THE LAUKUNKANGAS NICKEL - COPPER OCCURRENCE IN SOUTHEASTERN FINLAND

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The Laukunkangas Ni-Cu deposit in a Svecokarelidic synorogenic plutonite is located at the southeastern end of the Kotalahti nickel belt. The mineralization is associated with the norites, olivine gabbros and peridotites of an olivine tholeiitic suite. It contains about 4.5 million tons of ore in situ averaging 0.33 % Ni and 0.10 % Cu.
The intrusive is a rather small pipelike body with an elliptical surface plan. It extends to a depth of at least 300 m; its largest horizontal dimension is about 1 km and its width in the middle of the intrusive is some 200 m.
The variations in the Ni and Fe contents in silicates, the MgO content in rock types and the Ni content in the sulphide phase clearly indicate the internal layering in the intrusive. Emplacement probably took place in two or three stages. The boundaries between the layers show contamination that is reflected in the distribution of MgO and trace elements. »The model crystallization temperatures» suggest that the intrusion was emplaced in three separate phases.
The mineralization occurs near the contact zone at the eastern end of the intrusive. The few nickel-rich portions encountered inside the intrusive are small and discontinous lenses or slabs.
The mineralization is characterized by the following parameters: Ni/Co = 17.31, Ni/Cu = 3.15, Cu/Co = 5.49, and the Ni content in sulphide phase 4.81 %.

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Introduction

The objective, the mafic Laukunkangas intrusive, is located in southeastern Finland (Fig. 1) in the area called the »main sulphide ore belt» by Kahma (1973). From this belt Gaál (1972) has distinguished the separate »Kotalahti nickel-copper ore zone» in which Laukunkangas is located. Häkli (1970, 1971), Gaál (1972), Häkli et al. (1978) and Tontti et al. (1979) have studied the characteristic features of the Ni-Cu occurrences in the zone. Papunen et al. (1979) and Häkli et al. (1979) pointed out that the Ni-Cu occurrences of southern Finland are located in a roughly circular area around the central Finland granitoid batholith, and the »Kotalahti Ni-belt» is a part of that area.

During exploration of the sulphide ore belt, the Exploration Department of Outokumpu Oy undertook geological mapping in the Haukivesi area in 1963—1971. In 1967 the mafic and ultramafic rocks were systematically sampled and studied for the distribution of nickel between olivine, pyroxenes, amphiboles and the coexisting sulphide phase according to the method described by Häkli (1963).

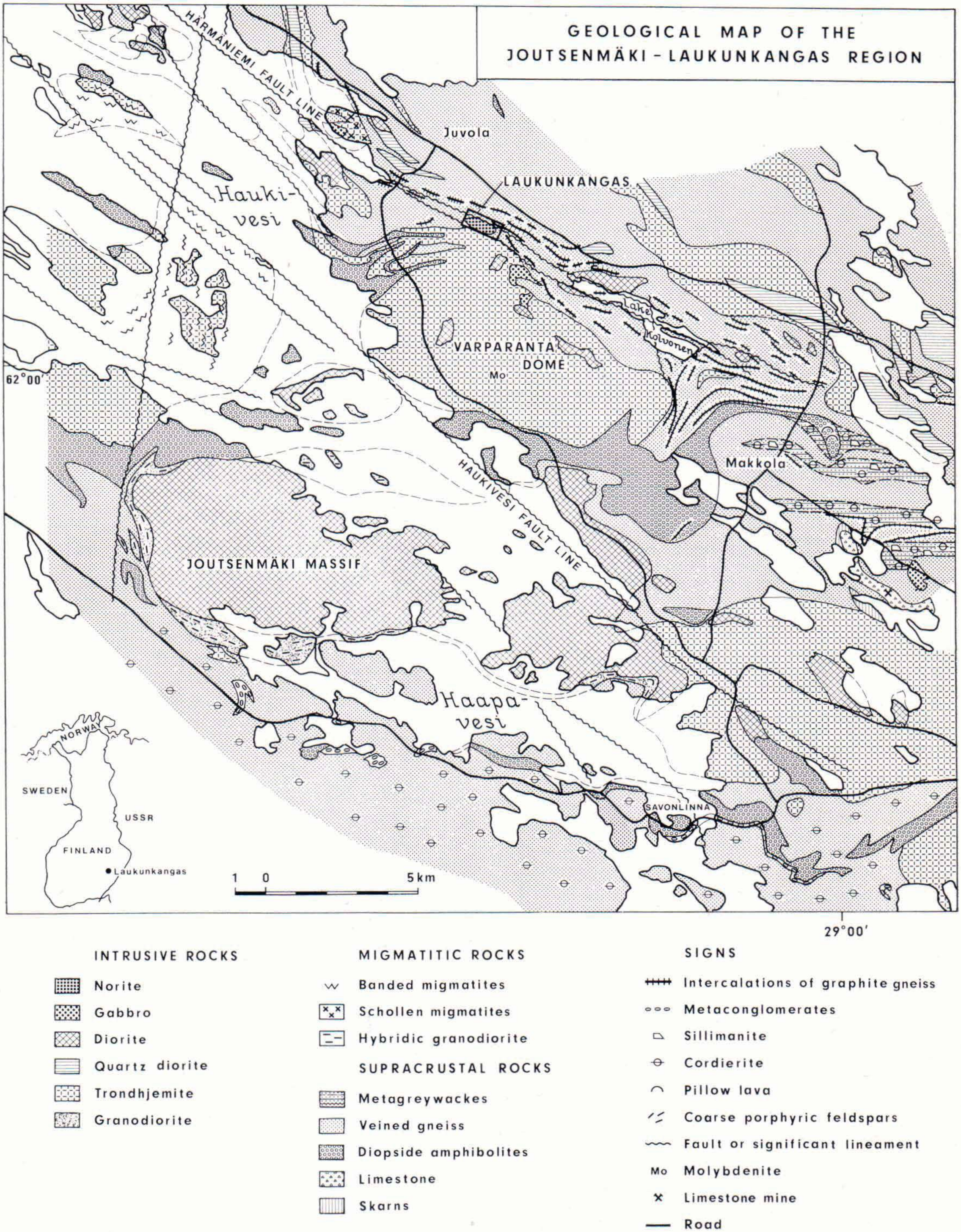


Fig. 1. A simplified geologic map of the Joutsenmäki—Laukunkangas region. Partly after Gaál and Rauhamäki (1971).

The Laukunkangas norite intrusive was discovered in connection with sampling in the autumn of 1969. The intrusive contained Ni and Cu sulphides in such abundance that the studies were continued. The first indication of the sulphide occurrence had, however, probably been obtained as early as 1962 when a layman sent a sample from a sulphide-bearing boulder assaying 0.2 % Cu, 0.7 % Ni and 8.3 % S from about 10 km southeast of Laukunkangas. Despite geological investigations in the area in 1962 and 1964 the source of the boulder was not found.

The in-situ ore reserve estimate based on diamond core drilling and percussion drilling data indicates c. 4.5 million tons of ore averaging 0.33 % Ni and 0.10 % Cu. On account of the low grade, the prospect has been kept on the reserve.

Laukunkangas is a slightly layered and predominantly gabbroic intrusive and hence differs in type from the ultramafic intrusives of Hitura and Kotalahti (Papunen 1970). On the other hand, in terms of sulphide minerals, geochemistry, petrology and structure it is comparable to the large Joutsenmäki (Parkkinen, 1971, 1975) and Parikkala (Häkli, 1968) intrusives and thus, as a type occurrence, the ore deposit has been submitted to comprehensive examination.

Geology of the environment

The concept of a Ni-ore belt is largely based on the existence of known Ni-Cu occurrences in a linear belt stretching from Lake Ladoga to the Bothnian Sea. The belt parallels a negative gravimetric anomaly and a sub-parallel swarm of fracture zones (Gaál, 1972). According to Wahl (1963), the zone, which was later suggested to be potential for Ni-Cu ores, is characterized by hypersthene-bearing plutonites, the emplacement of which was controlled by two fracture lines trending NW-SE. The concept of the ore potentiality of the »Ladoga—Bothnian Sea zone» was originally proposed by Paarma and Marmo (1961); it was later corroborated by Mikkola and Niini (1968), Mikkola (1971) and Kahma (1973). Gaál (1972) suggested that the intrusives that act as host rocks for the nickel ores are associated with transcurrent faults, domes and brachyantiforms. Fault-tectonic analyses on the Ladoga—Bothnian Sea zone have been undertaken by Härme (1961) and Salli (1970), and lineament interpretations by Talvitie (1971), and Mikkola and Vuorela (1977). Parkkinen (1975) maintains that the intrusives were emplaced during large-scale regional movements.

The area of Laukunkangas (Fig. 1) is included in the general geological map made by Hackman (1931, 1933). Vorma (1975) has studied the silicate minerals of noritic rocks west of Laukunkangas. Parkkinen (1971, 1975) has investigated the structural history of the large mafic intrusion of Joutsenmäki west of Laukunkangas. Gaál and Rauhamäki (1971) have studied the Haukivesi area, extending SE and NW from Laukunkangas and including the major part of the area shown in Fig. 1. The broad context of the general geology of the Laukunkangas area is referred to in their study.

The supracrustal rocks and the plutonites that crosscut them constitute large lithologic units. The supracrustal series can be subdivided into a volcanogenic section, in which diopside amphibolites predominate, and into sedimentogenic schists, composed mainly of metagreywackes and lime-bearing metasediments.

The metasedimentary lithosome indicates an older eugeosynclinical series in the northern Haukivesi area and a younger Rantasalmi-Savonlinna miogeosynclinical series (Gaál and Rauhamäki, 1971).

The rocks in the schist area are migmatized to varying degrees, and the migmatites include several structurally different types. Breccia migmatites of varying degree are associated with boudinage structures. Schollen and schlieren migmatites grade into the more common banded migmatite structure. In Fig. 1 schollen migmatite is marked on the shore of Haukivesi, a lake west of Laukunkangas.

The plutonites occur as large silicic or intermediate intrusives or as smaller mafic-ultramafic bodies. Joutsenmäki is the largest massif (Parkkinen, 1971, 1975); Laukunkangas, the topic of the present study, is one of the smaller intrusives. The structure of the plutonite bodies marked in Fig. 1 is often very complicated, and the bodies frequently contain 3 to 5 different rock types. Usually only the predominant rock is marked on the map.

The Laukunkangas intrusive is embedded in a mica gneiss—veined gneiss environment. A narrow but distinct zone of migmatitic veined gneiss occurs between the Varparanta trondhjemite dome suggested by Saltikoff (1965) (in the west) and the Laukunkangas intrusive. The gneiss contains calc-silicate gneiss fragments and cummingtonite gneiss, amphibolite and pyroxene quartz diorite close to the conformable contact of the intrusive. The Laukunkangas intrusive does not seem to be associated with any sizeable pluton but occurs as a separate body in an intensely migmatized metasediment suite.

Tectonics

The importance of large-scale fault zones for the emplacement of Ni-Cu-bearing intrusives was proposed by Gaál (1972). The NW-SE trending lineaments have been interpreted as faults controlling the emplacement of mafic intrusives.

In the course of field mapping the area was submitted to a stereoscopic lineament interpretation on the basis of aerial photos. The lineament on the continuation of the Härmäniemi fault suggested by Gaál and Rauhamäki (1971), is clearly visible on the mainland. It continues as far as Lake Kolvonen, but forks into two parts as it passes Laukunkangas. There has, however, been no way of establishing whether or not it is a real fault. The present author feels that it is merely a lineament produced by coincidence in the direction of glacial transport, the trend in the schistosity of the bedrock and the graphite-rich and deeply weathered and eroded schist zones all trending in the same direction.

The general trend of the Laukunkangas mica gneiss zone is N 70 W. The dip varies from 60° to 90°, either to NE or SW, and the gneisses are isoclinally folded. Detailed observations show that the intrusive conforms with the orientation in the gneiss. The lineation in the schist is usually NW and the plunge varies from 30° to 65°. The average trend in the regional fold axes is 315°/80°.

The Laukunkangas intrusive

Shape

Geophysical data and observations on the bedrock suggest that the surface plan of the intrusive is an ellipse or lens-shaped. Vertically the intrusive seems to be a pipe-like body that plunges 75° to 85° NW. The body, which is over 300 m deep, is about 1 km long and some 200 m wide in the middle. The only part of the intrusive that is known in detail is the eastern end (Fig. 2). Earth was removed over an area of about one hectare. This area was intersected by 31 diamond drill holes, totalling 6745 m in length, and 19 percussion drill holes totalling 537 m. On the basis of these and detailed geological mapping the geological maps and nickel distribution maps shown in Figs. 2 and 3 were drawn. The heavy line on the map outlines the exposed outcrop.

Fig. 2, which is a somewhat simplified geo-

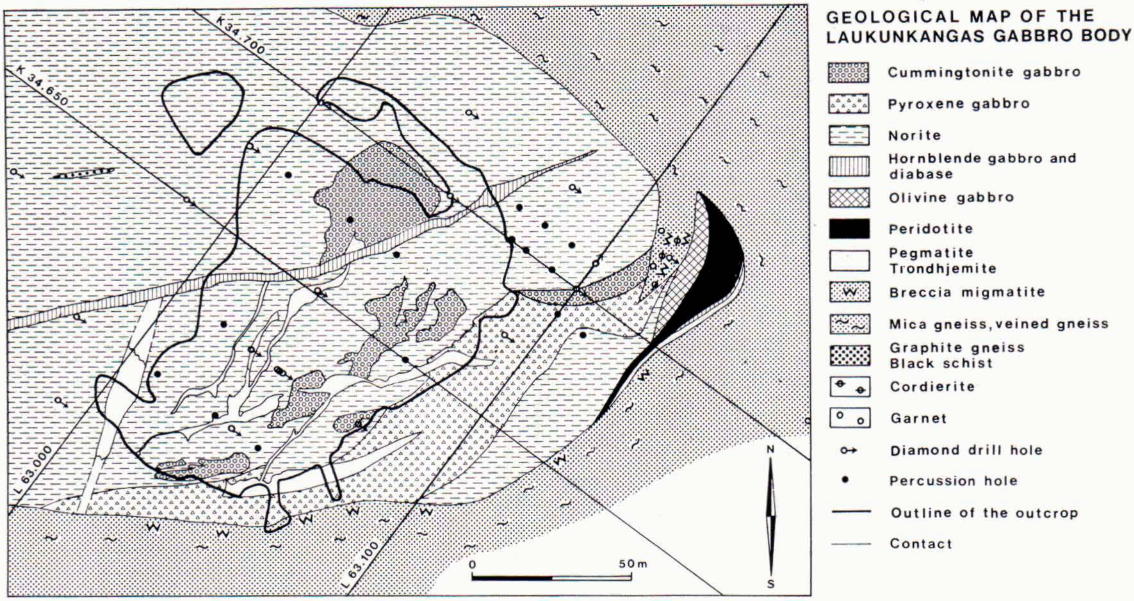


Fig. 2. A detailed geologic map of the eastern end of the Laukunkangas intrusive.

logic map, shows several crosscutting pegmatite veins and a brecciated, east-west trending diabase dyke that cuts the intrusive. The diabase is the youngest rock in the intrusive; it intersects all the structures and presumably extends to the wall rock.

The eastern end of the intrusive is structurally very heterogeneous and contains intensely brecciated and metamorphosed wall-rock tongues. Shear and breccia zones that often trend almost N-S are marked on the nickel distribution map (Fig. 3).

Rock types and dimensions

The Laukunkangas intrusive consists of a differention series ranging from peridotites to quartz diorites (Figs. 2 and 4a). Although the intrusive is a pipe-like body that dips steeply towards NW, the distribution of the rock types in its eastern contact zone indicates layered structure. At least in the comprehensively studied eastern part of the body the rock types occur as superimposed layers approximately parallel to the contact of the body. Wall-rock gneiss is occasionally encountered between the layers as »intercalations».

The rock types vary greatly in dimension. The peridotitic rocks crop out only as a narrow tongue in section L = 34.700; drilling data suggest, however, that the tongue extends downwards and northwards. In profile L = 34.725 the rock is already 10 m wide on the surface of the outcrop. Although irregular in shape, the peridotite portion is obviously coherent in the eastern part of the pluton. Peridotites also occur locally in other parts of the intrusive as narrow zones sandwiched between graphite-bearing gneisses and brecciated black schists. Olivine gabbros are invariably associated with the peridotites.

Norite, the predominant rock type in the intrusive, accounts for well over half of the mass of the intrusive in both the exposed areas and the sections. Pyroxene gabbros occur in the southern part of the outcrop as a zone with distinct boundaries that subdivides the eastern end of the intrusive into two parts.

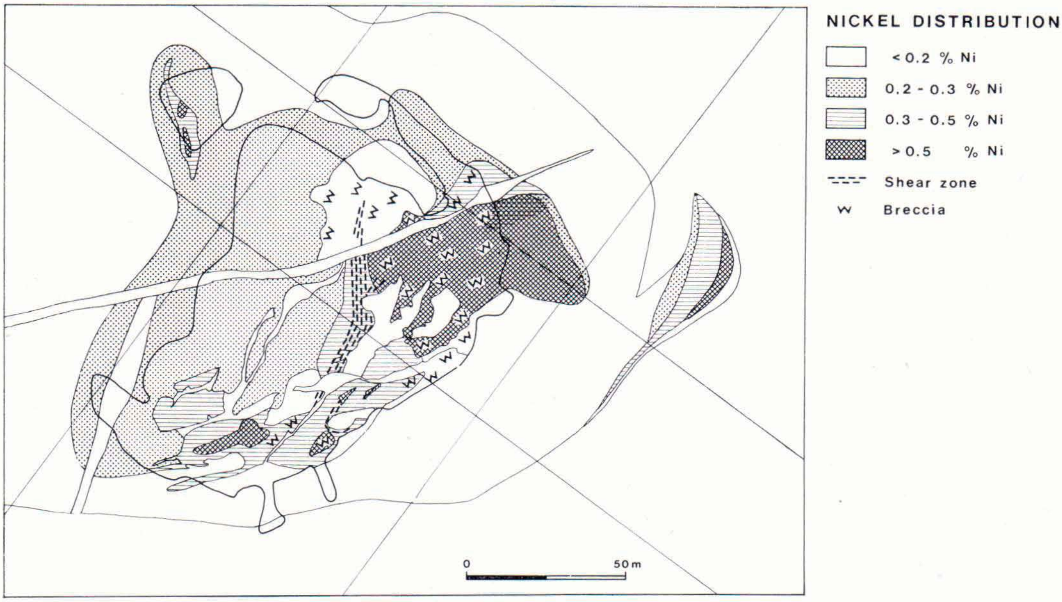


Fig 3. The distribution of nickel within the area shown in Fig. 2.

The contacts of the cummingtonite gabbro in the outcrop are sharp and distinct. Within the intrusive the cummingtonite gabbros often occur as layers 30 to 40 m thick in association with other variants of altered gabbros. The internal structure of the intrusive suggests that these zones are transitional ones.

The outcrop of the intrusive contains fragments of graphite gneiss. Similar intensely brecciated and folded rocks have been encountered within the intrusive in several drill holes. These have been interpreted as breccia fragments loosened from the wall rock during emplacement. Various silicic dyke rocks are characteristic of the Laukunkangas intrusive. The dykes trend preferably almost N-S and N70-80E. The dips are often gentle, although some subvertical dips are also encountered.

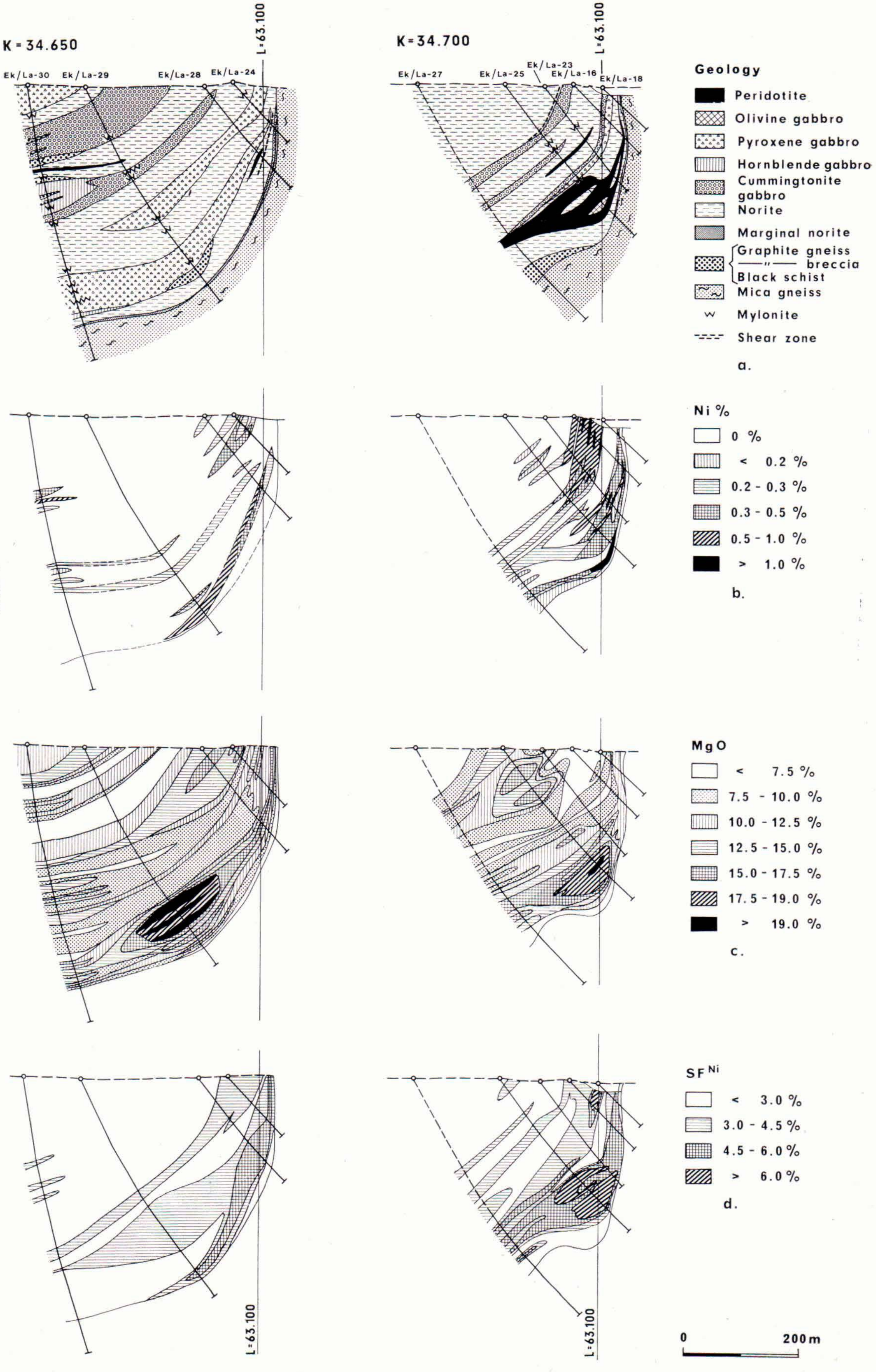
Description of rock types

The mineral compositions of the Laukunkangas intrusive and its wall rocks were determined on the basis of 430 thin sections (Table 1.) The intrusive consists of a differentiation series whose rock types often grade into one another. According to the classification of Yoder and Tilley (1962), the rocks of the intrusive belong mineralogically to the tholeiite- olivine tholeiite suite.

The ultramafic members of the series consist of harzburgitic peridotites which owing to serpentinization of olivine and alteration of pyroxene into cummingtonite, are locally metaperidotites. Phlogopite is a common constituent of the altered variety. Perknites, which contain orthopyroxene, hornblende and biotite as major minerals, are the alteration products of pyroxenites. They are fairly rare in the Laukunkangas intrusive.

The mafic members of the differentiation series abound in the body. They include oli-

Fig. 4. The geology, Ni and MgO contents and the Ni content in sulphide phase on profiles K = 34.650 and K = 34.700 across the Laukunkangas intrusive.



K = 34.650
K = 34.700
L = 63.100
Ek/La-30
Ek/La-29
Ek/La-28
Ek/La-24
Ek/La-27
Ek/La-25
Ek/La-23
Ek/La-16
Ek/La-18
Geology
Peridotite
Olivine gabbro
Pyroxene gabbro
Hornblende gabbro
Cummingtonite gabbro
Norite
Marginal norite
Graphite gneiss
—"— breccia
Black schist
Mica gneiss
Mylonite
Shear zone
a.
Ni %
0 %
< 0.2 %
0.2 - 0.3 %
0.3 - 0.5 %
0.5 - 1.0 %
> 1.0 %
b.
MgO
< 7.5 %
7.5 - 10.0 %
10.0 - 12.5 %
12.5 - 15.0 %
15.0 - 17.5 %
17.5 - 19.0 %
> 19.0 %
c.
SF Ni
< 3.0 %
3.0 - 4.5 %
4.5 - 6.0 %
> 6.0 %
d.
0
200 m

Table 1. Mineral compositions of the rocks of the Laukunkangas intrusion and contact zone

INTRUSIVE ROCKS	Olivine	Orthopyroxene	Clinopyroxene	Hornblende	Cummingtonite	Biotite	Phlogopite	Chlorite	Plagioclace	Quartz	Sericite	Saussurite	Carbonates	Serpentine	Apatite	Tremolite	Epidote	Microcline	Spinel	Titanite	Zircon	Sagenite	Rutite	Monazite	Opaques	Muscovite	Prehnite	Zeolite	Graphite	Garnet	Pinite	Cordierite
Peridotite	M	M	m	M		m		M	m	s				M	s				vs						M							
Metaperidotite		m	s	M	s		M	m	m					M					vs						M							
Perknite		M	s	M	vs	M		s	m						s				vs						m							
Olivine gabbro	M	M	m	M		vs		s	M					m	vs										M							
Olivine norite	M	M	s	M		s		s	M				vs	s	vs										M							
Metanorite		m		M			M		M		m		s	M	s				vs						M							
Norite		M	m	M	s	M			M	vs			vs	vs	vs	vs									M							
Pyroxene gabbro		M	M	M	vs	m			M	s					vs	vs									m							
Hornblende gabbro				M	c	M		vs	M		m				c					vs	vs				c							
Metagabbro		m		m	m	M		m	M	s	m		c		s		vs				vs				c							
Cummingtonite gabbro		vs		M	M	M			M	s	s		vs		vs		vs				vs				m							
Diorite				M	vs	M		vs	M	vs	c		c		c						vs				c							
Pyroxene quartz diorite		M		M	m	M		vs	M	M	s		s		s										c							
Quartz diorite				M	m	M		vs	M	M	s		s		s										c							
Trondhjemite						M		c	M	M	c		c		c			s		vs	c	vs		vs	c							
DYKES																																
Diabase				M	m	M		s	M	m	c	s	s	vs	c										c		vs	vs				
Pyroxene diabase		m	m	M	m	m			M	vs	vs		vs	vs	vs										c							
Pegmatite				n		o		t			s		t		u		d		i		e		d									
SUPRACRUSTAL ROCKS																																
Amphibolite		m	m	M	m	m			M	m															c							
Pyroxene amphibolite		M		M		M			M	m	m		s		c					c					c							
Amphibole rock		M				M				m						M													m			
Pyroxene-garnet gneiss		M				M		s	M	M	s		s		c						c				c				s	M		
Pyroxene gneiss		M			c	M			M	m					c						c				c							
Garnet gneiss			vs			M		c	M	M	c		s		c						c	s			c					M	vs	
Biotite gneiss				c		M		m	M	M	M		c		c										c				c			
Gummingtonite gneiss					M	M			M	M	c		c		c						c				c							
Chlorite gneiss						m	m	M	M	M	M		M		c						c	vs			s							
Hornblende gneiss				M		M			M	M	c		c		c										c							
Cordierite-graphite gneiss							m		M	m	c		c		c			M			c		c		c				M		m	
Graphite gneiss						m	c	c	M	M	s		c		c			m			c				c				M			
Black schist						M				M			c		c										c				M			
Pyroxene kinzigite		m		s	s	M		s	M	M	s		c		s				vs		c				c				s	M	c	M
Kinzigite						M			M	M	c		s		c				s		c	s								M	m	M
OTHERS																																
Blastomylonite				c		m		M	m	M			M		c						c				c	m						

M = major mineral present
m = minor "
c = characteristic accessory mineral: found in practically every thin section studied
s = rare accessory mineral
vs = very rare mineral, only in a few thin sections

vine gabbro, olivine norite, norite, pyroxene gabbro, hornblende gabbro, metagabbro and cummingtonite gabbro. The olivine gabbros and olivine norites are coarse-grained and rather equigranular rocks, with olivine, orthopyroxene, hornblende, fresh plagioclase (labradorite) and opaques (mainly sulphides) as main minerals. The orthopyroxene, which is cloudy and pleochroic hypersthene, is often intergrown with brown »basaltic» hornblende. In »metanorites» the olivine has completely altered into serpentine and the rock often contains coarse scales of phlogopite. Likewise, plagioclase has undergone sericitization.

Norite is by far the most common rock type in the intrusive. In texture it is hypidiomorphic-granular and often ophitic; in grain size it varies from the coarse-grained pegmatitic to the fine-grained foliated norites. Plagioclase is fresh and euhedral and the orthopyroxene frequently subhedral. The norites are free from clinopyroxene, whereas in the pyroxene gabbros augite is one of the major minerals. The hornblende gabbros are not as common as the pyroxene gabbros. Macroscopically the metagabbros and cummingtonite gabbros are paler than the other gabbros. In the cummingtonite gabbro the orthopyroxene has altered almost entirely into pale cummingtonite, which occurs as lamellar grains that have preserved the shape of the primary hypersthene.

Diorite and pyroxene quartz diorites are minor constituents in the intrusive and occur mainly in its brecciated and heterogeneous contact zones. Quartz diorites and trondhjemites are met with close to the contact zone as minor dykes. Silicic pegmatitic and mafic diabase dyke rocks abound in the intrusive. The mafic dykes are pyroxene diabases and »gabbroic amphibolites» granoblastic in texture. The mineral compositions of the supracrustal wall rocks in the intrusive are listed in Table 1. As a rule the wall rock mica gneiss is migmatitic in structure and brecciated along the contacts.

The graphite gneiss, black schist and graphite breccias that occur within the intrusive are very heterogeneous, often intensely folded and brecciated rocks in which wall rock and plutonite fragments are embedded in a graphite schist matrix. They frequently show yellowish or white carbonate veins and white quartz veins that are locally abundant. Pyrite veins and pyrrhotite-pentlandite disseminations are also common.

In places mylonites are associated with shear or breccia zones and with the contacts of the pegmatite dykes. In the plutonites the mylonites usually occur as narrow swarms of greenish veins rich in epidote.

Contact alteration

The marginal zone between the intrusive and the wall rock is from a few decimetres to a few metres thick. The contact is brecciated, particularly on the side of the wall rock, and hence on the ground plan, no clear alteration zone can be recognized at the contact. Several drill cores, however, demonstrate that there is a narrow zone of hornblende gabbro and diorite in the intrusive close to the contact with the wall rock. The zone passes into gneiss gradually as the intrusive rock grades into a fine-grained and oriented variant with the increase in the abundance of garnet.

The alteration of norite begins locally with metanorite followed by garnetiferous hypersthene gneiss or kinzigite. Occasionally norite grades into the wall rock through cummingtonite-bearing pyroxene gabbro, and the pyroxene gabbro zone may attain several metres in thickness. In places after norite the transitional series in the contact zone has quartz-norite followed by a fine-grained or medium-grained quartz diorite that grades into garnetiferous hypersthene gneiss.

Table 2. Chemical compositions of the Laukunkangas rocks.

Arithmetic means

Rock type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Number of samples analysed	14	2	124	134	17	33	6	33	2	19	5	3	10	2	5	3	29	441
SiO_2	41.24	49.29	50.91	47.04	51.24	52.31	52.65	67.39	49.84	64.74	43.51	60.15	51.64	57.34	65.51	57.03	50.43	51.65
TiO_2	0.54	0.82	0.66	0.63	0.91	0.87	0.52	0.43	0.68	0.75	0.65	0.76	0.49	0.66	0.39	0.60	0.58	0.65
Al_2O_3	6.79	11.21	14.22	11.28	11.28	15.21	15.31	14.14	13.10	13.40	11.72	14.06	12.61	15.06	15.01	14.35	12.33	12.82
FeO *	16.86	13.36	10.29	15.25	11.52	9.14	8.15	4.11	12.48	6.66	12.59	8.20	12.67	8.19	5.41	8.16	13.77	11.55
MnO	0.09	0.11	0.13	0.13	0.15	0.11	0.11	0.03	0.13	0.06	0.13	0.07	0.09	0.04	0.03	0.06	0.09	0.11
MgO	17.92	10.76	10.72	11.92	14.39	8.13	9.69	2.35	9.95	3.00	7.69	4.06	7.26	3.85	2.39	5.78	7.77	9.79
CaO	4.53	5.35	7.19	5.81	5.86	7.60	8.34	3.20	7.91	3.44	8.75	3.63	3.97	3.17	3.75	4.82	5.05	5.93
Na_2O	0.93	1.33	1.99	1.38	1.45	2.30	2.33	3.55	1.78	2.67	1.17	2.96	1.42	1.11	3.56	2.64	1.93	1.92
K_2O	0.28	1.42	0.60	0.55	0.64	1.01	0.68	1.67	0.83	2.18	0.83	1.84	1.58	2.77	1.23	1.33	1.14	0.85
S	2.21	1.83	0.59	3.07	0.47	0.48	0.13	0.29	2.68	0.37	1.91	0.39	4.11	3.16	1.61	0.59	3.93	1.69
	91.39	95.43	97.30	97.06	97.91	97.16	97.91	97.16	99.38	97.27	93.95	96.12	95.84	95.35	98.89	95.36	97.02	96.96

* Total Fe as FeO

Standard deviations.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	5.77	6.84	2.19	5.49	2.16	1.97	1.59	5.94	4.72	5.14	10.10	4.72	4.40	3.34	3.32	4.01	12.66	8.14
TiO_2	0.09	0.25	0.19	0.18	0.45	0.39	0.08	0.28	0.01	0.33	0.33	0.31	0.08	0.12	0.25	0.07	0.29	0.26
Al_2O_3	1.62	2.91	2.52	2.87	2.16	1.86	3.13	1.37	0.73	1.46	3.72	1.55	3.35	1.53	1.61	1.39	3.31	3.10
FeO	3.05	5.97	2.55	4.47	1.38	1.42	1.39	1.86	6.00	1.17	7.52	1.17	3.19	0.65	2.17	0.30	11.46	5.45
MnO	0.06	0.03	0.04	0.04	0.03	0.03	0.06	0.03	0.01	0.04	0.07	0.03	0.04	0.02	0.01	0.07	0.04	0.05
MgO	1.18	0.98	2.57	3.57	3.47	2.03	4.80	1.25	0.12	1.36	1.61	1.12	5.57	0.97	0.68	2.29	3.76	4.58
CaO	1.02	0.20	1.24	1.32	1.57	1.23	2.41	1.01	0.19	1.46	5.14	1.24	0.97	0.94	0.73	1.19	2.22	2.01
Na_2O	0.23	0.43	0.58	0.50	0.38	0.58	0.90	0.68	0.27	0.62	1.05	0.39	0.40	0.54	0.40	0.86	0.91	0.87
K_2O	0.14	1.01	0.17	0.22	0.15	0.28	0.29	0.73	0.83	0.23	0.57	0.33	0.85	0.25	0.27	0.56	0.66	0.60
S	0.69	2.03	0.68	2.55	0.42	0.67	0.05	0.24	2.12	0.51	2.37	0.17	1.66	0.69	0.85	2.01	8.55	2.89

1 peridotite
2 perknite
3 norite
4 norite, ore-bearing
5 pyroxene gabbro
6 hornblende gabbro
7 diabase
8 pegmatite
9 pyroxene gneiss
10 biotite gneiss
11 mylonite
12 garnet kinzigite
13 black schist
14 graphite gneiss
15 trondhjemite
16 marginal norite
17 migmatitic rocks
18 whole intrusive

Geochemistry of the host rocks

Compiled in Table 2 are the XRF data on the rock types. The samples were analysed at the laboratory of the Exploration Department of Outokumpu Oy. The sulphur contents were determined by an automatic Leco titrator. Most of the 441 samples were taken from the drill holes of profiles K = 34.650 and K = 34.700. The sampling was systematic, and pieces 1 to 2 m long drill cores were taken from each hole at intervals of 3 to 5 m. The analytical data were grouped according to rock types.

The sum of the analysed components in peridotites in Table 2 is only 91.39 %. The samples were not, however, assayed for water, whose content in the altered chlorite- and serpentine- bearing rocks may be several percentages. Neither are included the Ni and Cu concentrations incorporated in sulphides.

Comparison of these data with the corresponding rock compositions at Kotalahti and Hitura (Papunen, 1970) and Parikkala (Häkli, 1963) shows that the SiO_2 contents in the peridotites are very close to each other: at Laukunkangas the peridotites contain 41.24 % SiO_2 at Kotalahti 45.14 %, at Hitura 41.64 % and at Parikkala 45.05 % SiO_2. The lowest Al_2O_3 content, 1.63 %, is at Hitura; the highest, 6.79 %, at Laukunkangas: at Kotalahti and Parikkala the figure is 5.84 %. The MgO content is distinctly lowest, 17.92 %, at Laukunkangas and highest, 26.77 %, at Hitura; at Parikkala the corresponding content is 19.87 % and at Kotalahti 25.05 %. The Hitura peridotite is richest in alkalies: $Na_2O + K_2O$ is 2.42 %, whereas in the other peridotites it is from 1.21 to 1.65 %. The CaO content is 10.44 % at Parikkala; in the other peridotites it is between 3.44 and 4.53 %.

The gabbros also differ. At Laukunkangas the hornblende gabbros assay 52.31 % SiO_2, but at Kotalahti 50.69 % SiO_2. The differences are even more marked in the MgO con-

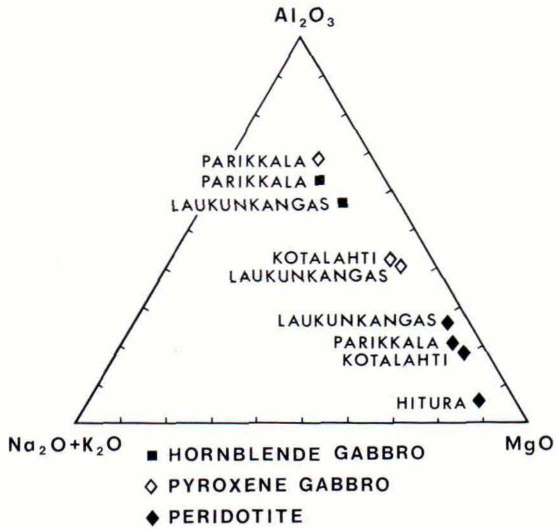


Fig. 5. Compositional variations in peridotites and gabbros at Kotalahti, Hitura, Parikkala and Laukunkangas.

tents: the Kotalahti gabbros assay 14.84 % MgO; the Laukunkangas varieties 8.13 % and the Parikkala ones 5.17 %.

Fig. 5 shows the compositional variation of the above rock types in a ternary diagram.

The analytical data on Laukunkangas are characterized by the rapid decrease, especially in MgO contents, from peridotites (17.92 %) to hornblende gabbros (8.13 %). Correspondingly the Ca, Al, Na and K abundances increase at a high rate towards the acidic rocks.

The compositions of the rocks of the Laukunkangas intrusive have been plotted on a ternary diagram $MgO — Al_2O_3 — (Na_2O + K_2O)$ (Fig. 6). The rocks of the differentiation series and the dyke rocks were sampled from profiles K = 34.650 and K = 34.700. Supracrustal samples were taken from the wall rock close to the contact zone.

The diagrams demonstrate that the differentiation series is continuous, extending from peridotites through norites to pyroxene and hornblende gabbros. The compositions of the different rock types frequently overlap, possibly because of contamination between the

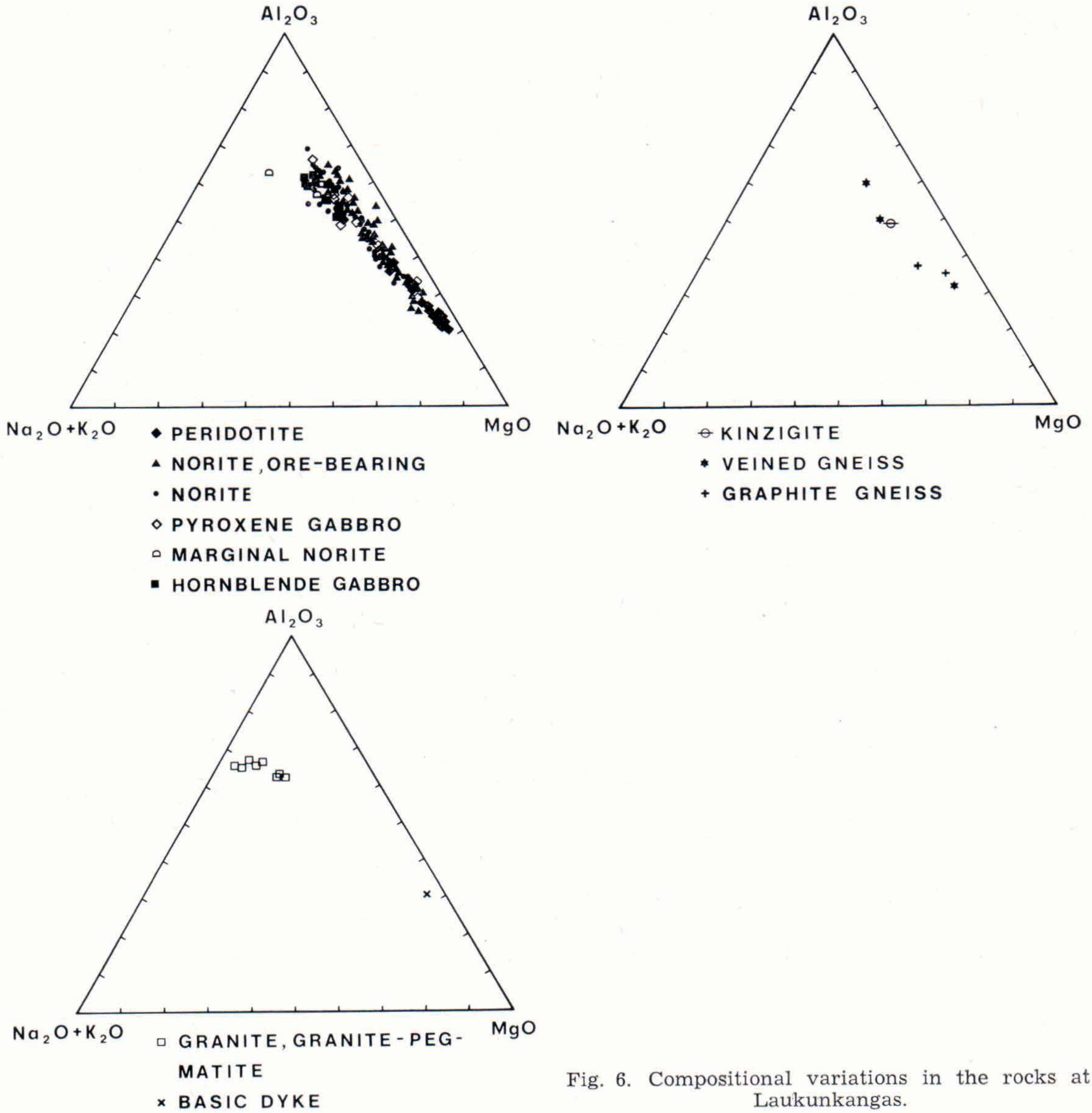


Fig. 6. Compositional variations in the rocks at Laukunkangas.

layers in the intrusive. The norite in the marginal zone is richest in alkalies and aluminium. The magma type is close to tholeiitic in composition.

Comparison of the differentiation series at Laukunkangas with those at Kotalahti and Parikkala (Papunen, 1970) shows that the rocks at Laukunkangas are distinctly poorer in MgO, and that the alkali contents are lower at Laukunkangas than at Kotalahti.

The compositions of the silicic dyke rocks plot within a restricted area and form a well-outlined field. A rock with the composition of the mafic dyke varieties falls within the field of norites and gabbros.

The supracrustal rocks are homogeneous in

Table 3. C.I.P.W. norms of the Laukunkangas rocks.

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Quartz		—	—	—	—	—	1.63	0.26	—	23.96	15.71	24.24
Orthoclase		1.65	8.39	3.54	3.25	3.78	5.97	4.02	4.91	12.88	10.86	7.27
Albite		7.87	11.25	16.84	11.68	12.27	19.46	19.71	15.06	22.59	25.05	30.12
Anorthite		13.52	20.42	28.10	22.96	22.38	29.19	29.31	25.30	17.06	18.01	18.60
Corundum		—	—	—	—	—	—	—	—	0.39	0.60	1.00
Diopside		7.31	5.03	6.19	4.84	5.43	7.80	9.82	11.49	—	—	—
Hypersthene		21.36	45.01	38.27	37.77	48.43	31.97	33.67	31.74	18.57	24.05	15.30
Olivine		36.44	1.98	2.52	12.30	3.41	—	—	6.91	—	—	—
Ilmenite		1.03	1.56	1.25	1.20	1.73	1.65	0.99	1.29	1.42	1.44	0.74
Sum		89.18	93.64	96.71	94.00	97.43	96.67	97.78	96.70	96.87	95.72	97.27
Diopside	Wo	3.74	2.55	3.16	2.45	2.79	3.97	5.04	5.82	—	—	—
	En	2.13	1.33	1.80	1.25	1.70	2.16	3.00	3.00	—	—	—
	Fs	1.44	1.16	1.23	1.14	0.94	1.67	1.78	2.67	—	—	—
Hypersthene	En	12.73	24.04	22.84	19.71	31.12	18.08	21.13	16.80	7.47	10.12	5.96
	Fs	8.63	20.97	15.43	18.06	17.31	13.89	12.54	14.94	11.10	13.93	9.34
Olivine	Fo	20.86	1.01	1.44	6.12	2.11	—	—	3.49	—	—	—
	Fa	15.58	0.97	1.08	6.18	1.30	—	—	3.42	—	—	—
Plagioclase An		63.22	64.47	62.53	66.29	64.59	59.16	59.78	62.68	43.03	41.82	51.13

1. = peridotite
2. = perknite
3. = norite
4. = norite, ore-bearing
5. = pyroxene gabbro
6. = hornblende gabbro
7. = diabase
8. = pyroxene gneiss
9. = mica gneiss
10. = kinzigite
11. = trondhjemite

terms of alkalies but show a large variation in Al_2O_3 contents.

The C.I.P.W. norms listed in Table 3 were calculated, as suggested by Bingler et al. (1976), from the average compositions compiled in Table 2. Comparison of these results with the microscopic observations (Table 1) reveals conspicuous differences. Pyroxene gabbros and norites are olivine normative, although olivine has not been revealed by microscopic examination. Similarly, there are differences in the plagioclase abundances. One of the reasons for the differences is that iron was determined as total iron, which includes the iron incorporated in sulphides and calculated to FeO. Examination of the normative compositions, however, shows that the rocks at Laukunkangas contain abundant hypersthene and that the orthopyroxene has slightly more enstatite than ferrosilite. Likewise, olivine is forsterite-predominant. The normative anorthite content in the plagioclase is consistent with the values determined from thin sections; the composition is close to the labradorite in norites as well.

The differentiation indices calculated according to Bingler et al. (1976) were compared with the SiO_2 and MgO contents in the rocks. The results presented in Figs. 7 and 8 demonstrate two differentiation trends in the rock types of the intrusive. This suggests that there were at least two emplacement stages at Laukunkangas: I) peridotites, ore-bearing norites and pyroxene gabbros; and II) perknites, barren norites and hornblende gabbros. The mineralization is associated with the first stage alone, although some relics of the sulphides are occasionally encountered in the rocks of the second stage as well.

The differentiation indices of granites and trondhjemites differ markedly from those of the mafic rocks and form an individual series on the diagrams.

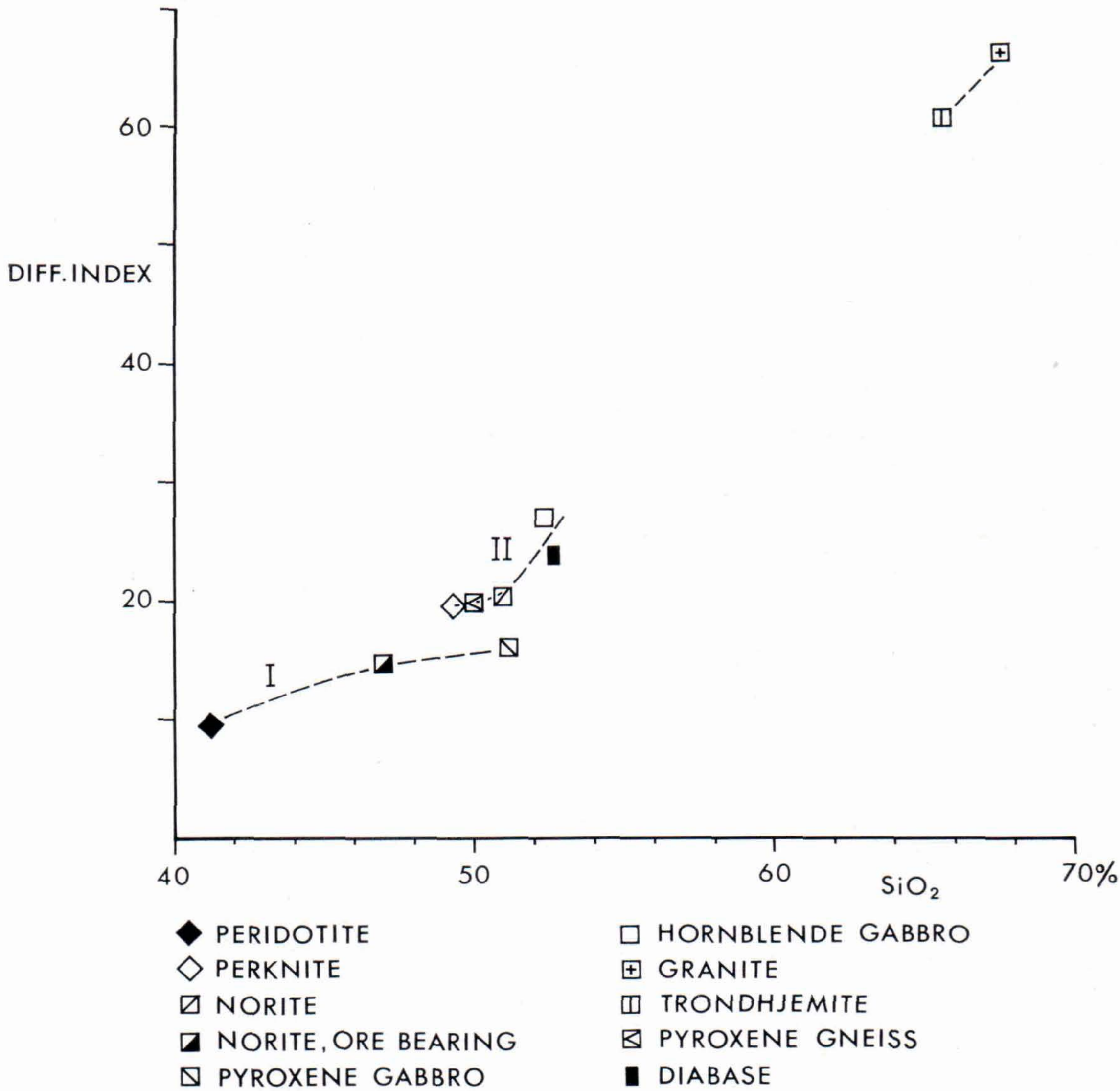


Fig. 7. The differentiation indices of plutonites versus SiO_2.

As shown in Fig. 8, the two differentiation series in the intrusive are well reflected in the MgO contents of the rocks. Further, the MgO contents were higher in the first stage than in the second.

Compiled in Fig. 4c are the MgO contents in drill cores taken from holes in profiles K = 34.650 and K = 34.700. The layered structure is clearly visible in the diagram, although it is difficult to outline the exact boundaries between the layers. The variation in MgO contents should probably be attributed to alteration and contamination in the transitional zones between layers and rock types.

Fig. 9 shows the elemental abundances in drill core EK/La-25 against its lithology. Owing to their low SiO_2 contents the peri-

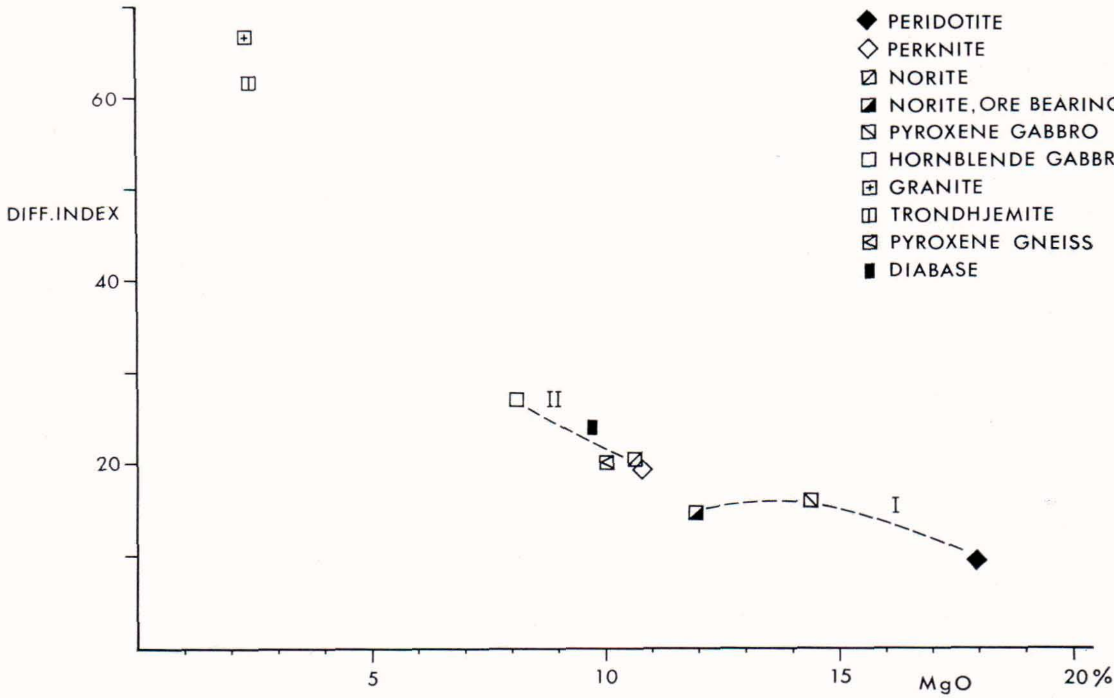


Fig. 8. The differentiation indices of plutonites versus MgO.

dotites show up clearly. The contamination is demonstrated particularly in the change in MgO, SiO_2 and Cr contents across the boundaries between the zones. The SiO_2 content in metagabbros and cummingtonite gabbros is slightly less than 50 %, whereas in norites it is above 50 %. In the MgO diagram the peridotites and olivine gabbros are at about the 20 % level whereas the norites, metagabbros and cummingtonite gabbros are at under 15 %. Down to a depth of 115 m, however, the surficial norite is fairly rich in MgO. In the marginal zone the MgO content in norite falls to 5 %; in veined gneiss it is less than 5 %.

On the basis of the MgO curve the intrusive can be subdivided into three parts: 1) the lower zone at a depth between 210 and 295 m; 2) the intermediate zone at 115 to 210 m; and 3) the upper zone from 0 to 115 m. The metagabbros and cummingtonite gabbros that occur on the boundaries of these zones show distinct changes in MgO contents. Particularly between the lower and intermediate zones there is a transitional zone that is characterized by enhanced SiO_2, intense fluctuation in MgO and depletion in Cr. The Cr content in the intermediate zone averages 0.10 to 0.15 %, whereas in the upper and lower zones it is between 0.2 and 0.3 %. However, in the lower part of the intermediate zone there is a Cr-richer portion that assays about 0.3 % Cr.

Also shown in Fig. 9 are the Ba, Sr and Zr contents. The peridotitic lower part, which also contains olivine gabbros, is clearly distinguished from the intermediate and upper zones. The strontium content in the lower zone is more or less constant at c. 150 ppm. The average Zr content is 35 ppm.

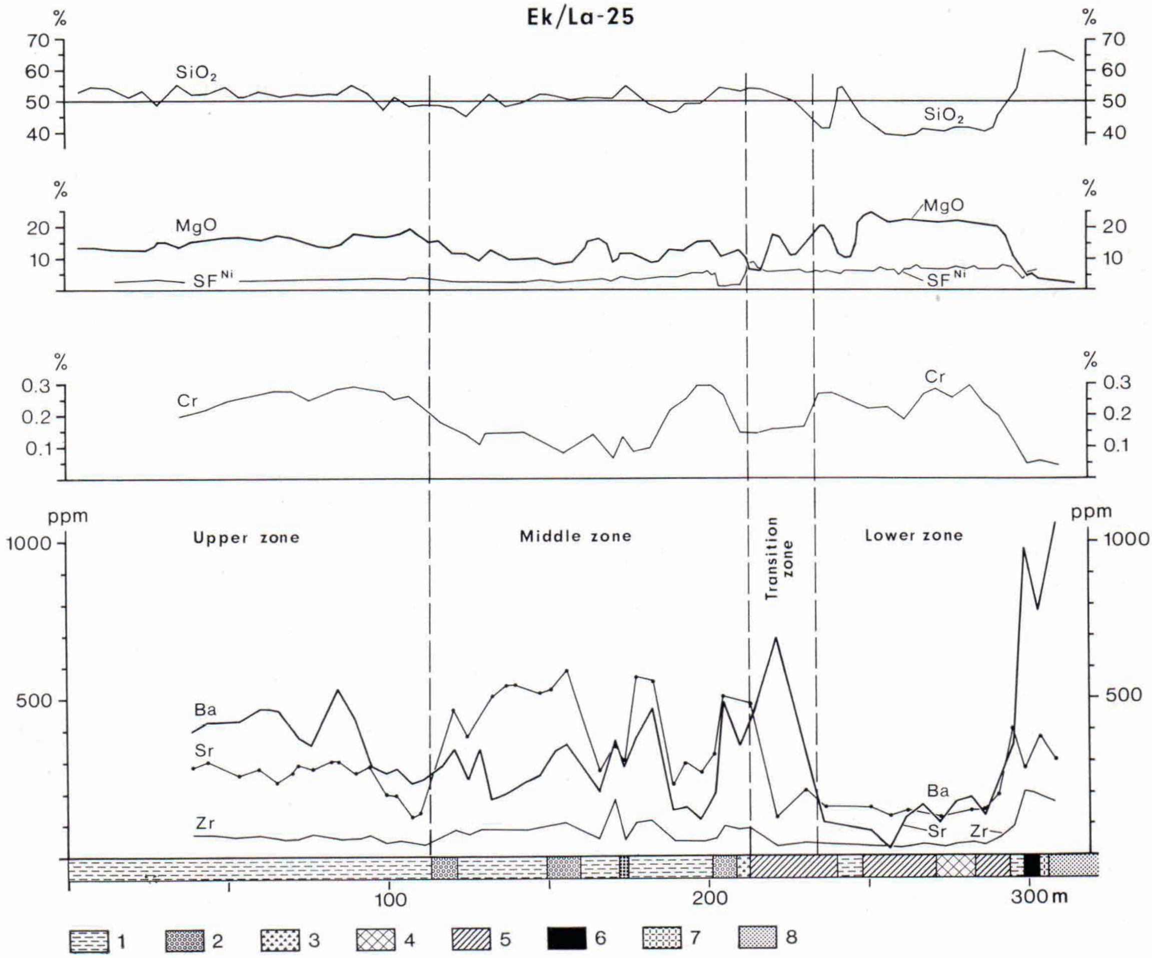


Fig. 9. The geology and variations in Ba, Sr, Zr, Cr, MgO and SiO_2 and in the nickel content of the sulphide phase (SF^{Ni}) in drill hole EK/La-25. 1. norite, 2. cummingtonite gabbro, 3. pyroxene gabbro, 4. olivine gabbro, 5. peridotite, 6. ore, 7. trondhjemite, 8. veined gneiss.

The barium content varies between 20 and 700 ppm. In the upper zone the corresponding averages are: 50 ppm Zr, 270 ppm Sr and 420 ppm Ba. In the intermediate zone the concentrations vary considerably; as a rule the highest concentrations are encountered in metagabbros and cummingtonite gabbros. The transitional zone shows up, particularly because of the Ba and Sr contents. The average contents in the wall rock veined gneisses are 160 ppm Zr, 290 ppm Sr and 1 050 ppm Ba. The pegmatitic veins may contain over 1 400 ppm Zr, about 1 200 ppm Sr and nearly 2 500 ppm Ba.

Ore occurrences

The sulphides at Laukunkangas are concentrated at the eastern end of the intrusive (Fig. 3), the richest occurrences being close to the contacts. On the horizontal plane the ore mineralization seems to form an arch-like zone in the eastern part of the intrusive. Only sporadic and small sulphide occurrences have been encountered in the middle of the intrusive.

The ore mineral paragenesis at Laukunkangas is simple. The main minerals are pyrrhotite, pentlandite and chalcopyrite. Magnetite, ilmenite, violarite, rutile, graphite and anatase are common accessories; sphalerite and molybdenite are rare. Narrow nickel arsenide veins are occasionally encountered in the contact zone.

Ore Types

The ore types include the dissemination in norites and gabbros, the dissemination in peridotites, the breccia ores and the sulphide-bearing graphite rocks.

The disseminated sulphides in norites and gabbros vary from fine-grained to coarse-grained, i.e. from less than 0.1 mm to several cm in diameter. The grains generally exhibit interstitial forms against the silicates. The anhedral pyrrhotite often contains euhedral or subhedral pentlandite as inclusions as well as small pentlandite exsolution bodies and »flames». Anhedral chalcopyrite portions are almost invariably present.

As a rule the sulphide grains are fresh, and replacement structures are rare. When abundant, the sulphides show an intergranular texture.

The disseminated sulphides in peridotites are either interstitial grains or constitute a network of intergranular dissemination in which the matrix is composed of sulphides. The sulphides average 6 wt-% as against less than 4 wt-% in norites. Violarization of pentlandite is more common in peridotites than in norites. Magnetite has commonly formed in and around the fractures of the sulphide grains as a result of the serpentinization of olivine. Rare accessoric ilmenite occurs as independent grains.

The sulphide breccias and veins, which favour the contact zone of the intrusive are composed of massive sulphides or contain wall rock fragments and inclusions. Pyrrhotite, pentlandite and chalcopyrite are the predominant minerals, chalcopyrite and pentlandite occurring as coarse grains or intergranular stringers between the pyrrhotite grains. Pentlandite »flames» are common in pyrrhotite. The accessories are sphalerite, gersdorffite, ilmenite, magnetite, rutile and graphite.

The sulphide mineralization in the graphite schist inside the intrusive is pyrite-predominant and thus differs markedly from that in peridotite. The sulphides occur as bands in an intensely folded graphite schist. Pyrite contains fine-grained inclusions of chalcopyrite, pentlandite and millerite; sphalerite may be fairly abundant.

Drill hole EK/La-16 intersected a nickel arsenide vein a few mm thick in the wall rock outside the intrusive. Within the vein a two-phase gersdorffite was observed in the reaction seam between niccolite and pentlandite. The compositions of the phases are shown in Table 4.

Table 4. Chemical composition of niccolite, gersdorffite (two reaction rims) and pentlandite. Electron microprobe determinations.

	S %	As %	Fe %	Co %	Ni %	Sum %
Niccolite	0.18	54.06	0.03	0.04	43.15	97.46
Gersdorffite; middle	18.81	45.58	5.15	7.50	23.98	101.02
Gersdorffite; rim	19.01	44.61	1.26	2.04	32.48	99.41
Pentlandite	32.86	0.00	29.64	0.12	37.19	99.81

Table 5. Calculated normative abundances of sulphides in drill hole Ek/La-25.

	1.	2.	3.	4.	5.	6.
Pyrrhotite	3.45	83.84	3.12	85.47	4.76	77.28
Pentlandite	0.62	11.78	0.51	10.24	1.08	18.05
Chalcopyrite	0.16	4.38	0.13	4.29	0.28	4.67
Sum	4.23	100.00	3.76	100.00	6.12	100.00
Number of samples	166	166	133	133	33	33

1. the whole drill hole, mean value
2. sulphide phase in the whole drill hole
3. norites and gabbros
4. sulphide phase in norites and gabbros
5. peridotites
6. sulphide phase in peridotites

Chemistry of the sulphide occurrence

Calculated from the analytical data of drill hole EK/La-25, the average sulphide concentration in the intersected intrusive is 4.23 wt-% (Hänninen, 1978). Of the sulphides, pyrrhotite accounts for 83.84 %, pentlandite 11.78 % and chalcopyrite 4.38 % (Table 5). The abundance of sulphides varies from under 0.5 % in disseminated ores to about 90 % in massive ores.

In peridotite, the calculated pentlandite abundance in sulphide phase is about 18 to 20 %, whereas in norites and gabbros it is c. 8 to 10 %. The corresponding Ni concentrations in sulphide phase are 5.7 % in peridotite and 2.5 to 4.5 % in norites and gabbros.

Fig. 4 b shows in detail the distribution of sulphide nickel in the Laukunkangas intrusive. The figures demonstrate clearly that the distribution of sulphides is heterogeneous. The pattern is the same as that on the ground plan (Fig. 3). The nickel abundances are highest at the eastern end of the intrusive close to the contact. The Ni accumulations inside the intrusive are sporadic and shaped like narrow lenses or slabs. Nickel contents exceeding 1 per cent are encountered in peridotites and ore norites, particularly in profile K = 34.700.

The metal contents calculated for the mineralized portion (Ni + Cu > 0.3 %) of profile K = 34.700 are given in Table 6. The following average ratios characterize the occurrence: Ni/Cu = 3.15; Ni/Co = 17.31; Cu/Co = 5.49. The corresponding ratios for the perknites at Kotalahti are Ni/Cu = 2.95; Ni/Co = 21.0 (Papunen, 1970).

In Finnish ultramafic and mafic intrusives the average Ni/Co ratio is 13.6 for peridotites, 10.1 for perknites, 6.4 for olivine gabbros, 5.9 for norites, 3.8 for gabbros, 2.4 for diorites and 1.9 for quartz diorites (Häkli, pers. comm.) Hence, the nickel content in the rocks decreases rapidly and the relative Co abundance increases as the SiO_2 rises.

The Co content at Laukunkangas is distributed in the profiles studied in roughly the same way as the Ni content. In the mineralization the cobalt content varies between 400 and 800 ppm. Maximum contents of over 1 600 ppm occur at sites where the nickel abundances exceed 1.0 %.

Table 6. Metal content of the mineralized portion of profile K = 34.700.

	arithmetic mean	standard deviation
Cu	1 460 ppm	1 315 ppm
Zn	46 ppm	22 ppm
Ni	4 600 ppm	5 400 ppm
Co	265 ppm	240 ppm
S	3.93 %	4.23 %

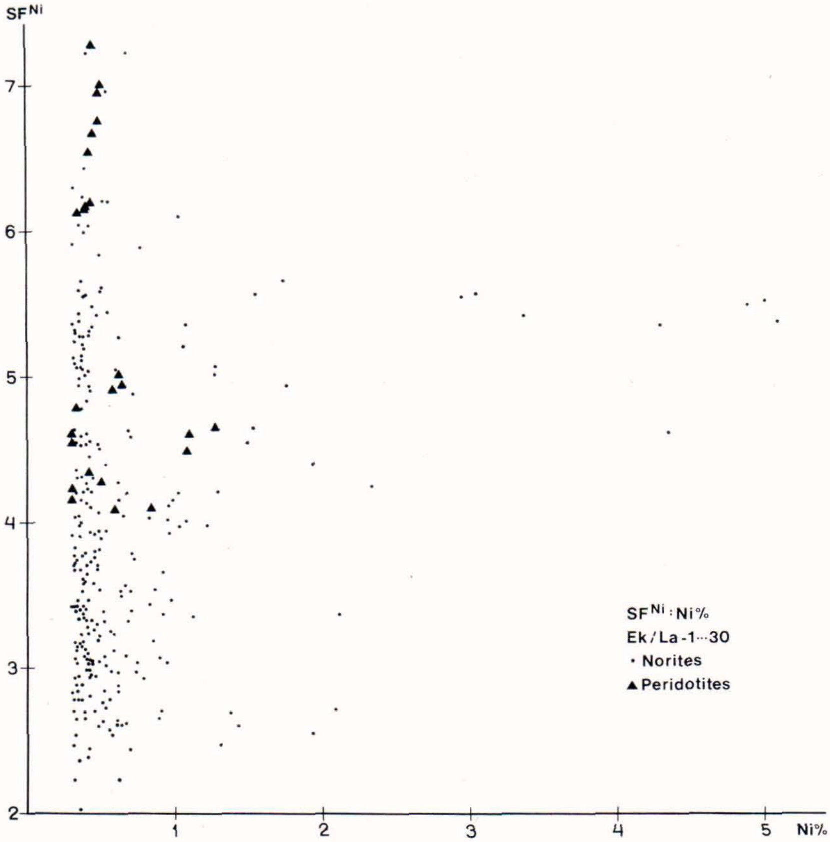


Fig. 10. The nickel content of the sulphide phase in drill cores EK/La-1 to EK/La-30 versus the nickel incorporated in sulphides. The data on samples that contained less than 0.3 % S are omitted.

The sulphur content in the ore is frequently from 3 to 6 %. Whenever the Ni content is 0.5 to 1.0 % the sulphur content is from 5 to 9 %. Massive ore veins have been encountered in some drill holes, e.g. EK/La-23 and EK/La-25, in which the sulphur content is above 30 %, the Ni content is from 4 to 5 % and the Co content up to 0.18 %.

Te Ni content in the sulphide phase, SF^{Ni}, was calculated from the analytical data as follows:

$$SF^{Ni} = 36.5 \times \frac{\text{Ni content}}{\text{S content}}$$

The calculated average Ni content in the sulphide phase in profile K = 34.700 is 4.81 %, with a standard deviation of 1.39 %. The results are shown in detail in Fig. 4d. The highest contents, over 6 %, are in peridotite and olivine gabbro in drill hole EK/La-25 and in norite in drill hole EK/La-16. In profile K = 34.700 the predominant level is 4.5 to 6.0 % Ni; in profile K = 34.650 it is 3.5 to 4.0 % Ni. The cryptic layering in the intrusive seems to be best reflected in the Ni abundance in the sulphide phase.

Fig. 10 shows the calculated Ni contents in the sulphide phase in the samples collected from drill holes 1 to 30 at Laukunkangas. Samples with a sulphur content under 0.3 % were omitted. The diagram exhibits a large and rather ill-defined scattering in SF^{Ni} from 2.0 to 7.5 %. The average SF^{Ni} contents in peridotites, over 4.0 %, are higher than those in norites. The highest Ni contents in the massive sulphide veins are about 5 %.

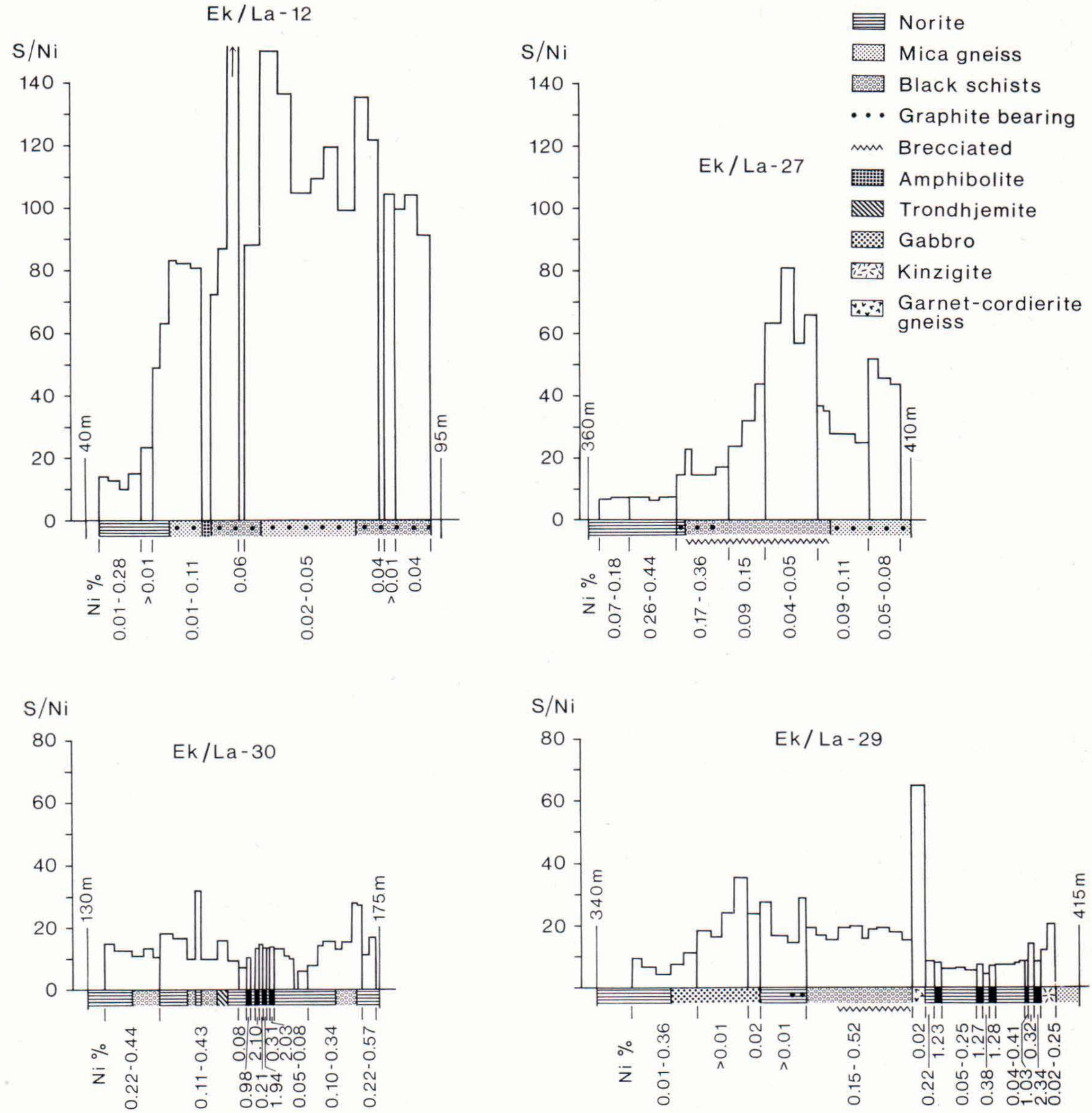


Fig. 11. The S/Ni ratio in the host rocks of the contact zone and in the wall rocks in drill holes EK/La-12 and EK/La-17 and in the black schist-graphite rocks within the intrusive in drill holes EK/La-29 and EK/La-30. The Ni contents on the abscissa refer to the averages of the sampling intervals.

Chemical composition of sulphides in graphite gneiss, graphite breccia and black schist

Graphite-bearing rocks are encountered within the Laukunkangas intrusive. Black schists and graphite breccias occur in the contact of the intrusive and in its wall rock.

The sulphur to nickel ratios of the contact rocks and wall rocks are shown by diagrams (Fig. 11) drawn on the basis of data from drill holes EK/La-12 and EK/La-27. Drill holes EK/La-29 and EK/La-30 demonstrate the cor-

Table 7. Average chemical composition of pentlandites. Electron microprobe determinations.

Sample	1.	2.	3.	4.	5.	6.
Number of analyses	3	4	3	3	3	3
Fe	29.68	27.84	29.06	29.87	29.67	29.33
Ni	34.33	38.54	34.05	35.54	34.21	34.71
Co	2.37	0.04	3.19	0.86	3.17	2.38
S	33.80	33.26	33.12	33.42	33.42	33.33
Total	100.18 %	99.68 %	99.42 %	99.69 %	100.47 %	99.75 %

1. Ek/La-30, 158.70 disseminated ore in norite (Ni = 0.12 %)
2. Ek/La-30, 170.00 black schist (Ni = 0.21 %)
3. Ek/La-1, 58.00 disseminated ore in norite (Ni = 1.32 %)
4. Ek/La-25, 300.25 massive ore (Ni = 5.12 %)
5. Ek/La-23, 89.15 mylonitized ore (Ni = 0.40 %)
6. Ek/La-16, 39.00 disseminated ore in norite (Ni = 0.83 %)

responding ratios in the graphite schists within the intrusive. These graphite schists are conspicuously rich in Ni, the nickel content incorporated in sulphides being as high as 0.52 %. This is markedly higher than in the corresponding rocks in the environment, where the Ni content is usually under 0.10 %. The sulphur content in the graphite schists intersected by drill hole EK/La-12 is between 4.0 and 8.5 %.

The influence of the mafic intrusive is clearly reflected in the S/Ni ratios in drill holes EK/La-12 and EK/La-27, which show that in the contact zone nickel has migrated into gneiss. Farther away from the contact, however, the S/Ni ratio in the gneiss gradually increases to 140. The graphite-bearing rocks within the intrusive seem to have been equilibrated at a S/Ni ratio of 10 to 20. The sulphur-nickel ratio thus varies distinctly in the graphite rocks, depending on their location.

The intraformational graphite schists may be fragments of the sulphide-bearing mica gneiss- black schist horizons in the environment. The fragments in the mafic intrusive have acquired nickel either from the silicates in the intrusive or through invasion of nickel-rich sulphides from the mafic rocks.

Chemical composition of the ore minerals

Tables 7 to 10 give the analytical data for pentlandite, pyrrhotite and pyrite.

Pentlandite occurs in two different sulphide associations. In Table 7 sample 2 represents the pyrite-millerite- pentlandite association; all the other samples belong to the monoclinic pyrrhotite- hexagonal pyrrhotite- pentlandite association. The average chemical compositions of pentlandites in associations are shown in Table 8. The associations differ clearly in their nickel and cobalt contents. The Ni concentration in pentlandite varies from 34.21 to 38.54 %. The highest Ni concentration, 38.54 % was recorded from the pyrite-bearing black schist that showed the lowest Co abundance, 0.04 %. Similarly the pentlandites in the Jussi orebody show higher

Table 8. Average chemical compositions of the pentlandites in mpo — hpo — pn and py — ml — pn associations.

	mpo — hpo — pn	py — ml — pn
Fe	29.52	27.84
Co	2.39	0.04
Ni	34.57	33.54
S	33.42	33.26
Total	99.90 %	99.68 %

Table 9. Average chemical composition of pyrrhotites. Electron microprobe determinations.

Sample	1.	2.	3.	4.	5.
Number of analyses	4	4	3	3	3
Fe	59.60	59.69	59.62	59.48	59.49
Ni	0.50	0.29	0.37	0.40	0.36
Co	0.04	0.01	0.02	0.02	0.03
S	39.53	39.33	39.72	39.80	39.99
Total	99.67 %	99.32 %	99.73 %	99.70 %	99.87 %

1. Ek/La-30, 158.70 disseminated ore in norite (Ni = 0.12 %)
2. Ek/La-1, 58.00 disseminated ore in norite (Ni = 1.32 %)
3. Ek/La-25, 300.25 massive ore (Ni = 5.12 %)
4. Ek/La-23, 89.15 mylonitized ore (Ni = 0.40 %)
5. Ek/La-16, 39.00 disseminated ore in norite (Ni = 0.83 %)

Ni content and lower Co contents than in any other orebodies in the Kotalahti deposit (Papunen, 1970).

The Co content in the pentlandite in the disseminated ores is between 2.37 and 3.19 %, whereas in the massive sulphides it is 0.86 %. The sulphur content of pentlandite is more or less constant, 33.12 to 33.80 %.

Harris and Nickel (1972) have demonstrated that the composition of pentlandite depends on the ambient sulphide association. The analytical data compiled in Table 8 are compatible with this concept.

The Fe and S contents in pyrrhotite are fairly constant (Table 9). The Co content is also constant and low, 0.01 to 0.04 %. The Ni content varies between 0.29 and 0.50 %, without a distinct relation to ore types and grade classes.

Pyrrhotite occurs as monoclinic and hexagonal variants. The cores of the crystals tend to be hexagonal pyrrhotite, whereas the margins and the portions along the cleavages are monoclinic. The composition of the pyrrhotites analysed indicates that they are admixtures of monoclinic and hexagonal variants.

The Co content in the pyrite in black schist is between 0.00 and 0.95 %, that of Ni between 0.00 and 0.26 (Table 10).

Sulphur isotopes

The aim of the sulphur isotope study was to clarify the origin of the sulphur in the norites and graphite-bearing rocks in drill hole EK/La-30. Twenty-five samples were analysed at the sulphur isotope laboratory of the University of Utah under the supervision of Dr. Jensen (P. Hautala pers. comm.). The average $\delta^{34}S$ in sulphides in norites and gabbros was —0.23, whereas for graphite

Table 10. Co and Ni contents in pyrites. Electron microprobe determinations.

	Co %	n	Ni %	n	av. Co %	av. Ni %
1.	0.00—0.93	(14)	0.00—0.21	(14)	0.025	0.10
2.	0.00—0.08	(6)	0.00—0.26	(6)	0.04	0.10

1. Ek/La-30, 170.00 black schist (Ni = 0.21 %)
2. Ek/La-12, 84.00 black schist

rocks and migmatites the corresponding figure was —2.59. The average of all samples was —0.64. The range for norites was from +3.13 to —4.28 and for graphite rocks from —0.47 to —6.53 (Hautala pers. comm.). It is widely accepted that $\delta^{34}S$ values close to zero refer to igneous origin. Although samples were not taken from the wall rock mica gneiss for comparison, the $\delta^{34}S$ values of the graphite rocks and contact rocks probably indicate that a major part of their sulphur derives from the wall rock.

Ni contents in silicates

Altogether 299 samples of olivine, enstatite, augite and amphibole were assayed for Ni and Fe by electron microprobe. Table 11 gives the average compositions, standard deviations and densities of the different rock types. The Ni content in silicates drops rapidly from peridotites to more silicic rocks and, since Ni and Mg correlate well, the iron content increases with the decrease in Ni.

Olivine was analysed for Ni and Fe from 17 peridotite and olivine gabbro samples. The Ni content varies from 778 to 1 519 ppm (Table 12) and the Fe content from 13.5 to 17.9 %. The large variation in the Ni content in olivine within such a narrow range of Fe variation suggests that the rock already contained sulphides during the crystallization stage (Naldrett et al. 1978).

Fig. 12 depicts the data from Table 11. The nickel incorporated in augite, Aug^{Ni}, and in enstatite (bronzite according to its Fe content), En^{Ni}, is plotted in the diagram versus the iron contents in these minerals. The augite curve demonstrates that the partition of nickel changes regularly from peridotites to diorites. There is a marked decrease in nickel content from 157 ppm in the augite in olivine gabbro to 97 ppm in the augite in pyroxene gabbro. At the same time the iron content increases from 4.5 to 5.10 %.

A peculiar feature of the En^{Fe}/En^{Ni} diagram is the high nickel content, 287 ppm, in the enstatite of perknite. The enstatite of olivine gabbro shows a higher nickel content than does the enstatite of peridotite. The nickel abundances in the enstatites of norites are markedly lower, and the curves show that most of the nickel had already been incorporated in the silicate lattices before the noritic rocks were crystallized. The higher En^{Ni} in perknite may be attributed to the fact that perknite does not belong to same emplacement series as peridotite and olivine gabbro. On the other hand, in the sulphide-bearing peridotites and olivine gabbros, the silicates may have been depleted in nickel owing to the subsolidus reaction $Ni^{Silic.} \rightarrow Ni^{Sulph.}$

Fig. 13 illustrates the Ni and Fe contents in amphiboles and orthopyroxenes on profile K = 34.650 (120 samples) and on profile K = 34.700 (109 samples). The samples were taken systematically at 10-m intervals. In profile K = 34.700 the nickel contents in amphibole, over 400 ppm, and those in orthopyroxene, from 200 to over 300 ppm, are highest in the peridotite- olivine gabbro zone (cf. Fig. 4a), i.e. in the lower zone in Fig. 9. Above this zone there is a narrow portion in which the nickel content in amphibole is low, under 200 ppm, and the nickel content in pyroxene varies from 100 to 200 ppm. This portion is located mainly in the metagabbro — cummingtonite gabbro zone, i.e. in the upper part of the transitional zone. Moreover, there are large areas with minimum Ni contents in the surficial parts of drill holes EK/La-25 and EK/La-27 in the middle of the intrusive. The nickel content in amphiboles and pyroxenes is under 100 ppm.

The drilling profiles show that in the eastern margin of the intrusive there are at least two or possibly three portions that differ in Ni content. In the middle portion the Ni contents in amphiboles vary but this

Table 11. The average nickel and iron contents in olivine, enstatite, augite and amphibole and the densities of some rock types.

Rock type	n	Ol^{Ni} ppm	Ol^{Fe} %	En^{Ni} ppm	En^{Fe} %	Aug^{Ni} ppm	Aug^{Fe} %	Af^{Ni} ppm	Af^{Fe} %	Density (g/cm³)
Peridotite	13	1 081.1	15.52	227.1	9.07	173.3	2.95	339.1	4.64	3.24
Perknite	7	—	—	287.0	11.35	166.0	3.80	397.8	6.63	3.12
Olivine gabbro	6	1 107.0	15.50	253.5	9.07	157.7	4.50	350.8	4.70	3.05
Norite	127	—	—	136.2	14.04	135.0	—	220.2	6.59	3.08
Pyroxene gabbro	64	—	—	109.9	14.29	96.7	5.10	169.3	7.40	3.00
Hornblende gabbro	56	—	—	108.8	14.10	33.0	7.60	224.3	8.77	2.97
Diorite	8	—	—	49.1	16.41	23.0	6.20	72.9	7.43	2.94
Quartz diorite	8	—	—	44.7	16.07	—	—	44.7	8.56	2.90
Diabase	6	—	—	43.0	15.80	23.0	16.30	62.5	8.20	2.93
Granite	2	—	—	—	—	—	—	28.5	12.70	2.86
Pyroxene gneiss	2	—	—	42.0	13.05	—	—	29.0	—	3.08

Standard deviations

Rock type	n	Ol^{Ni} ppm	Ol^{Fe} %	En^{Ni} ppm	En^{Fe} %	Aug^{Ni} ppm	Aug^{Fe} %	Af^{Ni} ppm	Af^{Fe} %	Density (g/cm³)
Peridotite	13	221.8	1.04	52.1	0.95	47.5	0.21	85.8	0.52	0.03
Perknite	7	—	—	43.0	0.50	—	—	67.9	1.57	0.04
Olivine gabbro	6	146.7	1.55	32.9	1.36	6.5	—	60.6	0.68	0.12
Norite	127	—	—	71.4	2.24	45.3	—	117.0	1.86	0.16
Pyroxene gabbro	64	—	—	57.6	2.19	61.2	0.40	195.0	1.99	0.11
Hornblende gabbro	56	—	—	28.8	1.60	—	—	156.3	2.43	0.12
Diorite	8	—	—	27.7	1.66	—	—	36.5	0.72	0.07
Quartz diorite	8	—	—	27.6	1.04	—	—	17.3	2.12	0.07
Diabase	6	—	—	—	—	—	—	48.0	1.03	0.10
Granite	2	—	—	—	—	—	—	19.1	4.10	0.05
Pyroxene gneiss	2	—	—	5.7	0.07	—	—	—	—	0.14

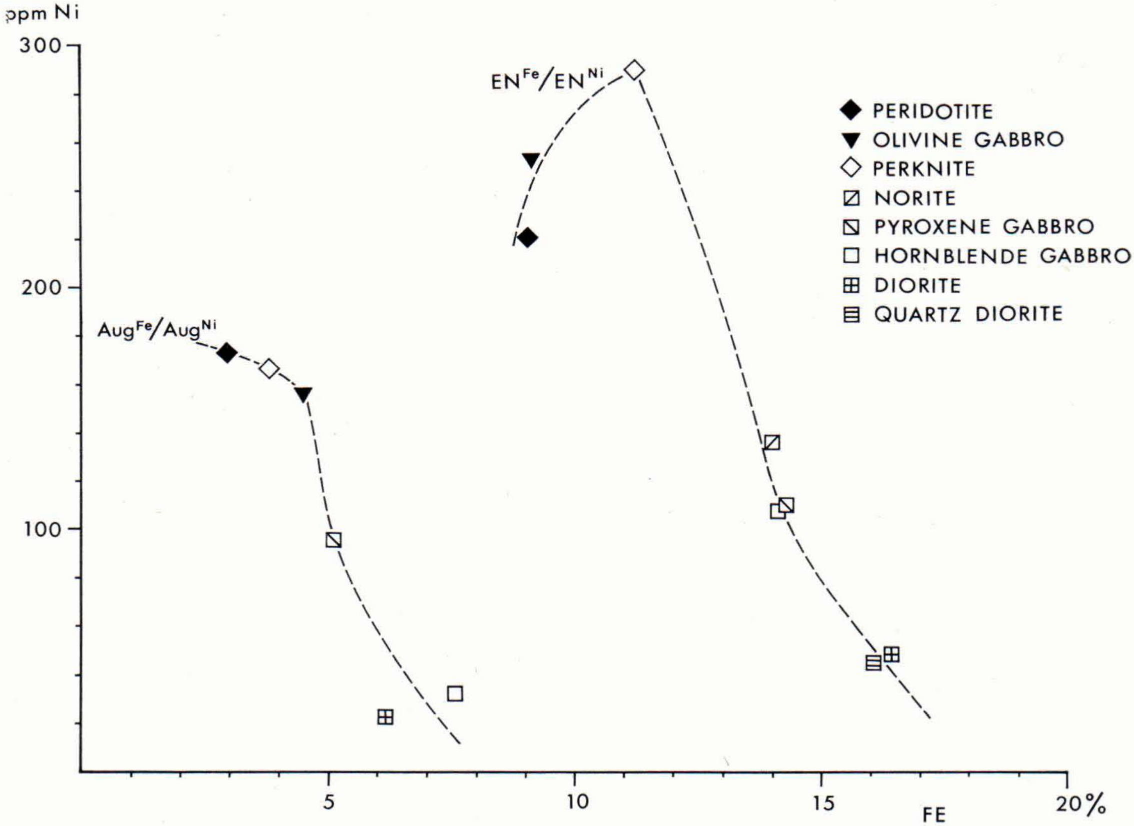


Fig. 12. Nickel in augite and enstatite versus iron in the same minerals in the rocks of the Laukunkangas differentiation series.

is due to the variation in the species. The Ni and Fe contents in pyroxene are more or less constant (100 to 200 ppm Ni).

The variation in the Ni content in silicates in profile K = 34.650 can be attributed to the layered structure of the intrusive. In the upper part of the intrusive, which is almost free from sulphides, the Ni contents in amphiboles and pyroxenes are generally under 100 ppm. The distances between drill holes in the profile are locally up to 200 m and hence the connection of the drill core data between the different holes is somewhat ambiguous. Nevertheless, if the data on the drill cores are compared with each other, the occurrence of plate-like units becomes evident; especially the Ni and Fe contents in silicates suggest the existence of coherent plates within the intrusive.

Crystallization temperature

Häkli (1968) applied the Ni partition coefficients of the mineral pair olivine-augite to estimate the crystallization temperature of the Parikkala mafic intrusive. Table 12 gives the Ni contents in the coexisting olivine, augite and orthopyroxene in peridotites and olivine gabbros from which the Ni partition coefficients of the mineral pair were calculated.

The olivine in peridotites shows a large variation in Ni content, from 778 to 1 519 ppm

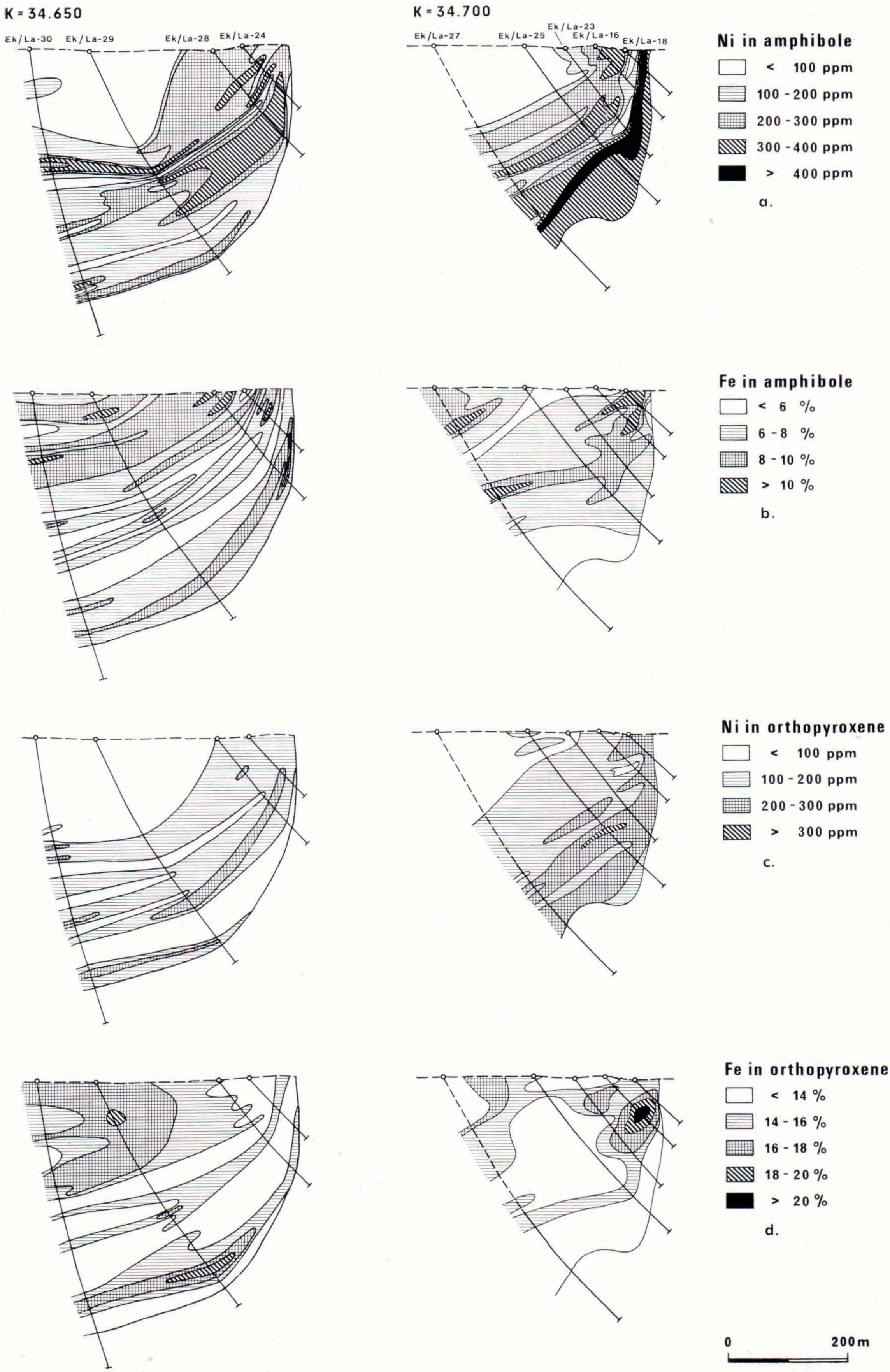

K = 34.650
Ek/La-30
Ek/La-29
Ek/La-28
Ek/La-24
K = 34.700
Ek/La-27
Ek/La-25
Ek/La-23
Ek/La-16
Ek/La-18
Ni in amphibole
< 100 ppm
100 - 200 ppm
200 - 300 ppm
300 - 400 ppm
> 400 ppm
a.
Fe in amphibole
< 6 %
6 - 8 %
8 - 10 %
> 10 %
b.
Ni in orthopyroxene
< 100 ppm
100 - 200 ppm
200 - 300 ppm
> 300 ppm
c.
Fe in orthopyroxene
< 14 %
14 - 16 %
16 - 18 %
18 - 20 %
> 20 %
d.
0
200 m

Table 12. Nickel partition coefficients of olivine-augite and olivine-enstatite.

Rock	Drill hole/depth	Ol^{Ni}	Aug^{Ni}	En^{Ni}	$K = Ol^{Ni}/Aug^{Ni}$	$K = Ol^{Ni}/En^{Ni}$
Peridotite	25/228.55	1 519	162	296	9.38	5.13
»	25/234.00	1 397	239	260	5.85	5.37
»	25/233.10	1 238	—	273	—	4.53
»	25/264.00	1 188	181	216	6.56	5.50
»	25/261.85	1 096	169	255	6.49	4.30
»	25/248.65	1 047	195	232	5.37	4.51
»	8/143.00	1 020	—	170	—	6.00
»	25/224.65	976	—	245	—	3.98
»	15/284.25	950	—	260	—	3.65
»	17/70.00	814	94	157	8.66	5.18
»	8/26.80	778	—	134	—	5.81
Olivine gabbro	15/310.40	1 344	—	283	—	4.75
»	15/300.50	1 200	164	277	7.32	4.33
»	15/294.80	1 092	—	286	—	3.82
»	15/272.00	1 078	—	239	—	4.51
»	25/274.00	985	158	208	6.23	4.73
»	25/284.00	943	151	228	6.24	4.14

Ni; the variation is also marked in olivine gabbros, from 943 to 1 344 ppm Ni.

The corresponding values for augite are 94 to 239 ppm Ni in peridotites and 151 to 164 ppm Ni in olivine gabbros. In peridotites enstatite contains 134 to 296 ppm Ni and in olivine gabbros 208 to 286 Ni.

The model crystallization temperatures for the intrusive given in Table 13 were calculated with the aid of the Ol^{Ni}/Aug^{Ni} and the equation $\ln K = -A/T + B$ given by Häkli (1968). The mineral pair olivine-augite shows a model temperature of 1 130° to 1 270°C and the mineral pair olivine-enstatite 1 075°C to 1 290°C.

The values obtained from Laukunkangas (Fig. 14) differ from those from the Parikkala intrusive (Häkli, 1968). Only two samples indicate model temperatures similar to those reported from Parikkala; the rest are markedly higher.

The model temperature data also suggest that there are at least three units with different crystallization temperature in the Laukunkangas intrusive. The highest temperatures, 1 270°C and 1 290°C, were obtained from the peridotite marked on the ground plan and which was intersected by drill hole EK/La-8 in profile K = 34.725.

Iin Fig. 15 the Laukunkangas data are compared with model temperature determinations reported by Häkli (1971) from some Finnish intrusives.

Fig. 13. The distribution of nickel and iron in amphiboles and orthopyroxenes on drilling profiles K = 34.650 and K = 43.700.

Conclusions

The contact relations, structures and metamorphic features of the Laukunkangas pluton show it to be a synorogenic Svecokarelidic intrusive. It contains plate-like portions that differ slightly in composition and were produced by emplacement that took place in two or three successive stages. Peridotites and olivine gabbros crystallized during the first emplacement stage and norites during the last. Emplacement was followed by alterations such as serpentinization of olivine and the replacement of orthopyroxene by colourless amphiboles. Perknites were obviously formed from pyroxenites as a result of the alteration processes. The alterations were

Table 13. Partition coefficients $K = Ol^{Ni}/Aug^{Ni}$, $K = Ol^{Ni}/En^{Ni}$ and the model crystallisation temperatures.

$K=Ol^{Ni}/Aug^{Ni}$	T	C°	$K=Ol^{Ni}/En^{Ni}$	T	C°
9.38	1544	1270	5.13	1487	1215
5.85	1424	1150	5.37	1508	1235
—			4.53	1434	1160
6.56	1451	1180	5.50	1519	1245
6.49	1449	1175	4.30	1412	1140
5.37	1404	1130	4.51	1431	1160
—			6.00	1560	1290
—			3.98	1382	1110
—			3.65	1350	1075
8.66	1522	1250	5.18	1491	1220
—			5.81	1544	1270
—			4.75	1453	1180
7.32	1479	1205	4.33	1415	1140
—			3.82	1366	1090
—			4.51	1432	1160
6.23	1439	1165	4.73	1452	1180
6.24	1439	1165	4.14	1399	1125

A=8643
B=7.836

A=4972
B=4.979

Equation $T = \frac{-A}{\ln K - B}$

probably associated with regional metamorphism, and the emplacement and crystallization of the intrusive took place before the culmination of metamorphism. Rapid changes in chemistry due to contamination are, however, sometimes visible in the contact zones between the layers. Thus, the transitional zone between the lower and intermediate layers contains material that derived from the wall-rock mica gneiss. Similarly the contact rock proper is a hybrid rock that was formed when the mafic magma assimilated components from the wall rock gneiss.

The ore mineralization at Laukunkangas is controlled by the following factors:

1) The ore mineralization is associated with the peridotites, olivine gabbros and ore norites of the first emplacement stage.

2) Ni-Cu sulphides occur close to the contact with the wall rock at the eastern end of the intrusive. The middle part of the body is only slightly mineralized. The bulk of the noritic intrusive is completely free from sulphides.

3) The silicates in the ore zone contain significantly more nickel than do the silicates elsewhere.

4) The ore mineralogy is simple: pyrrhotite, pentlandite and chalcopyrite. Replacement textures are rare.

Characteristics of the Laukunkangas intrusive are:

1) The distinct differentiation series from peridotites to quartz diorites. The rocks belong to the olivine tholeiitic series (Yoder and Tilley, 1962).

2) The internal layered structure, which manifests itself in the element contents, particularly in those of MgO, Sr, Ba and Zr as well as in silicate nickel and in the distribution of nickel in sulphide phase.

3) The graphite-bearing fragments, which were caught up from the wall rock by the intruding magma and which now occur as tonques in the intrusive. A nickeliferous sulphide mineralization differing distinctly from that in the wall-rock graphite rocks was generated in the fragments.

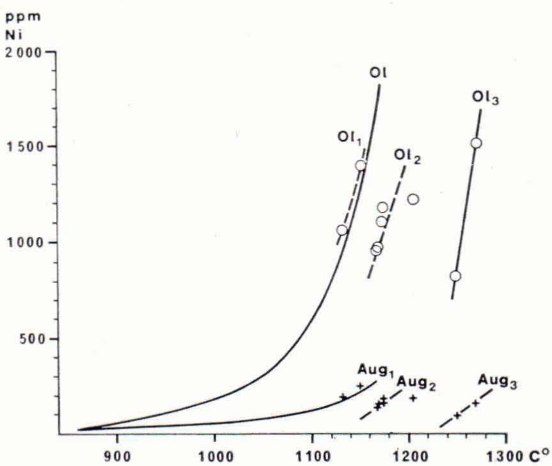


Fig. 14. The model crystallization temperatures at Laukunkangas calculated from the Ol^{Ni}/Aug^{Ni} ratio compared with the corresponding values in the Parikkala gabbro (Häkli, 1968). The circles refer to the Laukunkangas olivines and the crosses to the Laukunkangas augites.

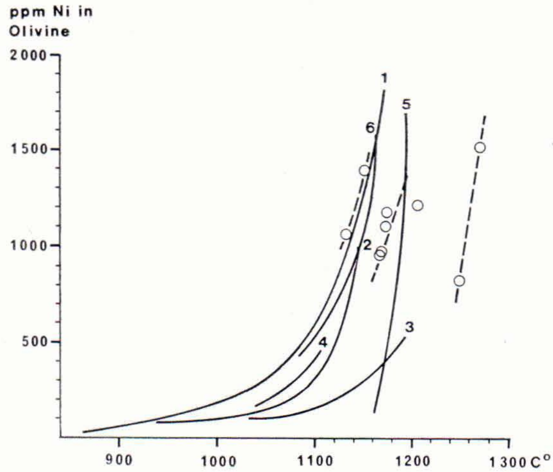


Fig. 15. The nickel content in olivine versus the model crystallization temperature calculated from the Ol^{Ni}/Aug^{Ni} ratio. Calculations based on the work by Häkli (1971) on the Finnish mafic intrusives: 1. Parikkala, 2. Joutsenmäki—Tolvaniemi I, 3. Joutsenmäki—Tolvaniemi II, 4. Kangasniemi, 5. Kevitsa and 6. Myhinkoski, Rautalampi. The circles refer to the Laukunkangas data.

4) The numerous silicic pegmatite dykes and mafic diabase dykes.

The host rocks in the Laukunkangas intrusive differ from those at Kotalahti and Hitura, the major Ni-Cu occurrences in the »Kotalahti nickel-copper ore zone». The Hitura occurrence is predominantly ultramafic and contains only small amounts of other differentiates; at Kotalahti the mineralization is also largely associated with ultramafics (Papunen, 1970). In many respects the Laukunkangas intrusive is similar to the Joutsenmäki massif (Parkkinen, 1971, 1975) and the Parikkala intrusive (Häkli, 1968):

1) The host rocks in the intrusives are generally rich in orthopyroxene.

2) The differentiation series prefer gabbroic rocks.

3) The indistinct layered structure is common.

4) The model crystallization temperature patterns are somewhat similar to those of the Parikkala intrusive, which, however, is slightly more homogeneous than the Laukunkangas intrusive.

On the basis of silicate nickel in mafic and ultramafic rocks, Häkli (1970, 1971) has demonstrated the existence in Finland of areas potential for the occurrence of Ni mineralizations. The most important of these is the »Nickel arch» around the Central Finland granite area (Papunen et al., 1979; Häkli et al. 1979). The application of silicate nickel to detailed studies of individual mafic or ultramafic intrusives has obvious advantages. With the aid of the Ni contents in silicates it has been possible to establish the trend of the differentiation in the Laukunkangas intrusive and to direct activities to locating ultramafic rocks, the potential host for nickel ores.

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