north-south direction across the migmatized mica gneiss area. The ultramafic intrusions have undergone deformation and metamorphism, and the alteration has totally obliterated the primary mineral composition. The rocks are serpentinites (metadunites) and metaperidotites whereas amphibole rocks abound along the contact zones against the gneissic wall rock. Although the shapes of the intrusions vary, the most common seems to be a subvertical pipe or stock and vertical dimensions are more extensive than horizontal ones. Geochemically all the ultramafic intrusions are much alike and show striking similarities to the ultramafics of Oravainen. The weak fractionation is due to the small variation in the MgO/FeO ratio. High values of the Al_2O_3/CaO ratio are typical of the metaperidotites in the area.

Intense hydration of the silicate minerals is the result of hydrothermal processes which, accordingly, altered the sulphide minerals into assemblage of valleriite, mackinawite and pentlandite occurring together with hydrous sheet silicates (chlorite). The high values of the Al_2O_3/CaO ratio are also due to the hydrothermal alteration of the peridotitic host rocks and the primary composition of the ultramafics is hard to decipher.

The content of titanium is very low and that of chromium rather high. The tenor of chromium, however, is somewhat lower in metadunite than in metaperidotite. Both elements have been considered rather resistant against hydrothermal leaching and they thus reflect the primary composition of the ultramafics. Low tenors of incompatible elements like titanium and phosphorus and high chromium reflect the depleted, residual character of the magma type of Hitura and Makola.

At Hitura the accumulation of sulphides is controlled by the amphibole rocks of the contact zone of the intrusion. At Makola one of the metaperidotite bodies in a heterogeneous belt of ultramafics is mineralized. In the final stage deformation and metamorphism affected the accumulation of massive and breccia sulphides, but there is no doubt that the premetamorphic history, development and intrusion of ultrabasic magma are responsible for the mineralization in some parts of the intrusions. Despite the ultramafic host rock the sulphides are fairly rich in copper, possibly because of late immiscibility of the sulphide melt from an interstitial magma from which the bulk of the cumulus olivine has already been crystallized.

GEOLOGY OF THE KOTALAHTI NICKEL-COPPER ORE

H. PAPUNEN and J. KOSKINEN

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 orebody and the Huuhtijärvi occurrence continue below the +600 level.

Annual production has lately been in the region of 450,000 to 500,000 tonnes of ore. A total of 10 million tonnes of ore averaging 0.7 % Ni and 0.27 % Cu has been treated in the mill to date.

The geology of the Kotalahti Ni-Cu deposit has been described by Haapala (1969), Papunen (1970), Isokangas (1978) and Papunen and Koskinen (1978, 1980). The rock types surrounding the ultramafic body have been studied by Niskanen (1980), and Gaál (1980) has reported the tectonic setting of the intrusion.

The Kotalahti Ni-Cu ore is the most important of the deposits located between the Svecokarelian granitoid complex of central Finland and the Archean basement area in the northeast. The nickel occurrences form an apparently linear belt that trends from Parikkala in the southeast to Raahe in the northwest, and includes, in addition to Kotalahti, also the Laukunkangas and Hitura deposits. The belt has been called »the Kotalahti Nickel Belt» by Gaál (1972) and by Kahma (1973), and its broad tectonic and structural features have been discussed by Gaál and Rauhamäki (1971, 1975), Tuominen *et al.* (1973), Parkkinen (1975), Gaál *et al.* (1978), Papunen *et al.* (1979) and Tontti *et al.* (1979). The belt is characterized by lineaments in topography and geophysical maps and a parallel gravimetric trough extending from Lake Ladoga to the Bothnian Bay. In this issue, Gaál gives his current interpretation of the tectonic features and location of Ni-Cu deposits.

GENERAL GEOLOGY OF THE AREA

The environment of the Kotalahti deposit is part of the Savo schists belt, which is characterized by migmatitic and veined gneisses (Fig. 42). In general, the origin of the gneisses cannot be recognized, but some wellpreserved portions indicate that they are metamorphosed pelitic to psammitic rocks. The primary material of the diopside amphibolites is of volcanic origin (Niskanen 1980), although some of them might be calcareous metasediments.

In the schist area around Kuopio and in North Karelia there are numerous domes of Prekarelian gneisses mantled by metasediments of epicontinental facies (Wilkman, 1932, Preston, 1954). One such dome, located east of the Kotalahti ore deposit, is mantled by a zone of metasedimentary quartzites, calc-silicate rocks and metavolcanic diopside amphibolites. The associated black schists cause geophysical anomalies and hence the shape of the dome shows up on the geophysical map. The dome is composed of banded or veined gneisses, very similar in appearance to the migmatitic leucocratic gneisses surrounding the mantled dome. Amphibolite and metadiabase dykes are common in the dome and in the surrounding gneisses. According to the recent interpretation by Gaál (1980), the structure of the dome, »Valkeinen brachyantiform», is an interference structure of several foldings and hence the result of subsequent deformation phases, the oldest of which are Archean in age. Similarly, the leucocratic gneisses surrounding the rocks of the epicontinental facies form a brachysynform at the site of the Kotalahti ultramafic intrusive complex.

A heterogeneous belt of amphibolites and

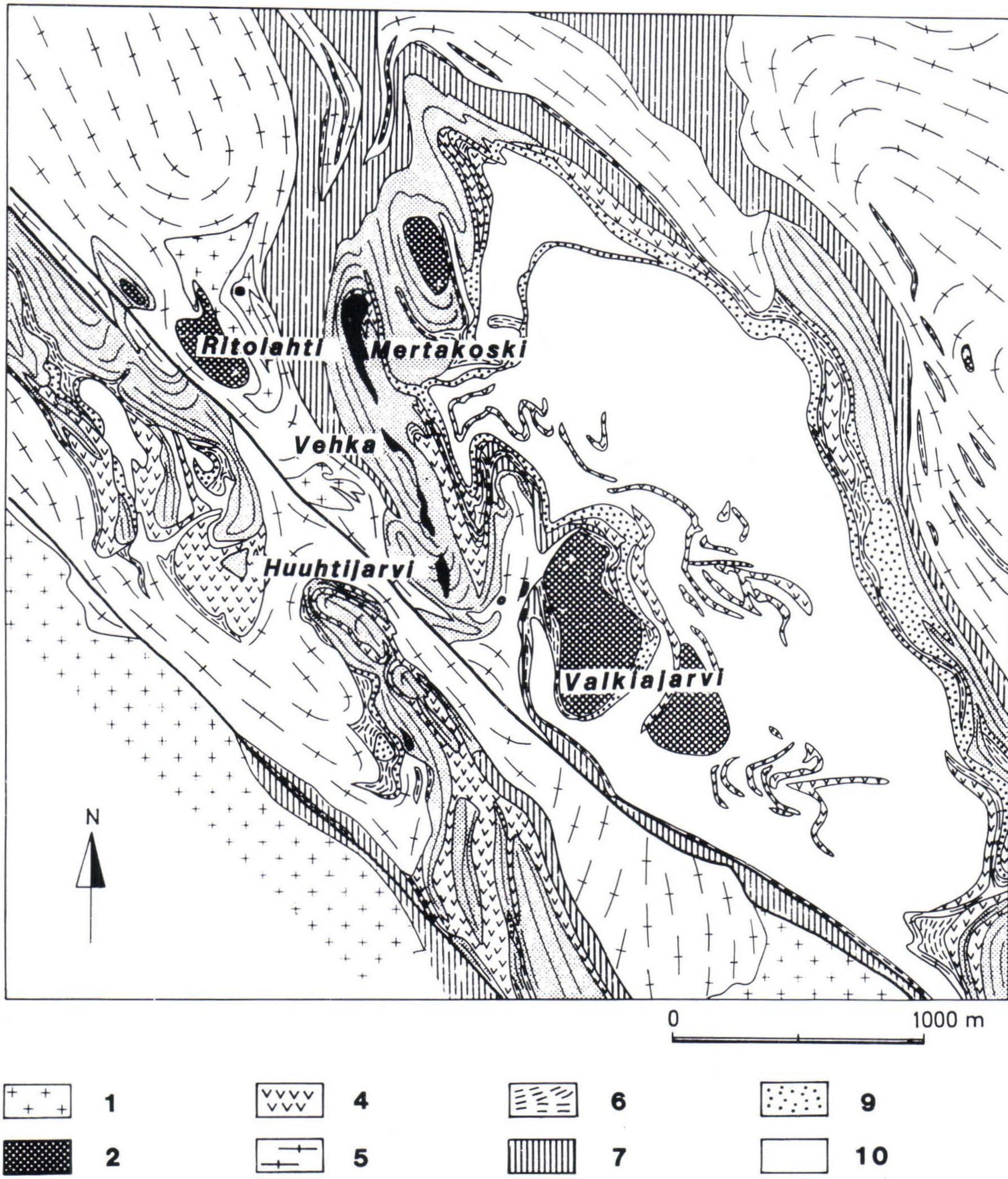

Fig. 42. Geological map of the Kotalahti area (Gaál 1980). 1. Svecokarelian granitoids; 2. Gabbro; 3. Ultramafics; 4. Amphibolite; 5. Veined mica gneiss; 6. Graphite schists; 7. Hornblende gneiss; 8. Leucocratic gneiss; 9. Quartzite and calc-silicate rock; 10. Granite gneiss.

black schists is encountered one kilometre southwest of the Kotalahti deposit. In composition the schists resemble the epicontinental metasediments surrounding the dome. Their stratigraphic position, however, has not been established.

Various types of intrusive rocks exist in the area. According to Gaál (1980), the amphibole dykes, gabbroic to quartz dioritic in composition, intrude the basement granite gneiss complex as well as the leucocratic gneiss but not the mica gneiss complex. The structural and metamorphic features of the mafic to ultramafic intrusions indicate that these rocks intruded at the beginning of Svecokarelidic orogenic activity. The ultramafic host rock of the Kotalahti ore is of this type. The mafic to ultramafic intrusions were succeeded by synkinematic to late-kinematic series of intrusives mainly quartz dioritic to granodioritic in composition. These series, too, begin with ultramafic members but most of them are iron-rich hornblendites in composition. The youngest intrusive phases are pegmatitic granites and porphyritic granite in the southwestern part of the Kotalahti area.

According to Gaál (1980), at least five deformation phases can be recognized in the area. During the first two deformation phases the Archean granitoids with supracrustal inliers were deformed into banded gneisses. The third phase of deformation was Proterozoic in age and it refolded the rocks into NNW-trending synforms and antiforms. During this phase of deformation the ultramafic complex of Kotalahti was intruded along the subvertical axial plane of the Kotalahti synform and the »Valkeinen bracyantiform» was formed as an F_2/F_3 interference structure. According to Gaál (1980), the fourth deformation phase, F_4, is indicated by a zone of high strain and refoliation with a NW-SE strike and subvertical dip. Thus, the subparallel swarm of NW-trending shear fractures, which Gaál (1972) maintains characterize the »nickel belt of Kotalahti», seem to postdate the intrusion of sulphide-bearing ultramafics, and their genetic congruence is obscure. The fifth phase of deformation appears only as narrow ENE-trending belts identified as culminations and depressions of F_3 folds.

DATING

Gaál (1980) has given the isotope ages of the rocks of the Kotalahti area. Although the U-Pb ages of the zircons from the Valkeinen brachyantiform are strongly discordant, the dates indicate that the granite gneisses have an age of c. 2800 Ma. A similar age was obtained for the zircons of the leucocratic gneiss that is the wall rock of the Kotalahti ultramafic complex. Stratigraphically, this gneiss should originally have overlain the rock group of epicontinental facies; therefore, it has been considered as a member of the Proterozoic Svecokarelian sequence. The old age of the zircon prompted Gaál (1980) to state that even the leucocratic gneiss and the wall rock of the ultramafic complex are Archean in age, and that a considerable portion of the Savo schists cannot be of Proterozoic age. Nonetheless, the high amount of zircon in the leucocratic gneiss might prove that the rocks have a metasedimentary origin. Hence, the zircons may be detrital and indicate only the age of the area of provenance, which in this case could be the Presvecokarelidic granitoid area (cf. Niskanen 1980). The zircons of the mafic plutonic rocks associated with the ultramafic complex of Kotalahti have been dated at 1883 $\pm$ 6 Ma. The K-Ar ages of the granite gneiss, 1670—1730 Ma, indicate the last phase of metamorphic events.

THE GEOLOGY OF THE KOTALAHTI INTRUSION

Host rocks

The host rock of the Kotalahti ore is an ultramafic — mafic intrusion shaped like a subvertical plate (Fig. 43). It is about 1,300 m long and a maximum of 200 m wide. From north to south the following ore bodies have been recognized in the intrusion: Mertakoski, Välimalmio, which swells downwards and extends to a depth of at least 700 m, and Vehka, a platy part of the intrusion, a few tens of metres wide, which extends down to a depth of about 300 m. The intrusion tapers out south of Vehka but continues for some tens of metres as the subvertical and pipelike Huuhtijärvi orebody. It extends downwards for at least 900 metres and widens in its lower parts in an E-W direction, attaining a horizontal extension of 200 metres. The Jussi orebody is a vertical slab some 150 m east of the Vehka orebody. Ultramafic rocks occur only at the southern edge of the Jussi ore.

The wall rocks of the Kotalahti intrusion consist of migmatitic mica gneisses and amphibolites. Owing to the abundance of trondhjemitic silicic vein material, Gaál (1980) has identified the wall rock as leucocratic gneiss. In broad lines, the intrusion is conformable with the schistosity and the trend of the wall rock, but,

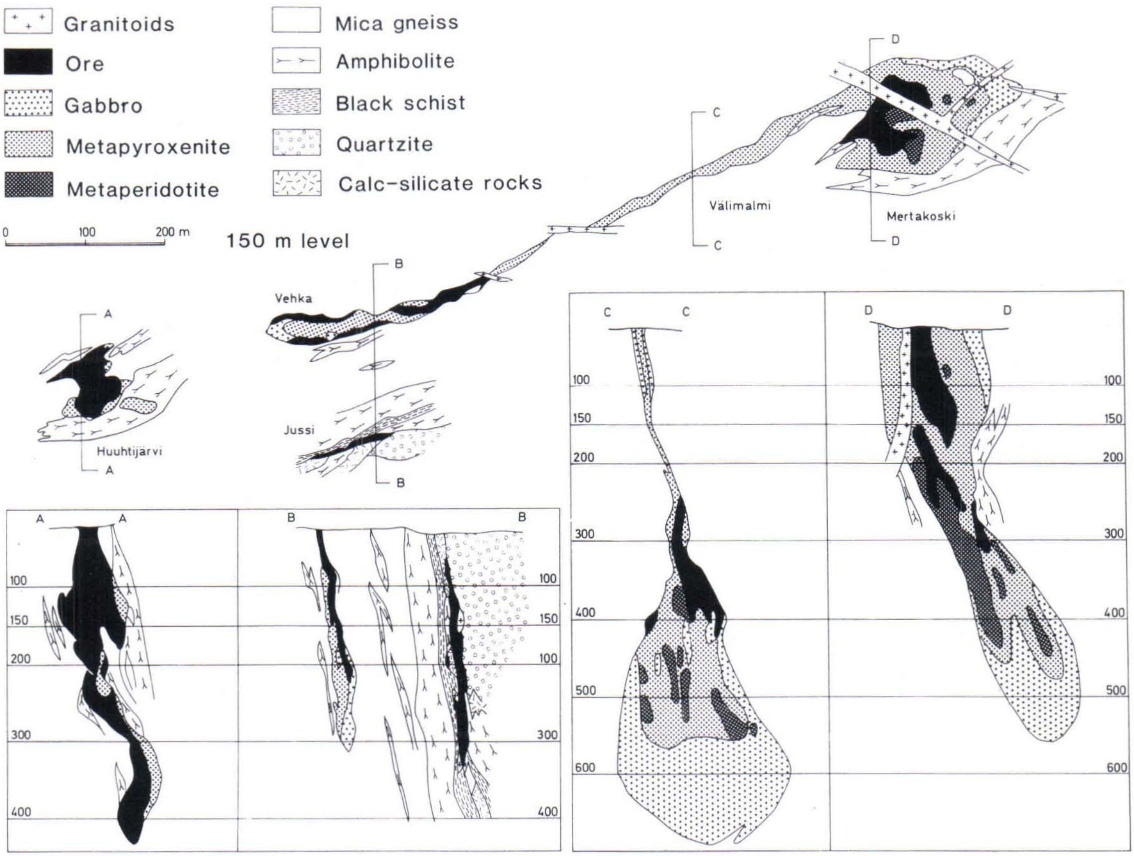

Fig. 43. 150 m plan and cross sections of the Kotalahti mine.

in detail, especially the gabbroic contact rock type cuts the structures. The Jussi orebody is located in a zone of calc-silicate rocks, quartzites, diopside amphibolites and black schists. These rocks represent the sedimentary epicontinental facies that encircles the Archean granite gneiss dome east of the intrusion.

The Kotalahti intrusion is cut by numerous dyke rocks of different composition (Fig. 43). The oldest dykes, coarse-grained and trondhjemitic in composition, are fairly common in the narrow parts of the intrusion, particularly in the upper portions of Vehka and Välimalmio. When in contact with the peridotitic rocks, these have given rise to reaction seams, the »ice float structure», in which a coarse-grained dyke is bordered by a seam of chlorite, antophyllite and talc. In composition these coarse trondhjemitic dykes may correspond to the neosome in the surrounding migmatite, being, as a rule, poor in potassium. Another group consists of potassium feldspar-bearing granite dykes that are structurally either coarse-grained pegmatitic or equigranular and fine-grained. A good example of the latter is the Mertakoski granite, a rectilinear, comparatively wide dyke that crosscuts the Mertakoski orebody. The third compositional group consists of mafic and intermediate dykes, some resembling diabases or amphibolites, some quartz diorites or diorites in composition. The amphibolite and diabase dykes are rectilinear and, hence, were emplaced into a solidified massive. The sulphides were then mobilized and accumulated on the margins of the amphibolite dykes.

The rocks in the Kotalahti intrusion range from peridotites, through pyroxenites, hornblendites and amphibolites to gabbros and diorites (Haapala 1969; Papunen 1970).

The peridotites include rare dunites and are mainly composed of harzburgites and lherzolites. Olivine is often moderately serpentinized; the orthopyroxene has altered into colourless cummingtonite, and the clinopyroxene, to a certain extent, into hornblende.

Pyroxenites proper are rather rare, whereas perknitic rocks are one of the major rock types in the intrusion. Perknites are pyroxenites that contain amphiboles, some of which may be primary. Most of the perknites, however, have secondary amphiboles and these rocks are obviously alteration products of pyroxenites. The amphibole in perknites is often colourless tremolite or cummingtonite.

Hornblendites are occasionally encountered in narrow parts of the intrusion where trondhjemitic dykes abound. The major mineral in the hornblendites is tschermakitic hornblende although some actinolite also occurs. Metamorphosed ultramafic rocks are called amphibole rocks if their origin cannot be determined. The amphibole minerals include tremolite, anthophyllite and actinolite. Gabbros are mainly restricted to the margin of the intrusion near the contact with the wall rock, although they also occur at deeper levels. A large gabbro body in the lower part of the Välimalmio orebody is heterogeneous in composition, containing olivine gabbros, olivine norites, norites, pyroxene gabbros and hornblende gabbros. In texture the gabbros can be classified into ophitic and poikilitic types. Poikilitic gabbros contain large grains of plagioclase, several centimetres wide, filled with inclusions of euhedral mafic minerals. The poikilitic texture is restricted to the more mafic gabbros where plagioclase-bearing areas exist like »clouds» in the ultramafic host rock. The texture bears out the interpretation that poikilitic portions formed as a result of assimilation of wall rock material in the ultramafic intrusion.

The uralitic gabbros and hornblende gabbros in the lower part of the intrusion and elsewhere are frequently ophitic in texture. The most silicic members of the intrusion series are the diorites and quartz diorites at the bottom of the intrusive complex. They are unaltered, coarse-grained rocks.

A fine-grained mafic rock type, which exists locally at the contacts of the intrusion, seems to form a link between the ultramafic rocks and the leucocratic wall rock. The thickness of this zone varies from nil to several metres. The rock type resembles the finegrained contact variety of the Oravainen ultramafic intrusion (Isohanni, this issue) which has both hybridic and hornfelsic character. The mineral and chemical compositions of the Kotalahti contact rock indicate more hybridic character.

Table 27. Chemical composition, Niggli values and C.I.P.W. norms of the rock types of Kotalahti.

	Peridotite	Pyroxenite	Poikilitc gabbro	Metapyroxen. (Perknite)	Ophitic gabbro	Diorite
n	12	13	17	5	8	3
SiO_2	41.49	46.74	46.88	47.88	48.70	50.60
TiO_2	0.33	0.39	0.47	0.36	0.52	0.90
Al_2O_3	6.77	7.13	9.77	6.80	15.71	16.33
Cr_2O_3	0.29	0.50	0.41	0.56	0.04	0.03
FeO	13.63	11.25	9.69	10.92	6.30	7.22
MnO	0.20	0.20	0.18	0.20	0.13	0.12
MgO	28.85	25.44	19.60	23.46	10.33	6.47
CaO	4.16	4.17	5.69	5.78	8.51	6.53
SrO	0.017	0.015	0.031	0.010	0.081	0.115
BaO	0.018	0.019	0.031	0.020	0.049	0.095
Na_2O	0.78	0.84	1.33	0.70	2.34	3.07
K_2O	0.28	0.48	0.47	0.78	0.70	1.26
P_2O_5	0.058	0.054	0.087	0.060	0.137	0.502
ZrO_2	0.005	0.005	0.008	0.004	0.018	0.024
Cu	0.018	0.034	0.022	0.075	0.005	0.041
Ni	0.195	0.166	0.111	0.224	0.021	0.063
S	0.250	0.280	0.099	0.451	0.088	0.327
Σ	97.33	97.71	94.90	98.29	93.71	93.68
si	65.0	81.8	92.2	86.3	116.7	140.6
al	6.25	7.36	11.3	7.22	22.1	26.7
fm	85.3	82.9	73.5	79.5	49.4	43.2
c	6.98	7.82	12.0	11.17	21.8	19.4
alk	1.46	1.95	3.14	2.12	6.51	10.5
qz	—40.8	—25.9	—20.3	—22.2	—9.30	—1.34
mg	0.79	0.80	0.78	0.79	0.74	0.61
k	0.19	0.27	0.18	0.42	0.16	0.21
o	0.01	0.01	0.02	0.02	0.03	0.06
ti	0.39	0.51	0.70	0.49	0.94	1.89
p	0.04	0.04	0.07	0.04	0.14	0.59
Qz	—	—	—	—	—	3.87
Or	1.71	2.90	2.95	4.73	4.43	7.98
Ab	6.77	7.28	11.93	6.09	21.15	27.84
An	14.63	14.72	20.30	13.42	32.35	29.02
Pl	21.39	22.00	32.23	19.52	53.50	56.86
An	68	67	63	69	60	51
Di	5.00	4.96	7.15	12.43	9.39	1.75
Hy	6.41	34.11	32.80	33.68	25.24	22.43
Ol	61.61	31.78	20.18	25.44	2.68	
Mt	2.74	2.81	3.02	2.77	3.13	3.73
Im	0.65	0.76	0.95	0.70	1.06	1.84
Ap	0.14	0.12	0.21	0.14	0.36	1.28
Sal	23.11	24.89	35.18	24.24	57.94	68.71
Fem	76.55	74.55	64.32	75.17	41.87	31.03

n = number of analyses.

Geochemistry of the intrusion

The rock types of the intrusion display an iron-enriched fractionation trend from peridotite to pyroxenite and further to poikilitic gabbro. The difference from unaltered pyroxenite to metapyroxenite means a slight increase of silica and potassium and decrease of magnesium. The tenor of chromium is highest in pyroxenite supporting the observation that primary chromite does not exist in ultramafics of Kotalahti. Compared with pyroxenites the poikilitic gabbros have higher abundances of aluminium, calcium and sodium and lower tenors of magne-

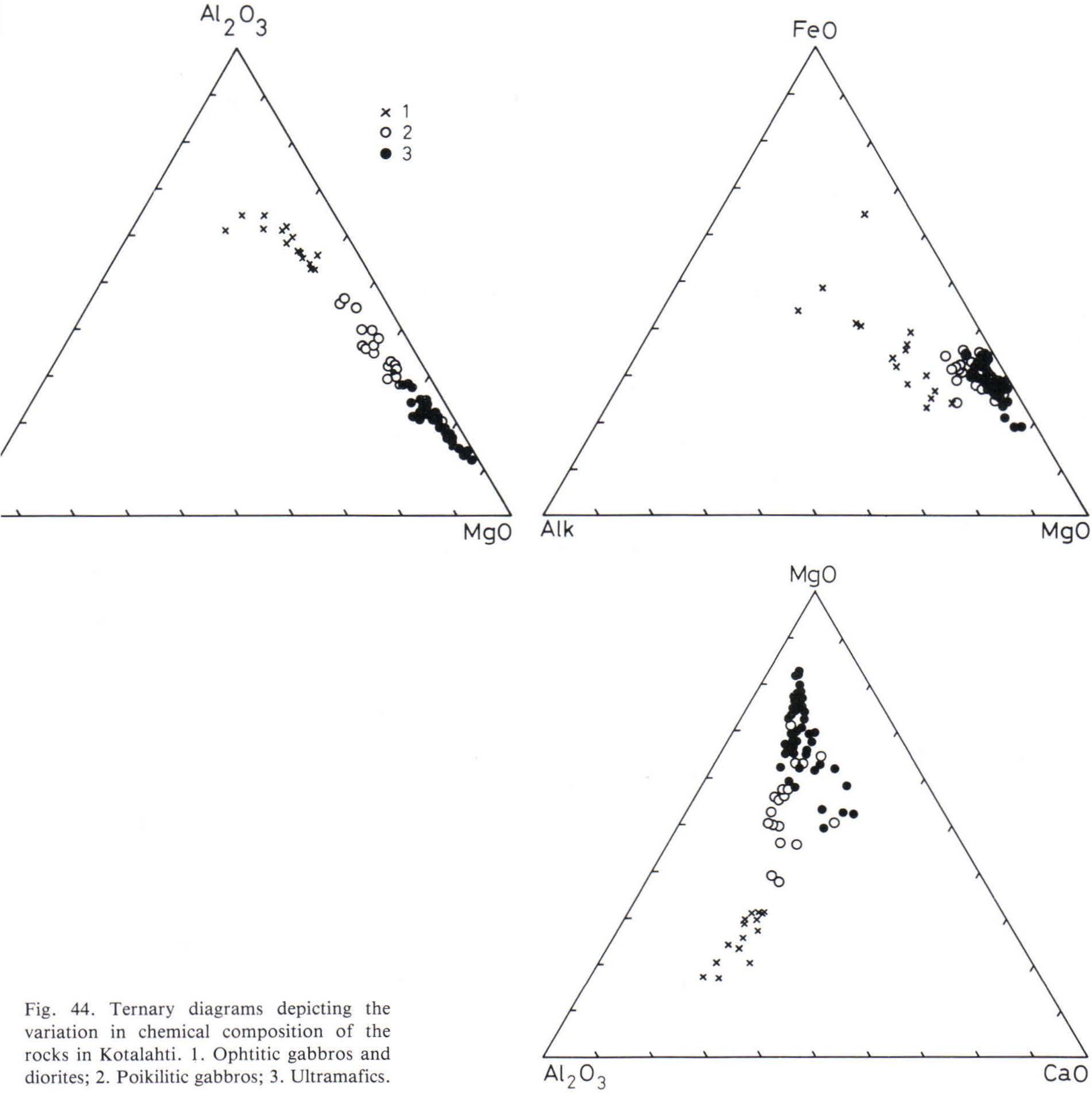

Fig. 44. Ternary diagrams depicting the variation in chemical composition of the rocks in Kotalahti. 1. Ophtitic gabbros and diorites; 2. Poikilitic gabbros; 3. Ultramafics.

Table 28. Trace element compositions of the Kotalahti rock types.

	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Th	U
Peridotite	5.1	10.7	6.0	1.28	0.41	0.14	0.52	0.092	0.53	0.15
Orthopyroxenite	2.8	6.9	5.0	1.13	0.39	0.17	0.82	0.13	0.23	< 0.1
Metapyroxenite	5.0	13.4	9.7	2.2	0.58	0.25	0.93	0.14	0.51	0.31
Poikilitic gabbro	3.2	8.0	3.4	1.23	0.46	0.18	0.74	0.099	0.34	< 0.1
Ophitic gabbro	19.8	37	18.3	3.8	1.17	0.40	1.22	0.14	2.6	0.56
Diorite	19.9	38	20	4.3	1.26	0.45	1.61	0.20	2.2	0.63

sium and iron. Of the trace elements Sr and Ba are markedly and P slightly enriched in poikilitic gabbro. In normative composition this indicates an increase of the plagioclase content probably as a result of wall-rock contamination (Table 27).

The ophitic gabbros and diorites differ markedly from the other rock types by their main and trace element contents. In ternary diagram the difference is obvious (Fig. 44, Table 27).

The REE, U and Th analyses in Table 28 and the chondrite normalised pattern in Figure 45 indicate a slight LREE enrichment in most of the rock types. The overall abundances of REE are rather low (Sm_N = c. 7). For pyroxenite the profile is flat. A slight positive Eu anomaly

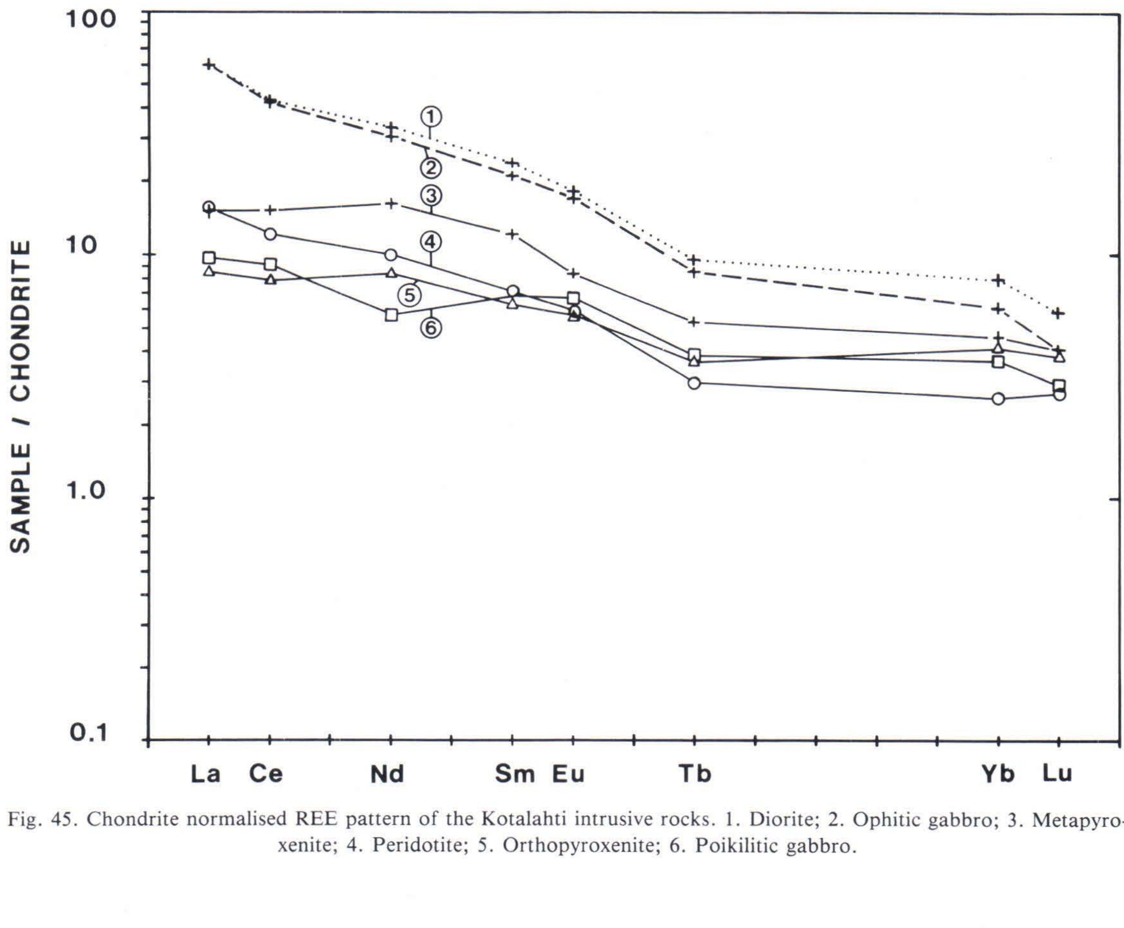

Fig. 45. Chondrite normalised REE pattern of the Kotalahti intrusive rocks. 1. Diorite; 2. Ophitic gabbro; 3. Metapyroxenite; 4. Peridotite; 5. Orthopyroxenite; 6. Poikilitic gabbro.

exist in the poikilitic gabbro owing to the enrichment of Eu in plagioclase. For the ophitic gabbros and diorites the pattern is mutually very similar but differs from the other rock types by more pronounced enrichment of LREE.

Nickel in silicate minerals

Numerous determinations conducted on the silicate nickel from the Kotalahti deposit (Häkli 1973) reveal that the abundance of nickel in olivine varies from 1000 to 3000 ppm. The olivines poorest in nickel usually occur wherever the abundance of sulphides is high, whereas the olivines rich in nickel favour samples poor in sulphides. The abundance of nickel in enstatite varies from 100 to 850 ppm, the bulk containing about 100 to 400 ppm Ni. The nickel tenor in augite is generally somewhat lower than that in enstatite and fluctuates between 50 and 400 ppm, averaging 250 ppm Ni.

The nickel in hornblende is frequently higher than that in the coexisting enstatite or augite. The nickel in hornblende also varies from one rock type to another as follows (averages of 10—13 samples): in peridotite 490 ppm, in pyroxenite 420 ppm, in perknite 370 ppm, in pyroxene-hornblende gabbro with poikilitic plagioclase 450 ppm, in gabbro with ophitic plagioclase 106 ppm and in diorite 30 ppm. The difference between the hornblendes of the two gabbro types is distinct, probably because the gabbro with poikilitic plagioclase belongs to the differentiation series with pyroxenites and peridotites, whereas the gabbro with ophitic plagioclase at the bottom of the ultramafic body belongs to another intrusion pulse of different magma type.

Sulphur isotopes

Papunen and Mäkelä (1980) reported sulphur isotope compositions analysed from 36 samples of the deposit. The variations of $\delta^{34}S$ values is very limited ranging from +1.3 to +2.8 per mil with an arithmetical mean of +2.1 per mil. In the massive Jussi ore body the $\delta^{34}S$ values are slightly lower than those in the ultramafic body proper. The mineral assemblages of the Jussi ore indicates more oxidating conditions during mineralization than in the ultramafic body. The oxidation process was probably brought about by H_2O-rich wall rocks. The slight increase in the oxidation state might have resulted in a $\delta^{34}S$ average slightly lower than that in the sulphide melt of the ultramafic body.

The ore types

The sulphides in the intrusion are associated with peridotites, pyroxenites and perknites, and in the upper parts of the intrusion with gabbros as well. At the deeper levels, however, the gabbros and diorites contain only traces of sulphides. In structure the ores can be classified into disseminated, breccia and massive vein ores (Papunen 1974). Interstitial dissemination occurs in the peridotites filling the interstices between the silicate grains. In some places the disseminated ore grades through the net ore into breccia ore; mostly, however, the breccia ores exhibit sharp contacts with the wall rock. In the gabbros, the dissemination occurs as rounded »buck-shot» drops.

The breccia ores are irregular in shape. In some localities they are platy owing to the amphibolite dyke, pegmatite vein or contact of the intrusion controlling the occurrence of the ore. The breccia ore contains wall rock fragments, some of which are distorted. Embedded in the sulphides are euhedral hornblende and plagioclase grains. The hornblende in the breccia ore is invariably richer in iron than is the hornblende in the wall rock. The veins of massive sulphides tend to be fairly small and to fill the tectonic fractures. In some places massive sulphide veins grade into quartz veins before pinching out altogether.

The Jussi orebody is structurally a breccia ore whose upper parts are devoid of rocks of the mafic-ultramafic suite. Brecciated ultramafic and mafic rocks have been encountered, however, at the SE end of the orebody between the +200 and +400 levels. The rock types are hornblendites with disseminated sulphide drops or talc-carbonate rocks; gabbroic rock types exist only locally. The sulphides of the Jussi ore body are associated with a coarse-grained pegmatite and fill the fractures in their silicic wall rocks or in calc-silicate rock. Red andradite garnet is a common accessory mineral in the ore, and a few green uvarovite grains have been met with locally.

The composition of the ore types varies in such a way that in the disseminated ores the nickel content in sulphide phase depends on the

Table 29. Chemical composition of different ore types of Kotalahti calculated in 100 % sulphides.

	Ni	Cu	Co
disseminated ore in peridotite	9.81	2.90	0.41
disseminated ore in pyroxenite	9.19	2.79	0.45
disseminated ore in perknite	8.41	2.86	0.40
disseminated sulphides in diorite and quartz diorite	1.37	1.54	0.38
breccia ore, Mertakoski orebody	6.53	2.75	
breccia ore, Välimalmi orebody	6.14	2.05	
breccia ore, Vehka orebody	6.38	1.74	
breccia ore, Huuhtijärvi orebody	6.65	2.10	
breccia ore, Jussi orebody	11.23	6.47	

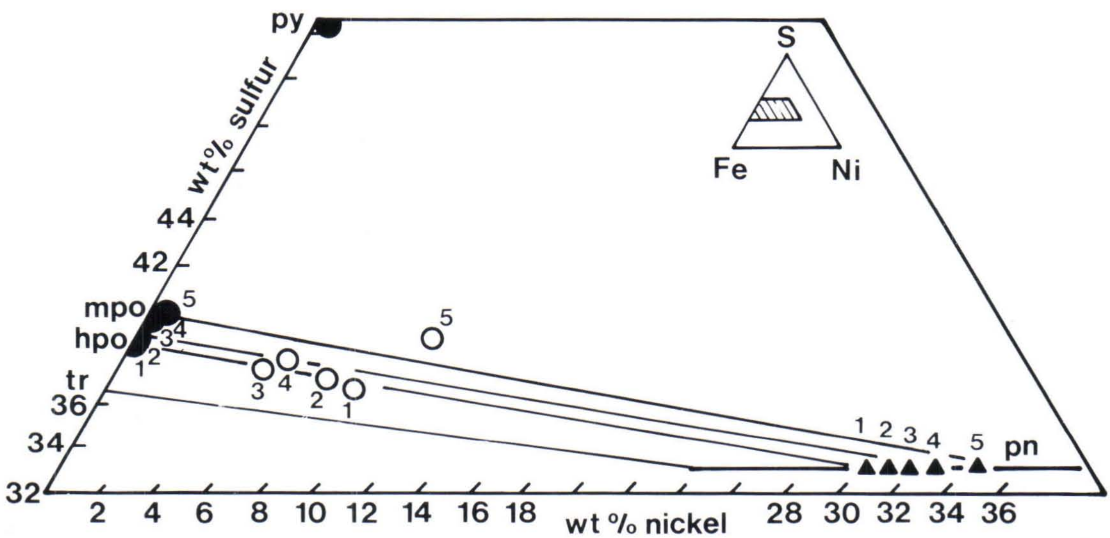

Fig. 46. Part of a Fe-Ni-S diagram depicting bulk composition of the sulphides (○) with corresponding composition of pyrrhotite (●) and pentlandite (▲). Ore types: 1. Disseminated ore in peridotite; 2. Disseminated ore in pyroxenite; 3. Disseminated ore in gabbro; 4. Breccia ore; 5. Massive offset ore (Jussi).

magnesium-iron ratio in the host rock (Table 29). Hence the dissemination in peridotite is richer in nickel than is the dissemination in gabbros or diorites (Fig. 46). The nickel content in the breccia ore is almost constant throughout the formation, i.e. slightly over 6 % Ni calculated in 100 % sulphides. The exception is the Jussi orebody, where the corresponding figure is about 11 % Ni. The copper content of the disseminated ore tends to decrease slightly from peridotites to gabbro but in the breccia ore the copper content remains fairly constant. In some parts of the breccia ores, however, chalcopyrite forms accumulations, particularly where the breccia ore penetrates the wall rocks of the mafic intrusion.

The ore averages 0.2 % Cr, 0.005 g/t Pt, and less than 0.005 g/t Pd and Rh. The nickel concentrate contains 0.015 g/t Pt, 0.05 g/t Pd and 0.005 g/t Rh. The corresponding figures for the copper concentrate are 0.015 g/t Pt, 0.02 g/t Pd and 0.0059 g/t Rh.

Ore-mineralogically the Kotalahti Ni-Cu ore is comparatively simple (Papunen 1970, 1974). The main minerals are pyrrhotite, pentlandite and chalcopyrite, and, in the Jussi orebody, pyrite (see Fig. 46). The composition of the pyrrhotite varies. In the disseminated ores it is troilite and hexagonal pyrrhotite, but in the breccia ores and in the Jussi orebody in particular, the monoclinic variant predominates. Depending on the composition of the pyrrhotite, the nickel to iron ratio varies in pentlandites, being lower in the peridotitic disseminations than in the gabbros. In the breccia ores, pentlandite is still richer in nickel, being richest of all in the Jussi orebody. Magnetite is very rare in the Kotalahti intrusion, where the predominant oxide is ilmenite. The only place where megnetite occurs substantially is in the Jussi orebody, where it is encountered as small rounded grains or stringers in association with sulphides. Gersdorffite, mackinawite and argentian pentlandite are the accessories, the latter being mainly restricted to the Jussi orebody. The Jussi orebody also contains portions rich in millerite and bornite.

CONCLUSIONS

The sulphides of the Kotalahti intrusion display textures and structures common to Ni-Cu ores in differentiated basic bodies throughout the world. The sulphides are mainly located in the ultrabasic members of the differentiation series; especially the perknitic rock (an altered pyroxenite) is always sulphide-bearing and the breccia ore type, too, is spatially associated with it. However, the vertical zoning with sulphide-rich portions and ultramafics at the base and intermediate and acidic members at the top, which is common in many nickel deposits, is reversed in Kotalahti. This is an indication of the complex history of the Kotalahti deposit. The only sign of primary gravitative layering is the weak, almost horizontal layering observed in disseminated sulphides in the upper part of the Välimalmio orebody.

The main and trace element geaochemistry of the rock types in the Kotalahti intrusion indicates that there is a break in the differentiation series between the poikilitic gabbros and the ophitic gabbros. The difference between the gabbros has been explained by assuming that the poikilitic gabbros are contamined ultramafic rocks which formed during the intrusion of ultramafic magma by the assimilation of gneissis wall rock material.

The ophitic gabbros and diorites probably represent another magma pulse that was originally poor in nickel. The ophitic gabbros resemble in mineral composition and whole rock chemistry the Valkiajärvi gabbro complex reported by Gaál (1980).

The fine-grained contact rocks have gabbroic composition but also hornfelsic character, and they are rather similar to the rock type observed at the contacts of the Oravainen ultramafic body (Isohanni, this issue).

The ultramafic body of Kotalahti is premetamorphic in origin and the different rock types as well as the sulphide ore types were altered during regional metamorphism in the upper amphibolite facies. The trondhjemitic vein system in the ultramafic body might also have originated from the enveloping migmatites. It is thus probable that basic magma intruded and crystallized before the main metamorphic phase and migmatization, and that the irregular external forms of the body are an outcome of folding. The relative abundances of compatible and incompatible trace elements in ultramafic rocks and ophitic gabbros respectively indicate that the sulphide-bearing ultramafic rock suite has a depleted residual character. The ophitic gabbrodiorite suite could thus form from the magma pulse inherited from the first melt fraction of the mantle and the subsequent more basic pulse represents more advanced melting of the mantle material. The sulphide melt was primarily combined with the last pulse and hence the disseminated sulphides exist in ultramafic rocks. The final accumulation of the breccia type of ores is controlled by zones of deformation.

THE LAUKUNKANGAS NICKEL-COPPER DEPOSIT

L. GRUNDSTRÖM

The Exploration Department of Outokumpu Oy undertook geological mapping in the Haukivesi area (Fig. 47) in 1963—1971. In 1967 the mafic and ultramafic rocks were systematically sampled and studied for the distribution of nickel and iron between olivine, pyroxenes, amphiboles and coexisting sulphide phase. Research on this topic was started in Finland by Häkli in 1960 (Häkli 1963). The Laukunkangas norite intrusion was discovered in connection with sampling in autumn 1969. The intrusion contained Ni and Cu sulphides in such abundance that the studies were continued without interruption until 1971. Based on diamond core drilling and percussion drilling data, the 1971 in-situ ore reserve estimate indicates c. 4.5 million tonnes of ore averaging 0.33 % Ni and 0.10 % Cu. On account of the low grade, the prospect has been kept in reserve.

The next phase of investigation started in summer 1979, when a region of 30 × 50 km was measured aeromagnetically by the Geological Survey of Finland, and all the old drilling data on Laukunkangas were reexamined by applying the »nickel program method» (Grundström 1980). This study suggested the existence of a potential ore deposit, higher in grade than the one located earlier, in the SE part of the intrusion. The assumption was corroborated by new ground geophysical survey data.

The intrusion has been studied most intensely at the eastern end where earth was removed from an area of about one hectare (Grundström 1980).

To date, 85 diamond drill core holes with a total length of 25,572 m and 19 percussion holes with a total length of 534 m have been drilled in the area.

The latest research stage started in the spring of 1980 after careful study of the old drill cores by the procedures of the nickel programme. The olivines, pyroxenes and amphiboles from about