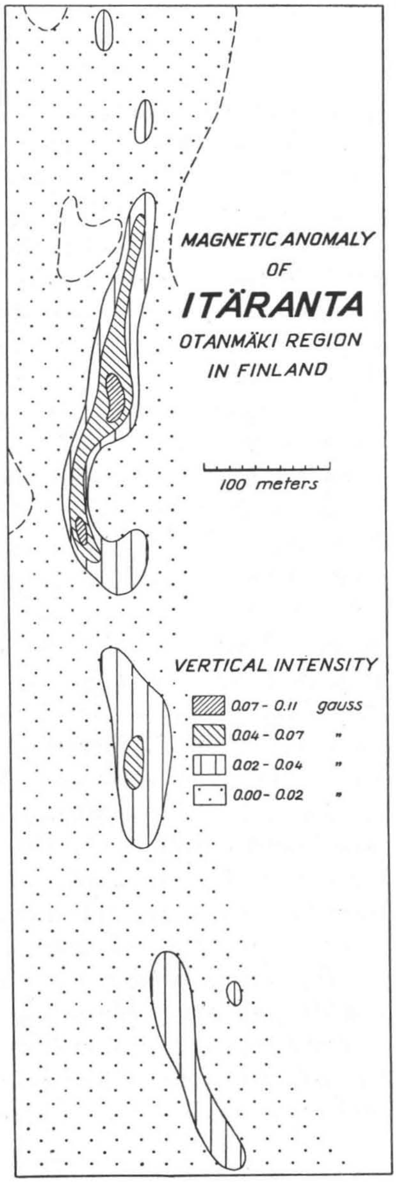


Fig. 41.

Some slight magnetic disturbances have been noticed by the aeromagnetic investigations carried out in the area south of the Itäranta field.

The foregoing descriptions show that all the ore formations of the region have the same mode of occurrence and adjoin similar amphibolites. The main differences between the ore fields are only in area and quantity of profitable ore. It is also noticeable that typical gabbro is only found in the Vuorokas and Otanmäki districts.

DISCUSSION

During the investigations the author formed the opinion that the formations of two different pre-Cambrian ages occur in the Vuolijoki region. The older forms the Archaean bedrock containing gneisses of different types as gneissose granites, mica gneisses, veined and banded gneisses or the older rock material is met with only as nebulous and ghost-like remnants in the younger granite. Because of the strong metamorphism their genesis is at present impossible to determine accurately. The amphibolitic rocks seem to belong to the same geological period, even though they sometimes have a penetrating character in regard to the rocks of the striped gneiss formation; but both have the same regional metamorphism, evidently caused in part by the movements during pre-Karelian times. The younger series of the rocks in the region was evidently generated in connection with the Karelian folding, which in this part of the mountain chain first acted in an E—W direction and produced a strike of the formations running, on the average, N—S, which direction is seen in the neighbouring schist zones. At a later stage of the movements the strongest stress seems to have been in a NW—SE direction, causing the stress lineation nearly in a perpendicular direction and great disturbances of the strike in the amphibolite zone of the Otanmäki area and forming the large, eastwards-directed curve. Evidently during the same action the younger granite massifs were intruded into the center of the distension and between the curved zones of amphibolite and striped gneiss in the vicinity. In some places and especially in the center, where the stress was strongest and latest in action, the granite has a distinct strike of foliation or shear structure; but in the surroudings the same granite is more homogeneous, having evidently crystallized under conditions of lower stress.

The strong injection of granitic material into the striped gneiss formation and the younger gabbroic intrusions give the impression that the region in question had been mobilized very deeply by the Karelian folding and the latest regional stress action had metamorphosed also the older rocks once more. The same distinct direction of the lineation as in gneissose granites and amphibolites of the surroundings is to be seen in places of the boundary zones of the gabbro massifs, but no strike of schistosity at all can be found in it. Therefore it is evident that the gabbro was intruded between the zones of amphibolite and striped gneiss during the last movements of the Karelian folding period.

Several pegmatite granite veins without marks of a dynamic metamorphism penetrate the gneissose and amphibolitic formations and therefore are regarded as the youngest kind of rock in the region.

Since the amphibolites of Otanmäki and its surroudings bear no traces of sedimentary origin, they must have been norite, gabbro or diabase before metamorphism. The average chemical composition of these rocks does not greatly differ from that of the dark amphibolite of the region of Otanmäki. The quantity of iron and titanium is somewhat greater in the analysed amphibolite (Tab. IX) than is usual in gabbroic rocks, though sometimes this can be very similar; but it does not contain enough ore minerals to be called ore.

The general impression is that there is an amphibolite formation having an extraordinarily heterogeneous structure formed during a process resembling venitization[1]) and caused by a strong stress action during mountain folding. The process may be called metamorphic diffusion (F. L. Stillwell 1918). Segregation of the ore material and formation of the ore bodies may be termed metamorphic differentiation (P. Eskola 1932).

On account of the dynamometamorphic habit of the ore formation, which can be seen so distinctly in the field and is also noticeable in the microscopic investigations of the ore, it is quite evident that the ore material had been forced to migrate by a stress action and had recrystallized at a temperature so low that the ilmenite and magnetite components could not crystallize together as titanomagnetite in any noteworthy quantity, but have both consolidated as separate grains. Therefore the lamellar segregations of ilmenite, so usual in some titaniferous iron ore formations, are very scarce in the Otanmäki field.

P. Ramdohr in 1941 studied under the microscope some ore samples from Otanmäki and wrote in a letter to P. Eskola expressing his opinion as follows: »dass das Erz durchbewegt und rekrystallisiert ist und dass dann das fast völlige (doch nicht absolute) Fehlen von Ilmenitlamellen im Magnetit durch Rekrystallisation bei relativ niedriger Temperatur zu deuten wäre».

O. Vaasjoki (1947), on the basis of only a few analyses and microscopical investigations, has presented the following assumption regarding the origin of the iron ore of Otanmäki: »though it in many details resem-

[1]) Venitization is a term for the process, by which the venites are formed (P. J. Holmquist 1921).

bles the titaniferous iron ore of early magmatic origin, it has gained the prevailing features of its structure as a mobilization product, caused by disturbances of a later tectonical period and thus in its whole, the ore resembles also the Routivare occurrence, explained by P. Ramdohr».

The gabbroic rock now occurring as amphibolite has evidently been originally somewhat heterogeneous at the time of intrusion with regard to the content of ilmenite and magnetite grains, but it is difficult to imagine such strongly striped structure and such extraordinary zoned differences between the contents of ore minerals in an igneous rock as seen in the ore-bearing amphibolite rock of Otanmäki. However, it is difficult to comprehend how it could have been caused by gravitative or crystallization differentiation.

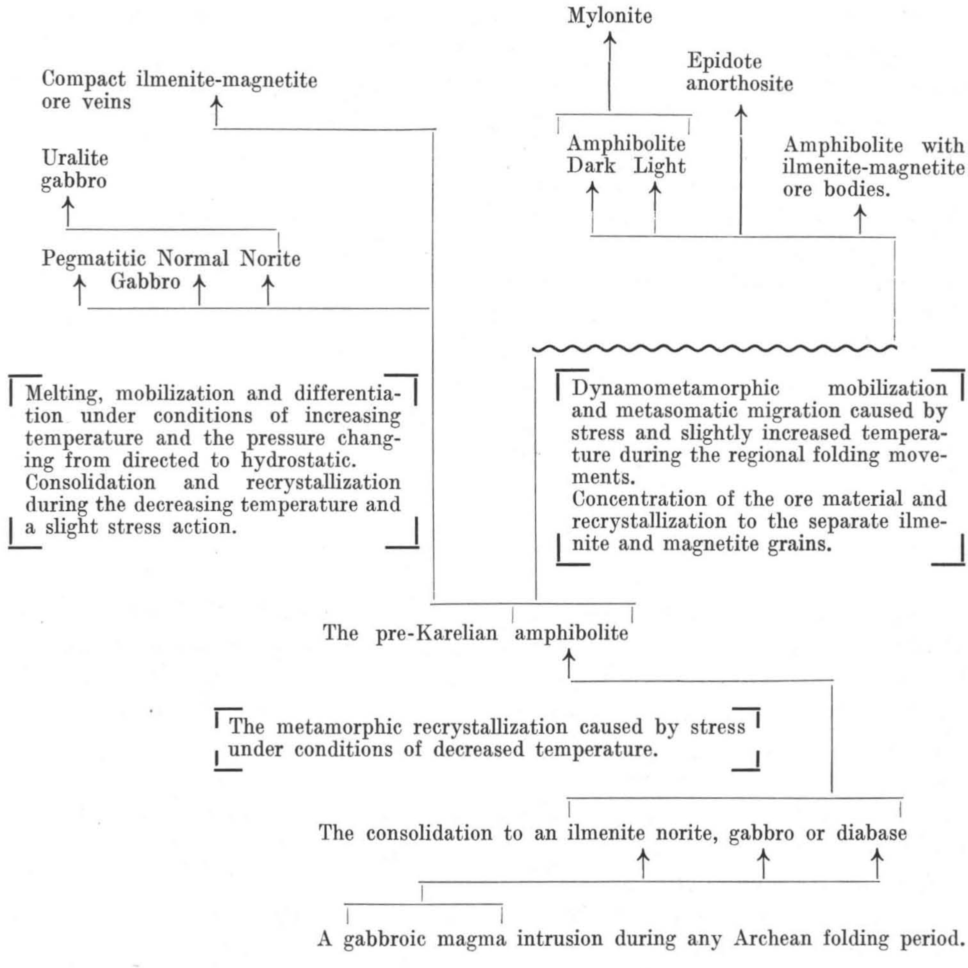
Since the richness of impregnations of the ilmenite and magnetite grains is so closely connected to the amphibolitic rock and the actual ore bodies are situated in the same amphibolite zone, the ore material originally is syngenetic with the amphibolite, which must accordingly be the mother-rock of the ore segregations.

The ore formations of the region and especially the ore zone of Otanmäki are situated in the large curves of the amphibolite belts. There is reason to believe that the genesis of the ore deposits is connected with the folding tectonic structure of the region and the strongly regionally metamorphosed habit of the rocks adjoining the ore formations. Evidently the centers of low pressure (the minima of the pressure) were formed by bending during the regional folding, and the ore material had been forced to migrate from the centers of high pressure to those of low pressure. At higher levels with lower temperatures this migration might have taken place laterally but not reaching far, whereas at greater depths the ore material might have been more mobile, owing to higher temperature and pressure and might have formed large massifs, which were able to intrude upwards as large veins. A process which causes the formation of ore mineral accumulations by directed pressure may be called stress metamorphic differentiation.

Investigations of drill cores have shown the zoned heterogeneity of the amphibolite at Otanmäki, the darker zones being usually more schistose than the lighter ones; and at greater depths the amphibolite seems to be more like gabbro. Light anorthositic veins and zones occur alongside the ore bodies, so it is possible to assume that even the salic components of the amphibolite have been partly mobilized to form these veins and zones (anorthositization, Barth 1952), while still deeper the amphibolitic rock as a whole has become able to intrude upwards as a large new gabbroic (plutonic-looking [1]) massif, such as is seen on the S side of the ore zone

[1]) Drescher-Kaden 1936.

Table XIX. Résumé of all the results observed in the ore zone and the imaginable geological processes that seem to have had one influence upon their forming.



at Otanmäki. The compact ore veins, penetrating the amphibolite, might have originated contemporaneously with the genesis of this new gabbro by a process resembling liquation. In this case, however, the differentiation has taken place due to a rise in temperature. Such a process may be called palingenetic differentiation. At the stage of mobilization of the gabbro, the stress action changed into hydrostatic pressure, and there was no more possibility of differentiation by stress. According to the definition of Eskola (1932) there takes place »differentiation within a rock mass, due to the extraction and redeposition of the most soluble substances», with the solutions having been mobilized mainly by orogenic forces. Schneiderhöhn (1949 p. 285) refers to the same phenomenon by the expression »Metamorphe Mobilizierung».

The strongly schistose zones of the almost homogeneous amphibolite, the distinct fragments of amphibolite in the gabbro, as well as the abundance of epidote and other products of alteration in the gabbro and amphibolite as well as the richness of chlorite in the ore show that the formation has lastly been metamorphosed in part metasomatically; and evidently the process took place at such a low temperature that a perfect fusion was not possible. These phenomena may have been caused by a slight increase of temperature, that is, the conditions of the epidote-amphibolite facies; but the uralitization of the gabbro shows that conditions during the last metamorphism of the Otanmäki formations were those of the epidote-uralite facies.

In some places the light as well as the dark amphibolite has a mylonitic habit, and also the gneissose granite sometimes has a strongly crushed structure, showing the low temperature conditions during the last movements.

COMPARISON AND CONCLUSIONS

The interesting geological phenomena observed in the ore field of Otanmäki and especially the problem of the genesis of the ore segregations cannot be compared with ilmenite-magnetite ore formations in Scandinavia by reference to other publications, as the descriptions partly are old and inadequate. It is also very difficult to represent the geological phenomena so distinctly that the reader can get a true picture. Therefore an expedition to some other important ilmenite-magnetite ore fields in Fenno-Scandia was necessary.

The results of such an expedition made by the author in 1946 were very satisfactory. Personal observations led to a better comprehension of the formations in question than the descriptions in the literature, which, of course, are more comprehensible now.

The ilmenite-magnetite ore field of Rödsand in Norway most closely resembles that of Otanmäki. The ore bodies adjoin schistose gabbro or amphibolite. The small as well as the large features of the ore formations are very similar. The action of the regional metamorphism is also quite evident in the structure of the ore bodies of Rödsand. The narrow amphibolite zones contain ore strips and heterogeneous ore bodies. The amphibolite zones themselves are situated in the middle of the veined gneisses or gneissose granites resembling the striped gneiss of the Otanmäki area. The main differences to be noticed are the absence of distinct massive gabbro and compact ore veins such as at Otanmäki; but at Rödsand there are pegmatite granite veins, that have not been observed yet in close connection with the ore rock of Otanmäki. The amphibolitic rock is very similar in both, but corundum is found only at Rödsand and biotite occurs more richly than at Otanmäki.

In regard to the ilmenite-magnetite ore deposits of Rödsand J. H. L. V o g t (1910) wrote (op. cit. p. 66): »Die hiesigen Titaneisenerzvorkommen sind somit i n d i r e k t — mit Gabbromagma als Zwischenstufe — aus einem granitischen Magma entstanden». He has established that the ore is located in »die gepressten Gabbrogesteine» but has not drawn any conclusion on the basis of it.

The differences between the habit of the ore at Otanmäki and that of the ilmenite-magnetite ores in the S o k n d a l region in Norway are considerably greater. In the ore fields of T i t a n i a and B l a a f j e l d the mother rock of the ore is norite, which has a somewhat different mineral composition from the amphibolite of Otanmäki. However, the metamorphic habits of the ore formations at Otanmäki and Titania are rather similar, both having a schistose habit, though caused by metamorphism of different strength. In addition the hypersthene grains of norite are orientated parallel to the distinct lineation. The ore rock is striped and heterogeneous similar to that of Rödsand and Otanmäki. The compact type of ore is found only at the narrow ends of the formation. The labradorite beside the ore zone resembles the gabbro of the Otanmäki region; but the latter, however, often contains more femic minerals. In the labradorite of the Sokndal area there are traces of a strike of foliation and of fragmental remainders of a rock resembling actual norite in the neighbourhood. According to J. H. L. V o g t (1893) one gets the impression that »Storgang» is a compact intrusive vein of ore mineral, but the observations made by author give reason to believe that the ore zone of Titania is a large fragment of the adjacent slightly schistose norite area rich in ilmenite and separated by a younger labradorite intrusion.

In the district of Blaafjeld nebulitic strips can also be observed in spite of the general massive character of the labradorite. The ilmenite-magnetite ore bodies of this area are more vein-like than in Titania, but the fragmental features of the ore zones give the impression of a segregation of the components of the ore minerals from an earlier, schistose norite at the same time as the rest of the rock material crystallized to labradorite. Under the prevailing conditions of this recrystallization such amounts of femic and salic material evidently could not crystallize together, but separated. However, some ilmenite-magnetite grains or a disseminated type of ore can be noticed in the border zone of the labradorite.

Unfortunately only three days could be devoted to investigation of this area, but all the observations led to the conclusion that the labradorite is a palingenic result of the partial anatexis of the earlier regionally metamorphosed norite.

P. Michot (1939) has also noticed two phases in the consolidation of anorthositic rocks in the region of Egersund-Sokndal and according to him the ilmenite ore formations are connected with the latter phase.

In Sweden some ilmenite-magnetite ore fields have also been visited briefly. They are all somewhat different from Otanmäki.

Of these the ore bodies of Kramsta in Järvsö most closely resemble that of Otanmäki. The ore rock is a slightly compressed gabbro in which metamorphism has been so slight that the hornblende is well preserved and remnants of pyroxene can still be noticed as inclusions or adjoining the hornblende grains. The plagioclase, however, occurs in two generations. The large older grains are turbid and ragged, but the grains of medium-size are clear and seem to have been formed during the recrystallization and using the material of the earlier large grains. In some places the rock is now a distinct amphibolite, but gives the impression that it has been a diabasic formation containing slight segregations of ilmenite-magnetite inside the border zone.

A quite different type of ilmenite-magnetite ore is represented by the formations of the Ulvö islands on the E coast of Sweden. These ore bodies are connected with an olivine diabase intrusion thoroughly described by José Sobral (1913).

There does not appear to be any remarkable abundance of ore, but slight segregation zones of ilmenite-magnetite run horizontally under the surface zone of the diabase massif. No signs of regional metamorphism are to be seen, but a very slight orientation of dark minerals is noticeable in the ore zone, evidently caused by friction on the resisting power of the wall rock during the intrusion of the diabase. It is difficult to believe that the ore bodies of Ulvö are primary magmatic gravitative differentiates of fractionating crystallization, but they have more probably been segregated by the effects of the slight stress caused by the wall rock and thermal diffusion (W. Wahl 1946) during the intrusion. Before regional metamorphism the ore formations of Otanmäki were possibly quite similar to those of Ulvö.

An olivine diabase, richer in ore minerals than usual, forms the titaniferous iron-ore of Smålands Taberg in southern Sweden. The ore minerals occasionally form compact segregations, but the whole central part of the hyperitic massif forms a poor titaniferous iron ore. Traces of a regional metamorphism cannot be seen, but the long plagioclase phenocrysts with reaction rims are mostly orientated parallel to the evident direction of the movement of the massif during the intrusion. Microscopic observations indicate that the plagioclase phenocrysts crystallized before the olivine and ore grains.

The titaniferous iron-ore deposit of Taberg is thoroughly described by Sven Hjelmqvist (1950) and both his investigations as well as those of the present author show that the formation is so different that further comparison cannot be made with the Otanmäki ore field.

Also very different are the ilmenite-magnetite ore segregations connected with the alkalic rocks of Alnö island not far from Sundsvall on the E coast of central Sweden (Högbom 1895 and von Eckermann 1946). There, the ore bodies seem to occur in places where the alkalic rock and the limestone have had a contact influence on each other. The origin of the titaniferous iron ore is due to these contact conditions. The same phenomenon is to be noticed in the alkalic rock areas of Fen in Norway, thoroughly described by W. C. Brögger (1921), and at some other occurrences of the alkalic rock.

Unfortunately the author has not yet had an opportunity to visit the titaniferous iron-ore formation at Routivaara in northern Sweden. From the descriptions by P. Ramdohr (1945) the conclusion can be drawn that it has many features in common with the Otanmäki field, but the mineral composition is somewhat different. According to P. Ramdohr the ore bodies of Routivaara are formed by a magmatic differentiation of the gabbroic mother rock during its intrusion, and regionally metamorphosed by the Caledonian folding. He explains that the silicate rocks are much more easily metamorphosed by stress action than the compact ore bodies, because the former contain minerals that are more like stress minerals than those of the ore bodies. This, however, is quite opposite to the usual case where the ore material seems to have been the first mobilized by stress action and the last to consolidate when the compressing force ceased. The oxides, which form the ore minerals, seem to have been capable of wandering all the time during the stress action. Ilmenite and magnetite grains are often elongated when included in silicate rocks, and the whole of the compact ore bodies have been elongated by the action of the stress. Evidently regional metamorphism has also taken part in the genesis of the ore segregations at Routivaara.

The descriptions and discussions of many titaniferous iron ore formations made by Kemp (1897), Singewald (1913), Warren (1918), Zavaritsky (1927), Lindgren (1928), Osborne (1928), Gillson (1932) and Newhouse (1936) show that each occurrence has its special features and has been formed under somewhat different conditions. Therefore it is difficult to form a general acceptable hypothesis for the genesis of the different titaniferous iron ore formations. Gillson's idea seems to be the most suitable to explain the features of ore fields in the Otanmäki region. According to his hypothesis there has never been a magmatic intrusion rich in ilmenite and magnetite, but the ore segregations have been formed after the consolidation and metamorphism of the anorthositic massifs by the agency of vapour and water solutions.

Based on the investigations and comparisons of the titaniferous iron ore formations of Fenno-Scandia, a division into two groups may be made as follows [1]).

1. The formations which have gained their habit without stress action or have been formed by a very slight compression during the intrusion.

2. The formations which have been subject to a strong stress action caused by orogenic forces.

Consequently the ore formations of the first group are connected to the gabbroic massifs, which have a diabasic character, and the formations of the second group adjoin the metamorphic gabbro or distinct amphibolite occurrences.

It is noticeable that certain gabbroic massifs, which have consolidated at great depths, contain slight ilmenite and magnetite impregnations or real ore segregations of these minerals; but those gabbroic rocks, which have a more diabasic character usually contain abundant mineral grains of titaniferous iron ore. In these, however, the ilmenite and magnetite are generally lamellar intergrowths or have crystallized as titano-magnetite (Hjelmqvist 1950) but not real ilmenite-magnetite ore formations containing rich ore bodies occur.

The ore segregations of the formations of the second group are often of economic importance because the ilmenite as well as the magnetite has crystallized as separate grains forming a dressable ore. Evidently strong stress action has caused the mobilization of the ore oxides and has forced them to migrate into places where the pressure is lowest. This phenomenon has happened at such a low temperature that the whole rock has not been fused, and the migrated ore components could only consolidate as separate ilmenite and magnetite grains (P. Ramdohr 1945). Usually, however, small inclusions of ilmenite and hematite occur in the magnetite.

Belonging to the first group, but somewhat exceptional, are the titaniferous iron ore formations in connection with some occurrences of alkalic rocks, where contact metamorphism has caused the segregations of the ore minerals.

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[1]) J. H. L. Vogt presented in 1900 (page 370) nearly the same division of the titanium-iron ore segregations in the basic eruptive rocks.

The conclusions of these comparisons is that the formation of a workable titaniferous iron ore is usually possible only when a gabbro or diabase very rich in titanium and iron oxides is strongly metamorphosed by a stress action.

Agreeing with P. Ramdohr (1937), the genesis of the titaniferous iron ore formations is not easy to explain, but the investigations in the ore fields of the Otanmäki region have shown that the occurrence of these ilmenite-magnetite ore segregations can hardly be a primary result of magmatic differentiation by crystallization. When ilmenite and magnetite seem to have crystallized later than the plagioclase in a magma, containing abundant calcium and magnesium oxide, differentiation caused by specific gravity is not possible.

In the classification of Ramdohr (1937) the ilmenite-magnetite ore formation of Otanmäki may belong to the main group of metamorphic ore, and to the sub-division when metamorphism is caused by stress and a slight increase of temperature.

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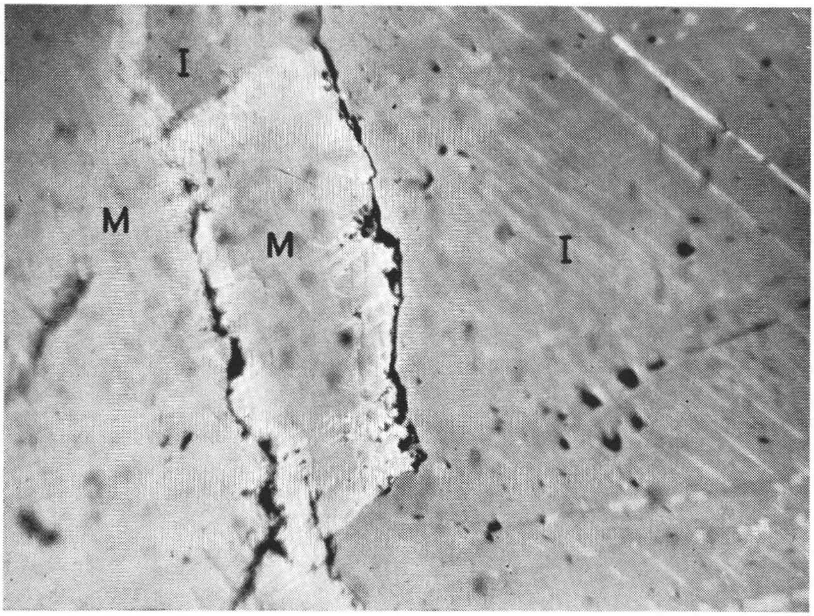
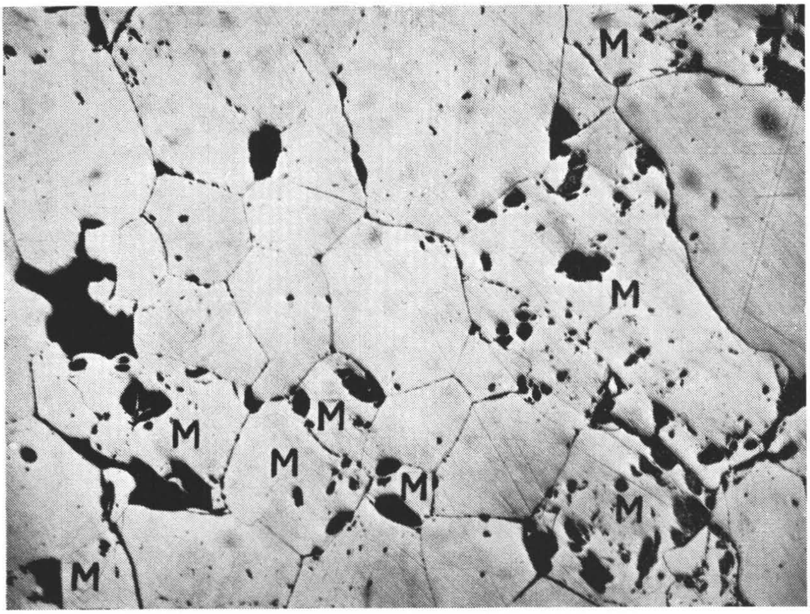
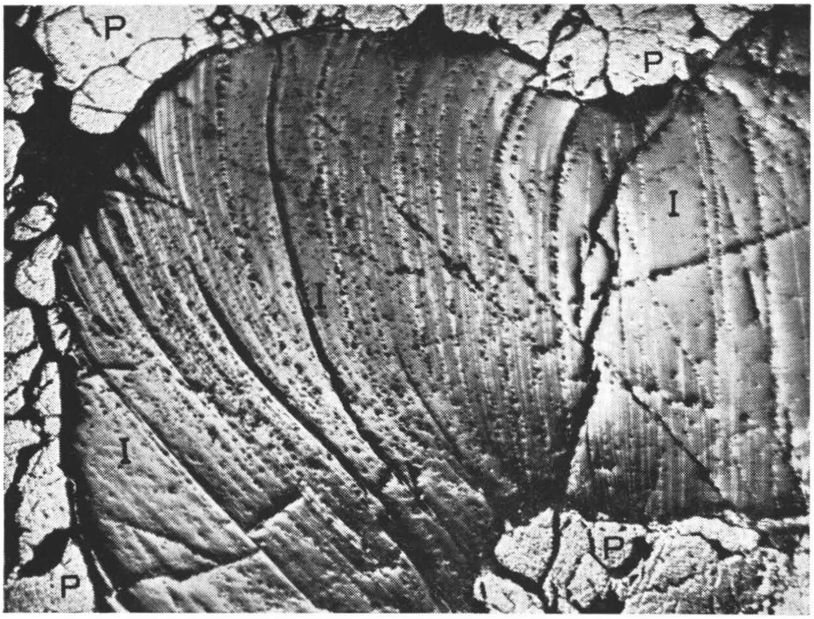


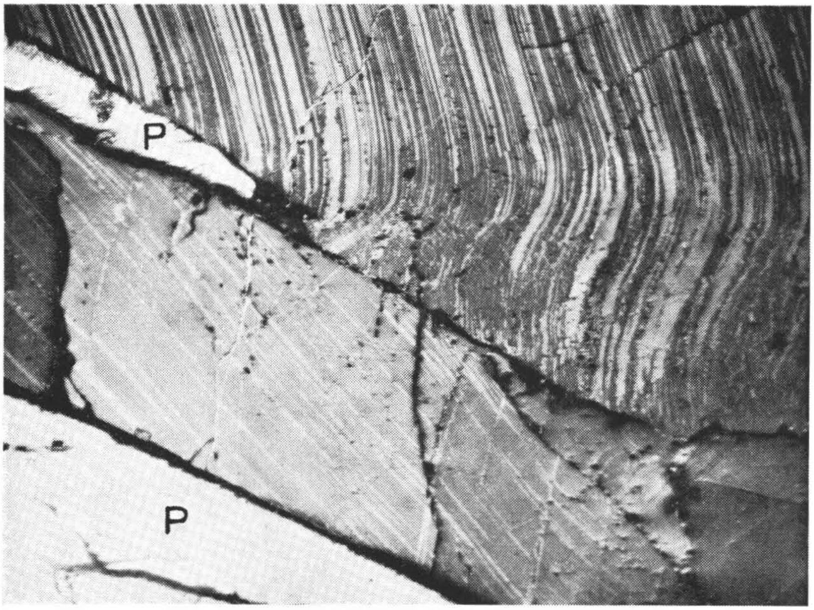
Lighter skeletal structure of martite indicates magnetite (M) grains; lamellar hematite inclusions occur in ilmenite (I). Magn. 580 x. Photo Erkki Halme.



Structure of first class ore. Light grey = ilmenite; the somewhat lighter grains containing numerous black (silicate) inclusions are magnetite (M). Magn. 90 x. Photo Erkki Halme.



Bent fragment of ilmenite (I) in larger pyrite (P) vein of ore zone at Otanmäki. Nic. +, magn. 25 x. Photo Erkki Halme.



Twin lamellae of ilmenite brecciated by light pyrite veins (P). Nic. +, magn. 70 x. Photo Erkki Halme.

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N:o 96. M i k k o l a, E r k k i. On the Physiography and Late-Glacial Deposits in Northern Lapland. P. 1—88. 25 fig. 5 plates. 1932 .... 250: —

N:o 97. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, V. P. 1—77. 15 fig. 1932 .... 200: —

N:o 98. S e d e r h o l m, J. J. On the Geology of Fennoscandia. P. 1—30. 1 map. 1 table. 1932 .... 150: —

N:o 99. T a n n e r, V. The Problems of the Eskers. The Esker-like Gravel Ridge of Čahpatoaiv, Lapland. P. 1—13. 2 plates. 1 map. 1932 ...... 100: —

N:o 100. S e d e r h o l m, J. J. Über die Bodenkonfiguration des Päijänne-Sees. S.1—23. 3 Fig. 1 karte. 1932 .... 250: —

N:o 101. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, VI. P. 1—118. 17 fig. 5 planches. 1933 .... 250: —

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N:o 103. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, VII. P. 1—48. 2 fig. 1933 .... 150: —

N:o 104. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, VIII. P. 1—156. 33 fig. 7 planches. 1934 .... 250: —

N:o 105. L o k k a, L a u r i. Neuere chemische Analysen von finnischen Gesteinen. S. 1—64. 1934 .... 150: —

N:o 106. H a c k m a n, V i c t o r. Das Rapakiwirandgebiet der Gegend von Lappeenranta (Willmanstrand). S. 1—82. 15 Fig. 2 Taf. 1 Analysentab. 1 Karte. 1934 .... 200: —

N:o 107. S e d e r h o l m, J. J. † On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland. Part III. The Åland Islands. P. 1—68. 43 fig. 2 maps. 1934 .... 200: —

N:o 108. L a i t a k a r i, A a r n e. Geologische Bibliographie Finnlands 1555—1933. S. 1—224. 1934 .... 250: —

N:o 109. V ä y r y n e n, H e i k k i. Über die Mineralparagenesis der Kieserze in den Gebieten von Outokumpu und Polvijärvi. S. 1—24. 7 Fig. 1 Karte. 1935 .... 100: —

N:o 110. S a k s e l a, M a r t t i. Über den geologischen Bau Süd-Ostbothniens. S. 1—35. 11 Fig. 1 Titelbild. 1 Taf. 1 Karte. 1935 .... 150: —

N:o 111. L o k k a, L a u r i. Über den Chemismus der Minerale (Orthit, Biotit u. a.) eines Feldspatbruches in Kangasala, SW-Finnland. S. 1—39. 2 Abbild. 1 Taf. 1935 .... 150: —

N:o 112. H a c k m a n, V i c t o r. J. J. Sederholm. Biographic Notes and Bibliography. P. 1—29. With a vignette. 1935 .... 100: —

N:o 113. S a h a m a (S a h l s t e i n), Th. G. Die Regelung von Quarz und Glimmer in den Gesteinen der finnisch-lappländischen Granulitformation. S. 1—110. 5 fig. 80 Diagr. 3 Taf. 1936 .... 200: —

N:o 114. H a a p a l a, P a a v o. On Serpentine Rocks in Northern Karelia. P. 1—83. 21 fig. 2 maps. 1936 .... 150: —

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N:o 116. V ä y r y n e n, H e i k k i. Petrologie des Nickelerzfeldes Kaulatunturi —Kammikivitunturi in Petsamo. S. 1—198. 71 Abbild. 36 Tab. 1 Karte. 1938 .... 250: —

N:o 117. K i l p i, S a m p o. Das Sotkamo-Gebiet in spätglazialer Zeit. S. 1—118. 36 Abbild. 3 Beil. 1937 .... 250: —

N:o 118. B r a n d e r, G u n n a r. Ein Interglazialfund bei Rouhiala in Südostfinnland. S. 1—76. 7 Fig. im Texte u. 7 Fig. auf 2 Taf. 1937 .... 200: —

N:o 119. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, X. P. 1—170. 30 fig. 4 planches. 1937 .... 250: —

N:o 120. H y y p p ä, E s a. Post-Glacial Changes of Shore-Line in South Finland. P. 1—225. 57 fig. 21 tab. 2 append. 1937 .... 250: —

N:o 121. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, XI. P. 1—166. 47 fig. 8 tab. 2 cartes. 1938 .... 250: —

N:o 122. H i e t a n e n, A n n a. On the Petrology of Finnish Quartzites. P. 1—118. 20 fig. 2 plates. 3 maps. 1938 .... 250: —

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N:o 127. M ö l d e r, K a r l. Studien über die Ökologie und Geologie der Bodendiatomeen in der Pojo-Bucht. P. 1—204. 7 Abbild. 1 Karte. 14 Diagr. 14 Tab. 1943 .... 250: —

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*N:o 130. H i e t a n e n, A n n a. Über das Grundbebirge des Kalantigebietes im südwestlichen Finnland. S. 1—105. 55 Fig. 8 Tafeln. 1 Karte. 1943 .. —

N:o 131. O k k o, V. Moränenuntersuchungen im westlichen Nordfinnland. S. 1—46. 12 Abb. 4 Tab. 1944 .... 150: —

N:o 132. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, XVI. P. 1—196. 41 diagr. 9 tabl. 3 vartes. 3 fig. 1944 .... 250: —

N:o 133. R a n k a m a, K a l e r v o. On the Geochemistry of Tantalum. P. 1—78. 1 fig. 8 tables. 1944 .... 200: —

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*) Loppuunmyyty.
Out of print.

N:o 134. Suomen Geologisen Seuran julkaisuja — Meddelanden från Geologiska Sällskapet i Finland — Comptes Rendus de la Société géologique de Finlande, XVII. P. 1—91. 59 fig. carte. 1944 .... 200: —

N:o 135. S a h a m a, T h. G. Spurenelemente der Gesteine im südlichen Finnisch-Lappland. S. 1—86. 12 Fig. 29 Tab. 1945 .... 200: —

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N:o 141. S i m o n e n, A h t i. On the Petrochemistry of the Infracrustal Rocks in the Svecofennidic Territory of Southwestern Finland. P. 1—18. 7 tabl. 5 fig. 1948 .... 50: —

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N:o 148. E d e l m a n, N i l s. Structural History of the Eastern part of the Gullkrona Basin, SW-Finland. P. 1—48. 16 fig. 2 tabl. 8 plates. 1949 150: —

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N:o 151. L o k k a, L a u r i. Chemical Analyses of Finnish Rocks. P. 1—75. 1950 200: —

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N:o 155. V i r k k a l a, K. Glacial Geology of the Suomussalmi Area, East Finland. P. 1—66. 26 fig. 1 plate. 1951 .... 200: —

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N:o 158. N e u v o n e n, K. J. Thermochemical Investigation of the Åkermanite — Gehlenite Series. P. 1—57. 7 fig. 12 tabl. 1952 .... 150: —

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N:o 161. D i s l e r, J ü r g. Die Kupferkieslagerstätte von Outokumpu, Finnland. (Ihre Lage, ihre Struktur und ihre Form.) S. 1—114. 39 Fig. 9 Diagr. 4 Taf. 1953 .... 400: —

N:o 162. K a i t a r o, S i m o. Geologic Structure of the Late Pre-Cambrian Intrusives in the Åva Area, Åland Islands. P. 1—71. 37 fig. 6 tabl. 1 map. 1953 .... 200: —

N:o 163. V a a s j o k i, O k e. On Migmatites and Ore Mineralizations in the Pernaja District, Southern Finland. P. 1—62. 24 fig. 3 tabl. 1 plate 1 map. 1953 .... 200: —

N:o 164. V ä h ä t a l o, V e i k k o O. On the Geology of the Outokumpu Ore Deposit in Finland P. 1—99. 9 fig. 13 tabl. 19 plates and 3 maps. 1953 .... 650: —

N:o 165. W i i k, H. B. Composition and origin of Soapstone. P. 1—57. 11 fig. 6 tabl. 1953 .... 150: —

N:o 166. Suomen Geologisen Seuran julkaisuja. — Meddelanden från Geologiska Sällskapet i Finland. — Comptes Rendus de la Société géologique de Finlande XXVII. P. 1—106. 16 tabl. 43 fig. 1954 .. 350: —

N:o 167. H y y p p ä, E s a. On the Pleistocene Geology of Southeastern New England. P. 155—225. 33 fig. 1955 .... 200: —

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N:o 169. S a l m i, M a r t t i. Prospecting for Bog-Covered Ore by Means of Peat Investigations. P. 1—34. 6 fig. 8 tabl. 1955 .... 150: —

N:o 170. O k k o, V e i k k o. Glacial Drift in Iceland, its Origin and Morphology. P. 1—133. 35 fig. and. one table in text. 32 fig. in plates I—XVI. 1955 .... 400: —

N:o 171. P ä ä k k ö n e n, V e i k k o. Otanmäki, the Ilmenite-Magnetite Ore Field in Finland. P. 1—71. 41 fig. 19 tabl. 2 plates and 3 maps. 1956 300: —

N:o 172. Suomen Geologisen Seuran julkaisuja. — Meddelanden från Geologiska Sällskapet i Finland. — Comptes Rendus de la Société géologique de Finlande XXIX. P. 1—100. 24 fig. 30 tabl. 1956 .... 350: —

N:o 173. R a m d o h r, P a u l. Die Beziehungen von Fe-Ti-Erzen aus magmatischen Gesteinen. (painossa — in print)

N:o 174. S a v o l a h t i, A n t t i. The Ahvenisto Massif in Finland. The Age of the Surrounding Gabbro-anorthosite Complex and the Crystallization of Rapakivi. P. 1—96. 22 fig. 11 tabl. and 1 map 1956 .... 350: —

N:o 175. S a l m i, M a r t t i. Peat and Bog Plants as Indicators of Ore Minerals in Vihanti Ore Field in Western Finland. P. 1—22. 6 fig. 1 tabl. 1956 .... 100: —

TOTAL INTENSITY

FLIGHT ALTITUDE 150 m ABOVE GROUND LEVEL

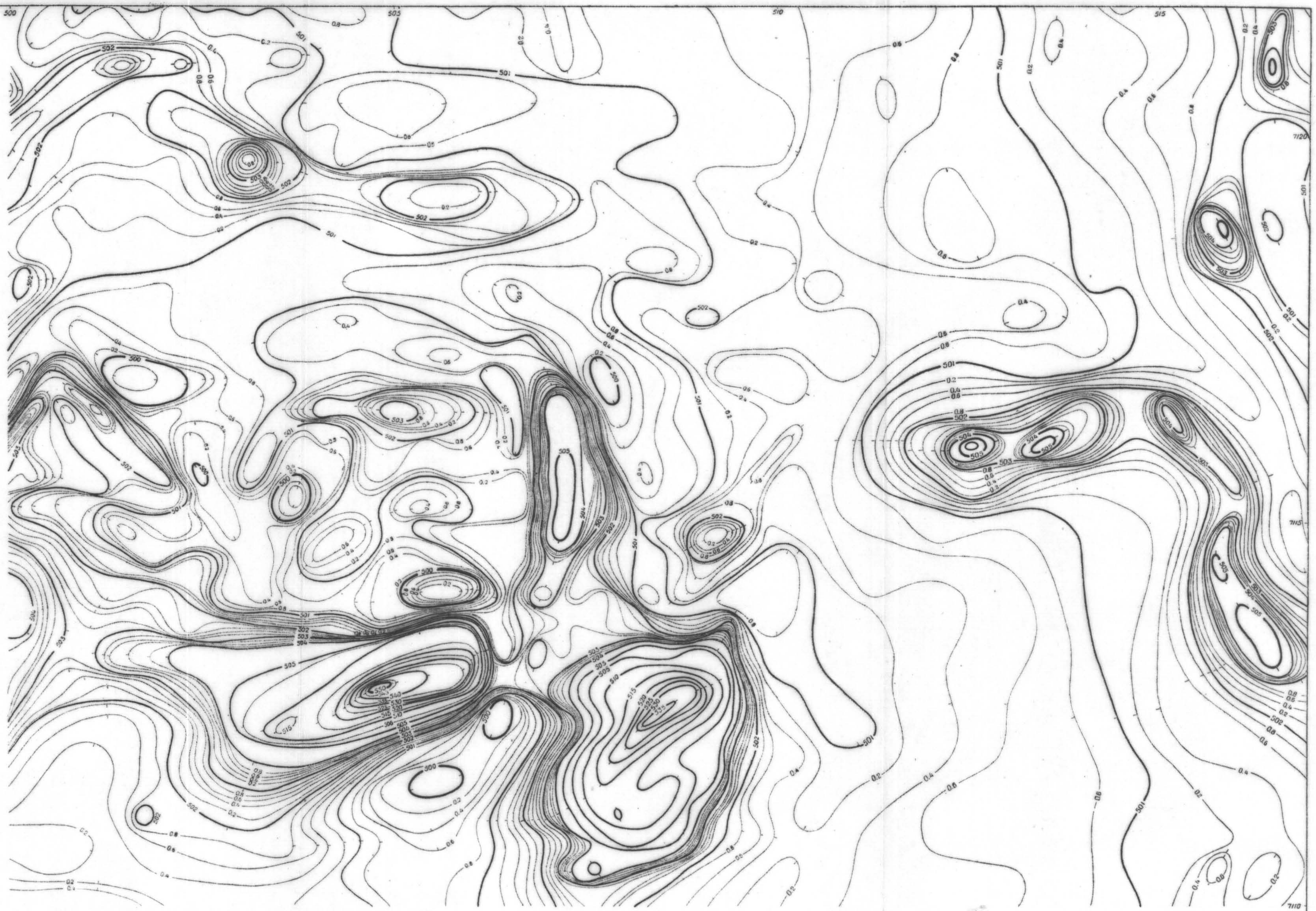
ISOMAGNETIC LINES (TOTAL FIELD)

500 ≈ 50000 gammas

0.4 = 40 gammas

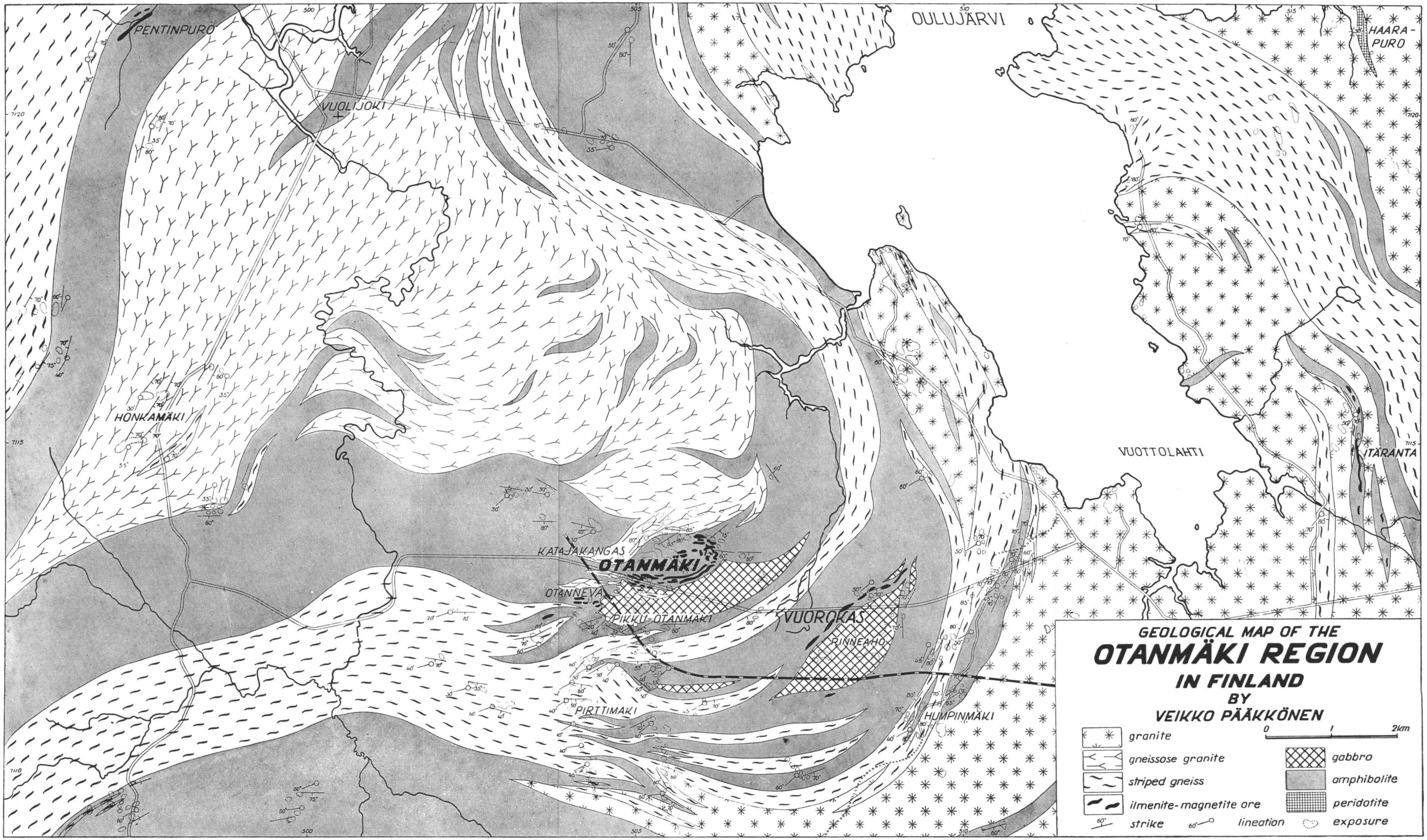
SCALE

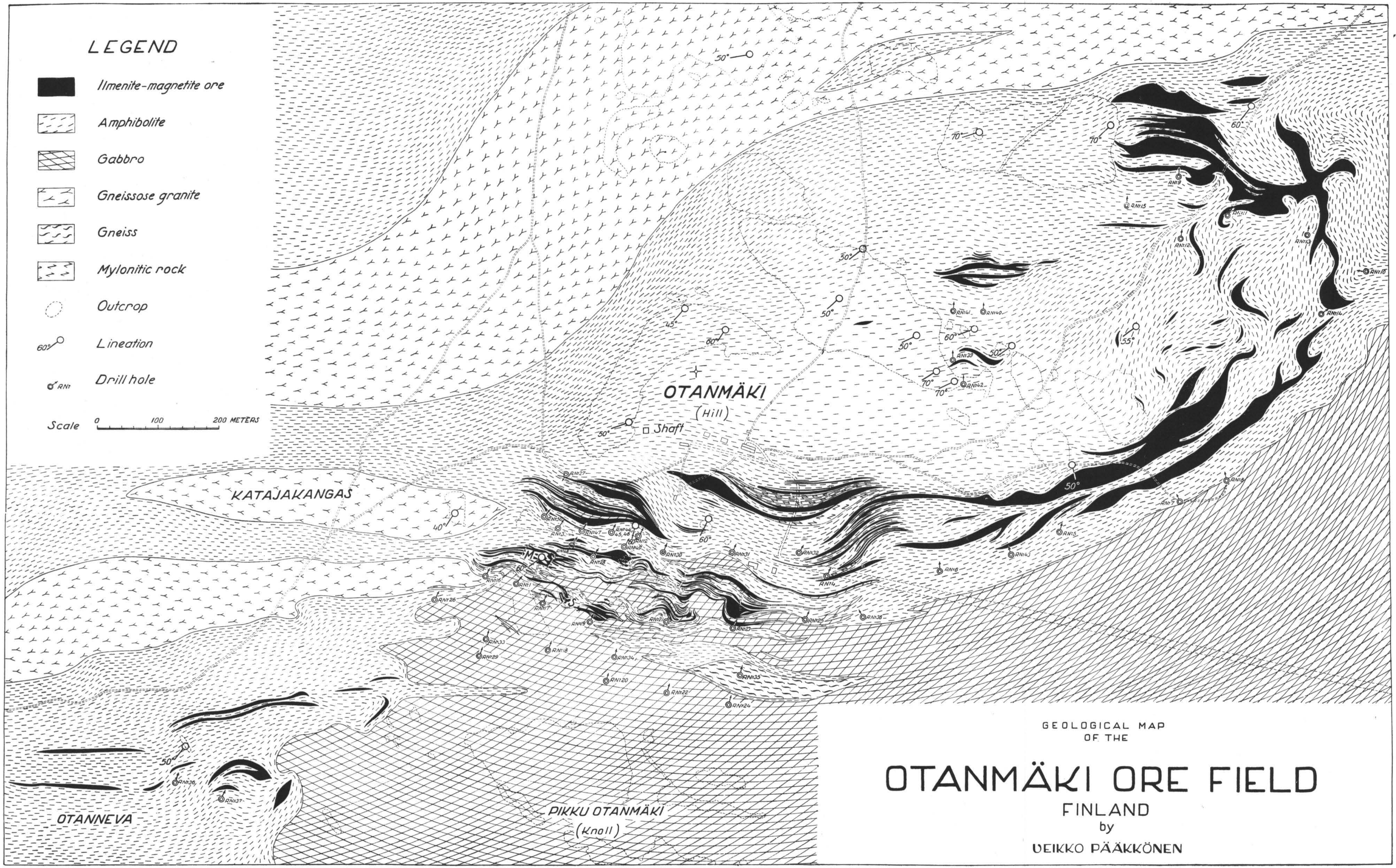
0 1 2 KM



AEROMAGNETIC MAP OF OTANMÄKI REGION

AEROMAGNETIC SURVEY BY GEOLOGICAL SURVEY OF FINLAND


GEOLOGICAL MAP OF THE
OTANMÄKI REGION
IN FINLAND
BY
VEIKKO PÄÄKKÖNEN
granite
gneissose granite
striped gneiss
ilmenite-magnetite ore
strike
lineation
gabbro
amphibolite
peridotite
exposure
0 1 2km
OULUJÄRVI
PENTINPURO
VUOLIJOKI
HAARA-PURO
HONKAMÄKI
VUOTTOLAHTI
ITÄRANTA
KATAJAKANGAS
OTANMÄKI
OTANNEVA
PIKKU-OTANMÄKI
VUOROKAS
RINNEAHO
PIRTTIMÄKI
HUMPINMÄKI


LEGEND
Ilmenite-magnetite ore
Amphibolite
Gabbro
Gneissose granite
Gneiss
Mylonitic rock
Outcrop
Lineation
Drill hole
Scale 0 100 200 METERS
OTANMÄKI
(Hill)
Shaft
KATAJAKANGAS
OTANNEVA
PIKKU OTANMÄKI
(Knoll)
GEOLOGICAL MAP
OF THE
OTANMÄKI ORE FIELD
FINLAND
by
VEIKKO PÄÄKKÖNEN