26th International Geological Congress
Paris 1980

Precambrian ores of Finland

Guide to excursions 078 A+C, Part 2 (Finland)

Edited by T. A. Häkli

Geological Survey of Finland
Espoo 1980

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The following Precambrian ore deposits in Finland and their geological settings are described: Kemi chromite deposit, Vihanti Zn—Cu ore, Otanmäki vanadium-bearing Ti—Fe ore, Outokumpu copper ore and Kotalahti Ni—Cu deposit.

Key words: economic geology, ore deposits, chromite, iron, zinc, nickel copper, Precambrian, Finland.

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DAILY ROUTES

Excursion 078A: 27th June— 5th July, 1980
Excursion 078C: 19th July—27th July, 1980

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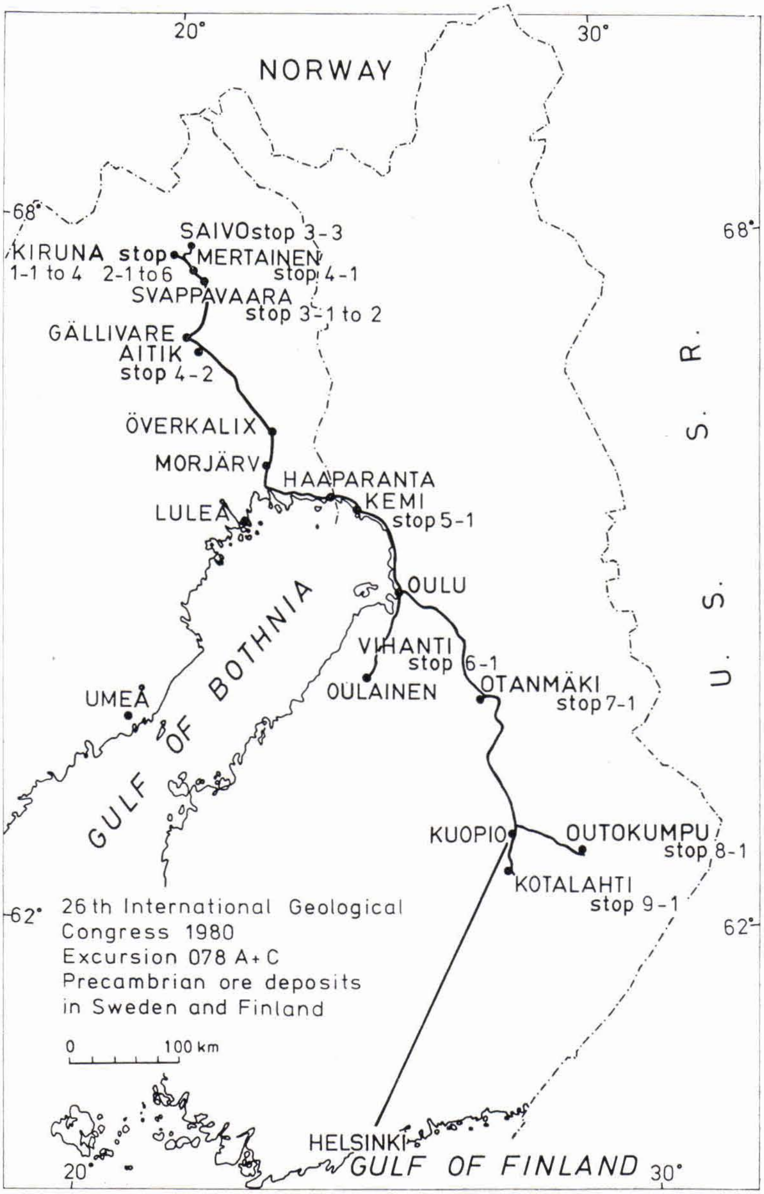

Excursion route and daily stops.

GEOLOGY OF THE KEMI CHROMITE DEPOSIT — by J. Kujanpää

Location and history

The Kemi chromite mine (stop 5) and mill are located 10 km northeast of the town of Kemi, Finland, near the northeastern shore of the Gulf of Bothnia at a latitude of about 65° 45′N. The Tornio works (ferrochrome plant and stainless-steel works) are situated 10 km south of Tornio, 25 km west of the Kemi mine (Fig. p. 5).

The chromite deposit was discovered in 1959. The decision to start benefication of the ore was made in 1964 as a result of comprehensive studies and financial calculations. After running the mine for two years as a pilot plant; mining started on an industrial scale in 1968.

A ferrochrome plant was built in Tornio to utilize the chromite concentrates produced in Kemi. Production of ferrochrome started in 1968.

Outokumpu Co. produces chromium and nickel, the most important raw materials for stainless steel, from its own ore deposits. Thus it was only natural that the company should build a stainless-steel works in Tornio, next to the ferrochrome plant. The production of cold-rolled sheet and strip started in 1976.

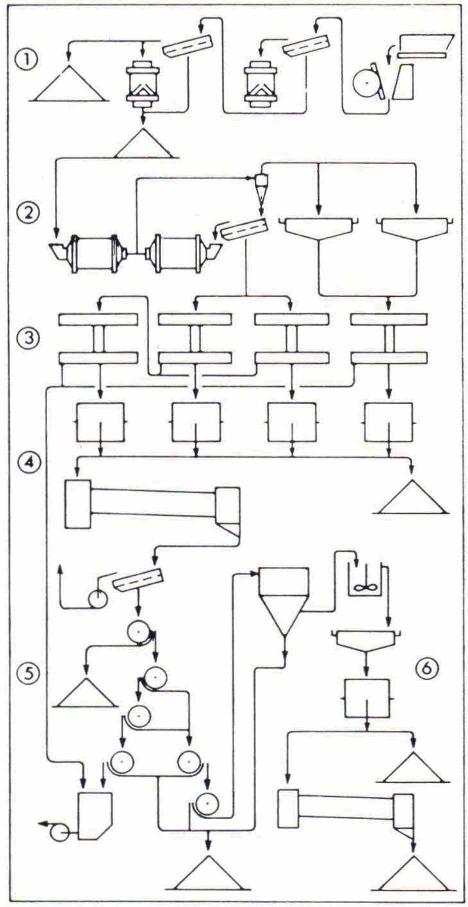

Fig. 1. Flow sheet of the concentrator.
1. Crushing; 2. Grinding; 3. Wet concentration; 4. Dewatering; 5. Dry concentration; 6. Foundry sand prod.

Mining

At present ore is extracted from open pit with a bench height of 12 m. Blast holes are drilled by 10) rotary drills and blasted by AN/Fo and ammonium nitrate or slurry cartridge as an initiator. Hydraulic excavators and front-end loaders load the blasted ore and gangue on diesel powered dumpers for transport to the crusher or the dump.

The Viia orebodies, which are currently being mined, contain 6.3 mill. MT ore, 15.8 mill. MT of waste and 1.4 mill. cubic meters of soil as overburden.

The Viia pit was planned by computerized pit-design program to be 110 m deep with a total pit wall inclination of 45°.

Concentrator

After crushing, the ore is ground to a fineness of minus 0.5 mm for final concentrating in wet and dry magnetic separators. Part of the chromite concentrate is processed further into foundry sand by air classification and washing.

Chromite concentrate is processed at the company's Tornio works into ferrochrome and stainless steel. The annual concentrate demand at the Tornio works is approximately 140 000 tons; the rest is marketed to the metallurgical and chemical industry.

The 15 000 tons of foundry sand produced annually is used in steel foundries. The latest product of the Kemi mine is an extremely fine-ground concentrate, chromite powder, which is sold principally as pigment material for the glass industry. The flow sheet of the concentrator is shown in Fig. 1.

Geology of the Kemi area

The Kemi—Tornio—Rovaniemi area, or the Peräpohja schist formation, is a distinctly defined geological unit of triangular shape (Fig. 2). It is bordered in the north by the Central Lapland granite area and in the south by the Pudasjärvi granite gneiss area. The base of the triangle, from Tornio to Ylitornio, is formed by the river Tornionjoki; the apex is the Misi iron ore district some 150 km northeast of Tornio.

The Peräpohja area is a bowl-shaped unit composed of two furrows trending roughly westward and separated by a ridge. Mikkola (1949) calls the northern furrow the Martimojoki syncline and the southern one the lower Kemijoki syncline; the ridge that separates the furrows he calls the Korpikylä anticline. Each furrow includes smaller subsynclines.

The Peräpohja schist area is characterized by supracrustal rocks and the abundant products of initial magmatism and volcanism associated with them both temporally and spatially. In general, the rocks show low-grade metamorphism.

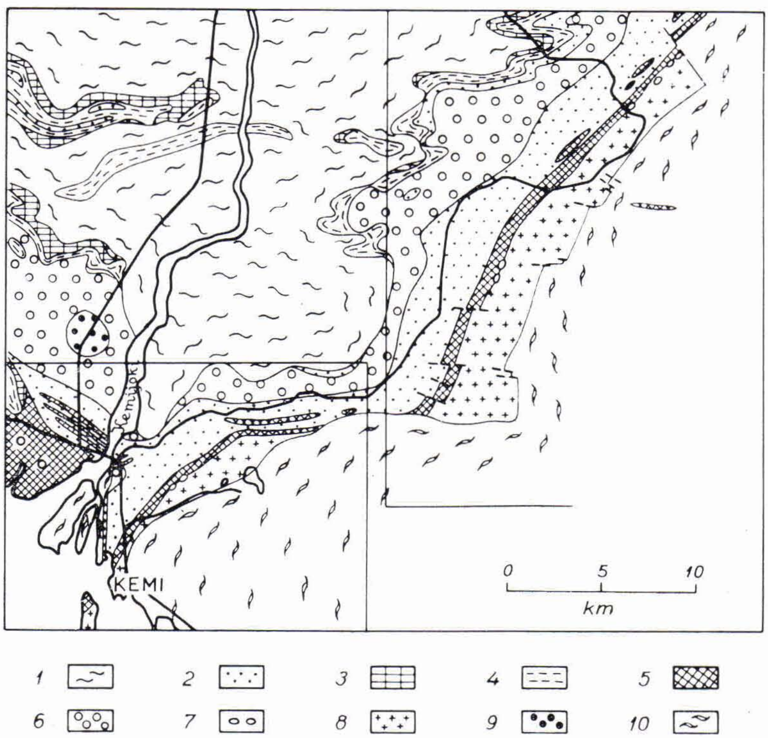

Fig. 2. Geological map of the the Kemi area. According to Perttunen 1971. 1. Phyllite; 2. Quartzite; 3. Dolomite; 4. Tuffitic greenstone; 5. Greenstone, mainly as sills; 6. Extrusive greenstone, mainly amygdaloidal; 7. Conglomerate; 8. Kemi and Penikka formations; 9. Granodiorite; 10 Granite gneiss.

The stratigraphy of the sedimentary rocks is best established in the southern part of the area, although locally it has also been traced elsewhere. The following description of the rocks is based on the latest geological maps (by Vesa Perttunen) of the Geological Survey of Finland (Sheets: Kemi, Runkaus, Karunki and Simo) and proceeds from the oldest to the youngest units. Lowest in the sequence is a basal conglomerate resting on the basement gneiss complex. It has been encountered at Laurila, on the western shore of the river Kemijoki, in the Kemi belt in the cut of the Veitsiluoto fresh water canal, in the Penikat zone northwest of Ala-Penikka, at Sompujärvi and at Suhanko in the Ranua area. This unit is succeeded by products of the first stage of volcanism, e.g. the agglomerates west of Kemi airport and at Sompujärvi. The volcanites are overlain by a quartzite formation — the Kivalo quartzite — that, averaging 2 km in thickness, extends for at least 100 km northeast of Kemi. The Kivalo quartzite is overlain by a formation, 1—5 km thick, of spilitic greenstones of the second stage of volcanism. They are typically amygdaloidal mafic lavas with local agglomerates and metadiabases. The lavas are free from acid differentiates.

The lavas are covered by another orthoquartzite formation up to half a kilometer in thickness, which is exposed e.g. in the Kvartsimaa quarry in Alatornio and shows alternating intercalations of dolomite. This quartzite is overlain by the topmost volcanic formation, in which the tuffitic rocks are metamorphosed into graded-bedded mafic schists. The largest dolomite occurrences in the area occur in the highest horizon of the schist zone. The thickness of the greenschist-dolomite zone is one kilometer at the most. Black schists are encountered in association with greenschists in the central part of the Peräpohja area particularly in the northwestern corner. The mafic schists grade upwards into graded-bedded phyllitic schists. As an intraformational speciality, the Taivalkoski conglomerate lends a spot of colour to the topmost unit in the stratigraphy of this area.

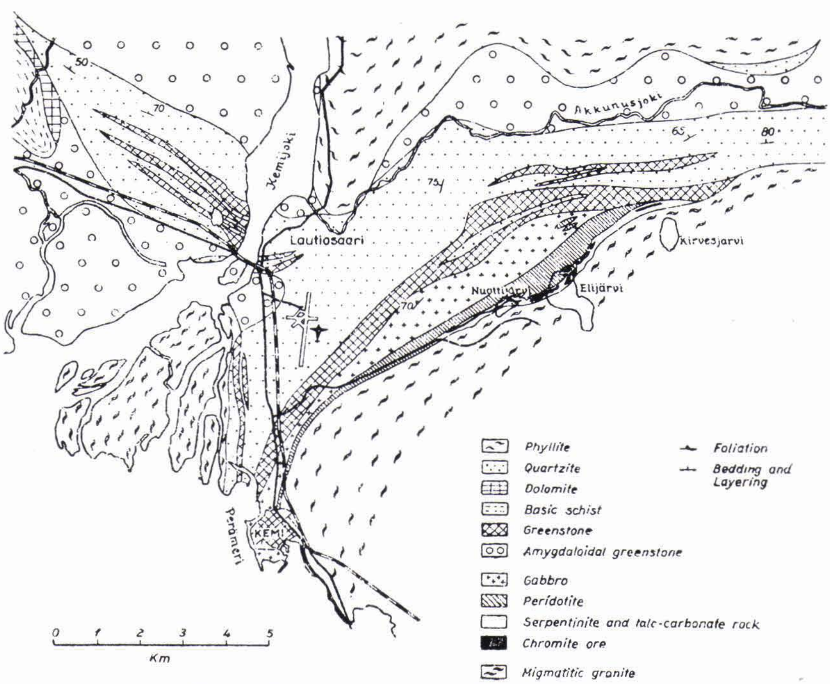

Fig. 3. Geologic structure of the Kemi zone.

A continuous albite diabase sill, from 0.5 to 1 km in thickness, and local stratified sill-like mafic-ultramafic plutonic rocks (the Kemi and Penikat formations in the Kemi area, the Suhanko and Särkikämä formations in the Ranua area) occur between the basement gneiss complex and the Kivalo quartzite and the underlying volcanites. Parts of the old basal conglomerate and the overlying volcanites were displaced by the intrusions from their original position to between the albite diabase and mafic plutonites.

The plutonites that intersect the southwestern part of the Peräpohja area belong to the Haaparanta Suite, which includes mafic to acid members; mention should be made of the extensive gabbro area at Tornio, which grades into granodiorite towards Kaakamo. A small gabbro-peridotite body of the Suite is encountered some 14 km north of Tornio, on the river Liakajoki; the large granodiorite massif of Nosa with dioritic marginal variants is located immediately to the east of it.

Geologic structure of the Kemi zone

The Kemi zone is a typical example of a stratified sill-like in situ differentiated mafic-ultramafic plutonic intrusion. Starting at the town of Kemi on the shore of the Gulf of Bothnia, the Kemi zone extends 15 km towards NE, varying in width from 300 to 1 900 m. In shape the formation is a slightly bent plate that dips northwestwards at an average angle of 70° and trends NE. The Kemi zone is a flat region 20—25 metres above sea level, and largely covered by bogs and shallow lakes; outcrops are few.

The known part of the zone begins at Kemi, where it is about 500 m wide; south of the air-port it narrows down to 250 m and then widens again until at Elijärvi it is as much as 1 900 m in width. The formation narrows very rapidly from Elijärvi northeastwards and pinches out north of Kirvesjärvi (Fig. 3). The zone is very poorly exposed. It has been observed in only a few scattered small outcrops, in a rail-road cut at Kemi, in a shallow fresh-water canal west of Nuottijärvi and in a few clusters of outcrops in the Elijärvi—Nuottijärvi area. Nowhere are the contacts of the formation exposed. Nevertheless, owing to a fairly dense drilling grid the south-eastern boundary of the zone is well established in the Nuottijärvi—Elijärvi—Kirvesjärvi area. In 1977 the southeastern contact of the zone was exposed in the course of earth removal from the Viia open pit; at present it is visible in the foot-wall of the pit close to the ramp.

The upper part of the sequence is composed of amphibolitized and saussuritized pyroxene gabbros with anorthitic and pyroxenitic interlayers. In the middle of the formation, immediately above the ultramafic lower part, these rocks are unaltered and mainly norites in composition. The gabbro unit is up to 1 km in thickness. The lower part of the formation is composed entirely of ultramafic rocks, largely of alternating peridotite, pyroxenite and dunite layers and chromite ore. The coherent chromite-rich horizon occurs at a level about 50 to 200 m from the bottom of the formation. As a result of autometasomatism, peridotites have altered into serpentinites and talc-carbonate rocks around the ore; however the primary features of peridotite are still rather well preserved. Magmatic layering is best developed immediately above the coherent chromite horizon in a zone from 20 to 50 m thick. The layering is due to the alternation of narrow peridotite, pyroxenite, serpentinite, talc-carbonate rock and chromite layers. At the base of the sequence the talc-carbonate rock is intensely tectonized against the basement gneiss complex, where it is altered into mylonitic talc-chlorite schist 5 to 50 m thick. The ultramafic unit attains the same thickness as the gabbro unit, i.e. up to 1 000 m.

Chromite ores in the Kemi zone

The continuous chromite horizon, conformable with the southeastern contact of the formation, varies from a few centimetres to a few metres in thickness. At Nuottijärvi—Elijärvi, the thickest part of the formation, however, the chromite horizon shows several successive swells for a distance of about 4.5 km. Moreover, the horizon has two forks, one on the eastern shore of the lake Nuottijärvi and one on the north-eastern end of the lake Elijärvi. The swells in the chromite horizon constitute eight separate orebodies, whose names and locations are shown in Fig. 4, and in which the thickness of the chromite horizon varies from 30 to 90 m. By means of a computerized two-dimensional ore inventory register, an ore model and the optimization of the open pit, six open pits were planned, which at the end of 1978 totalled some 14.5 million tons of ore with a cut-off limit of 20 % Cr_2O_3. The bottoms of the optimized open pits reach a depth of 120 m below the ground surface.

The Elijärvi orebody has been studied by means of drill sections 100 m apart down to a depth of 300 m; the deepest drill hole intersected the ore at a depth of 450 m. Information on the Viianranta and Viianlahti orebodies is from a depth of some 200 m, and the Viianmaa orebody has been intersected by two drill holes at a depth of 250 m. Data are not available on other orebodies from below open pit depth.

The Elijärvi orebody is the best known part of the ore horizon; about 3.5 million tons of ore were mined from it between 1966 and 1977. The detailed structure of the orebody is illustrated in Fig. 5, which shows the surface plan and cross-sections across the centre and both ends of the open pit. The layered structure in the hanging-wall country rock and in the upper part of the ore is a typical feature of the Elijärvi orebody. The lower part of the orebody and the whole western end are intensely brecciated and the ore contains abundant serpentinite and country rock fragments, which cause trouble in mining. The footwall of the ore consists of talc-carbonate rock with small serpentinite portions showing disseminated chromite and chromite nodules and accumulations varying in size and shape. In terms of host rock, the ore can be

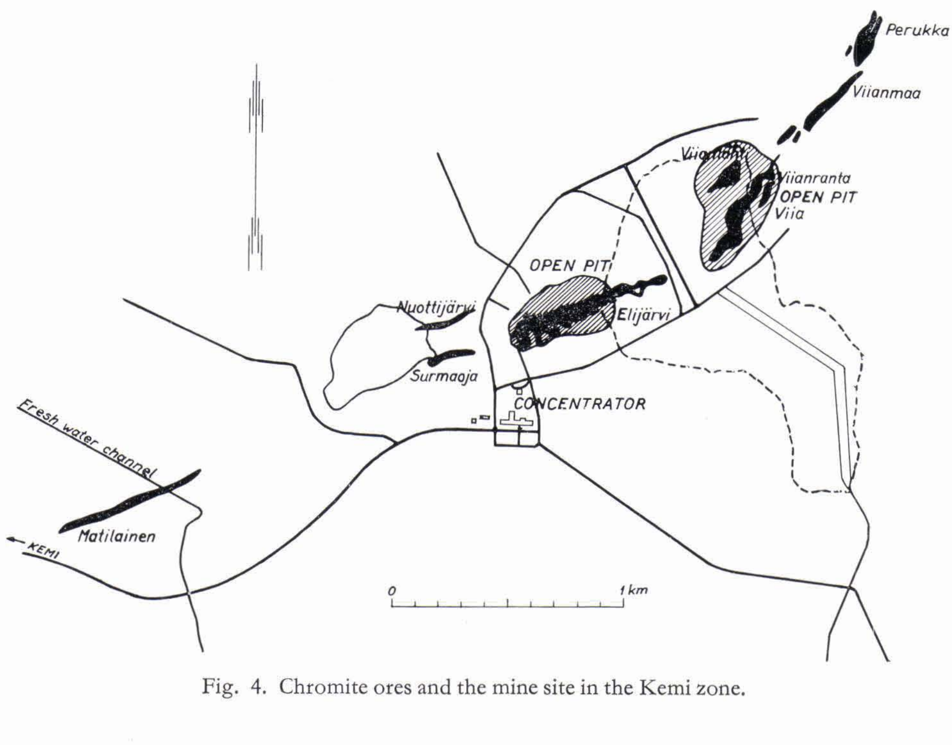

Fig. 4. Chromite ores and the mine site in the Kemi zone.

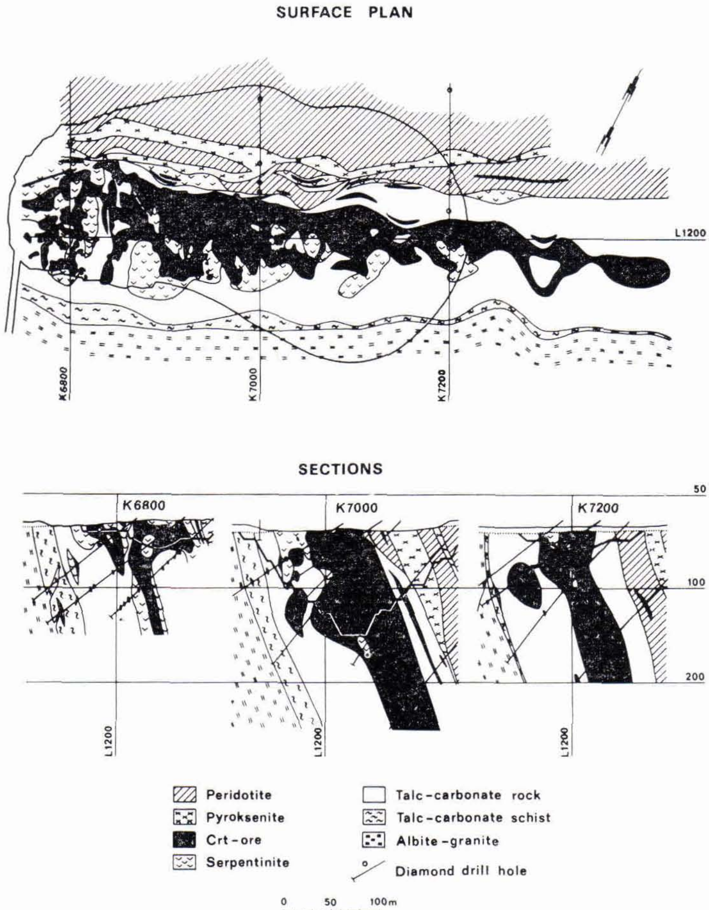

Fig. 5. Surface plan and three sections of the Elijärvi orebody, with open pit plan.

divided into two main types: soft talc-rich ore and hard, serpentine-rich ore. The latter accounts for about 15 % of the total ore reserves. The euhedral chromite grains average 0.2 mm in size. The gangue minerals include talc, serpentine, magnesite and dolomite as well as kämmererite, a fairly abundant chrome-bearing chlorite. Very fine-grained uvarovite occurs locally in the upper parts of the ore horizon. The other accessory oxides are magnetite, ilmenite, hematite and rutile; the sulphides, which occur only as microscopic grains, include pyrite, chalcopyrite and millerite. The ore mined from the Elijärvi open pit averages 26.5 % Cr_2O_3, corresponding to 65 % chromite; the density of the ore is 3.45 and of the pure chromite 4.65. Fig. 6 shows the averages of the main components as a function of the Cr_2O_3 in the ore, giving Cr_2O_3 = 26.5 %, FeO_{tot} = 12 % (FeO: Fe_2O_3 = 3.5), Al_2O_3 = 9.5 %, MgO = 19.5 %, SiO_2 = 18.5 % and Cr: Fe = 1.54 for the average ore. Chromite contains 0.15—0.35 % Ti, 0.15—0.20 % Mn and less than 0.1 % V. Platinum-group metals have not been detected.

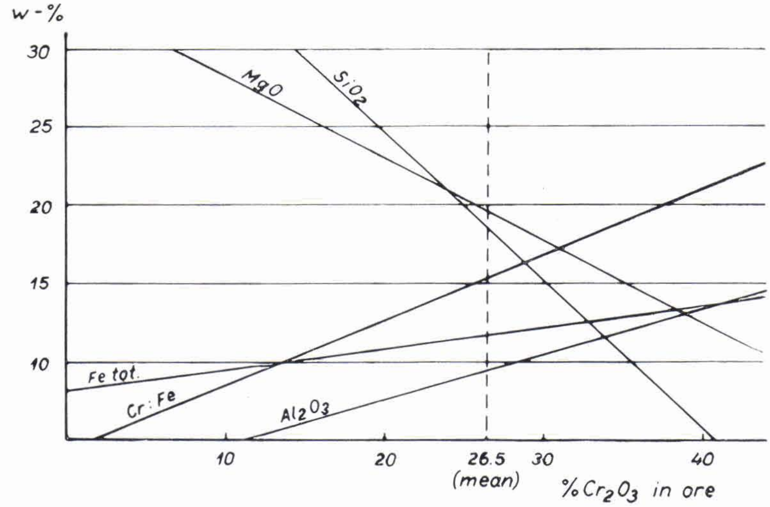

Fig. 6. Variation in the chemical composition of the Elijärvi orebody.

At the end of 1976 and beginning of 1977 mining moved to the Viia open pit, which includes the Viianranta and Viianlahti orebodies (Fig. 4). In two years over one million tons of ore have been extracted from this pit, and the ore reserves are now some five million tons. Fig. 7 shows the surface plan of the Viia orebodies and two sections, one across the western end of the Viianranta orebody and the other across the Viianlahti orebody and the eastern end of the Viianranta orebody. Geologically the environment of these ores differ from that at Elijärvi, in that hanging wall peridotites have turned extensively into talc-carbonate rocks and the typical layered structure is lacking or almost completely obliterated. Serpentinite portions are very rare in both hanging wall and footwall, and the ore does not contain the serpentine-rich type. Talc and dolomite are practically the sole gangue minerals in the ore. The Viianranta orebody is broken into several parts and shows a breccia structure similar to that in the lower part of the Elijärvi orebody. The Viia area is further characterized by wide transversal albite diabase dykes, in whose environment the ore and wall rock are intensely fractured. Cataclasis is marked in the chromite in the Viia ores; hence the average grain size is very small and the ore is difficult to concentrate. This is particularly true of the Viianlahti orebody, whereas the Viianranta orebody has large areas with unbroken chromite.

In the Viia orebody the average Cr content is over one percent point higher and the Cr: Fe ratio about one tenth higher than in the Elijärvi orebody; otherwise the variation in main components is as shown in Fig. 7. The trace element abundance are also very similar at Viia and Elijärvi.

The other orebodies are known only from drilling data. They show that the structures and types encountered at Elijärvi predominate in the whole area. The grade of the orebodies varies between 24.5 and 30.5 % Cr_2O_3 and the Cr: Fe ratio from 1.52 to 1.69. In the whole area the average Cr_2O_3 content in the ores is 27.5 %, the Cr: Fe ratio 1.58. The Cr_2O_3 content in chromite averages 34 %, but it may reach 51—52 %.

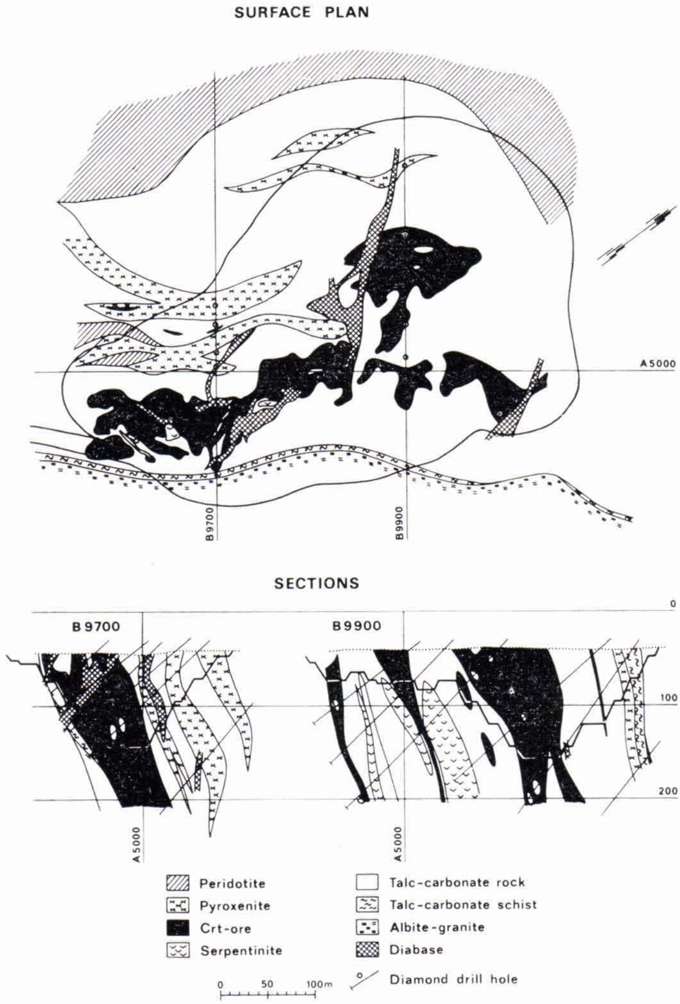

Fig. 7. Surface plan and two sections of the Viianranta and Viianlahti orebodies, with open pit plan.

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GEOLOGY OF THE VIHANTI MINE — by E. Rauhamäki, T. Mäkelä and O.-P. Isomäki

Introduction

Location

The Vihanti mine (stop 6), located about 70 km south of Oulu, is one of the largest mines belonging to the state-owned company, Outokumpu Oy. It employs somewhat more than 400 persons, most of whom live in the mine town, where the company has erected 250 houses for the personnel.

Discovery and development

The first indications of ore in the Vihanti area came from pyrite-, chalcopyrite- and sphalerite-bearing floats discovered by local people in the years 1936—1941. Geological and geophysical investigations were set in motion; the Lampinsaari anomaly was pin-pointed in 1945 and the associated ore deposit in the following years. In 1951 gravimetric surveys guided diamond drilling to the site of the Vihanti ores proper.

The development of the deposit began in November 1951, and the exploitation of the zinc ore in October 1954. By 1957 the production of zinc ore exceeded 400 000 tons; currently it is roughly 500 000 tons a year.

Subsequent studies revealed pyritic ores in excess of the reserves estimated at the time the decision was made to exploit the deposit. In 1963 the Kokkola works of Outokumpu Oy started to process pyrite ores and in 1967 the mining of pyrite orebodies began at Vihanti.

Owing to a deteriorating sulphur market, mining was shifted in 1972 to the copper-rich portions of the pyritic ores and to disseminated copper ores. These have since been mined at an annual rate of 250 000 to 400 000 tons, which brings the current annual production to 900 000 tons of ore. By the end of 1978, about 10.7 million tons of Zn ore with 8.5 % Zn, 0.6 % Cu, 0.5 % Pb and a total of 3.3 million tons of pyritic disseminated copper ore, averaging 1.3 % Zn, 0.4 % Cu and 13.8 % S had been mined.

Mine and concentrator

The mine is provided with four shafts, a ramp, and main level drifts at intervals of 50 to 75 m (Fig. 2). Since 1958, transversal sub-level stoping with pillars has replaced shrinkage and cut-and-fill stoping and top slicing as the main stoping method. Once the sublevel stopes have been filled, the pillars are mined out by cut-and-fill stoping and top slicing. Trains haul the ore to the hoisting shaft along the main haulage level at + 325.

At the concentrator zinc, copper and lead concentrates are produced by flotation from combined feed of zinc ore and disseminated copper ore. The tailing sand is used as back filling and the fines are pumped to the tailing pond. Much of the effluent is returned to the concentrating process. The zinc concentrate, which is the principal product, is transported by rail to the Kokkola works for metallurgical treatment. The copper concentrate goes to the Harjavalta works, and the lead concentrate is exported.

Geology of the environment

The Vihanti area is part of the Vihanti—Pyhäsalmi Zn-ore belt, which includes several occurrences of sulphides. The terrain is fairly flat and outcrops are few. The thickness of the overburden fluctuates from 10 to 30 metres.

Previous studies (Wilkman 1931, Salli 1964) and more recent observations (Gaál *et al.* 1974) indicate the following stratigraphy for the Central Bothnia region (south of Vihanti):

Silicic and intermediate intrusives 1 700 to 1 900 Ma.
Mafic and ultramafic plutonic rocks 1 900 to 1 950 Ma.

	Metaturbidites Quartzite, meta arkose Conglomerate	Upper geosynclinal unit
	.... Discordance	
	Basic and acid volcanics	Lower geosynclinal unit
Vihanti area	Mica gneisses (meta-greywackes) Basic volcanics Epicontinental metasediments	
	.... Great discordance	(c. 2 500 Ma)
	Presvecokarelian basal complex	(2 800 Ma)

The supracrustal rocks in The Vihanti area belong to the basal group of the lower geosynclinal unit. Weakly sorted pelitic and greywacky sediments, which at present exist as heterogeneous, partly migmatic biotite gneisses and biotite hornblende gneisses, were deposited during the whole period of sedimentation. In addition to clastic weathering products, the supracrustal rocks contain ubiquitous volcanic matter as in situ formations and as fine-grained weathering products. The volcanic activity took place in two main phases. The earlier cycle, at the initial stage of sedimentation, was predominantly rhyolitic-basaltic with the emphasis on dacitic rocks. The acid volcanics of that cycle constitute, together with the dolomites and skarns, a zone of »Lampinsaari-type» rocks that,

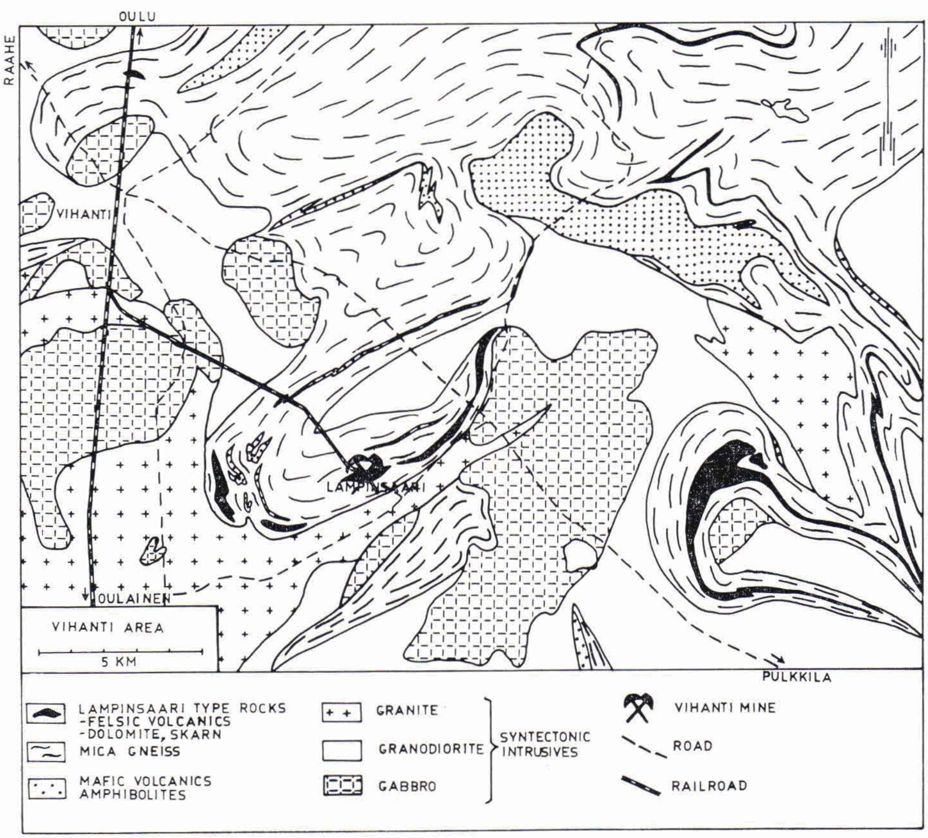

Fig. 1. Geological map of the Vihanti area.

with some local gaps, can be traced as a persistent horizon for several tens of kilometres. Besides the Lampinsaari ore complex, this rock association contains subeconomic Zn-Cu sulphide showings. Associated with the same horizon is a zone of uraninite- and apatite-bearing rocks with a distinct regional distribution.

The geological map (Fig. 1) shows three units of syntectonic infracrustal rocks: gabbro, granodiorite and granite. In the southern part of the map area there is a late-orogenic microline granite that occurs as crosscutting veins and is largely exposed in the Haapavesi—Oulainen area south and southeast of the Vihanti area.

The geological pattern is characterized by multiphase folding, of which the two major folding trends are discernible. The most intense folding phase created the SW- trending synform-antiform structure, in which the synforms of the supracrustal rocks alternate with the antiform ridges of the gabbro zones.

The axes of the synforms and antiforms plunge gently towards NE. The less intense folding phase gave rise to NW- trending structures. Deformations trending SW (or S) and NW are common throughout Central Bothnia (Salli 1961, 1964, 1965). However, unlike in the Vihanti area, folding parallel to the NW- axis clearly predominates south and southwest of Vihanti.

Geology of the ore deposit

The Lampinsaari ore complex

For lack of outcrops near the mine, geological observations on the Lampinsaari ore complex have been confined to underground. The rock association favourable for the occurrence of ore is enveloped by intensely metamorphosed mica gneiss with amphibolite intercalations.

The ore complex consists of acid volcanics, dolomites, skarns and cordierite gneisses, all of which are crosscut by granitic and basic dykes (Figs. 2 to 4). The acid volcanics include homogeneous quartz porphyry, banded tuffs and tuffites. The rock components alternate with each other in numerous ways, and thus metamorphism has been able to generate composite rocks such as skarn-banded acid volcanics.

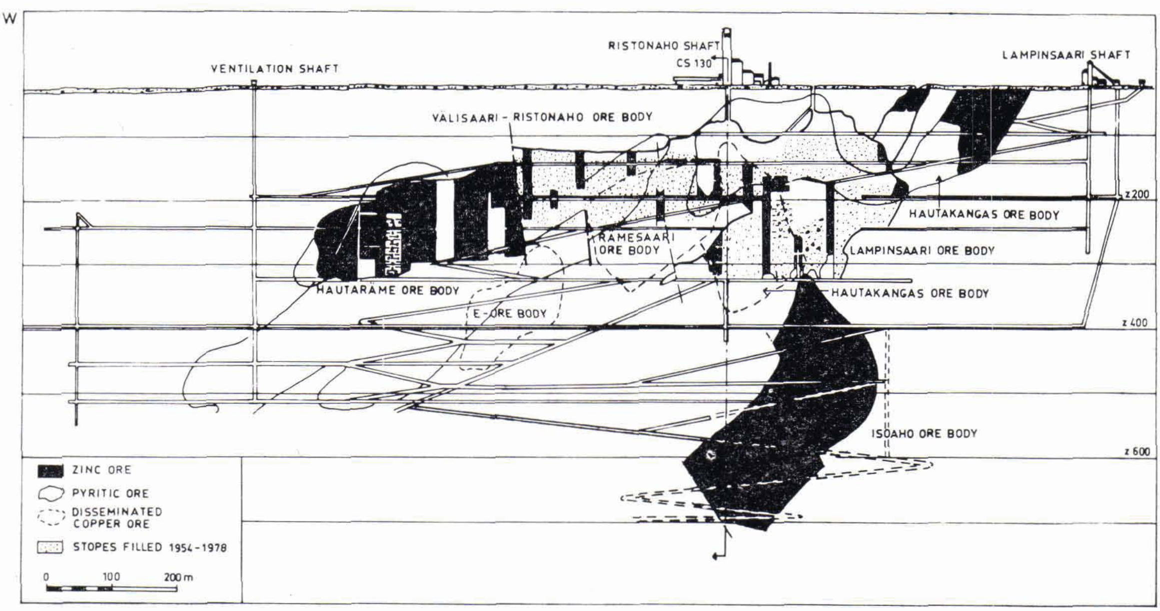

Fig. 2. Longitudinal projection of the Vihanti mine.

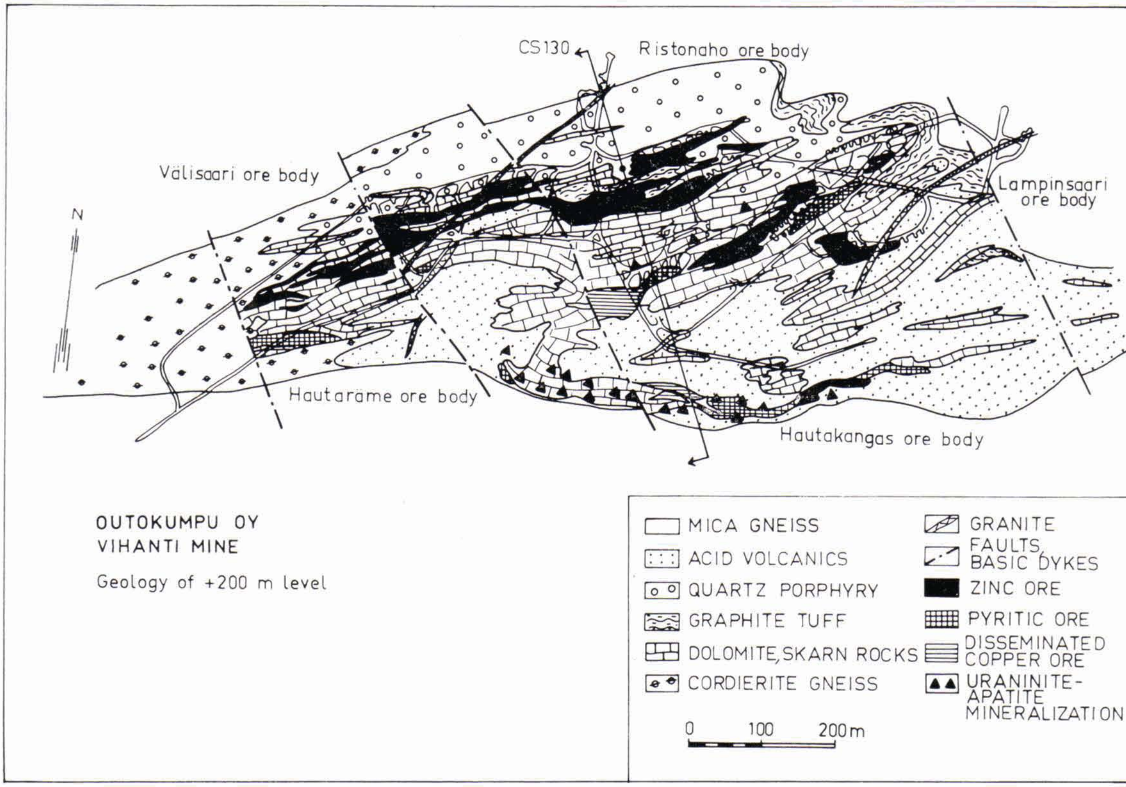

Fig. 3. The Vihanti mine + 200 m level plan.

Furthermore, movements have caused various kinds of breccia structures. The cordierite gneiss occurs mainly in the western part of the formation.

The Vihanti ore formation trends roughly east-west and has an average dip of 45° southwards. It crops out in the east but, owing to the axial plunge and transversal faults, it descends towards W-SW (Fig. 2) at an angle of 20° to 40°. These faults, with displacement up to 50 m, are filled with diabase. The known length of the formation in the longitudinal section is 2 kilometres and the maximal width 0.5 km. Diamond core drilling has demonstrated that the rocks favourable for ores continue at depths exceeding 700 m (Figs. 2 and 4).

The ore deposits have been classified as zinc ore, pyrite ore, disseminated copper ore and uraninite-apatite showing. Except for their remobilized portions, the orebodies conform with the bedding of the formation.

The mineral and chemical compositions of the rocks in the ore complex are compiled in Tables 1 and 2. The data have been collected from previous papers (Mikkola 1963; Rouhunkoski 1968) in which the acid volcanics were considered as quartzites, quartzitic rocks or quartz-feldspar rocks and schists. The quartz porphyry was classified as greywacke, and the graphite tuff as black schist.

Zinc ore

Sphalerite (averaging 7 to 8 % Fe) is the chief mineral in zinc ore (chemical composition in Table 3). The ore also contains chalcopyrite,

STRATIGRAPHY OF THE LAMPINSAARI ORE COMPLEX			
Rocks	Mineralizations	Metals	
Mica gneiss, with amphibolite intercalations			
Acid volcanic-sedimentary formation			
- Acid volcanics, skarn, dolomites	Uraninite-apatite mineralization	U, P	
	Pyrite ore	Fe, Cu, Zn	
- Acid volcanics	Disseminated copper ore	Cu, Fe, Zn	
- Dolomites, skarns	Zinc ore	Zn, Ba, Cu, Pb, Fe	
- Skarns, dolomites	Lead-zinc ore	Pb, Zn, Cu, Fe, Ag	
- Graphite tuff		Fe, Cu	
- Quartz porphyry (acid tuff)			
Mica gneiss			
Crosscutting acid and basic dykes			TOP

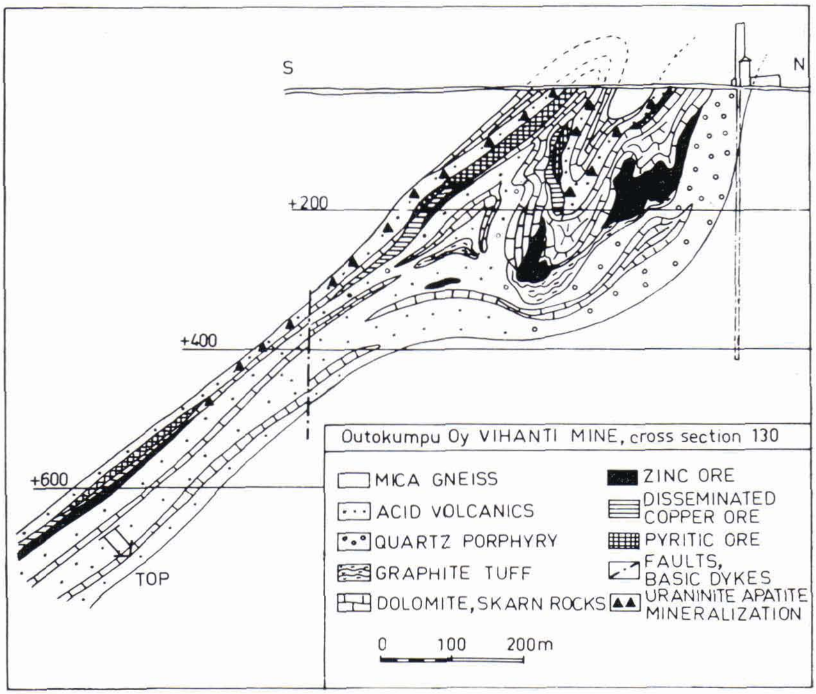

Fig. 4. Stratigraphy of the Lampinsaari ore complex and a section across the thickest part of the complex.

galena and iron sulphides, with cubanite, valleriite, gudmundite, tetrahedrite, tennantite and occasionally native gold as accessories. Most of the zinc ore lodes are confined to the folded contact zone of the footwall quartz porphyry- and skarn-bearing dolomite (Fig. 4) in which discontinuous graphite tuff indicates the horizon favourable for mineralization. The metal contents in the zinc ore fluctuate from 5 to 14 % Zn, 0.4 to 1.0 % Cu, 0.3 to 0.7 % Pb. The ore also contains small amounts of gold and silver. Depending on the host rocks, the predominant

Table 1.
Mineralogical composition of rocks from the Lampinsaari ore complex in percentages by volume (after Rouhunkoski 1968).

Minerals	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Quartz	39.2	26.0	38.5	85.2	43.4	40.6	46.4	38.7	—	25.9
Micas	33.4	3.2	28.5	6.0	—	28.6	6.0	9.7	20.8	—
Plagioclase	24.6	22.8	3.0	3.6	21.2	8.9	26.2	5.8	—	3.8
Amphiboles	—	43.7	—	—	17.4	—	11.4	6.0	—	37.4
Diopside	—	—	—	—	—	—	—	—	—	20.9
Epidote	—	—	—	—	4.8	—	—	—	—	—
Carbonate	—	—	—	—	6.8	—	—	—	54.3	—
Olivine	—	—	—	—	—	—	—	—	11.2	—
Cordierite	—	—	23.7	—	—	—	—	—	—	—
Sulphides	—	3.0	4.7	4.3	3.7	11.2	1.5	32.2	11.8	7.8
Graphite	—	—	—	—	—	—	—	4.8	—	—
Phenocrysts (Pebbles)	—	—	—	—	—	7.6	6.2	—	—	—
Accessory	2.8	1.3	1.6	0.9	2.7	3.1	2.3	2.8	1.9	4.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Mica schist. DH 913, depth 8.40 m, CS 110.
2. Hornblende schist. DH 911, depth 27.00 m, CS 106.
3. Cordierite gneiss. Average of four determinations.
4. Acid volcanics, (quartzite). 200 m level, Mikkola, 1963.
5. Acid volcanics, (quartz-feldspar rock). DH 912, depth 74.50 m, CS 110.
6. Quartz porphyry, (greywacke). 250 Ap 7.
7. Quartz porphyry, (greywacke). 250 RP 3.
8. Graphite tuff, (black schist). Average of three determinations.
9. Dolomite. DH 897, depth 11.70 m, CS 92.
10. Tremolite skarn. DH 962, depth 38.70 m, CS 144.

gangue is either dolomite, diopside-tremolite skarn, acid volcanic or, in high-grade zinc ore, barite that averages 5 %.

The footwall and hanging wall contacts of the high-grade zinc ore are often sharp. The chalcopyrite and pyrrhotite disseminations, which gradually die out away from the contacts, are more common in the hanging wall than in the footwall.

In many places primary layering imparts a banded or striped structure to the zinc ore. In compact zinc ore the banding is weakly developed, but in barite-bearing ore and particularly in pyritic zinc ore the banding is distinct.

Pyrite ore

As a rule the iron sulphide ores are predominantly pyritic, showing low contents of chalcopyrite and sphalerite. Pyrrhotite-predominant variants are, however, also encountered, usually in the margins of the pyrite orebodies, where pyrite occurs as porphyroblasts in pyrrhotite. The largest coherent iron sulphide orebodies (chemical compositions in Table 3) constitute discrete units close to the hanging wall contact of the fromation (Fig. 4), and above the skarn-dolomite that occupies the core of the formation. The sulphur content fluctuates between 20 and 35 %. The copper and zinc tenors average 0.2 to 0.4 %. In the eastern part of the complex, the iron sulphide ore grades into a zinc-bearing variant (The Hautakangas orebody), and in the extensions of the Lampinsaari zinc orebody some smaller separate pyrite orebodies occur.

The compact iron sulphide ores display massive structure. Whenever the host is an acid volcanic the structure is layered and, in the tectonised zones, brecciated, but whenever it is skarn, the sulphides tend to be disseminated.

Table 2.
Chemical composition of rocks from the Lampinsaari ore complex (after Rouhunkoski, 1968).

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
SiO_2 .	61.80	65.80	72.7	65.0	43.78	13.84	27.16	39.32	49.25	35.25	31.58	47.31	55.81
TiO_2 .	0.84	0.71	0.45	0.76	0.51	0.25	0.24	0.40	0.38	0.39	0.85	0.36	0.51
Al_2O_3.	15.00	12.57	12.9	14.22	10.37	3.44	6.11	8.92	9.07	10.59	20.79	9.04	13.14
Fe_2O_3.	1.18	1.78	1.43	1.84	Fe18.20	1.26	1.99	3.36	2.52	5.75	2.85	4.26	1.93
FeO ..	7.08	5.97	2.88	4.50	—	3.48	3.34	7.41	3.98	12.86	6.03	11.32	3.78
MnO .	0.15	0.06	0.02	0.1	0.05	0.09	0.10	0.30	0.12	0.25	0.20	0.25	0.12
MgO .	3.10	4.06	0.76	2.35	1.44	17.33	19.46	11.03	14.70	15.72	23.85	14.08	13.57
CaO .	5.28	0.86	2.67	3.61	1.57	29.70	21.45	20.30	13.46	7.97	3.47	3.01	1.55
Na_2O .	2.46	0.70	3.20	3.03	2.14	0.37	0.31	0.54	0.41	0.40	0.28	0.33	0.82
K_2O .	2.02	2.71	0.60	1.90	1.92	0.65	0.27	0.32	0.62	0.28	0.36	0.18	1.40
P_2O_5 .	0.13	0.14	0.14	0.36	0.09	0.13	0.32	0.25	0.14	0.11	0.25	0.07	0.23
H_2O^+	0.98	2.25	1.07	0.75	1.10	4.20	4.53	0.75	1.20	2.27	4.50	2.70	4.84
H_2O^-	0.13	0.20	0.06	0.05	—	0.21	0.17	0.65	0.08	0.20	0.21	0.40	0.52
S	0.22	3.43	2.55	0.19	13.13	1.49	2.08	4.72	2.70	9.22	3.92	8.42	1.94
CO_2 ..	0.4	0.5	0.1	1.0	0.0	23.90	12.21	4.66	0.88	0.70	1.54	0.33	0.29
BaO .	—	—	—	—	—	0.17	0.10	0.25	0.20	0.15	0.10	0.10	0.10
Cu ...	0.007	0.015	0.006	0.015	0.35	0.01	0.00	0.02	0.50	0.30	0.03	0.25	0.02
Zn ...	0.007	0.01	0.02	0.009	0.07	0.01	0.01	0.10	0.02	0.20	0.02	0.03	0.01
Pb ...	0.007	0.003	0.004	0.003	0.01	0.01	0.01	0.01	0.25	0.07	0.01	0.03	0.01
V_2O_5 .	—	0.03	0.03	0.04	0.17	—	—	—	—	—	—	—	—
C	—	0.06	0.3	0.27	4.8	—	—	—	—	1.09	0.29	—	—
B	0.002	0.002	0.003	0.003	—	0.00	0.01	0.00	0.00	0.40	0.30	0.25	0.01
F	0.27	0.42	0.20	0.28	—	0.38	0.80	0.19	0.38	0.11	0.13	0.23	0.10
—O ..	0.24	1.90	1.37	0.22	—	0.92	1.44	2.46	1.59	4.66	2.03	4.32	1.02
	100.8	100.4	100.7	100.1	99.7	100.00	99.23	101.04	99.27	99.62	99.53	98.63	99.68
MgO/CaO	—	—	—	—	—	0.58	0.91	0.54	1.09	1.97	6.87	4.68	8.75

1. Mica schist. DH 618, depth 4.25—5.25 m, CS 102.
2. Cordierite gneiss. 200 RP 3.
3. Quartz porphyry, (greywacke). 200 RP 1. Anal. A. Heikkinen of the Geological Survey of Finland.
4. Acid volcanics, (quartz-feldspar schist). DH 593, depth 53.00—54.00 m, y 1550.
5. Graphite tuff, (black schist). DH 640, depth 54.00—56.50 m, CS 130.
6. Dolomite. DH 133, depth 70.60—71.60 m, y 1850.
7. Dolomite, skarn bearing. DH 49, depth 22.00—26.40 m, y 1650.
8. Skarn rock, carbonate-bearing. DH 56, depth 129.50—132.50 m, y 2400.
9. Tremolite skarn. DH 558, depth 12.70—18.00 m, y 1400.
10. Tremolite skarn, talcose. DH 698, depth 29.50—33.50 m, CS 139.
11. Micaceous rock, carbonate-bearing. DH 996, depth 82.00—86.00 m, CS 122.
12. Micaceous rock. DH 168, depth 86.50—89.20 m, y 1850.
13. Micaceous rock. DH 626, depth 87.00—90.30 m, CS 104.

Disseminated copper ore

The disseminated copper ore occurs as irregular bodies in the centre and hanging wall of the formation (Figs. 3 and 4). The host rocks are predominantly acid volcanics. The major sulphides are pyrrhotite and pyrite; also present are chalcopyrite and sphalerite in such abundance that the ores average 0.5 % Cu, 0.1—0.5 % Zn and 10—15 % S.

Uraninite-apatite showing

The uraninite-apatite showing occurs in acid volcanics, skarns and dolomites as a discontinuous bed following the hanging wall contact of the formation. In detail it has been studied by Rehtijärvi *et al.* (1979).

The characteristic rock types in this horizon are phosphorite-banded dolomite and apatite-bearing fine-grained quartz-plagioclase gneiss,

Table 3.
Chemical composition of zinc and pyrite ores from the Lampinsaari ore complex (after Rouhunkoski 1968).

	1.	2.	3.	4.
SiO_2	42.70	34.74	23.6	30.6
TiO_2	0.3	0.06	—	—
Al_2O_3 ...	6.04	6.45	0.6	3.2
Fe	5.64	7.05	31.3	26.8
MnO	0.06	0.08	—	—
MgO	5.87	9.54	3.8	5.6
CaO	8.79	9.72	4.8	7.4
Na_2O ...	1.30	0.59	0.0	0.3
K_2O	0.41	0.65	—	—
P_2O_5	0.14	0.14	—	—
H_2O^+ ..	0.95	1.56	—	—
H_2O^- ..	0.05	0.07	—	—
S	9.79	9.84	33.6	22.7
CO_2	3.48	4.90	—	—
BaO	2.56	2.33	0.2	0.2
Cu	0.53	0.85	0.19	0.29
Zn	11.22	9.97	0.65	0.03
Pb	0.54	0.46	—	—
Cd	0.03	0.03	—	—
Mo	0.02	0.005	—	—
Ni	0.01	0.007	—	—
Co	0.005	0.003	—	—
As	0.05	0.012	—	—
Sb	0.02	0.015	—	—
Se	0.004	—	—	—
B	—	0.02	—	—
F	—	0.19	—	—
Ag g/t ..	26	26	—	—
Au g/t ..	0.4	0.4	—	—
	100.5	99.3	—	—

1. Zinc ore. Average mill feed in 1955.
2. Zinc ore. Average mill feed in 1960.
3. Hautaräme ore body, DH 1035, depth 59.4—97.8 m
4. Hautakangas ore body, DH 1091, depth 32.0—78.4 m

a metamorphic derivative of phosphatic tuff. Some of the phosphatic metatuffs contain pyrite bands.

Uranium shows a strong correlation with apatite in both distribution and content. In the phosphorite bands uranium seems to be incorporated mainly in uraninite and in the phosphatic metatuff in apatite. The mean uranium content in the horizon is 0.03 % and the mean P_2O_5 content 3—5 %. Thorium assays less than 10 ppm.

Age determinations and isotope studies

The isotopic constitution of lead from galena is very homogeneous suggesting a »lead model age» of 1 935 Ma. Preliminary whole rock lead data for quartz porphyry show an age of 1 920 Ma. Age determinations from the vicinity of the mine based on U-Pb analyses from zircon give 1 895 Ma for gabbro and 1 875 Ma for syntectonic granodiorite and granite. Lead isotope studies from the hanging wall uraninite-apatite showing indicate an age of 1 880 Ma for the last homogenization. Titanite from the basic dykes in the fault zones that cut the complex

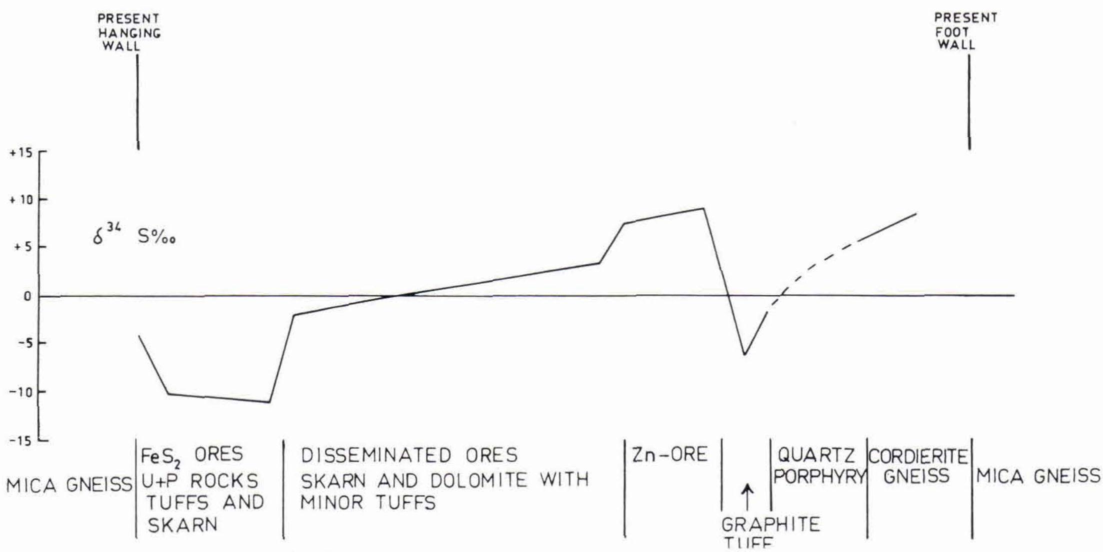

Fig. 5. Isotopic constitution of sulphide sulphur in the Lampinsaari ore complex. Based on the determinations on 83 samples of pyrite, pyrrhotite and sphalerite. Data compiled from Rouhunkoski (1968) and Meriläinen (1977).

Table 4.
Average trace element content (in ppm) of rocks and ores from the Lampinsaari ore complex (after Rouhunkoski 1968).

	Cu	Zn	Pb	Ni	Co	Number of samples
Mica schist	70	40	10	20	15	17
Amphibolite	65	30	15	45	20	3
Cordierite gneiss	160	220	30	9	12	17
range	50—300	70— 450	5— 70	5— 17	9— 23	—
Quartz porphyry (greywacke)	35	30	30	30	15	10
Quartz-feldspar rock	120	160	75	90	25	30
range	30—250	35— 450	10—380	10—200	10— 40	—
Graphite tuff (black schist)	230	700	60	290	90	11
range	110—380	190—1 100	10— 90	190—600	20—370	—
Dolomite	80	100	60	100	30	12
range	10—180	25— 170	10—130	15—220	10—110	—
Skarn rock	50	30	25	35	20	6
» slightly mineralized	870	560	260	55	30	23
Granite	20	45	50	5	5	4
Plagioclase-porphyrite	100	35	10	55	30	3
Zinc ore (average for years —63, —64, —65)	6 600	104 000	4 400	35	15	3
Pyritic ore						
Hautaräme	2 600	1 500	55	25	60	27
Hautakangas	900	2 800	95	160	75	26

gave an age of 1 840 Ma. (All data mentioned are personal information supplied by Dr. M. Vaasjoki of the Geological Survey of Finland). Lead from microcline in a granite dyke cutting the ore complex dates at 1 860 Ma (Rouhunkoski 1968).

The isotopic constitution of sulphidic sulphur has been studied and discussed by Rouhunkoski (1968), Meriläinen (1977) and Rehtijärvi *et al.* (1979). The results shown in Figure 5 indicate ^{32}S enrichment in graphite tuff and in rocks near the present hanging wall, whereas zinc ore is characterized by positive values of $\delta\,^{34}S\,^0/_{00}$.

Geochemistry

Geochemical studies (Wennervirta and Rouhunkoski 1970) demonstrate that the entire Lampinsaari ore complex has been contaminated by an ore-generating process (Table 4). Nevertheless, the mica gneiss adjacent to the complex does not exhibit anomalous sulphide abundances. In the complex, a distinct positive correlation exists between its thickness and the intensity of the mineralization: zinc is typically concentrated into the thickest carbonate- rich portions, whereas copper and lead are more widely spread. Characteristic of the occurrence of lead is its enrichment in the extensions and margins of the zinc orebodies, particularly in their footwall.

According to Rouhunkoski (1968), geochemical and sulphur isotope data indicate that the cordierite gneiss and some of the skarns were formed through the action of ore solutions. Nevertheless, the formation of most of the skarn rocks can be attributed to regional metamorphism. Signs of alteration, such as sericitization, are rare, except in the cordierite gneiss, whose genesis is associated with the mineralization.

Stratigraphy

As indicated by the stratigraphic column in Figure 4, the current opinion is that the formation is overturned.

Both the country rock mica gneisses and the volcanogeneous acid schists (quartz-feldspar schists) are layered, although no primary sedimentary structures have been observed. As a rule, the quartz porphyry and the dolomites are subhomogeneous rocks. The graphite tuff exhibits layering and grades locally into quartz-feldspar schists and quartz porphyry, and is closely associated in origin with acid volcanics. Cordierite gneiss is encountered at the western end of the formation, from where it penetrates the formation in a fingerlike fashion. The rock also exhibits a fairly coarse-grained non-oriented texture. All these features suggest secondary and, particularly, metasomatic origin for the cordierite gneiss. This interpretation implies that the dolomites were chemical sediments and that the bulk of the skarns were formed during metamorphism.

Structure

It used to be thought that the structure of the Lampinsaari ore complex was caused by an overthrust (Mikkola 1963, Rouhunkoski 1968), and that the zinc ores were located in the dragfolds of the lower flank. Drilling has, however, revealed that the structure continues downwards along the dip. Gaál (1977) suggests that the structure of the ore complex is an outcome of four-stage deformation. In the second stage, the formation was folded into an overthrust isoclinal antiform, and the zinc ores accumulated in the crests of the folds. In the third deformation stage, the isoclinal structure refolded into a righthand synform along whose axes the orebodies were arranged en echelon. During the fourth deformation stage, the formation was cut by transversal faults.

Nowadays, the Vihanti ore complex is considered to be an overturned monocline in structure, and composed of a dragfolded volcanic association with diverse sulphide ore components (Rauhamäki *et al.* 1978). Neither the synclinal (Mikkola 1963; Rouhunkoski 1968) nor the isoclinal antiform (Gaál 1977) interpretation was based on observation of the primary sediments. The mode of occurrence of the orebodies, the mineralized zones and the rocks of the ore complex (Fig. 4), together with the lack of symmetry favour the monocline interpretation. This concept is corroborated if comparisons are made with the stratigraphy of the stratiform volcanic-exhalative sulphide ores. (Stanton 1972, p. 522). The observations show clearly that the ore complex was folded in at least two stages (Gaál 1977).

Discussion

Two concepts have been put forward for the genesis of the Vihanti ore. The first of these, suggesting that the Lampinsaari ore complex is of volcanic origin was proposed by Marmo and Mikkola (1951).

They reported a rock, in addition to clastic quartzites, that might be acid volcanite in origin. In his paper dealing with the mineralogy of the ore, Mikkola (1963) maintained that the deposit is either epigenetic or exhalative-sedimentary in origin; the epigenetic origin is supported by hydrothermal and epigenetic features, whereas the exhalative-sedimentary origin is contradicted by the lack of volcanites adjacent to the deposit. Later, in his paper on alteration phenomena Mikkola (1969) suggested that the observed features could be explained by synsedimentary volcanic-exhalative genesis. Rouhunkoski (1968) considered the ore to be a high-temperature epigenetic variety. Mikkola and Väisänen (1972) maintained that the layered structures in the ore are primary, whereas Gaál (1977) interpreted them as products of deformation.

Current opinion (Fig. 4) holds that the Lampinsaari ore complex is produced by acid volcanism. The volcanic cycle started under marine conditions favourable for the formation of an uraninite-apatite horizon. The first stage was the deposition of quartz-feldspar rocks, which have been interpreted as acid tuffs and tuffites, and chemically precipitated carbonate rocks. This stage is characterized by the formation of massive iron sulphide orebodies. The deposition of the volcanics and carbonate rocks continued concurrently with the formation of the sulphide dissemination. In places the abundance of copper was high enough to give rise to disseminated chalcopyrite ore. The deposition of carbonates reached its culmination, and during its closing stages the zinc ores proper precipitated. More acid volcanics — quartz porphyry in type and presumably crystal tuffs in origin — where then erupted. Graphite tuff, which constitutes a discontinuous horizon between the zinc ore and the quartz porphyry, refers to a stage of reducing conditions.

The thickest part of the Vihanti ore complex is intensely folded and represents either the immediate environment of the volcanic eruption channel or topographically the most suitable place for the acid volcanics, the thickest carbonate beds and the main sulphide orebodies to deposit. The greater the distance from the thickest part of the deposit, the more distinct is the layered structure of the tuffite variants in the acid volcanics. Downwards in stratigraphy, the boundary of the Vihanti ore complex is distinct and sharp; upwards, at the boundary with the overlying mica gneiss, there are mica-bearing quartz-feldspar schists interpreted as weathering products of the volcanic complex.

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GEOLOGY OF THE OTANMÄKI MINE — by Ole Lindholm and Risto Anttonen

Introduction

Location

The Otanmäki mine (stop 7) lies close to the geographical centre of Finland, south of the large lake Oulujärvi. The nearest town is Kajaani, about 40 km to the east. The mine and adjacent plants employ about 650 persons.

Discovery and development

The history of the discovery of Otanmäki is very similar to that of other ore deposits found in the thirties. In 1937 two magnetite-ilmenite floats were found about 40 km southeast of Otanmäki. One year later, in 1938, their source was pinpointed on the basis of magnetic indications. Further studies revealed several smaller magnetite-ilmenite deposits within a radius of 10 km around Otanmäki.

The state-owned company of Otanmäki Oy was founded to exploit the ore deposit. The production started in 1953. In 1938 Otanmäki Oy was amalgamated with Rautaruukki Oy, the major state-owned steel producer in Finland.

The current annual hoist of Otanmäki mine is 1 000 000 tons of ore, from which are produced:

2 400	tpa	V_2O_5
265 000	tpa	iron concentrate as Fe_2O_3 pellets
135 000	tpa	ilmenite concentrate
6 000	tpa	pyrite concentrate

The principal mining method is sublevel open stoping with levels spaced at intervals of 20—30 metres. Shrinkage stoping and sublevel caving were also used at one time.

Investigating methods

The magnetite-ilmenite deposits at Otanmäki are distinguished by their heterogeneity. Several hundred known ore lenses are spread over a fairly large zone. Lenses of unequal size containing abundant gangue inclusions and often with illdefined boundaries occur capriciously. Mining geology has to provide an exceptionally large amount of detailed information to aid the design of the stopes and to direct the stoping. About 45 000—50 000 m of investigation drilling is required annually. To make this economically feasible, diamond drilling is supplemented and partly replaced by inexpensive and fast percussion drilling. With the percussion drilling no sludge samples are taken, instead the holes are surveyed geophysically by permeameter, which is calibrated to show the magnetite content of the rock. This method is made viable by the constant magnetite-ilmenite ratio in the ore. The annual amount of percussion drilling is 30 000—35 000 m. The corresponding diamond drilling amounts to 12 000—15 000 m.

The diamond drill holes are all surveyed by a three-component magnetometer which makes it possible to define the intensity and orientation of the magnetic field caused by ore lenses. Unintersected ore lenses in the vicinity of drill holes are also indicated. The distance between diamond drilling profiles varies from 30—60 metres.

Regional geology

The bedrock in the Otanmäki region is poorly outcropped, owing to the extensive cover of swamps and low till or sandy hillocks. Thus the geological map relies heavily on geophysical survey supplemented by diamond drilling. As shown by the aeromagnetic map (Fig. 1), there

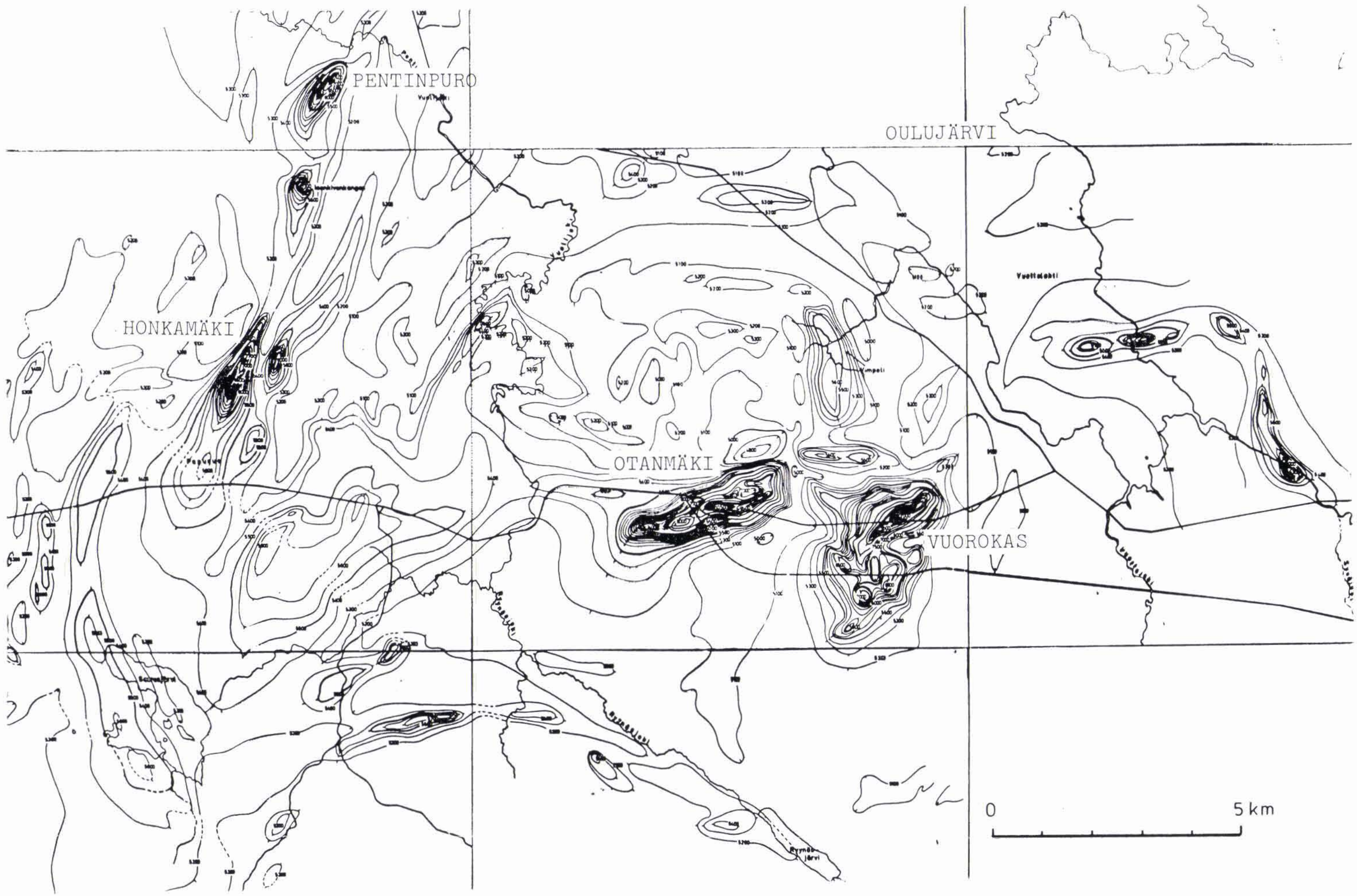

Fig. 1. Aeromagnetic map of the Otanmäki region.

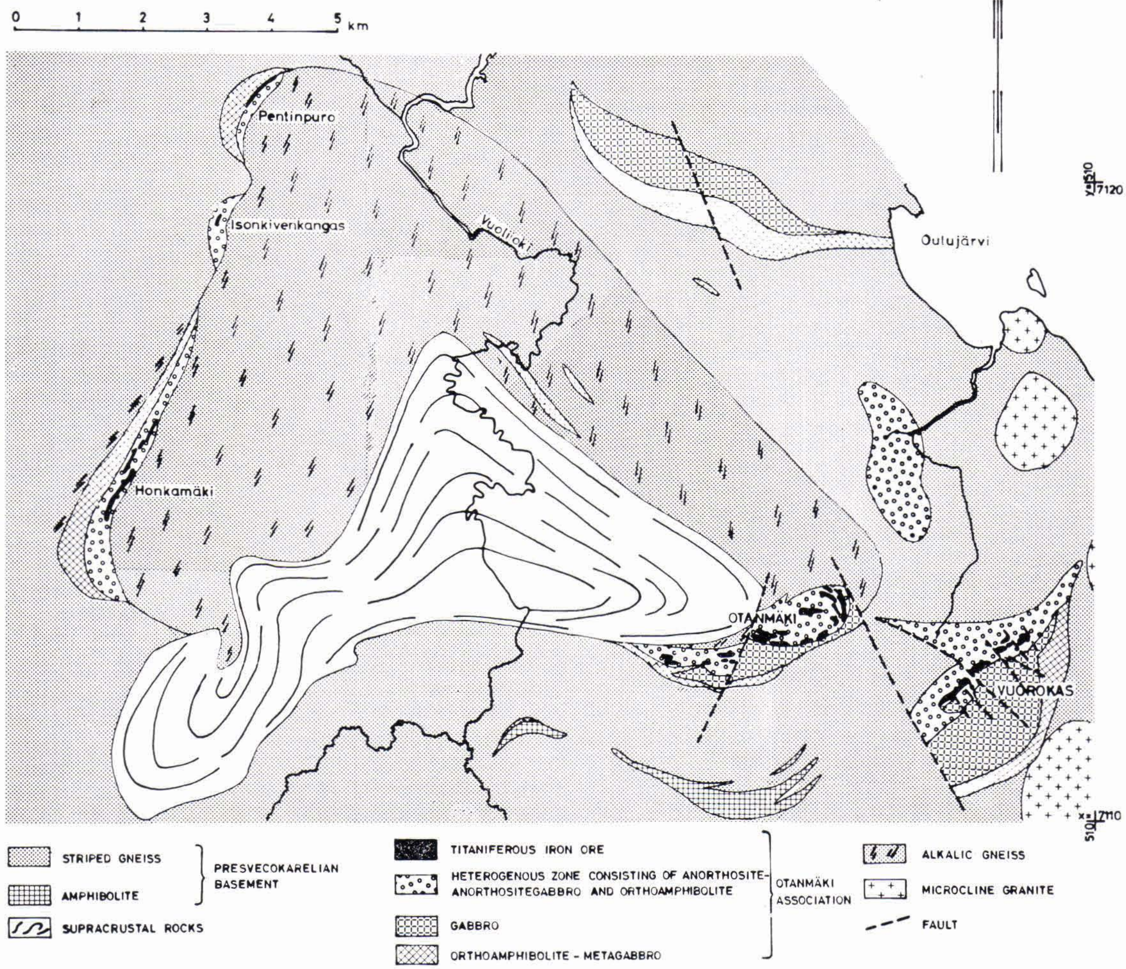

Fig. 2. Geological map of the Otanmäki region.

are several positive anomalies in the region. Most of these are proved to be due to magnetite-ilmenite ore associated with gabbroic intrusions. The rock units of the Otanmäki region can be classified as follows:

— pre-Svecokarelian basement
— supracrustal rocks
— Otanmäki association
— alkalic gneiss
— microcline granite

Pre-Svecokarelian basement

The striped gneiss in the southern and western parts of the geological map (Fig. 2) is part of the pre-Svecokarelian basement complex and is the oldest rock type in the region. It is structurally very heterogenous, containing inclusions of amphibolites, veins of pegmatitic granite and fragments of mica gneiss. The rock varies in texture from fine- to medium-grained gneissose granite to strongly compressed and contorted veined gneiss.

Supracrustal rocks

This rock association consists of quartz feldspar schists, mica schist and metavolcanics. The supracrustal rocks seem to form a basin structure.

Otanmäki association

Vanadium-bearing magnetite-ilmenite ores are associated with layered gabbro-anorthosite intrusives (Otanmäki, Vuorokas, Honkamäki, Pentinpuro, Isonkivenkangas). The gabbros are of the uralitic variety with relict pyroxene and olivine. The mineral assemblage of the anorthosite zone is mainly gabbro anorthosite. The ore zone is located in a heterogenous orthoamphibolite zone, which is the contact zone between gabbro and anorthosite.

Alkalic gneiss

The alkalic gneiss is a large, very heterogenous rock unit with metasomatic features. It has a peculiar mineral assemblage. In addition to quartz and feldspar it contains alkalic amphibole, alkalic pyroxene, abundant fluorspar, zircon and sphene, local carbonate and many rare minerals, e.g. columbite, bastnaesite, danalite, thorite and enigmatite. An anomalously high Nb-concentration and molybdenite mineralisation occur together with magnetite dissemination.

Microcline granite

The granite occurrences in the eastern sector of the geological map are parts of the extensive microcline granite intrusion, the »Kajani granite», which is largely outside the mapped area. Farther east it is bounded by the Karelian schist belt.

Age relations

The pre-Svecokarelian basement is the oldest rock unit in the region. Its age has not been determined radiometrically, but from datings of similar rocks elsewhere in eastern Finland, an age of 2 600—2 800 Ma is inferred. The gabbros of Otanmäki and Vuorokas, dated radiometrically on their zircon, show an age of 2 060 Ma. The age of the alkalic gneiss at Honkamäki deposit, dated by the same method is 2 000 Ma. It has still not been established whether these are the ages of formation or of metamorphism (metasomatism) of these rocks. Whichever is the case, alkalic gneiss intersects the orebearing zone at Otanmäki.

The Otanmäki deposit

The magnetite-ilmenite deposit at Otanmäki is by far the largest of the deposits known in the region. It lies on the northern flank of a large hornblende gabbro intrusion in a heterogenous zone of metagabbros, gabbros and anorthosites. This ore-bearing zone is about 3 kilometres wide and forms a semicircle at the eastern end. It is confined in the north by pink alkalic gneiss; in the south the gabbro intrusion is in contact with striped gneiss and, close to the contacts, is rather strongly schistose (Fig. 3).

The magnetite-ilmenite ore occurs as irregular, partly elongated lenses of various size in a heterogenous, locally schistose, gabbro-anorthosite zone. Cross-section A-A (Fig. 4) depicts the mode of occurrence of the ore lenses and their tendency to follow large irregular gabbroic and anorthositic bodies and fragments. The contacts of the orebodies with these bodies and fragments are capricious, whereas the contacts with metagabbro are fairly straight. The gabbros within the ore zone are like those of the main intrusion, i.e. they vary from leucogabbro to melagabbro and from coarse to medium in grain size. The composition of plagioclase is An_{45-60}, even in anorthosite. The orebodies contain as inclusions variable amounts of all the rock types that exist in the ore zone. The ore zone is characterized by its heterogeneity and the abundance of anorthosites. The ore lenses vary

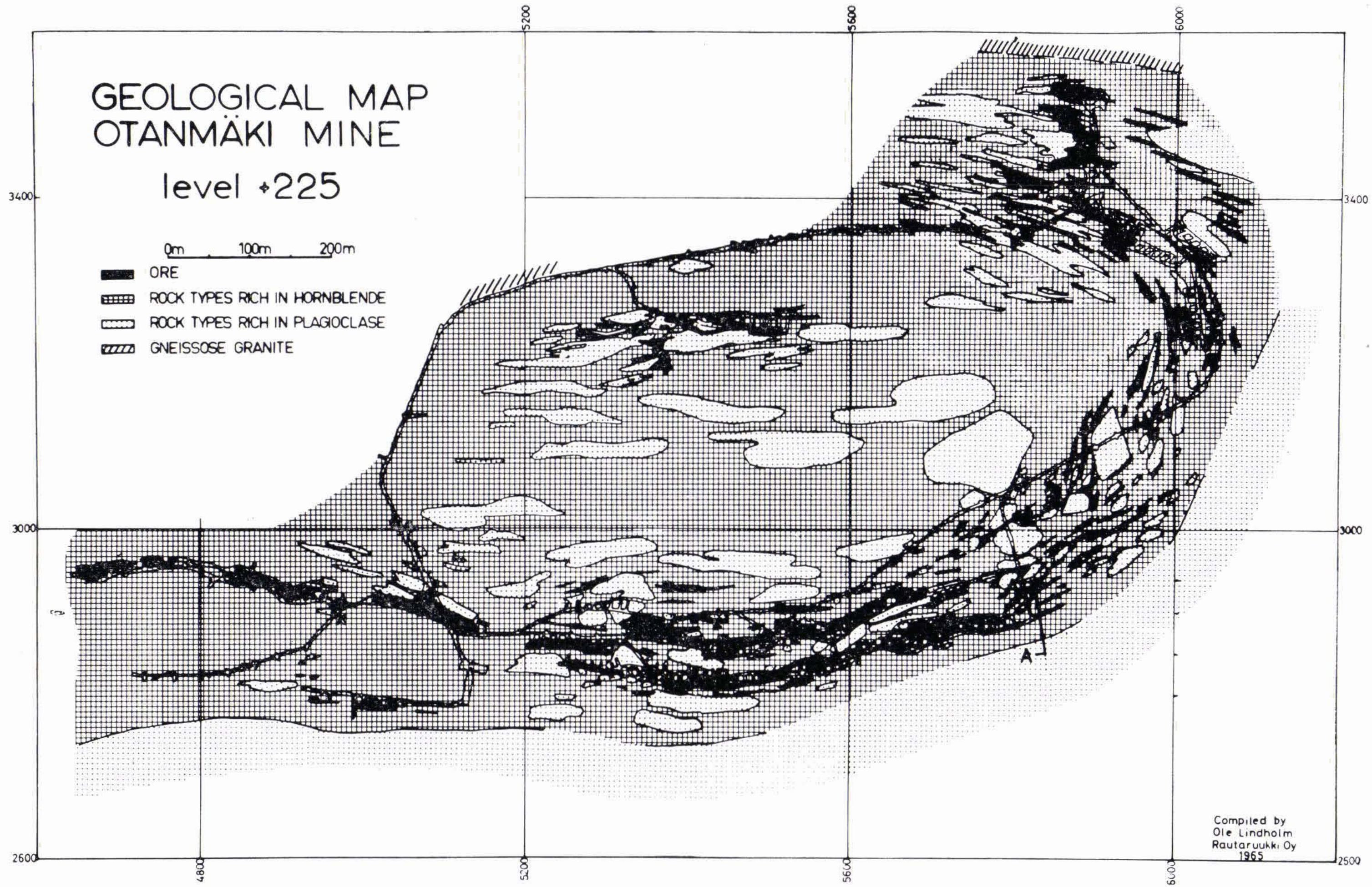

Fig. 3. Geological map, Otanmäki mine, level + 225.

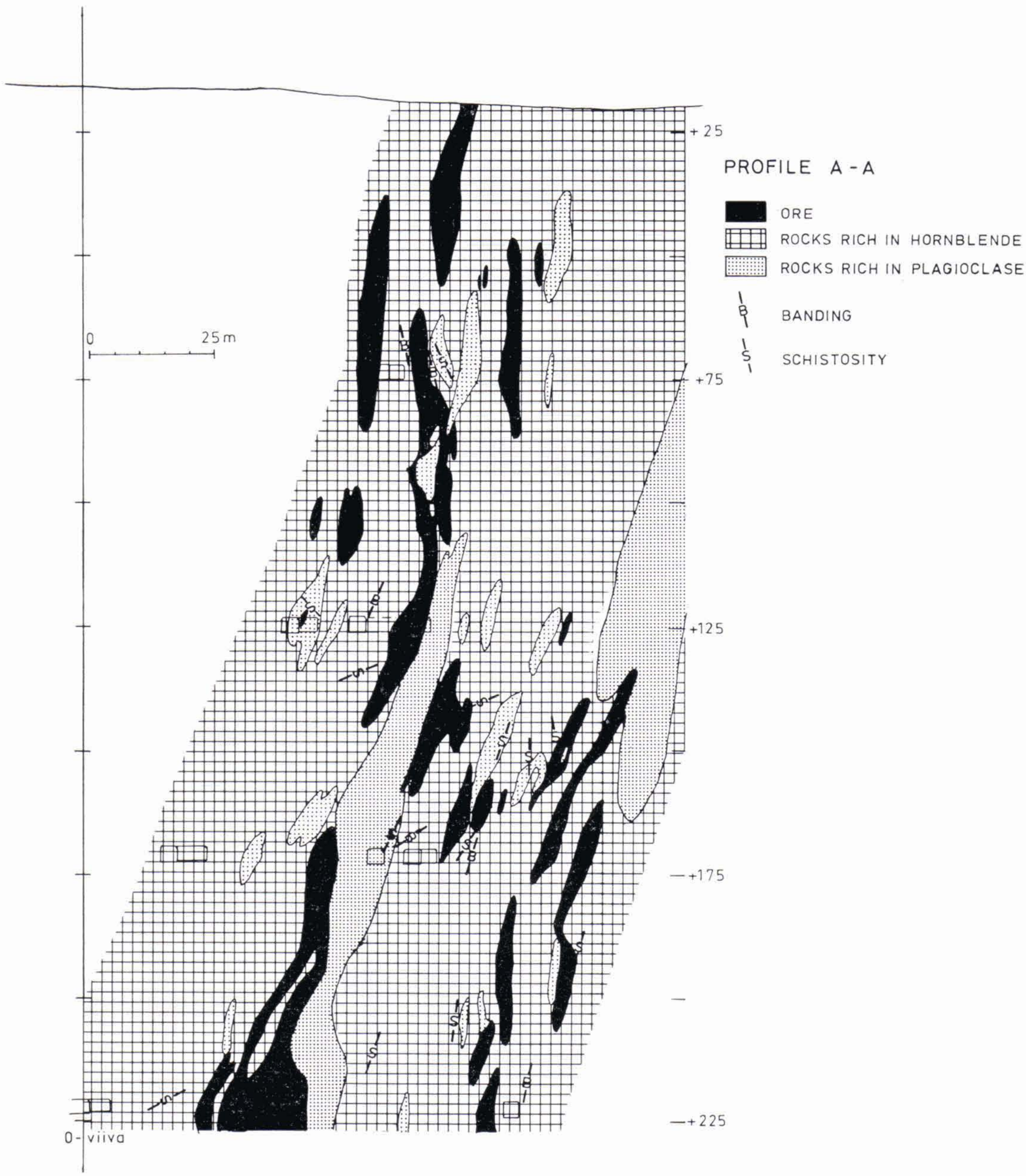

Fig. 4. Cross-section showing the mode of occurrence of the ore lenses at the Otanmäki mine.

from 20 to 200 metres in length and from 5 to 30 metres in width. Most of the lenses are E-W oriented, dip steeply to the north and south and plunge 40°—60° to the west. Locally, the ore minerals form flow structures around the gangue inclusions. The ore is mainly medium-grained and massive and consists of magnetite and ilmenite. Chlorite, hornblende and plagioclase occur as gangue minerals in varying amounts. The richest of the ores is that with the chlorite

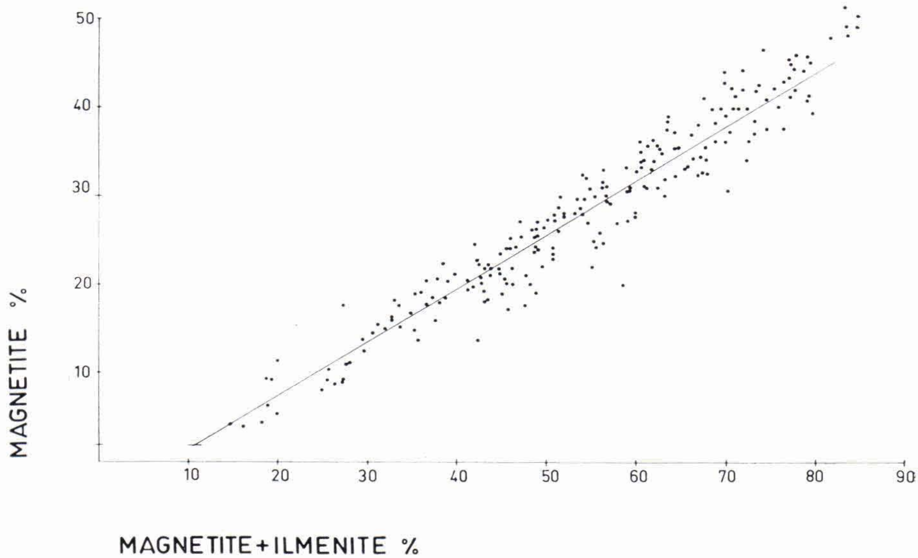

Fig. 5. Diagram showing the ratios of magnetite to ilmenite in the Otanmäki ore.

matrix. Some gabbros are banded and, in places, the metagabbro contains conformable bands of magnetite and ilmenite as well as disseminated ore minerals. As a curiosity disseminated magnetite and ilmenite are found in anorthosite as well.

The intensity of schistosity varies at random in the ore zone; it seems to be higher in certain zones and tends to grow towards the northern parts of the ore zone. The schistosity cuts the banding in the ore and the metagabbro at an angle that is usually rather small. The plane of the ore always conforms with the banding, which makes it easier to connect the drill data. The tectonic event that brought about the schistosity did not materially affect the shape of the orebodies. The schistosity is barely visible within the ore.

Although the individual orebodies plunge 45°—60° to the west, the ore zone as a whole has a somewhat shallower plunge of ca 40° to the west. The ore is known to extend to a depth of over 800 metres, but the western extensions of the complex have still not been established.

Mineralogy of the ore

The ore consists of the same minerals as the rocks of the Otanmäki association. The ore minerals are vanadium-bearing magnetite and ilmenite; the gangue minerals are chlorite in the high-grade ore, hornblende and minor plagioclase in the low-grade ore. The mutual amounts of hornblende and plagioclase may vary very widely in the disseminated ore. The amounts of magnetite and ilmenite vary as the diagram (Fig. 5) shows. The high-grade ore contains 35—40 % magnetite and 28—30 % ilmenite, which generally occur as discrete and isometrically developed crystals. The mutual relations of magnetite and ilmenite change as the abundance of oxides in the rock decreases, the disseminated ore containing even twice as much ilmenite as magnetite.

The sulphides (pyrite, pyrrhotite, chalcopyrite) are also economically significant and account for as much as 20 % of the contents of the ore and host rock.

Magnetite

The average grain size of magnetite is 0.2—0.8 mm; in some parts of the high-grade ore the grain size is well over 1 mm. Lineation cannot be detected in the high-grade ore, but in the low-grade ore magnetite and ilmenite are elongated parallel to the lineation in the host.

Intergrowths of magnetite and ilmenite are insignificant as regards the whole mine, but they may be predominant in some small restricted areas. A typical medium-sized magnetite crystal contains 5 to 20 exsolution lamellae, 1—2 microns wide and less than 60 microns long parallel to octahedron planes (111). The very smallest crystals seem to lack these exsolution lamellae. In some parts of the high-grade ores the grain size of magnetite is larger than normal; in these cases magnetite contains ilmenite inclusions 0.002—0.06 mm in diameter. In places wide (111) oriented ilmenite lamellae are visible, in others the lamellae may be broken and bleblike; they then also occur in (100) orientation.

Al-spinel occurs as (100)-oriented exsolutions in two generations: a) 1—3 micron wide and less than 80 microns long lamellae, and b) almost dustlike clouds. The (100)-orientation of the second generation is not always distinct owing to the small grain size and the rounded grain shape. When the ilmenite lamellae and Al-spinel occur together, the Al-spinel represents the later stage of exsolution.

The vanadium percentage in magnetite is fairly contant 0.90 % V_2O_3 within the range 0.80 %—1.05 % V_2O_3. No variations of vanadium content due to layering have been detected. Magnetite assays an average of 0.03 % chromium and 0.06—0.12 % zinc.

Ilmenite

In the high-grade ore the grain size of ilmenite equals that of magnetite but in the low-grade ore disseminations of ilmenite less than 0.15 mm in diameter abound.

Hematite exsolutions are an essential part of ilmenite. They usually occur as rounded, 4—5 microns ø, bodies. They also occur to a lesser extent in rows of elongated drops along the (0001) planes of ilmenite. Zoning has not been detected in the exsolution textures. The coarsest hematite exsolutions show ilmenite exsolved from hematite.

In addition to the hematite exsolutions in ilmenite, there are also magnetite lamellae in the (0001) orientation. A zone 5—20 microns wide and free of hematite exsolutions occurs around these magnetite lamellae. In areas of mechanical shearing ilmenite displays pressure-twinning which has produced magnetite from hematite exsolutions through reduction.

Discussion

Three possible origins are postulated for the banded structures found in the ores and gabbros of Otanmäki:

1) metasomatism
2) tectonic movements
3) magmatism

The magmatic origin seems best suited to the banded structures. As seen in Figures 3 and 4, the ore zone contains abundant large and small anorthositic and gabbroic bodies and fragments which impart an appearance of breccia to the zone. In the banded ore, the bands flow around the fragments with turbulent features.

In several places, the plagioclase laths are parallel to the anorthosite bands. The light and dark rocks of the complex presumably belong to the same phase, anorthosite occurring as alternating bands with gabbros and ores. No crosscutting dykes of ore are known to exist and thus, evidence of late oxide melt is lacking.

Intergrowths of magnetite and ilmenite are rare. This and the mode of occurrence of pyroxene and olivine indicate that some metamorphism took place. Owing to this metamorphism, the magnetite and ilmenite probably exsolved from each other under the conditions of amphibolite facies. No evidence is found to suggest mobilisation of ore.

In conclusion, the Otanmäki complex is regarded as a magmatic intrusion in which the orebodies are in their original sites in relation to their nearest wall rocks. Later-stage regional metamorphism purified the magnetite and ilmenite at a temperature of ca. 560° C but did not play any part in the formation of the deposits. It is not clear how the magmatic differentiations the primary structures (bands etc.) show could point to a higher mobility than what is expected in the less steeply dipping layered intrusives (Bushveld). Another unanswered question is, whether the basic intrusions at Otanmäki, which are now subvertical, were originally emplaced at an essentially different attitude. The pattern of the geological map changes in pace with the progress made in studies. Further investigations will pay attention also to non-oxidic mineralisations.

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Eighth day

GEOLOGY OF THE VUONOS ORE DEPOSIT — by Esko Peltola

Introduction

The Vuonos ore deposit (stop 8) is situated in eastern Finland at approximately 62° 46′ N, 29° OE, and about 6 km east of the Outokumpu ore deposit.

During the last few decades intensive exploration around the Outokumpu deposit has led to the discovery of seven ore deposits or showings in the area depicted in Fig. 1 and called the Outokumpu district. Because of the similarity in ores, geological environment and rock types and in geochemistry and structure, and because the deposits are unique among sulphide occurrences in the Baltic shield, this type of ore is known as the »Outokumpu type». Three of the deposits are being mined currently, viz. Outokumpu, Vuonos and Luikonlahti. Luikonlahti is exploited by a private company, Myllykokis Oy, and Outokumpu and Vuonos by Outokumpu Co.

Vuonos is a blind orebody, which was found in 1965 as a result of extensive lithogeochemical prospecting. The exploitation of copper ore began in 1972. Until 1976 a low-grade nickel ore was also mined from an open pit above the copper orebody.

With its total reserves of about 1 million tons of copper, the Outokumpu mine has been the main producer of copper in Finland. In 1978 the annual production of Outokumpu mine was 426 000 tons of copper ore and of Vuonos 600 000 tons of copper ore.

The Vuonos copper ore is mined by inclined-wall stoping with fill, except in the low-grade parts of the ore body, where the pillar system is also used.

General geology of the Outokumpu district

The bedrock of the Outokumpu district is part of the Karelian formations, which in the east are separated from the granite gneiss basement by a marked unconformity. Karelian sedimentation started with basal conglomerates and arkosic quartzites directly overlying granite gneiss. The deposition of the initial formation was followed by that of epicontinental sediments consisting mainly of quartzites.

The epicontinental Jatulian formation is overlain by a thick accumulation of geosynclinal Kalevian sediments composed mainly of phyllites and mica schists. The mineralogical and chemical compositions of the micaceous schists suggest incomplete weathering, which indicates that they are flysch sediments of Karelian geosynclinal sedimentation.

In the western part of the Karelian schist area, there is a long, ribbon-like zone that consists mainly of serpentinites, skarns, carbonaceous black schists and quartzitic rocks. The latter differ from the epicontinental quartzites, and in the following are referred to briefly as »Outokumpu quartzites».

The copper deposits and prospects in the Outokumpu district occur in the Outokumpu zone (Fig. 1). Intensely folded, the zone appears on the map as a sinuous horizon that conforms with the surrounding mica schists as it curves around the Prekarelian domes. The metamorphic grade of the Karelian rocks increases from east to west as the phyllites and mica schists in the east grade into the migmatitic mica gneisses and granites in the west.

In the eastern part of the Outokumpu district, the bedding dips westwards, and the folding is isoclinal and overturned so that it faces eastwards. In the west, large anticlines occur around the Juojärvi and Maarianvaara domes. The Outokumpu synclinorium is located between them and the dome of Sotkuma. The dominant plunge in the Outokumpu district is southwest, but locally it is reversed owing to axial depressions and culminations. The Outokumpu and Vuonos ore deposits are located in axial depressions where the bedding dips to the southeast.

The late-orogenic granite body of Maarianvaara is northwest of the Outokumpu synclinorium. Pegmatite dykes emanating from the Maarianvaara granite cut the surrounding gneisses and schists as well as the nearby Outokumpu zone.

Geology of the Vuonos copper deposit

The Outokumpu zone

The Outokumpu and Vuonos deposits are located in the middle of the Outokumpu zone, which extends northeast from the lake Juojärvi to the commune of Polvijärvi (Fig. 2). The zone dips gently to the southeast, reaching a thickness of 1 200 m at the Outokumpu mine.

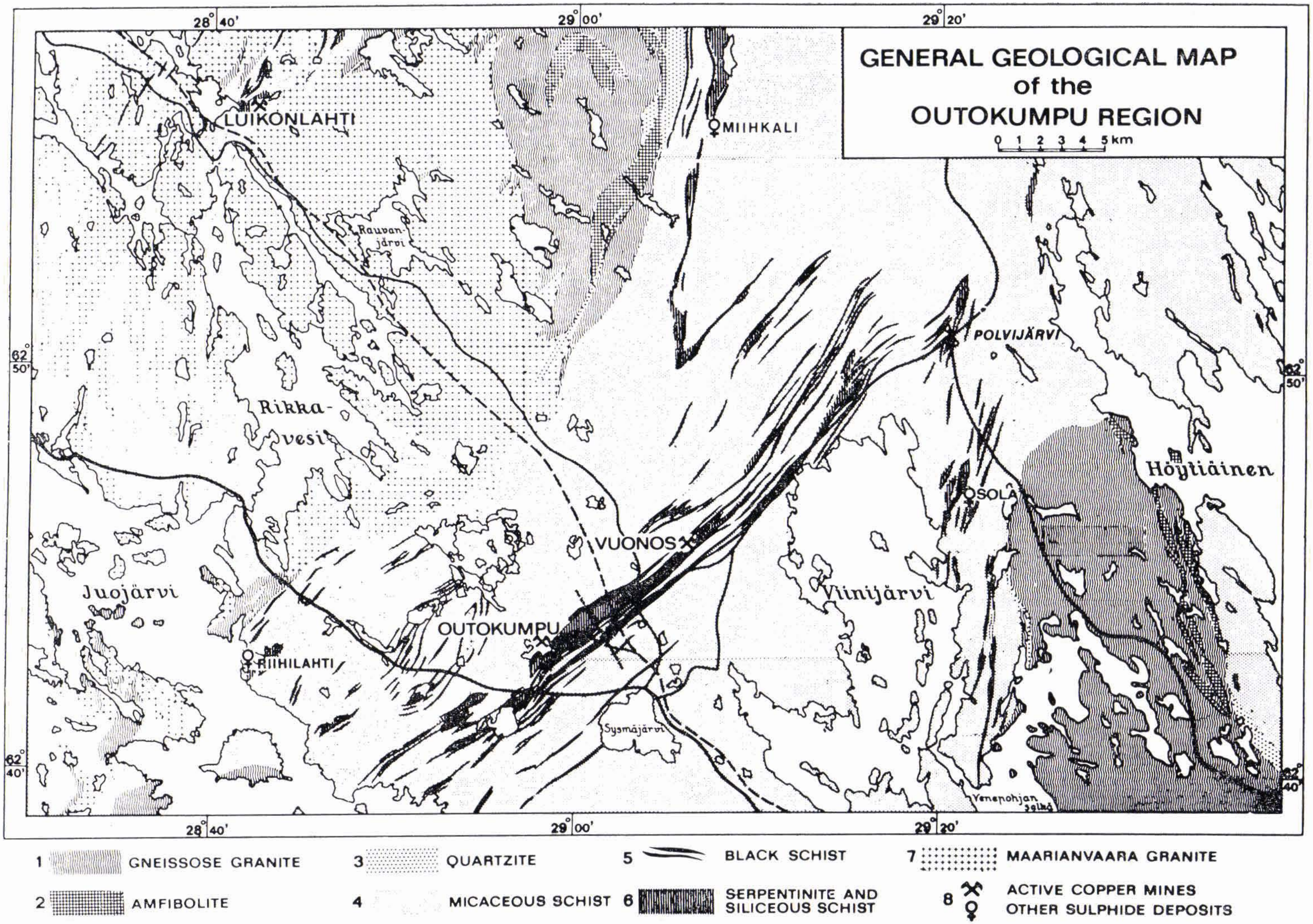

Fig. 1. Map of the Outokumpu district showing the location of the Outokumpu zone (after Huhma, A., 1976).

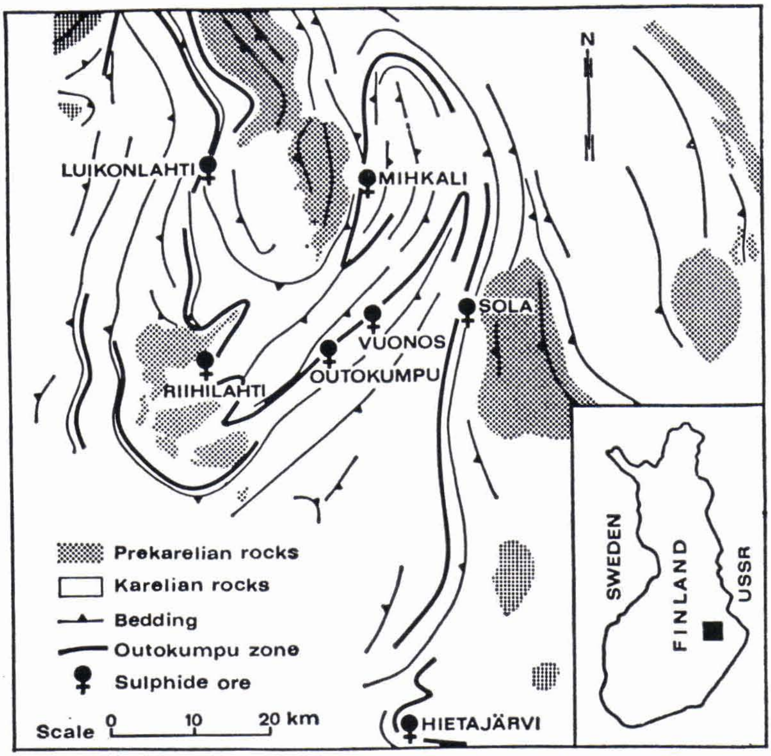

Fig. 2. General geology of the Outokumpu region (after Huhma and Huhma 1970).

The Outokumpu zone is usually bounded by black schists that, towards the middle of the zone, grade into Outokumpu-quartzites and serpentinites (Fig. 4). The conformable, elongate lenses of serpentinite are surrounded by thin envelopes of dolomite and various types of skarns. The latter are usually chrome-bearing. A few discrete and thin black schist intercalations are encountered in the mica schist area proper as well.

Rock types

The Outokumpu zone is embedded in Karelian geosynclinal metasediments. *Phyllites* abound in the eastern part of the region, whereas *mica gneisses* and migmatites occur in the west, where the metamorphic grade is higher. In the Outokumpu district, the micaceous schists are characterized by elevated Na and Ca (Tables 1 A and B).

In the Outokumpu zone, carbonaceous *black schists* occur commonly between the Outokumpu quartzites and the surrounding mica schist formation. The banded structure is due to the alteration of fine-grained carbon- and mica-bearing layers with coarse-grained quartz- and sulphide-bearing layers. The chemical composition (Table 1 C) indicates that the black schists were originally argillaceous carbon- and sulphide-bearing sapropelic sediments (Peltola 1960). In the black schists of the Outokumpu district the abundances of some typical trace elements, e.g. vanadium (0.11 % V_2O_5) and boron (0.015 % B), are of the same order of magnitude as are those in several well-studied marine carbonaceous deposits.

Outokumpu-quartzites are intercalated with black schists, skarns and serpentinites. They are spatially associated with the serpentinite bodies and the thickness of the quartzite envelope roughly correlates with the size of the ultramafic

Table 1.
Chemical compositions of the rocks of the Outokumpu district.

	A	B	C	D	E	F
SiO_2 .	67.07	67.42	50.07	89.39	37.76	38.31
TiO_2 .	0.80	0.71	0.91	0.02	0.01	0.01
Al_2O_3	13.70	13.08	13.91	0.93	0.79	0.54
Cr_2O_3	0.02	0.02	0.08	0.24	0.50	0.03
Fe_2O_3	0.87	0.40	0.18	0.28	0.59	—
FeO . .	4.54	4.41	1.66	0.44	2.41	—
MnO .	0.05	0.03	0.04	0.02	0.08	0.07
MgO .	2.55	2.26	4.13	1.47	38.29	0.53
CaO .	1.84	2.31	4.20	2.11	0.45	0.33
Na_2O	2.39	2.67	2.06	0.23	0.04	0.19
K_2O .	2.70	1.72	2.17	0.10	tr.	tr.
H_2O^+.	—	1.28	1.46	0.61	13.12	0.40
H_2O^-.	1.23	0.06	—	—	1.15	0.14
P_2O_5 .	0.08	0.01	0.07	0.02	tr.	0.02
CO_2 . .	0.14	0.10	0.08	1.16	0.45	0.11
C	0.44	0.66	8.18	0.46	—	tr.
F	0.04	0.06	0.09	0.08	—	tr.
S	0.71	0.70	4.81	0.67	1.18	25.30
Fe (S)	1.08	1.08	6.12	1.02	1.79	28.10
Ni . . .	—	—	0.03	0.12	0.18	0.12
Cu . . .	—	—	0.05	tr.	—	3.80
Zn . . .	—	—	0.03	tr.	—	1.00
Co . . .	—	—	0.01	0.02	—	0.24
V_2O_5 .	0.03	0.03	0.11	0.02	0.01	0.01
Total .	100.28	99.01	100.45	99.41	99.80	99.25

A. Phyllitic schist, Lake Höytiäinen, Polvijärvi.
B. Micaceous schist, Outokumpu.
C. Argillaceous black schist (average of 10 analyses), Outokumpu district.
D. Siliceous schist (average of 10 analyses), Outokumpu district.
E. Serpentinite (average of 10 analyses), Outokumpu district.
F. Outokumpu copper ore, average composition.

bodies. In its purest form, Outokumpu quartzite is an almost monomineralic pale grey quartz-rock (Table 1 D). Low-grade sulphide and graphite disseminations, however, darken it and, in places, chromite dust might tinge it brown. Outokumpu-quartzite is banded, but it does not contain feldspar or detrital heavy minerals, which are invariably present in sedimentary Karelian quartzites (Huhma and Huhma, 1970). Close to the Outokumpu and Vuonos mines, the quartzites have an anomalous and constant nickel content of about 0.10 to 0.20 % Ni. According to Huhma and Huhma (1970), the Outokumpu-quartzites are not clastic sediments but chemical silica precipitates.

Serpentinites form elongated and parallel lenses of variable size. The most coherent bodies occur in the middle of the Outokumpu zone, close to the Outokumpu and Vuonos orebodies, where the largest lenses are a few hundred metres wide and several kilometres long. Although the frayed edges of the conformable serpentinite bodies are regularly enveloped by Outokumpu-quartzites, the immediate contacts of the serpentinite are occupied by skarn and carbonate (dolomite) rocks (Figs. 3 and 4).

As a whole the serpentinites are fairly homogeneous, undifferentiated ultrabasic rocks that have undergone all the deformation phases of regional metamorphism (Table 1 E). The inner parts of the bodies consist of dark to pale green serpentine, which is antigorite in the eastern part of the area and chrysotile in the west. Pseudomorphs after olivine are common relict textures; relics of pyroxene (enstatite and augite) are more rare. Chlorite, talc and carbonate minerals occur in varying amounts.

Skarns, chlorite schists and carbonate rocks abound at the contact between serpentinite and Outokumpu-quartzite. According to Haapala (1936), the dolomites are metasomatic alteration products and the skarns the product of a reaction between dolomite and Outokumpu-quartzite. The skarn rocks are chrome- and nickel-bearing and are characterized by rare minerals such as chrome diopside, chrome tremolite, uvarovite, chromite, fuchsite and chrome tourmaline.

Vuonos ore deposit

Occurrence

The Vuonos orebody lies structurally in a position analogous to that of the Outokumpu orebody, that is, in association with a specific quartzite layer that binds the orebodies into the same stratigraphic horizon. The orebodies are roughly conformable with the Outokumpu-quartzite host rocks. The contacts with the country rocks are usually sharp and unaltered.

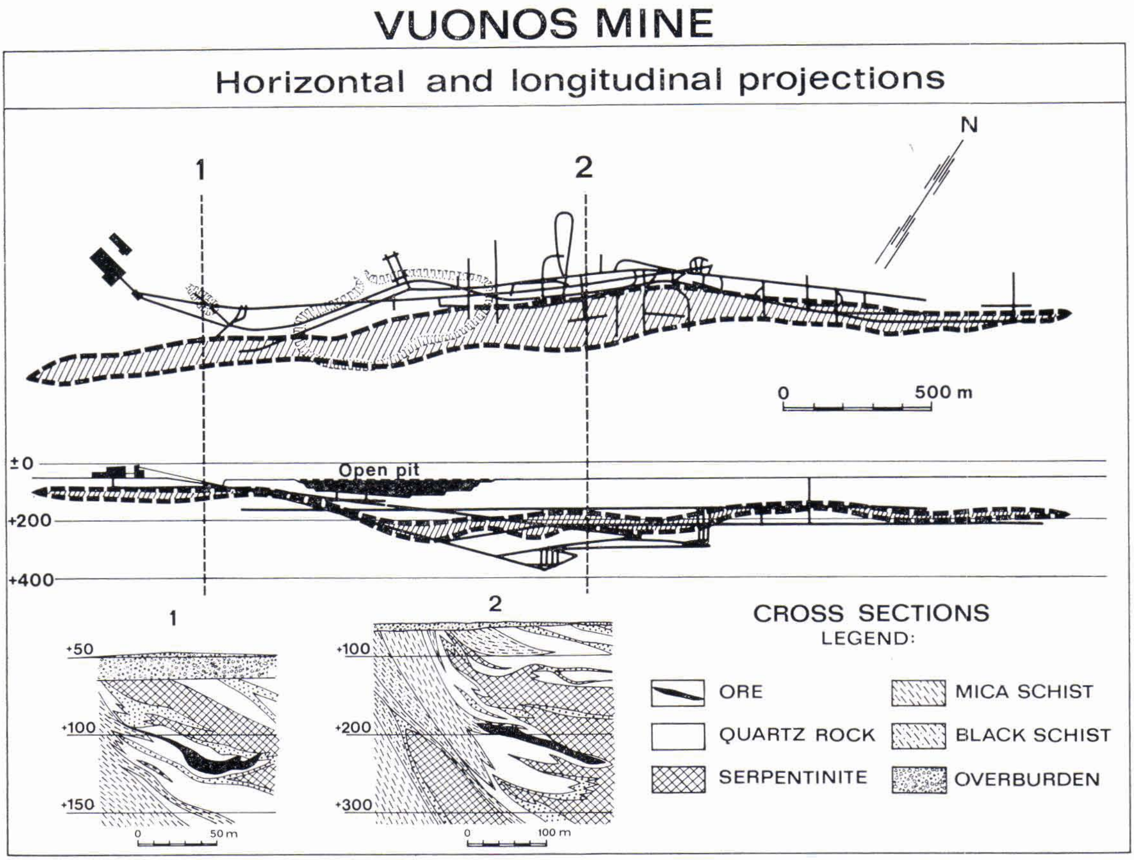

Fig. 3. Horizontal and longitudinal projections of the Vuonos mine.

The ores are lens-shaped bodies, elongated parallel to the depositional strike, the local linear structure and the gently undulating fold axis. The Vuonos orebody is horizontal and, in shape, reflects the regional folding (Fig. 3). Its upper edge often dies out in Outokumpu-quartzite, whereas, nearer the lower edge, its hanging-wall contact is commonly against serpentinite. Locally, the upper edge is surrounded by black schist and micaceous schists, which occur as conformable intercalations in the upper ore horizon as well (Fig. 4).

The orebody is cut by several fault systems characterized by older horizontal and younger vertical faults.

In addition to the massive copper ore, a disseminated low-grade nickel ore exists in Outokumpu-quartzite and in the skarn rocks above the Vuonos copper orebody.

Structure and metamorphic features of the Vuonos copper ore

Structurally the deposit can be subdivided into two types: layered and massive ores. The layered type is composed of layers of sulphides alternating with quartzitic and carbonaceous layers. The layered structure is indicated by sulphide-free or weakly mineralized conformable

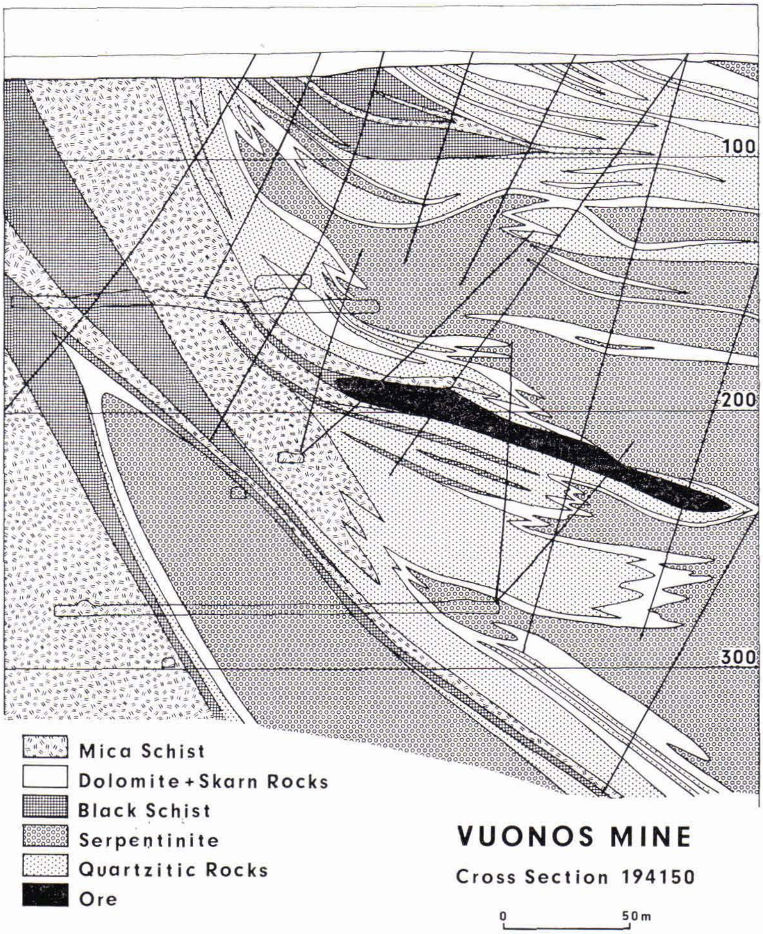

Fig. 4. Cross section 194150 of the Vuonos mine.

intercalations. The layers generally vary in thickness from one millimetres to several centimetres. This ore type occurs principally in the upper and middle parts of the orebody and at the footwall contacts.

The lower edge and thinner ends of the orebody, which are completely surrounded by serpentinite, are predominantly of the massive type. The stratified setting of the sulphides is still clearly visible as relict structures in the best preserved parts of the massive ore.

The folding and brecciation in the ore horizon resemble in places slump structures and may be considered as preconsolidation structures. The stratification of the sulphides is still distinct in the bent and broken fragments, which suggest that mineralization preceded folding and brecciation.

Lineation in the margins, external and internal folding and axial plane schistosity are frequent in the ore horizon. Pyrrhotite, chalcopyrite and sphalerite were remobilized into pressure shadows of boudins and into the crests and tension cracks of folds. Remobilized sulphides form crosscutting veins in the ore horizon and in the margins of the orebodies.

Mineralogy and composition of the Vuonos ore

The main sulphides are pyrrhotite, chalcopyrite and sphalerite; quartz is practically the only gangue mineral. The Vuonos ore contains 39.7 % pyrrhotite, 7.1 % chalcopyrite and 2.7 % sphalerite. Pyrite occurs occasionally. Cobaltian pentlandite (about 0.5 %) is the most important accessory sulphide. Minor accessories are cubanite, mackinawite, magnetite and stannite.

The Vuonos ore averages: Cu 2.45 %, Fe 25 %, S 17.5 %, Zn 1.6 %, Co 0.16 % and Ni 0.13 %.

The considerable concentration of copper, zinc and cobalt and the lack of lead is a distinctive feature of all the copper deposits in the Outokumpu district.

Zinc is enriched in both edges of the Vuonos orebody. Copper increases towards the NW edge and cobalt towards the SE edge.

The Vuonos ore differs in chemical composition from the Outokumpu ore by its lower sulphur content in sulphide phase. Mineralogically this is reflected in the relative amounts of pyrite and pyrrhotite: pyrite is abundant in Outokumpu but rare in Vuonos.

The mineralized quartzite and skarn rocks at Vuonos, which have been exploited as a nickel ore, contain disseminated pyrrhotite and pentlandite. In the open pit, the grade of the sulphides increased towards the contact with the serpentinite concurrently with the increase in abundance of the minute sulphide veins and disseminations. In contrast with copper ore, the pentlandite in the nickel ore is of a cobalt-poor variety.

Conclusions

The copper deposits in the Outokumpu district are associated with a lithologic complex that regularly consists of black schists, skarns, serpentinites and Outokumpu-type quartzites. This rock association constitutes the coherent stratigraphic sequence known as the Outokumpu zone, whose existence is a prerequisite for the occurrence of Outokumpu-type ores.

The lithological and structural setting and the high nickel and chromium content of the serpentinite-quartzite association indicate a genetic relationship between the rocks of the Outokumpu-zone.

The »Outokumpu ore type» is unique in rock types and associations as well as in trace element composition; therefore, it is not easy to find any other ore type that resembles it closely. Thus, the origin of the ore has long been debated and has given rise to divers theories.

The Outokumpu copper deposits show a clear stratigraphic association with the enclosing metasedimentary and metavolcanic rocks of the Outokumpu-complex and seem to be the Precambrian equivalent of more recent stratiform massive pyrite deposits of sedimentary-volcanogenic association.

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GEOLOGY OF THE KOTALAHTI Ni—Cu DEPOSIT — by J. Koskinen

Introduction

In August 1954 a sample of sulphide-bearing graphite-schist was sent to the Exploration department of Outokumpu Oy from the Kotalahti area. Field investigations were started and in september 1954 a sulphide-bearing ultramafic rock was discovered in a roadcut on Highway 5, about 40 km south of Kuopio. Diamond drilling proved that the adjacent magnetic anomaly was caused by a Ni-Cu ore in an ultramafic body.

Development work started in April 1956 with the sinking of an exploration shaft at Vehka and the driving of the associated drifts.

The mine went into operation of 1st October 1959 when the exploitation of the ores above the + 250 level started.

Underground exploration demonstrated that the ore deposit continues downwards below the + 250 level. The mine was deepened in 1971, and the + 600 level became the haulage level for the ore. Drilling data indicate that the Jussi and Huuhtijärvi orebodies continue below the + 600 level. A ramp is currently being driven to facilitate the investigation of ores below this level and to develop the area for production.

At present *the Kotalahti mine* (stop 9) is the deepest in Finland. The central shaft extends to a depth of 680 m. The ramp reached the workings below the + 600 level by the end of 1977.

Annual production has lately been in the region of 450 000 to 500 000 tons of ore. By the end of 1978 a total of over 8.5 million tons of ore averaging 0.7 % Ni and 0.27 % Cu had been treated in the mill. The main product is nickel concentrate whose annual output has been 55 000 tons; the corresponding figure for copper concentrate is 3 000 tons. From Kotalahti the concentrates are transported by lorry and train to the Harjavalta works of Outokumpu Oy for processing.

Mining and concentrating

At Vehka, Huuhtijärvi, Mertakoski and Välimalmi, where the distance between stoping levels is from 20 to 50 m, the ore is extracted mainly by sub-level stoping. In the Vehka—Mertakoski zone the empty spaces are filled with mill tailings. In the Jussi orebody exploitation started on the + 400 and + 600 levels with the cut and fill method but continued above the + 250 level with sub-level stoping.

The ore is concentrated by floating all the sulphides together and recovering the nickel and copper minerals as nickel and copper concentrates. By including pyrrhotite, a recovery of 92.5 % has been attained for the nickel concentrate, which contains 5.5—6 % Ni.

General geology of the area

The Kotalahti ore deposit is located in the Savo schist zone, which, in the Kotalahti area (Fig. 1), is characterised by migmatitic and veined plagioclase-rich mica gneiss with some garnet- or cordierite-bearing horizons. Hornblende-bearing varieties of gneiss grade into amphibolites.

The gneisses seldom have clear relics of primary structures; diopside amphibolites and fine-grained quarzites, however, often exhibit layered structure.

Domes of older Prekarelian gneisses mantled by epicontinental metasediments occur as »windows» in the schist area near Kuopio. During

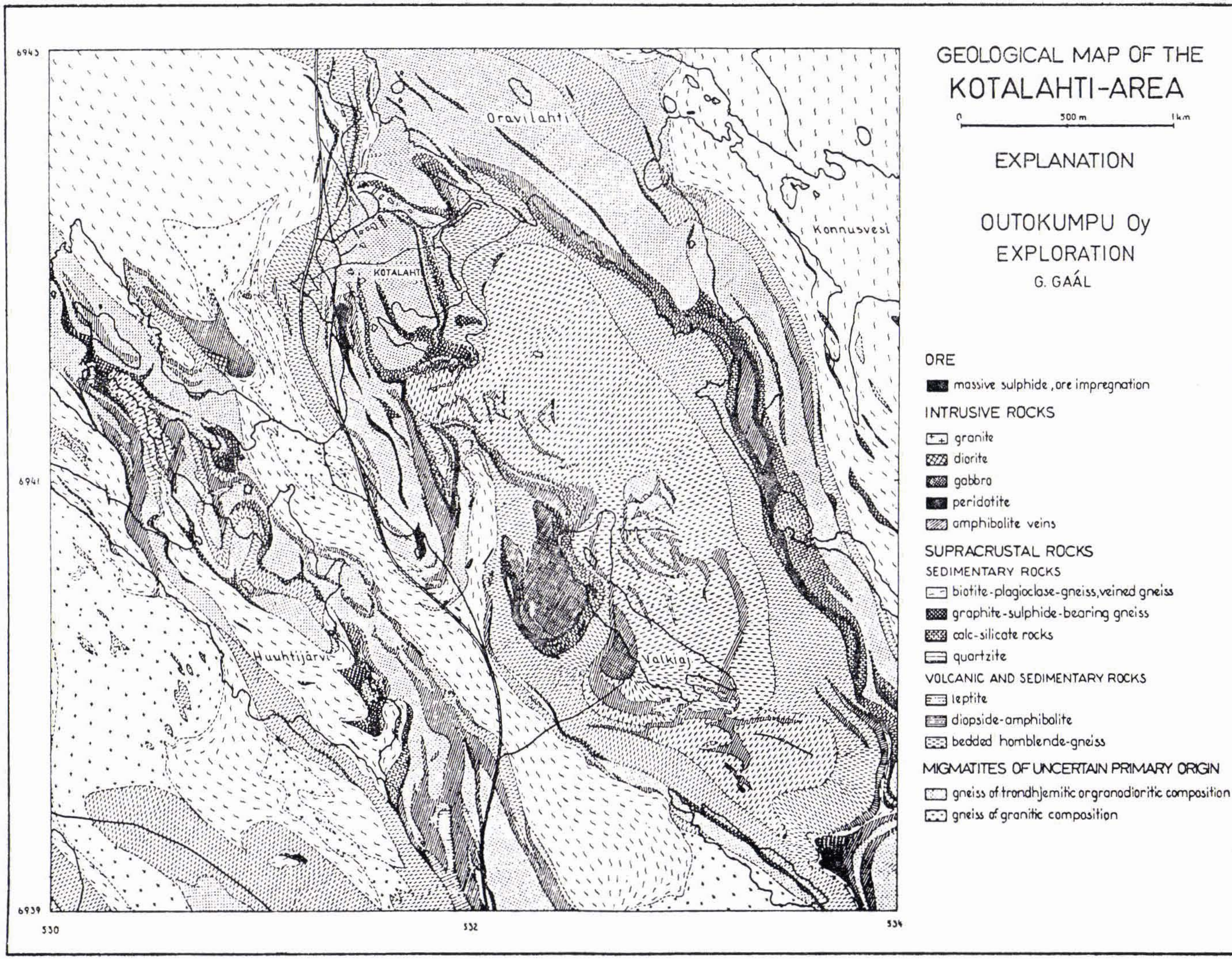

Fig. 1. Geological map of the Kotalahti area.

prospecting a similar dome was mapped east of the Kotalahti ore deposit. This dome is mantled by zones of quartzite, skarn and limestone, diopside amphibolite and black schist, which cause geophysical anomalies suggestive of a domelike structure. The gneisses within the dome contain more pink granite than the migmatic Svecokarelian gneisses around the mantled dome. Amphibolite and metadiabase are also common in the dome.

Various types of intrusive rocks exist in the area. The structural and metamorphic features of the Mg-rich ultrabasic intrusions indicate that these rocks intruded at the beginning of orogenic activity.

The general strike in the Kotalahti area is towards NW and the dip subvertical. According to Gaál (1972), the Kotalahti area is part of a major tectonic belt characterized by subparallel swarms of shear fractures trending NW. The Ni-Cu-bearing rocks are related to transcurrent faults.

The age of the granite gneiss in the dome is 2 800 Ma and that of the Kotalahti intrusive 1 880 Ma (O. Kouvo).

The geology of the ore deposit

The mafic complex of Kotalahti is composed of two separate parts (Figs. 2, 3). Vehka—Välimalmio—Mertakoski is a subvertical and rather narrow sill-form plate, which has a bulge 150 to 200 m wide at Välimalmio—Mertakoski. This part of the intrusion extends to a depth of 700 m. Huuhtijärvi is a pipe-like subvertical body. It is 100—150 m long and 20—60 m wide. Downwards the Huuhtijärvi body continues below the 800 m level.

The thin and tape-like Jussi orebody, which is only 80—90 m long but extends to a depth of at least 800 m is located 150 m east of the main Kotalahti intrusion. This orebody differs from the others in that the sulphides are in a horizon of skarn-quartzite-black schist. A very strongly brecciated and small peridotite body is encountered as host rock in the southern part of the orebody. Cataclastic peridotite seems to continue downwards in association with the ore. The total length of the Kotalahti complex is 1.3 km.

The differentiated Kotalahti complex contains rocks ranging from peridotites through pyroxenite-perknites and gabbros to diorites. The rock units are generally irregular in form and complex in interrelations. Perknite is the dominant rock type; it is usually an unoriented medium-grained rock composed of light-coloured amphiboles, such as hornblende, cummingtonite, tremolite and antophyllite. Pyroxenes are common as are phlogopite and minor plagioclase. The rocks in Huuhtijärvi are richer in micas and intensely sheared and altered.

The perknite is an amphibole-rich variety of pyroxenite and predominates in the upper part of the Vehka—Välimalmio—Mertakoski zone. At the deeper levels, where the complex is wider, pyroxenes are more abundant. In the pyroxenites orthopyroxene is often altered into cummingtonite along the borders of grains; likewise clinopyroxene is altered into hornblende. The pyroxenites are generally rich in orthopyroxene.

The peridotites are encountered mainly in the northern part of the complex in Mertakoski and Välimalmio; in Vehka peridotite occurs sporadically, and in Huuhtijärvi there are only rare and very small peridotite lenses. The peridotites are saxonitic or lherzolitic in composition. The amounts of olivine and pyroxenes vary considerably. Olivine is generally serpentinized, in some places even completely. Just above the + 400 level in Välimalmio the peridotite shows subhorizontal layering.

Gabbros and diorites occur mainly at the margin of the complex. The contact between the intrusion and the wall rock is generally sharp but locally gradual. Fine-grained varieties of gabbro are found against the gneiss. The amount of plagioclase increases in the middle of the complex and the composition of the rock grades

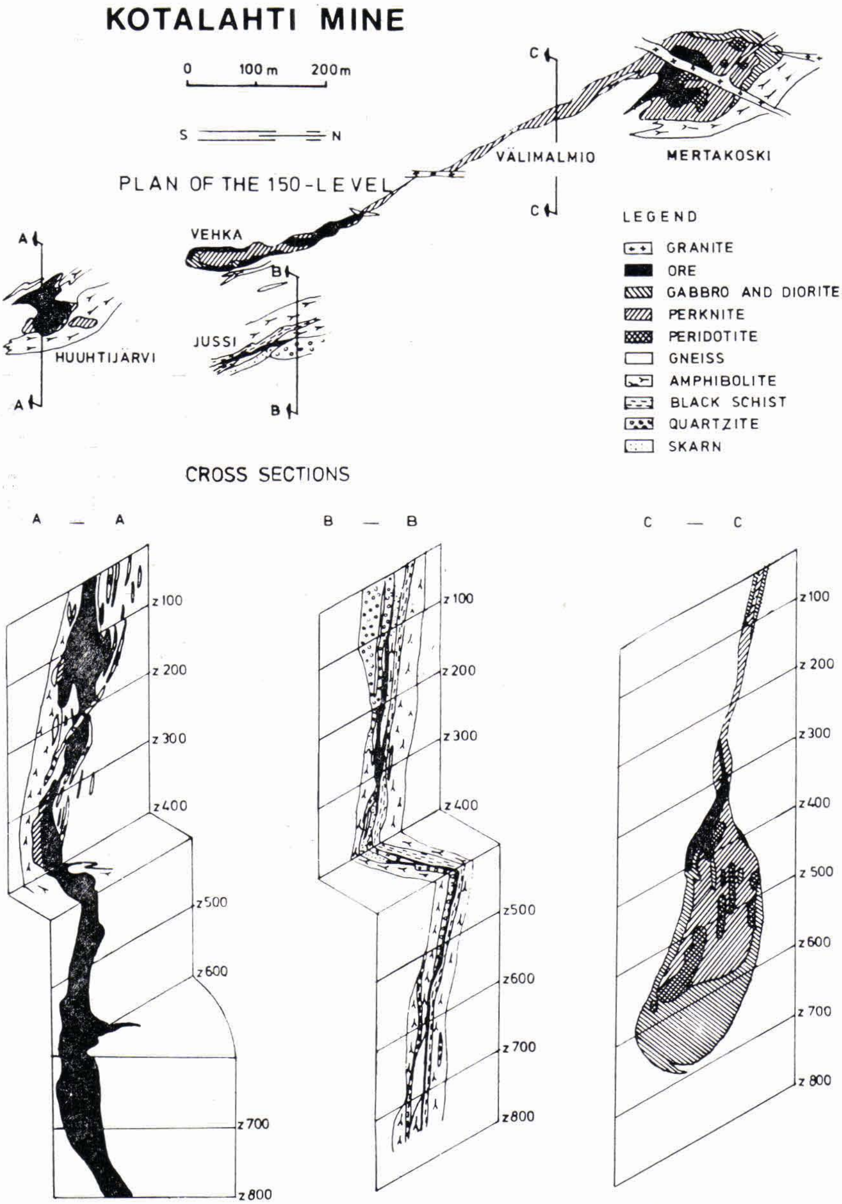

Fig. 2. The 150 level plan and three cross sections of the Kotalahti mine.

into olivine gabbros, olivine norites, pyroxene gabbros and hornblende gabbros. In texture the gabbros are often poikilitic or ophitic.

The most silicic members of the intrusion series are diorites and quartz diorites, the largest bodies of which occur at the deepest margin of the Välimalmio—Mertakoski area.

The chemical compositions of the rocks are listed in Table 1. Except for perknites, which show an anomalously high potassium and silica content (Papunen 1970) the variation in chemical composition is typical of a calc-alkalic series. The diorites and hornblende gabbros in the margin of the complex are relatively poor in

Table 1.
Average chemical composition of the rocks and ores of Kotalahti. According to Papunen (1970)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Number of analyses	10	9	9	18	4	26	23	15	29	47
SiO_2	45.14	47.99	49.61	50.69	58.63	—	—	—	—	—
Al_2O_3 ...	5.83	7.25	7.60	12.88	16.25	—	—	—	—	—
Fe_2O_3* ..	15.99	14.15	14.32	11.59	10.50	—	—	—	—	—
MgO	25.05	22.52	22.00	14.84	3.24	—	—	—	—	—
CaO	4.10	4.42	5.08	7.57	6.45	—	—	—	—	—
K_2O	0.34	0.47	1.20	0.72	1.65	—	—	—	—	—
Na_2O ...	1.31	1.23	1.18	2.02	3.40	—	—	—	—	—
Total	97.76	98.03	100.98	100.31	100.12	—	—	—	—	—
Ni_S	9.81	9.19	8.41	5.90	1.37	6.53	6.14	6.38	6.65	11.23
v_{Ni}	24.2	29.8	27.1	31.0	57.1	10.9	13.6	20.0	16.4	32.5
Cu_S	2.90	2.79	2.86	2.12	1.54	2.75	2.05	1.74	2.10	6.47
v_{Cu}	60.4	37.6	53.2	61.7	181	43.2	66.1	74.6	70.6	80.4
Co_S	0.41	0.45	0.40	0.49	0.38	—	—	—	—	—
v_{Co}	44.3	47.7	39.8	51.7	68.2	—	—	—	—	—
Ni/Cu ...	3.39	3.29	2.95	2.78	0.89	2.37	3.00	3.66	2.17	1.74
Ni/Co ...	23.9	20.4	21.0	12.0	3.61	—	—	—	—	—

* Fe_2O_3 denotes total Fe
Ni_S, Cu_S and Co_S are the calculated metal weight percentages of the sulphide phases based on 38.0 weight per cent sulphur in the sulphide phase
v_{Ni}, v_{Cu} and v_{Co} are the coefficients of variation of the calculated metal weight percentages

1. peridotites
2. pyroxenites
3. perknites
4. gabbros
5. diorites and quartz diorites
6. Mertakoski, breccia ore
7. Välimalmi, breccia ore
8. Vehka, breccia ore
9. Huuhtijärvi, breccia ore
10. Jussi orebody, breccia ore

magnesium. These hornblende gabbros contain less than 10 % MgO, whereas the pyroxene-rich gabbros rather poor in plagioclase in the middle of the Välimalmi—Mertakoski area contain 17 % MgO.

The wall rocks of the Kotalahti massif consist of migmatitic gneisses and amphibolites. In broda lines the intrusion is comformable with the schistosity of the wall rock, but in detail it cuts it.

The massif is crosscut by numerous dyke rocks of different composition. By far the most widespread, and peculiar especially to Huuhtijärvi and to narrow parts of Vehka and Välimalmio, are veins or vein networks of plagioclase (oligoclase to andesine) and quartz. In contact with the peridotite these veins have reaction seams, composed of tremolite perpendicular to the contact, chlorite and talc. In composition the dykes are similar to the potassium-poor neosome in the migmatite gneisses.

There are also rectilinear potassium feldspar-bearing dykes of either equigranular and fine-grained or coarse-grained pegmatitic granite; one of these is the Mertakoski granite, which divides the Mertakoski orebody into two separate parts.

The third group consists of fine-grained amphibolite or diabase dykes that cut with sharp contacts both the intrusion and the gneisses. These dykes are often distorted and broken by later movements.

The sulphides in the complex occur in all members of the differentiation series. Below the

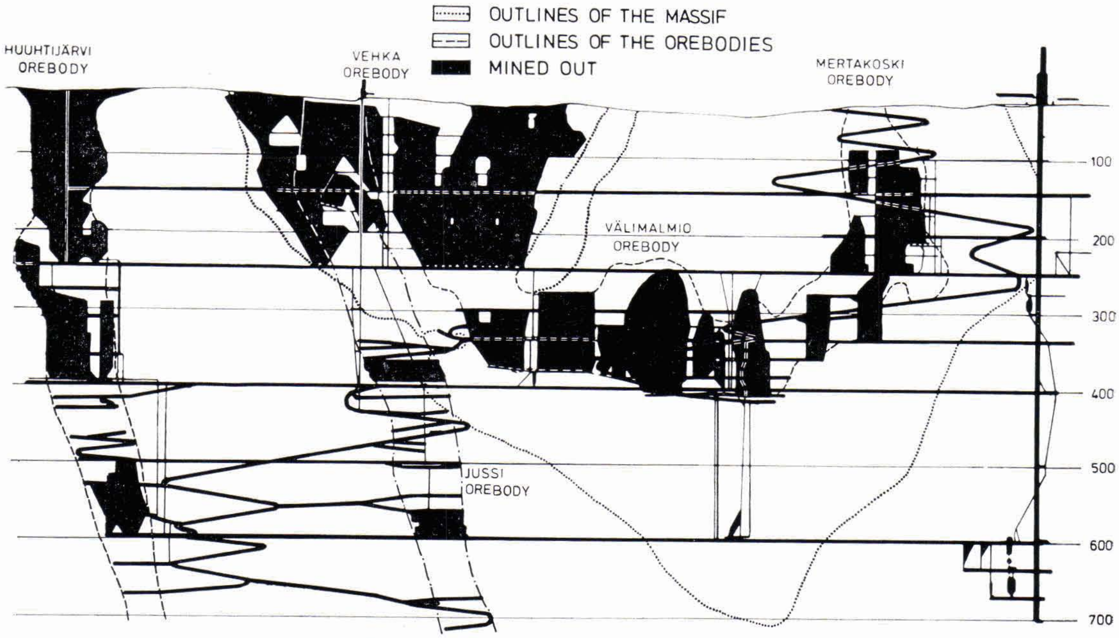

Fig. 3. Longitudinal projection of the Kotalahti mine.

+ 400 level in Välimalmio—Mertakoski the amount of sulphides is low and the gabbros and especially the diorites contain only local traces of sulphides. Similarly, the deeper parts of Huuhtijärvi are poorer in sulphides than the parts nearer the surface.

The orebodies contain disseminated and massive sulphides that generally occur together. The intensity of the mineralization varies within a wide range. Subgrade dissemination extends beyond economic limits in many places.

A typical dissemination consists of sulphide blebs, several mm in diameter, that occur interstially among silicates. In some places the sulphides form a continuous matrix enclosing silicate accumulations and grains; this may further grade into massive sulphides. Disseminated sulphides occur locally in gabbros and perknites as rounded blebs of a »buck shot» ore type.

The massive sulphides usually occur in breccias or stringers; they favour the contact zones and inner parts of the intrusion, and are often associated with amphibolite and granite dykes whose fractures they fill. The wall rock fragments in the breccia ore tend to be rounded and altered.

The location of the Jussi orebody is controlled by a fracture in the quartzite-skarn-black schist zone. The only connection with ultrabasic rock that this orebody is currently known to have is through a small peridotite lens in its southern end. The Jussi orebody consists of breccia ore, sulphide stringers and disseminations that favour skarn horizons. In places the massive sulphides crosscut the structure of gneisses and contain fragments of pegmatite granite.

The distribution and grade of the sulphides along the ore horizon in the Jussi orebody is very irregular.

The content of nickel in sulphide phase varies little; the sulphide dissemination in the peridotites shows slightly elevated values, the lowest values being in diorites. The nickel content in the sulphide phase of the breccia ore is the same as the average of the Kotalahti ore, i.e. 6—7 % Ni. The exception is the Jussi orebody, which is richer in nickel containing almost

11 % Ni in sulphide phase. Similarly the relative copper content in Jussi orebody is higher than in the main zone, where, however, the breccia ore is locally enriched in chalcopyrite, which occurs as blebs or small veinlets even in the wall rock.

The main ore minerals are pyrrhotite, pentlandite and chalcopyrite. The Jussi orebody contains millerite and bornite especially in its northern end. Fine-grained pyrite accumulations are also common in the massive ore. Pyrrhotite is either hexagonal or monoclinic (Papunen 1970). Troilite and hexagonal pyrrhotite are encountered in the primary disseminated ore whereas monoclinic pyrrhotite predominates in the breccia ore and in the Jussi orebody.

Gersdorffite, sphalerite and mackinawite are the accessories in the main zone; the Jussi orebody also contains argentian pentlandite.

Ilmenite is the predominant oxide in the Kotalahti massif. Magnetite exists only as an accessory in disseminated ores in peridotites. In some places the Jussi orebody contains appreciable magnetite in association with sulphides.

The Kotalahti ore assays Co = 0.03 %, Cr = 0.2 %, Ti = 0.4 %, V = 0.04 %, Pt = 0.005 g/t and less than 0.005 g/t Pd and Rh.

The nickel content in olivine varies between 950 and 3 450 ppm, in enstatite between 100 and 850 ppm, in augite between 50 and 400 ppm and in amphiboles between 10 and 1 050 ppm (Häkli 1963). The amphiboles and augite in the hornblende gabbros and diorites of the marginal zone of the intrusion show low Ni contents. The average Ni content in amphiboles is higher than in the coexisting enstatite and augite. The olivines are usually poorest in nickel wherever the abundance of sulphides is high. Correspondingly, olivines rich in nickel favour a sulphide-poor milieu.

Summary

The Kotalahti intrusion is a differentiated massif that contains rocks of a calc-alkalic series from peridotites to diorites. Basic magma was emplaced and crystallized during an early phase of movements. The structure and location of the members of the series indicate that the conditions during the crystallization processes favoured gravitative settling only locally. The gabbros and diorites in the marginal zone of the intrusion show features characteristic of reactions between basic magma and wall rocks.

The regional metamorphism and migmatization as well as later movements and dyke rocks have made their own impression upon the rock types of the intrusion and the ore.

The sulphides derrived from basic magma. Contact relations show that the primary dissemination and breccia ores were not formed coincidentally. The granite fragments in the massive ore indicate late emplacement for the sulphides involved. Gaál (1972) has proposed that a NW-trending deep fault system has controlled the »Kotalahti nickel belt» and the emplacement of the Kotalahti intrusion.

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