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GEOLOGICAL, GEOCHEMICAL AND MINERALOGICAL FEATURES OF SULFIDE-BEARING ULTRAMAFIC ROCKS IN FINLAND

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ABSTRACT

For purposes of exploration for sulfide nickel ores, mafic–ultramafic rocks in Finland have been tentatively classified into four age groups: Archean ultramafic rocks (older than 2.8 Ga); layered mafic intrusions (2.4 Ga); Karelidic ultramafic rocks (2.2 Ga) and Svecokarelidic intrusive rocks (1.9–1.85 Ga). By far the most important rocks economically are the Ni–Cu sulfide-bearing mafic to ultramafic intrusions in the Proterozoic Svecokarelidic migmatite belts in Central Finland. These favorable host rocks are characterized by elevated nickel abundances in mafic silicates such as olivine, pyroxenes and amphiboles, a feature that has been applied to discriminate them from unfavorable host rocks. Most of the host rocks of the economic Ni–Cu deposits are ultramafic bodies in which differentiation seems to be partly due to wallrock assimilation. The Karelidic serpentinites show the highest nickel contents in contact zones against quartz-bearing rocks and sulfide-rich metasedimentary black schists. In northern Finland layered basic intrusions have penetrated the contact of the Karelidic schists with the basement gneisses. Persistent but low-grade sulfide dissemination characterizes these intrusions. The Archean greenstone-belt association in eastern Finland includes ultrabasic complexes with some minor Ni–Cu sulfide occurrences. The ultramafic rocks of Lapland, which occur in an area that includes both Archean and Proterozoic formations, are either associated with metavolcanic rocks or related to structural features. Some of the ultramafic rocks are geochemically similar to komatiites, although metamorphism has commonly obliterated their volcanic textures. Replacement textures and the chemical composition of the spinel phase, like the texture of the silicate minerals, suggest metamorphic alterations. Certain belts of ultramafic rocks have been selected for follow-up exploration studies on account of their high sulfide abundances, and because their chromite contains Zn in abundances that may indicate sulfide deposits.

SOMMAIRE

Les roches mafiques et ultramafiques de Finlande sont provisoirement classées en quatre catégories chronologiques aux fins de la recherche des minerais de nickel sulfurés: (1) roches ultramafiques archéennes (> 2.8 Ga), (2) complexes intrusifs stratiformes mafiques (2.4 Ga) (3) roches ultramafiques karélidiques (2.2 Ga) et (4) roches intrusives svécokarélidiques (1.9–1.85 Ga). Les roches les plus importantes au point de vue économique sont les complexes mafiques à ultramafiques à sulfures de Ni et Cu qui recoupent les ceintures protérozoïques svécokarélidiques à migmatites de la Finlande centrale. Ces roches-hôtes favorables se caractérisent par la haute teneur en Ni de leurs olivines, pyroxènes et amphiboles, qui les distingue des roches stériles. Pour la plupart des gisements Ni–Cu, les roches ultramafiques hôtes montrent une différenciation attribuable en partie à l'assimilation des roches encaissantes. Les serpentinites karélidiques présentent la teneur en Ni la plus élevée au contact avec les roches quartzifères et les schistes noirs métasédimentaires riches en sulfures. En Finlande septentrionale, les complexes stratiformes basiques sont intrusifs au contact entre les schistes karélidiques et les gneiss du socle. Une dissémination des sulfures donnant un minerai pauvre en Ni est caractéristique de toutes ces intrusions. Dans les ceintures archéennes de roches vertes de l'Est, les complexes ultrabasiques offrent quelques indices locaux de minéralisation Ni–Cu. Les roches ultramafiques de Lapponie, d'une région de formations archéennes et protérozoïques, sont associées à des roches métavolcaniques ou en relation avec des éléments structuraux. Quelques-unes de ces roches ressemblent géochimiquement aux komatiites, quoique le métamorphisme ait souvent oblitéré les textures volcaniques de refroidissement brutal. Les textures de remplacement et la composition chimique des spinelles, tout comme la texture des silicates, indiquent des modifications métamorphiques. Certaines des ceintures ultramafiques ont été choisies comme sujets d'études plus approfondies, vu leurs hautes teneurs en sulfures et dans l'espoir que la concentration de Zn dans leurs chromites serait l'indicateur d'une minéralisation en sulfures.

(Traduit par la Rédaction)

INTRODUCTION

Since the early 1960s, comprehensive studies on the nickel ores and their host rocks have been conducted in Finland in an endeavor to clarify the factors that control the location of nickel deposits. Basic research on the topic was initiated by Outokumpu Oy and continued by the Universities of Turku and Oulu. The studies undertaken by Outokumpu Oy dealt with the sulfide/silicate equilibria in rocks, and the findings were applied to delineating and selecting areas and rock types favorable for the potential occurrence of nickel deposits (Häkli 1963, 1970, 1971, Gaál 1972). In 1972–1976 the University of Oulu made a study of layered intrusions in northern Finland (Koillismaa) with special emphasis on associated ore showings (Piirainen 1978, Piirainen *et al.* 1974). The University of Turku is presently engaged on research on ultramafic rocks in Lapland (Papunen *et al.* 1977). Intensified prospecting of ore showings, for example that performed by the Geological Survey of Finland, has markedly contributed to the information produced by special research projects.

Three nickel mines are currently in operation in Finland: Kotalahti, Vammala and Hitura. Six other nickel deposits, at Vuonos, Makola, Petolahti, Puumala, Telkkälä and Kylmäkoski, have also been submitted to mining activities (Fig. 1). This paper deals with the classification of the nickel deposits and showings in Finland as well as the latest findings on the geochemistry and mineralogy of favorable ultramafic host rocks.

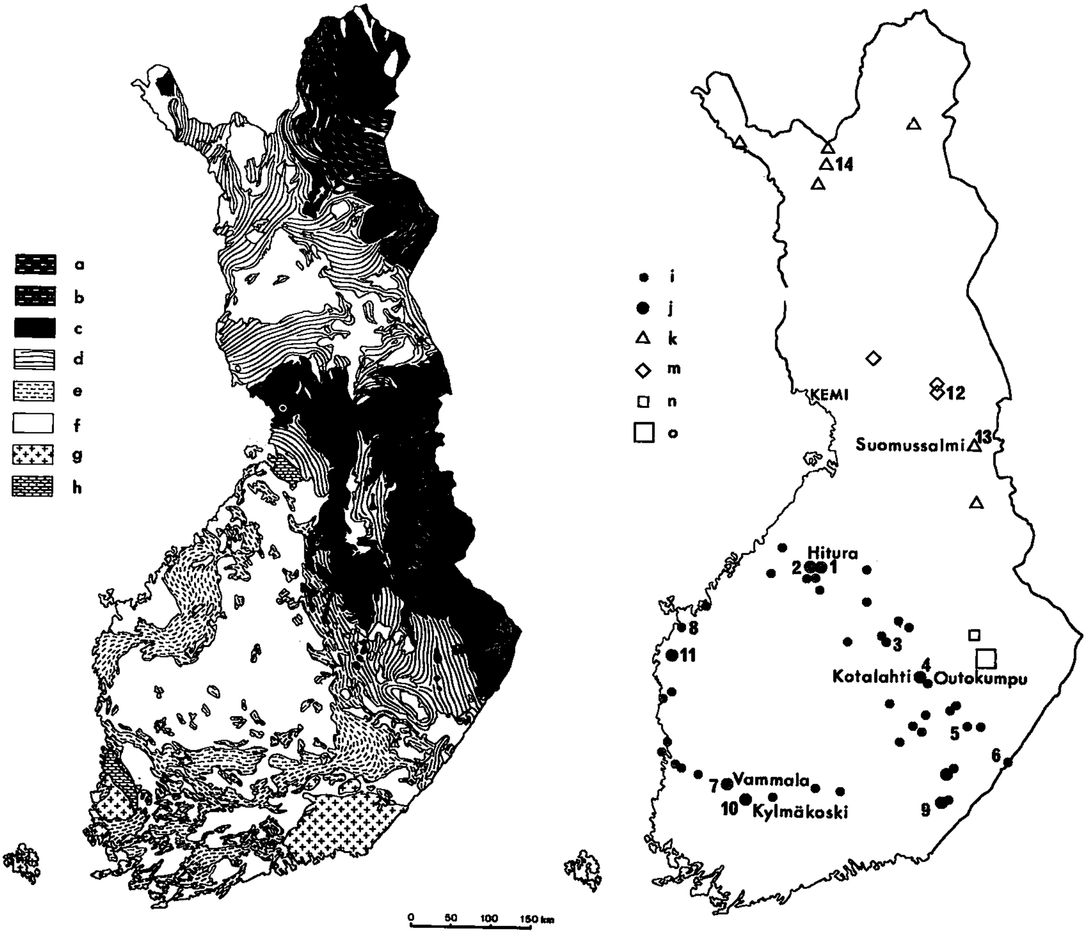


FIG. 1. Geological map and location of nickel deposits and mines in Finland. Numbers refer to the deposits in Fig. 8. Legend: a. schists of Archean greenstone-belt association; b. granulite belt; c. Archean basement; d. Karelidic schists; e. Svecofennian schists; f. Svecokarelidic granitoid rocks; g. rapakivi granites; h. sandstone (Jotnian). Nickel occurrences: i. nickel deposits in Svecokarelidic intrusions; j. nickel mines in Svecokarelidic intrusions; k. nickel deposits in Archean greenstone belts and Lapland; m. nickel occurrences in layered intrusions; n. nickel occurrence; and o. nickel mine in Karelidic serpentinite.

Areal Distribution and Classification of Nickel Deposits and Ultramafic Host Rocks

Based on the age and structure of Finnish bedrock, the map in Figure 1 illustrates the distribution of nickel deposits and showings. In Finland ultramafic and mafic rocks are associated with geologic units of the following ages: (1) Postorogenic diabase dykes ranging from 1.650 to 1.250 Ga in age occur here and there throughout the country, particularly in SW and W Finland. (2) Svecokarelidic intrusive rocks; pre- to syntectonic bodies with radiometric ages from 1.90 to 1.85 Ga (Kouvo 1976). (3) Serpentinites in the Karelidic schist belt, *e.g.*, in the Outokumpu area, with a tentative age of 2.2 Ga (Peltola 1978). (4) Layered intrusions, 2.45 Ga in age, in the border zone between Karelidic schists and their basement gneisses (Piirainen 1978). (5) Archean ultramafic bodies in greenstone belts and granitoid areas. Age exceeds 2.5 Ga.

Ultramafic and mafic rocks of groups 2–4 commonly exhibit signs of nickel mineralization; the most important deposits are those of group 2.

Svecokarelidic Intrusive Rocks

All the economically important nickel deposits in Finland are located in the southern half of the country in association with the plutonic suites of the Svecokarelidic orogenic cycle. The ultramafic to mafic host rocks are pre- to syntectonic intrusive bodies whose mineralogical and textural features indicate regional metamorphism. The distribution pattern of the Ni-bearing rocks exhibits a more or less circular structure that rims the granitoid area of Central Finland (Fig. 1). Gaál (1972) has proposed that the location of the major nickel deposits, Kotalahti and Hitura, and several minor deposits is controlled by a wide tectonic shear zone running in a NW–SE direction from Lake Ladoga to the Gulf of Bothnia, which he calls the "Kotalahti nickel belt". A linear negative gravity anomaly lies parallel to the southeastern part of the Kotalahti belt. Eckstrand (1976) has noted similarities between the Kotalahti

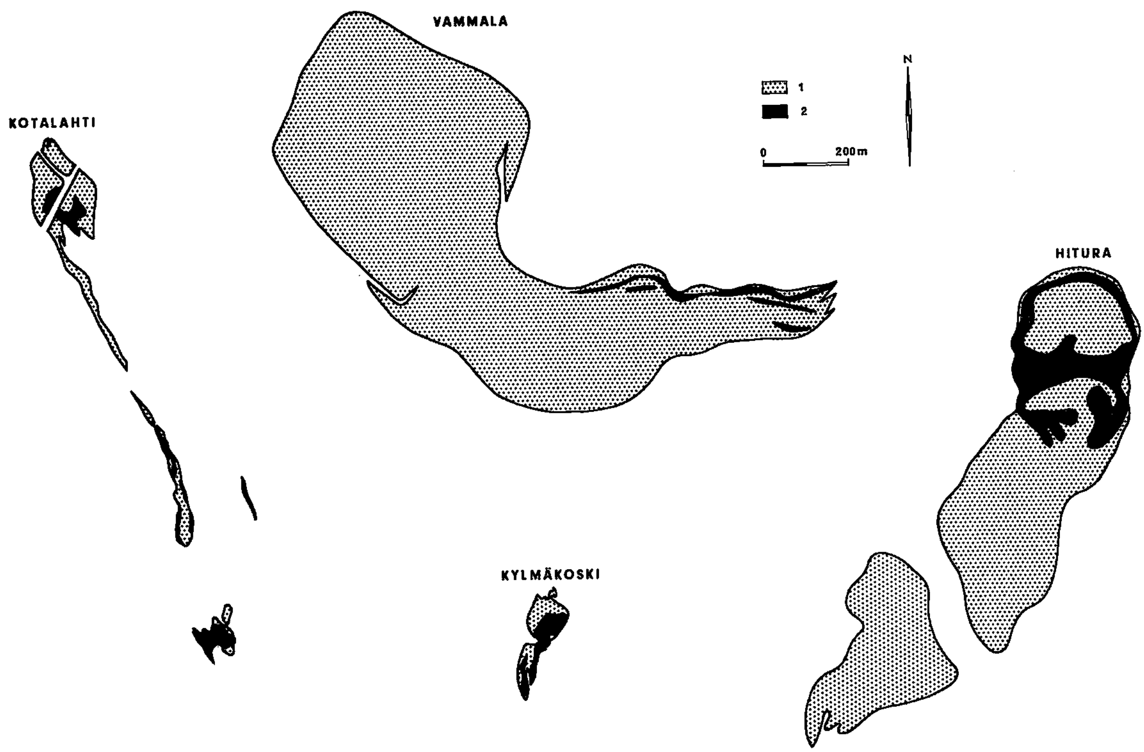


FIG. 2. Horizontal plans illustrating forms of the host intrusive bodies at Hitura, Kotalahti, Vammala and Kylmäkoski. 1 ultramafic rocks, 2 ore.

nickel belt and the Thompson belt in Canada.

The abundance of nickel in mafic and ultramafic rocks in this particular area had already been noted by Häkli (1970, 1971) in his reports on nickel distribution in intrusive rocks. In addition to the Kotalahti nickel belt, Häkli (1971) also pointed out another belt in southwestern Finland which also seemed to favor nickel-bearing intrusive complexes. The importance of the linear belts in exploration has come under criticism, for nickel deposits have been encountered outside the belts as well. The geological backround of the circular structure, so conspicuous on the distribution map of the deposits, still lacks a satisfactory explanation.

All the deposits and their ultramafic to mafic host rocks have some features in common; their petrological, geochemical and mineralogical characteristics are presented in the following brief review.

Geological environment and shape of the bodies

The ultramafic to mafic bodies are located in strongly metamorphosed migmatitic paragneisses. Primary volcanic or sedimentary structures are rarely preserved, and stratigraphy of the supracrustal formations can only occasionally be recognized (Gaál 1972, Papunen & Koskinen 1978). The intrusions exhibit diverse shapes, resembling plates, plugs or pipes, and their contacts conform to the banding of the enclosing migmatite (Fig. 2). Ultramafic rocks are also encountered as fragments in migmatite. It has been proposed that the ultramafic magma and the asociated nickel sulfides were emplaced conformably in the supracrustal rocks series. Because they were emplaced before the main peak of Svecokarelidic regional metamorphism, the rocks were folded together with the enclosing supracrustal rocks. According to Eckstrand (1976), the nickel belts probably represent long-lived crustal fracture zones.

Location of sulfides

The mode of occurrence of the sulfides varies: they may be encountered at vertical contacts, close to the basal contact of the host rock, in tectonic shear zones, or at the contacts of intersecting dykes. Structurally and texturally, the sulfides display all the types common in nickel–copper deposits: interstitial dissemination, round droplets, impregnation, brecciated bodies or massive sulfide veins (Papunen 1970). In differentiated bodies the sulfides favor the ultramafic member. Although the sulfides display textures that can be explained in terms of the magmatic segregation of sulfide melt with the contemporaneous crystallization of sulfides and silicates, the relationship of tectonic zones, contacts and dykes with the Ni–Cu sulfides indicates that the latter have undergone metamorphic redistribution and mobilization.

Host intrusive rocks

The ore deposits are hosted either by slightly differentiated ultramafic rocks, such as at Hitura

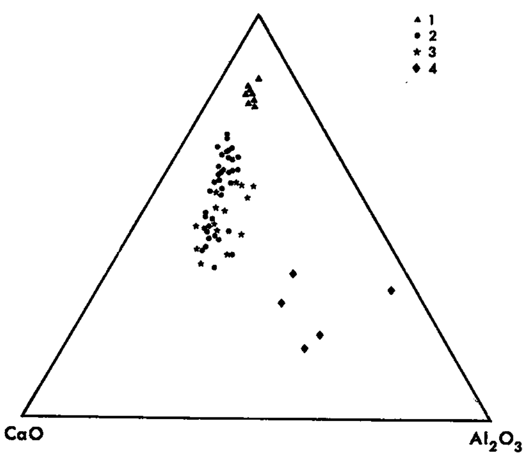


FIG. 3 AFM diagram showing the average composition of different rock types at Hitura (serpentinites and peridotites), Kotalahti (peridotites, pyroxenites, perknites, ophitic gabbros = G and diorites = D) and Kylmäkoski (peridotites, pyroxenites, hornblendites, gabbros). Data in this and following diagrams from Papunen (1970) and the Exploration Dep., Outokumpu Oy.

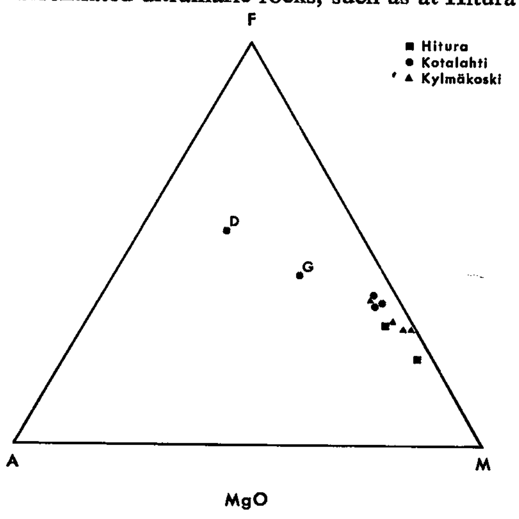


FIG. 4. MgO–CaO–Al_2O_3 diagram showing the compositions of rock types at Kylmäkoski: 1 peridotites; 2 pyroxenites; 3 hornblendites; 4 gabbros.

and Vammala (Papunen 1970) or by differentiated sequences ranging from peridotite to gabbro. The geochemistry of the host intrusive rock series at Hitura, Kotalahti and Kylmäkoski is depicted in an AFM diagram (Fig. 3). According to this diagram the differences between the rock types are quite small. However, the MgO–CaO–Al_2O_3 proportions (Fig. 4) demonstrate that the rock types, *e.g.* those in the Kylmäkoski body, differ markedly from each other. The peridotites form a coherent group, but the pyroxenites, hornblendites and gabbros vary conspicuously in composition. The same feature is apparent in Kotalahti, as shown by the MgO–Al_2O_3–alkalis diagram (Fig. 5). A brief description of the distribution of the rock types in the Kotalahti body will explain the variation.

The Kotalahti ultramafic body is shaped like a plate with a pipe-like form at its southern end (Haapala 1969, Papunen 1970, Papunen & Koskinen 1978). The plate-like body bulges at its deepest part. The shape and distribution of the rock types are depicted in a block diagram (Fig. 6). Peridotite, pyroxenite and perknite (a hornblende-rich pyroxenite with the ratio of hornblende to pyroxenes about 1:1) as well as poikilitic gabbro prevail in the plate-shaped part, whereas an ophitic hornblende gabbro and diorite occur in the lowest part of the body. The upper part is intersected by fine-grained basic (gabbroic) and dioritic as well as trondhjemitic and granitic dykes.

The MgO–Al_2O_3–alk diagram indicates a gap in the differentiation series between ophitic and poikilitic gabbros in spite of the fact that the samples analyzed represent all the rock types reported from the body. It is likely that thermal effects have caused the trondhjemitic neosome of the wall-rock migmatites to mix with the ultramafic magma resulting in the formation of diorite and ophitic gabbro in the lowest part of the body. This mixed magma has also cut the ultramafic plate at its upper levels as gabbro, diorite and trondhjemite dykes. Assimilation is well indicated by the MgO–Al_2O_3–(Na_2O+K_2O) diagram (Fig. 5), but is not that clear in the AFM diagram owing to the fact that Mg/Fe ratio was not markedly changed with the small addition of trondhjemitic wall-rock neosome to the ultramafic magma.

At Kotalahti, sulfides occur only in the ultrabasic to poikilitic gabbro series, whereas the ophitic gabbro–diorite–trondhjemite series is almost devoid of sulfides. The Ni content in hornblende is 4 to 5 times higher in the poikilitic and olivine gabbros than it is in the ophitic gabbro.

The small ultramafic body of Kylmäkoski is also contaminated by wall rocks as shown by the variation in composition of pyroxenites,

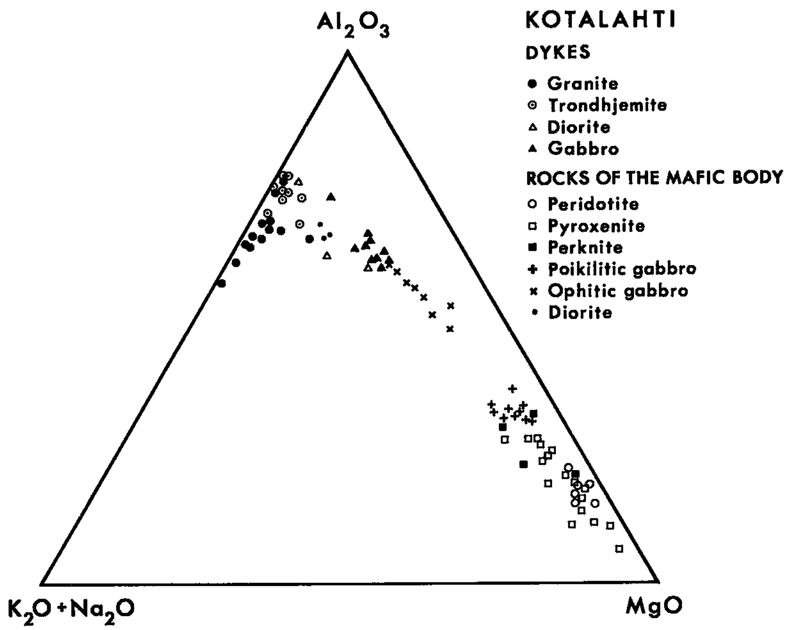


FIG. 5. (Na_2O+K_2O)–Al_2O_3–MgO plot of compositions or rock types in the Kotalahti intrusion.

hornblendites and gabbros in the MgO–CaO–Al_2O_3 diagram (Fig. 4). The distribution of TiO_2 and Cr *versus* MgO is depicted in Figure 7. A moderate negative correlation between Cr and MgO is apparent, whereas the relationship between TiO_2 and MgO is not well defined. In these cases, the contamination by wall-rock material has only slightly affected the ratio MgO/FeO. In contrast, the ratios MgO/CaO, MgO/Al_2O_3 and MgO/NaO + K_2O vary according to the degree of mixing.

Some of the ultramafic bodies exhibit compositional layering. This is the case in the Laukunkangas and Vammala deposits, where layers differing somewhat in composition rest one on top of the other. They range in thickness from a score or so to one hundred metres. The sulfides are invariably associated with the most mafic member of the layers. The cryptic variation in mineral composition within one and the same layer is under investigation. The structure is suggestive of cyclically repetitive magma intrusions.

The ultramafic-mafic bodies are brecciated and cut by dykes and veins of syn- to late kinematic granites. In some of the bodies, *e.g.*, at Kylmäkoski and Telkkälä (*cf.*, Häkli *et al.* 1975), the granite has partly obliterated the ultramafic body so that only a minor, non-representative portion is left.

Geochemistry of the sulfide phase

The nickel content in the sulfide phase varies with the host rock types, *e.g.*, from 0.5 to 20% with the median at 5% in ultramafic rocks. The corresponding figures for gabbros are 0.1–10% and 0.8%. In the economic and subeconomic nickel deposits, however, the variation is smaller and often within the range of 4–12% Ni. The average Ni–Co–Cu ratios of "normal" low-grade sulfide disseminations show a tendency to a higher relative Co tenors than do those of the ore deposits proper (Fig. 8). The Ni:Cu ratios generally range from 1 to 4, but in the economic ores from 1 to 2.

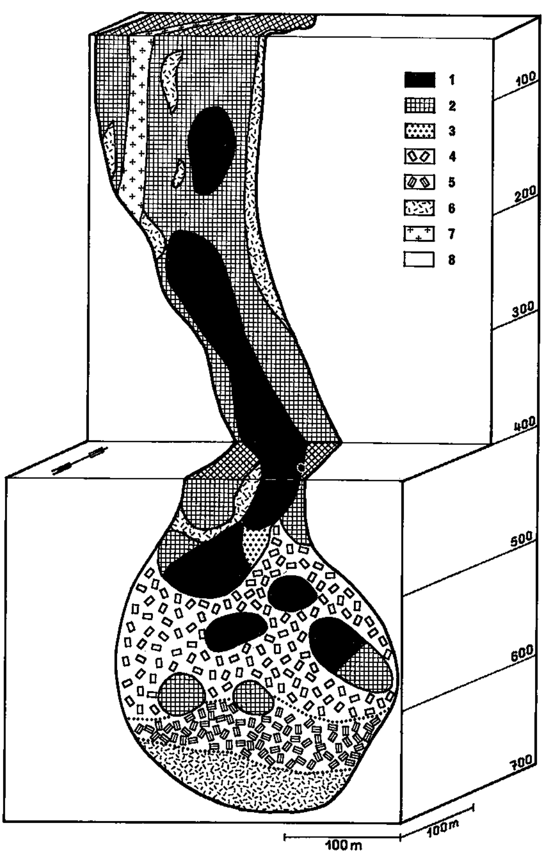


FIG. 6. Schematic block diagram of the northern part of the Kotalahti body. Rock types: 1 peridotite; 2 pyroxenite and perknite; 3 olivine gabbro; 4 poikilitic gabbro; 5 ophitic gabbro; 6 diorite; 7 granite; 8 mica gneiss and migmatite.

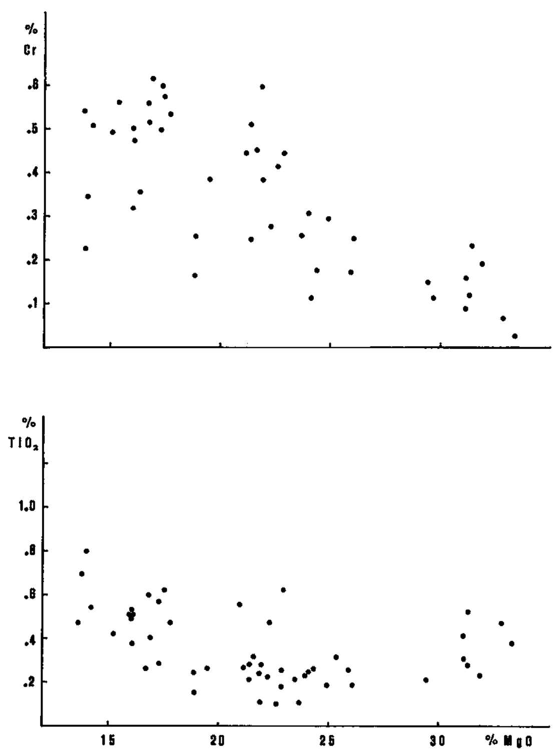


FIG. 7. TiO_2 *vs.* MgO and Cr *vs.* MgO plot of rock types of Kylmäkoski intrusion.

The distribution of platinum-group elements in the Hitura deposit is controlled by metamorphic processes as shown by Häkli *et al.* (1976). In the exhausted Kylmäkoski orebody platinum–palladium minerals occurred together with nickel arsenides in shear zones related to intersecting granodiorite dykes. At Kotalahti, PGE abundances are low, Ni concentrate assaying 0.015 ppm Pt, 0.05 ppm Pd and 0.005 ppm Rh. PGE minerals have not been detected in the orebody.

Silicate nickel and its significance

The zones in which ultramafic rocks exhibit sufficiently high nickel abundances in the sulfide phase to be potential hosts for nickel ores also contain barren ultramafic rocks that are genetically related to large syntectonic granodioritic bodies; in the barren type, the sulfide phase is depleted in nickel. In the field these rocks cannot always be distinguished from the favorable ultramafic bodies. By analyzing the nickel *versus* iron content of the silicates, however, the two rock types can be readily distinguished. Experimental studies on partitioning of nickel between coexisting silicates and sulfides (*e.g.*, Clark & Naldrett 1972, Rajamani & Naldrett 1978) indicate that the distribution coefficients depend on the temperature and composition of the silicate phase.

On the basis of the fairly extensive analytical data on Finnish rocks, Häkli (1970, 1971) has demonstrated that nickel is commonly equilibrated between coexisting silicate and sulfide phases. He has shown that the Ni content of olivine is lower adjacent to the sulfide accumulations than in those parts of the host that lack sulfides, presumably because of subsolidus reactions between sulfides and silicates. The depletion of silicates in nickel with respect to the silicates with the same Mg content elsewhere in the rock may thus indicate the occurrence of sulfides in the environment. Subsolidus reactions between silicates and sulfides have also played an important role in the metamorphic remobilization of nickel. In Central Finland silicate-nickel data have been used as a guide to delineate potential areas and intrusives for nickel exploration (Häkli 1971).

Sulfur isotopes

Sulfur isotopes have been studied from the Hitura, Kotalahti and Kylmäkoski deposits (Papunen & Mäkelä, in prep.). As a rule the sulfur isotope ratios are homogeneous, showing $\delta^{34}S$ values close to zero. They rarely deviate, and then only because of intense assimilation of wall-rock sulfides or the presence of secondary sulfides. Thus, in the low-grade pentlandite–mackinawite dissemination in the core of the Hitura body, the $\delta^{34}S$ values are about +2.5‰, deviating slightly from those in the massive orebodies close to the contacts of the ultramafic plug, where $\delta^{34}S$ is about 1.5–2‰ (Fig. 9). The wall-rock gneiss contains disseminated iron sulfide that is very low in nickel. Close to the contact, however, the nickel content gradually increases for a distance of about 10 m owing to the nickel sulfides that seem to have emanated from the massive orebody to the wall-rock gneisses. The average $\delta^{34}S$ value of the wall-rock sulfides is about +5‰. This differs

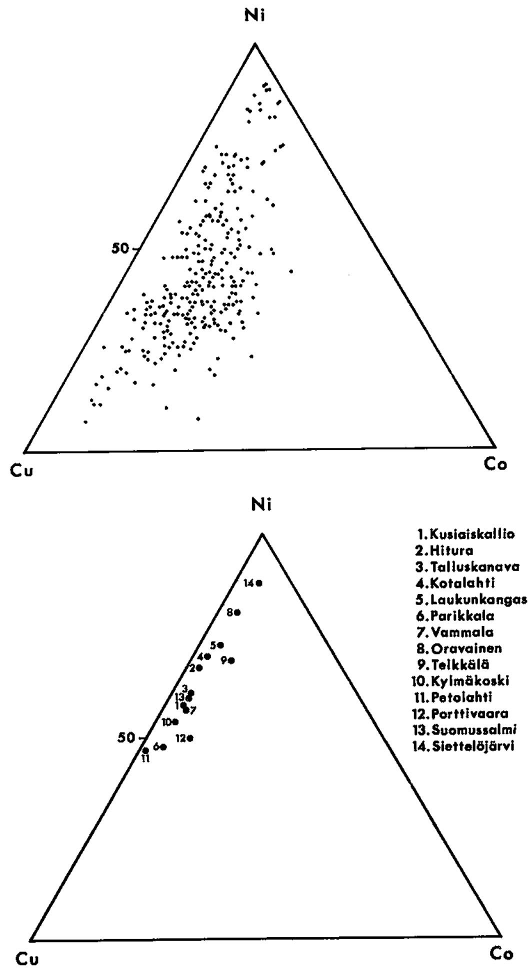


FIG. 8. Cu–Ni–Co diagrams showing the average contents of sulfide phases in 284 weakly mineralized basic to ultrabasic bodies in Finland (upper diagram), and those of the economic and subeconomic deposits. Numbers and localities as in Fig. 1.

markedly from values in the ultramafic body and indicates a different origin for the sulfides. Close to the contacts of the ultramafic body in the wall-rock, the $\delta^{34}S$ values grade from +3.5 to 5‰ owing to the mixing of sulfides which is also reflected in the nickel content of the sulfide phase.

The mixing of sulfides is also evident at Kylmäkoski, where the sulfides of the ultramafic body generally show uniform $\delta^{34}S$ values from −1.57 to +1.30‰, the average of 30 analyses being −0.20‰. Within a small area, however, the rock contains abundant graphite, plagioclase and hydrous silicate minerals. The $\delta^{34}S$ values of two samples, *i.e.*, −4.19 and −11.08‰, suggest that the anomalous graphite-bearing part of the mafic body was formed by wall-rock contamination. The sulfur isotopes of the Kotalahti deposit (42 analyses) also show uniform $\delta^{34}S$ values that average +2.08 and range from +1.40 to 2.80‰.

Karelidic Serpentinites

Long narrow belts of serpentinites characterize the schist area in North Karelia. The schists are metasedimentary in origin and their primary structures are locally well preserved. The serpentinites of the Outokumpu type are generally enveloped by a sequence of rocks that, from the serpentinite core outward, includes carbonate rock, tremolite/diopside skarn, quartzite and graphite schist, which is the outer member in contact with the mica gneiss (Gaál *et al.* 1975, Huhma 1976, Peltola 1978). The sequence is not always complete and occasionally some members are lacking. Various opinions have been expressed as to the origin of the rock complex; earlier the enveloping sequence was interpreted as sedimentary. Trace-element distribution, especially the high content of Ni and Cr in the quartzites, skarns and carbonate rocks, relate them genetically to serpentinites. The base-metal geochemistry of the Outokumpu complex has been studied by Huhma & Huhma (1970); more recently, the geology of the ore deposits has been reviewed by Peltola (1978).

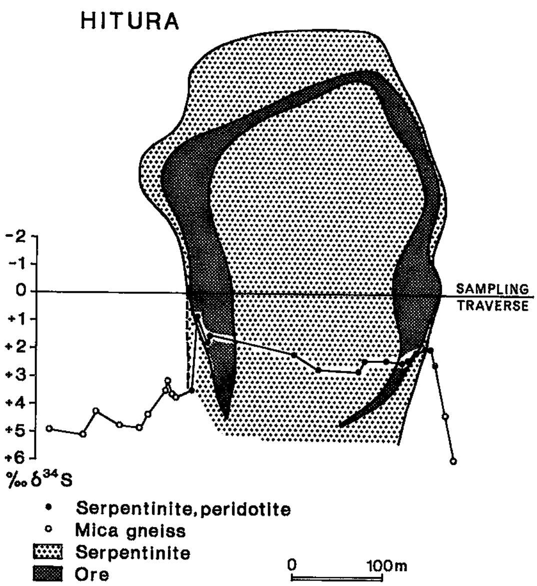


FIG. 9. Variation in sulfur isotope composition of the Hitura body.

Two types of ores occur in the serpentinite-quartzite association, *i.e.*, massive Cu–Co–Zn ores and nickel ores. Cu–Co–Zn ores of the Outokumpu type generally display low values of nickel and differ genetically from nickel sulfide disseminations that have been mined for nickel at Vuonos. At Kokka, about 50 km NE of Outokumpu, a Karelidic serpentinite body is in contact with a sulfide-rich black schist; a skarn is found in between. The nickel content of the black schist is about 300 ppm; it increases abruptly at the contact of the skarn and reaches the maximum value of about 0.5% in the skarn. In serpentinite the nickel content drops to a constant value of about 1500 ppm. According to Huhma & Huhma (1970), the nickel sulfides in skarn are due to the reaction between Ni-bearing serpentine and sulfide-rich black schist. Close to the Ni skarn the prevailing sulfide in black schist is pyrrhotite; away from the skarn it is pyrite. Huhma & Huhma (1970) concluded that the pyrite–pyrrhotite transformation liberated sulfur that formed nickel sulfides in the skarn.

There are no direct age determinations for Outokumpu-type and other Karelidic serpentinites; early Karelidic volcanism has, however, been dated at 2.15–2.20 Ga (Sakko 1971). Some students correlate the serpentinites with basic volcanism, which would imply that their age is about 2.2 Ga. The lead model age of galena from the Outokumpu Cu–Co–Zn ore, calculated according to revised decay constants, is about the same as that of Karelidic volcanism, *i.e.*, 2.2 Ga (Peltola 1978).

Layered Intrusions

In northern Finland, several layered basic intrusions occur in the contact zone of Karelidic schists and basement (Piirainen *et al.* 1974). The best documented of these is the Porttivaara intrusion. In the western extremity of the zone, in Kemi, a chromite deposit occurs close to the lower contact of a layered body, and at Mustavaara, there is a vanadium-bearing ilmenomagnetite deposit (Juopperi 1977) in the magnetite–gabbro horizon of the Porttivaara intrusion. According to Piirainen *et al.* (1977), the magma, tholeiitic in composition, intruded between the basement complex and the overlying sediments and formed a layered complex that was later split into blocks by tectonic movements. Border zones separate the complex from the overlying schists and from the underlying Archean granite gneiss. The lower marginal border group is composed of albite–quartz rock, a remobilized oligoclase gneiss in origin, contact gabbro and an ultramafic rock which is either metaperidotite or metapyroxenite. From the bottom upward the layered series is subdivided into the following units: olivine norite, gabbro norite I, gabbro, gabbro norite II, olivine gabbro norite, gabbro norite III, anorthositic gabbro, magnetite gabbro, anorthositic gabbro II.

The marginal border group is characterized by sulfide dissemination in and above the contact gabbro. The main sulfide minerals are chalcopyrite, pyrrhotite and pentlandite. The analyses in Table 1 illustrate the compositions (Piirainen *et al.* 1977).

Another sulfide-bearing horizon has been encountered in the layered series proper. Disseminated sulfides occur in pyroxene gabbro enriched in hydrous minerals owing to alteration processes. The sulfide dissemination is controlled not only by the alteration, but also by a fine-grained basic dyke rock. The main ore minerals are chalcopyrite, local bornite, pentlandite and rare pyrrhotite.

The layered gabbro complex has been dated to 2.45 Ga (Kouvo 1976). A layered intrusion of the Koillismaa type and age has been found at Koitilainen in Central Lapland, and has been dated to 2.45 Ga (Kouvo 1976).

Archean Rocks and Deposits

General

The Archean nucleus of the Baltic Shield is located in the Kola peninsula and in eastern Karelia, although it is also exposed in eastern Finland and Lapland (Fig. 1). This "Presvecokarelian basement" is composed mainly of granitoid rocks but also contains members of a typical greenstone-belt association. The classification of the Lappish formations is a subject of discussion that is rendered particularly difficult by the lack of data on the Central Lapland greenstones. Gaál *et al.* (1978) consider that most of the schists in Central Lapland are rocks of the Archean greenstone-belt association, whereas recent field data suggest that the volcanic units are related to the Karelidic cycle (J. Paakkola, oral comm. 1978).

TABLE 1. CHEMICAL COMPOSITIONS OF THE SULFIDES AT PORTTIVAARA AND SUOMUSSALMI (WT. %)

	Cu	Ni	Co	Fe	S	Cu/Cu+Ni	Pt/Pt+Pd
Porttivaara, top	0.10	0.04			0.10	0.71	
- " -	0.28	0.18			0.35	0.61	
- " -	0.27	0.08			0.15	0.77	
- " - near base	0.41	0.30			0.96	0.58	
Suomussalmi, Hietaharju	0.43	0.83	0.05	18.2	8.5	0.33	0.283
Suomussalmi, Peura-aho	0.24	0.55	0.04	25.0	15.5	0.31	0.254

Kuhmo–Suomussalmi schist belt

The Kuhmo–Suomussalmi schist belt and the Ilomantsi schists in eastern Finland represent an Archean greenstone-belt association (Gaál *et al.* 1978). According to Jahn *et al.* (1979), the Kuhmo–Suomussalmi belt can be divided lithostratigraphically into a lower and upper volcanic sequence. The lower one is composed of komatiitic and tholeiitic volcanic rocks and the upper one of andesitic tuffs, dacite–rhyodacite lavas and basalts of alkaline affinity.

The Ni deposits in Suomussalmi are associated with a strongly tectonized rock complex of serpentinites, talc–magnesite rocks and acid volcanic units. The sulfides are either disseminated in serpentinite or occur as concentrated breccia orebodies in tectonized talc–magnesite rocks and chlorite–amphibole rocks. Tectonic features evidently control the location of breccia and massive ores. Pyrrhotite, pentlandite and chalcopyrite are the main ore minerals, although the orebodies in the chlorite–amphibole host rocks also contain arsenides, mainly gersdorffite and löllingite and some sperrylite. The figures in Table 1 give the average composition of the deposits. Copper is slightly concentrated in breccia ores, and PGE follows Cu.

According to K. Kojonen (pers. comm., 1978), the major components of the ultramafic host rocks are similar to those in the tholeiitic rock series. TiO_2, however, is quite low and Ni high as in the komatiitic rock types de-

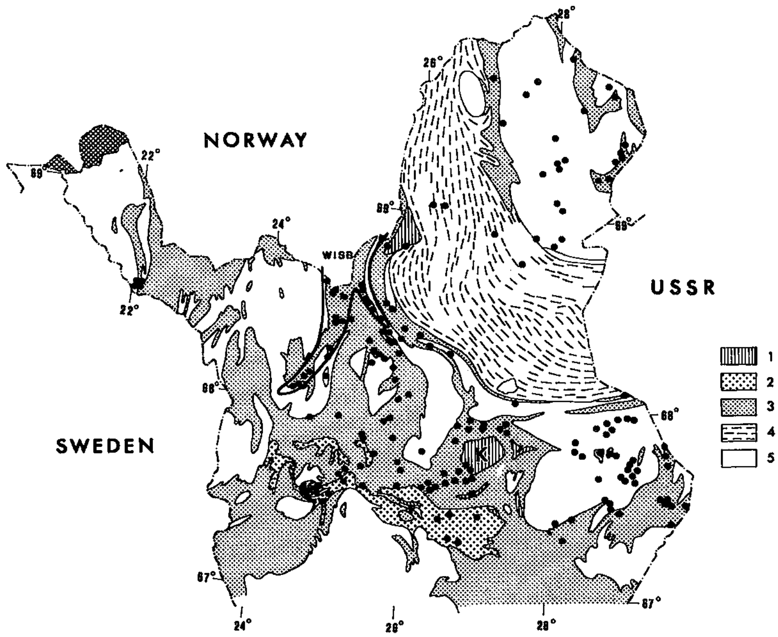


FIG. 10. Map of Lapland showing distribution of ultramafic bodies (dots) studied by Papunen *et al.* (1977). K = Koitilainen gabbro body. Legend: 1 gabbroic to anorthositic intrusions; 2 Karelidic metasedimentary rocks, 3 schist areas (metavolcanic and metasedimentary rocks); 4 granulite-belt; 5 granitoid rocks (Paleozoic schist cross-hatched); WISB = West Inari Schist Belt.

scribed from other localities of the Kuhmo-Suomussalmi belt by Jahn *et al.* (1979).

Lapland

There are hundreds of ultrabasic bodies in Lapland in addition to the large gabbro body of Koitilainen, which is contemporaneous with the 2.45 Ga layered intrusions (Fig. 10). Häkli (1971) has pointed out the high tenor of silicate nickel and the low content of sulfides in some of them. Direct indications of sulfide nickel occurrences are scarce throughout Lapland.

The boundaries between the Lappish Archean and Proterozoic formations are the subject of some controversy. Hence, the ultramafic rocks have been classified on the basis of their geological environment as follows (Papunen *et al.* 1977). (1) Utramafic rocks in a granitoid or metasedimentary schist environment: The location of the rocks is controlled by a fracture zone or lineament recognizable in aerial photographs. This type prevails in the Archean granitoid area in northern Lapland, eastern Lapland and in the area occupied by Karelidic metasedimentary rocks in Central Lapland. Peridotites and pyroxenites predominate, and some of the bodies show differentiation from peridotite to gabbro. (2) Ultramafic rocks in the metavolcanic suites of the Central Lapland greenstone area: They are enclosed by basic to intermediate lavas or pyroclastic rocks. In a few localities the ultramafic rocks exhibit volcanic structures, agglomerates, breccias and pillows. In composition the rocks are peridotites or pyroxenites, although in the eastern part of the Kittilä greenstone area serpentinites and dunites are also encountered (Paakkola 1971). (3) Ultramafic rocks in long belts in amphibolites: This group may be related to group 2 although intense regional metamorphism has destroyed the primary structures to such an extent that the origin of the enclosing rock complex cannot be established with certainty. Produced by metamorphism, the prevailing minerals in the ultramafic rocks are metamorphic olivine, pyroxenes and amphiboles as well as chlorite and serpentine. In some places, porphyroblasts of olivine occur as large (up to 5 cm) platy crystal similar to those described as metamorphic olivines by Evans & Trommsdorf (1974). A rock type called carbonate orthopyroxenite resembles the sagvandites described from Norway by Schreyer *et al.* (1972)

and Ohnmacht (1974). (4) Ultramafic bodies in the outer contact zone of the granulite arch in central and northern Lapland: The rock, cortlandite, characterized by a high abundance of green spinel, evidently attained its mineral composition in granulite-facies metamorphism. The location of the ultramafic rocks seems to be controlled by an overthrust surface.

Indications of Ni Sulfides

As noted above, direct indications of sulfides are rare in mafic and ultramafic rocks. Some heterogeneous gabbros close to the northern margin of the granulite belt at Inari contain Ni-Cu sulfides (Vallenkari deposit, Papunen *et al.* 1977). Similarly, the Tsohkkoaivi gabbro in the western part of Enontekiö commune has sulfide dissemination in its basal contact. The sulfides are copper-rich and the ratio Cu/Cu+Ni varies from 0.66 to 0.84. The serpentinite-dunite body of Nuttio (Papunen *et al.* 1977) in the volcanic-rock area of central Lapland shows a low-grade Ni-rich sulfide dissemination comparable in sulfide mineralogy to the Dumont type of deposit described by Eckstrand (1975).

On the basis of field and analytical data, the West Inari Schist Belt (=WISB) was chosen for further study (Fig. 10). Meriläinen (1976) regards WISB as an Archean formation on account of an albite diabase, 2.72 Ga old, that intersects the same belt at Karasjok, Norway. Small bodies of serpentinite, peridotite and carbonate orthopyroxenite are closely associated with long belts of amphibolites. Locally, the amphibolites grade into hornblendites or cortlandites. The belt also contains clastic and cherty quartzites, skarn rocks, mica gneisses and graphite-rich schists. Graphite schists, skarns and some thin beds of cherty quartzites are closely associated with the ultramafic bodies. The whole belt has undergone metamorphism that has almost completely obliterated the primary structures and textures. Rare agglomeratic structures, however, indicate that some of the amphibolites are of volcanic origin. If the belt is Archean in origin, the Svecokarelian orogeny and metamorphism may have left their imprint on it.

The MgO–Al_2O_3–CaO diagram (Fig. 11) depicts the variation in chemical composition of the ultramafic rocks, cortlandites and amphibolites. As shown by this diagram, the basic to ultrabasic rocks of the WISB are similar to komatiitic rock types of other Archean shield areas (*e.g.*, Arndt *et al.* 1977). The TiO_2 *vs.*

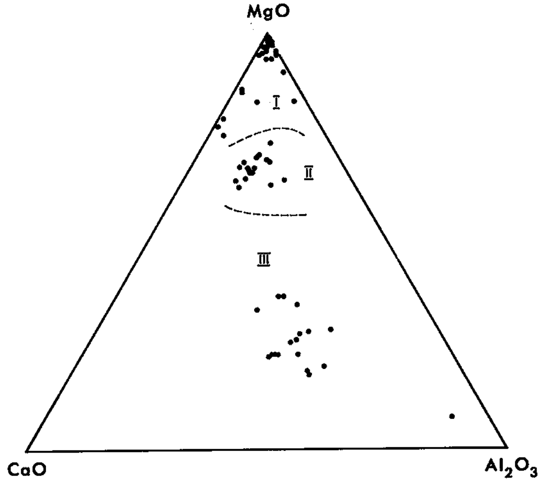


FIG. 11. MgO–CaO–Al_2O_3 diagram showing compositions of WISB serpentinites and metaperidotites (I), cortlandites (II) and amphibolites (III).

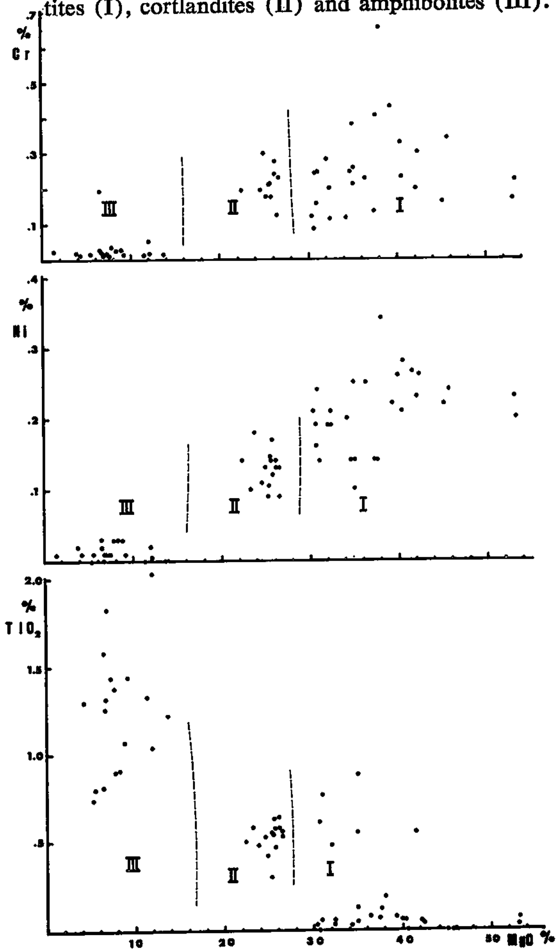


FIG. 12. MgO *vs.* TiO_2, Ni and Cr for WISB serpentinites and metaperidotites (I), cortlandites (II) and amphibolites (III).

MgO, Ni *vs.* MgO, Cr *vs.* MgO and Al_2O_3 *vs.* FeO/FeO+MgO diagrams support this view (Figs. 12, 13).

Geochemically related rock types exist in the granitoid area of eastern Lapland. There is, however, a conspicuous and significant difference: the average tenor of sulfides is higher in the ultramafic rocks of WISB. In these rocks it commonly exceeds 1%, whereas for the whole of Lapland the figure is 0.3% and for eastern Lapland 500 ppm. In WISB the sulfur content varies from one body to another. The carbonate orthopyroxenites especially seem to be depleted in sulfides; these are replaced by arsenides whose occurrence seems to be related to the carbonatization process.

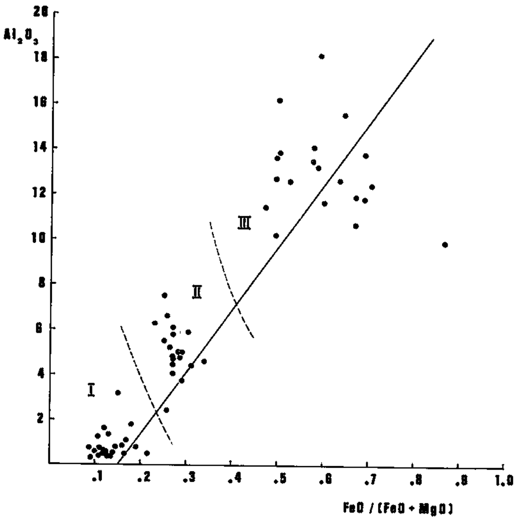


FIG. 13. Al_2O_3 *vs.* FeO/FeO+MgO plot of compositions of the WISB mateperiodites and serpentinites (I), cortlandites (II) and amphibolites (III).

The silicate mineralogy and textures of WISB ultramafic suite display metamorphic features. Typical igneous cumulus textures are lacking, and olivine occurs as large poikiloblastic grains that contain inclusions of amphiboles, orthopyroxene and chrome spinel.

A section of the weakly mineralized serpentinite body of Siettelöjoki (Papunen *et al.* 1977) was intersected by drill holes and chosen for detailed analysis. The section is depicted in Figure 14, together with the variations in MgO, Ni, S and $\delta^{34}S$ and Ni content in the sulfide phase (calculated on the basis of 38% S in sulfide fraction). The ultramafic beds separated by thin amphibolite or graphite-sulfide schist intercalations differ in MgO content.

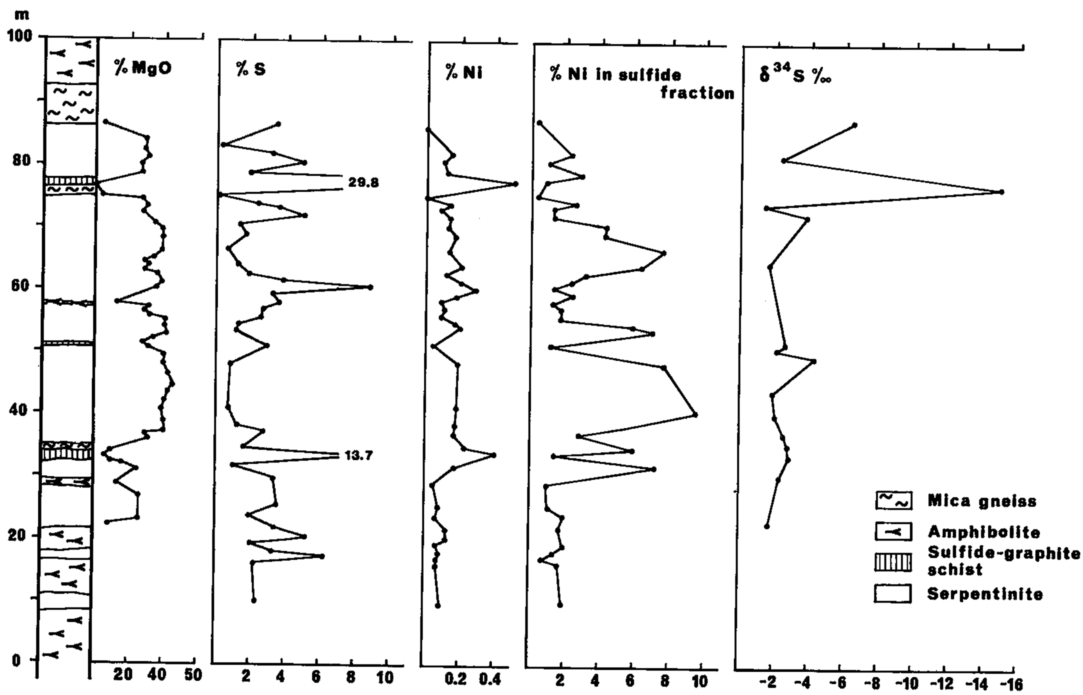
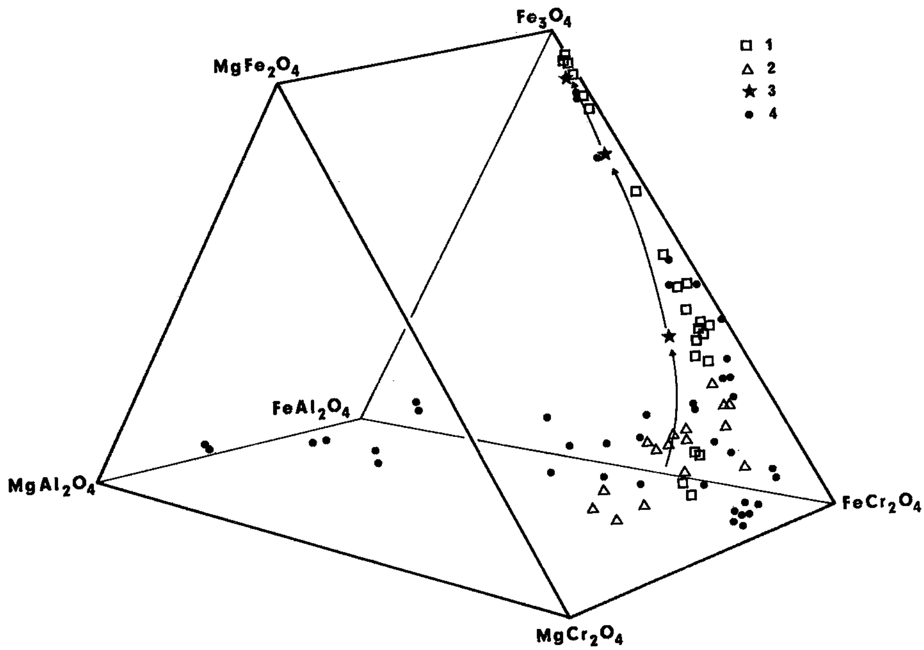
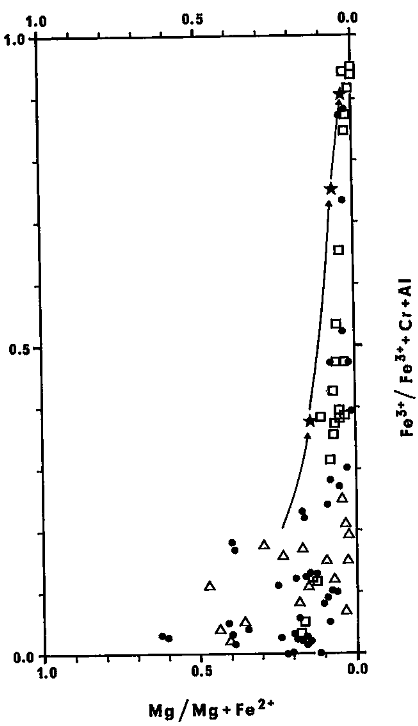


FIG. 14. A section of a serpentinite body at Siettelöjoki depicting variation in rock types, MgO (calculated on dry weight basis), Ni, S, $\delta^{34}S$ and the nickel percentage in sulfide phase.





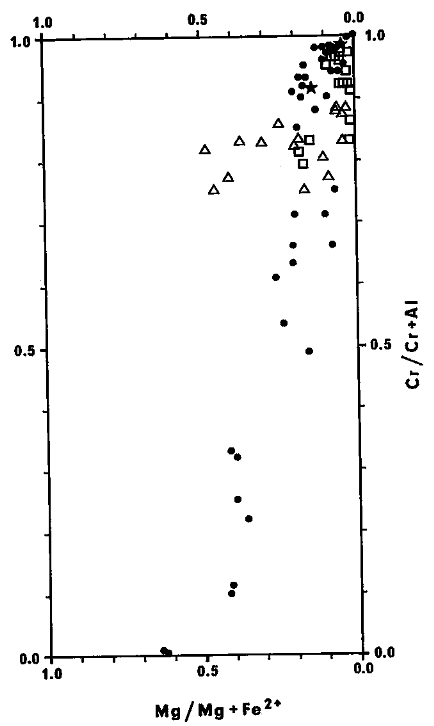


FIG. 15. A chromite prism (Haggerty 1976), and projections on rectangular faces of the prism showing compositions of analyzed chrome spinels. Symbols: 1 chromites from ultramafites in an Archean granitoid area, eastern Lapland; 2 chromites from ultramafic rocks in an area of the central Lapland metavolcanic belt; 3 trend indicating zoning of chrome spinels under greenschist-facies conditions; 4 chromites from WISB.

The sulfides favor graphite-bearing schist intercalations in which the main sulfide mineral is pyrrhotite. The nickel content in the sulfide fraction reaches 9%, being highest in the dissemination in serpentinite whereas in sulfide schists it is only about 1%. The Ni content in the disseminated serpentinite is generally below 0.3%. Copper is always very low and does not exceed 300 ppm. The Ni/Cu ratio is about 10. The $\delta^{34}S$ value of serpentinite varies between −1.8 and −4.2‰. In the graphite–sulfide schist close to the hanging-wall contact of the body it is, however, −14.8. Thus, sulfides in those rocks seem to be of different type and origin.

The mineralogy and composition of chrome spinel is of great importance to the metamorphic history of ultramafic rocks (Evans & Frost 1975, Groves *et al.* 1977). The chemical composition of chromites of Lapland is plotted in Figure 15. The cores of chromites of the ultramafic suite in the central Lapland volcanic-rock area exhibit igneous textures. Silicate minerals exist as cumulus grains that indicate a low degree of metamorphism and recrystallization. Depicted in Figure 15 are chromite alteration trends delineated on the basis of analytical data from the rims of chromite crystals; these correspond to greenschist-facies metamorphism.

The chromite alteration trends of the ultramafic specimens of eastern Lapland overlap those of the volcanic-rock area. The silicate textures and mineralogical composition, *i.e.*, olivine, augite, tremolite and chlorite, indicate conditions of amphibolite-facies metamorphism.

The metamorphic grade in WISB correspond to the high amphibolite facies and, in the granulite belt proper, reaches that of the granulite facies. The high metamorphic facies is evident in the composition of chrome spinels, whose plot in the prism (Fig. 15) falls in the area of ferrite–chromite–low-Al chromite – high-Al chromite. In the contact zone of the granulite area, the spinels are translucent Mg-Al ones that reflect the highest metamorphic grade in the whole of Lapland.

Sulfide-bearing volcanic-type ultramafic rocks in the Yilgarn area, W. Australia, contain chromites with high Zn (Groves *et al.* 1977). The high Zn in chromite is characteristic of sulfide-bearing ultramafic rocks (even barren) outside the mineralized portions. Although the ultramafic rocks were metamorphosed to the amphibolite facies, the Zn content of spinel in the Australian deposits remained unchanged and thus indicates the original magmatic silicate–sulfide–oxide melt relations. According to Groves *et al.* (1977), the high Zn in chromites might be indicative of sulfide deposits.

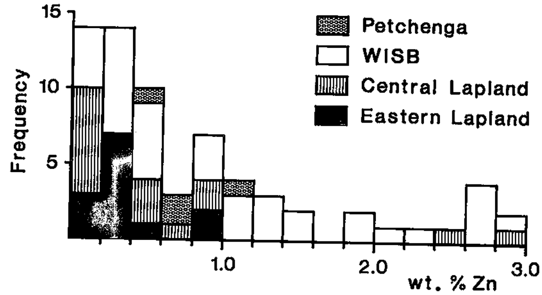


FIG. 16. Histogram of Zn content of chrome spinels from different ultramafic rocks of Lapland and from the Ni deposit of Pechenga, USSR.

The chromites of the ultramafic rocks in the granitoid area of eastern Lapland are often poor in Zn (below 0.5 wt.% Zn), the highest value being 0.9 wt.% Zn (Fig. 16). The primary, well-preserved cores of the chromites in the ultramafic rocks of the central Lapland metavolcanic area display Zn contents below 0.1 wt.%, except in two anomalous serpentinite bodies which have Zn contents up to 1.7–3 wt.%. The Mn content of these chromites is also high.

On the basis of the Zn content of chromite, the ultramafic rocks of WISB fall into two groups: those with high-Zn chromites (1–3 wt.% Zn) and those in which Zn content of chromite is below 0.5 wt.%. The sulfide-bearing ultramafic specimens belong to high-Zn group. In the granulite area, the ultramafic rocks with the highest metamorphic grade have a Zn content below 0.5 wt.%. Thus, data gathered from the chromites of Lappish ultramafic rocks seem to confirm the ideas of Groves *et al.* (1977), who maintain that Zn-bearing chromites are indicative of sulfide-bearing ultramafic bodies. Nevertheless, further study is needed concerning the existence of high-Zn chromites in the ultramafic rocks of the Central Lapland metavolcanic area, where indications of sulfides are totally lacking.

We may conclude by saying that certain ultramafic rocks of Lapland are komatiitic in chemical composition, but that metamorphism, which might have occurred during the Svecokarelian orogeny, destroyed the primary structures of the Archean ultramafic rocks. The mineralogical relations in silicate, oxide and sulfide phases also carry marks of metamorphism. The occurrence of sulfides is confined to a certain belt of amphibolite–ultramafic rock association (WISB). Consequently, follow-up research should be aimed at sulfide–silicate relations in high-grade metamorphism in ultramafic rocks and their bearing on sulfide accumulation.

Conclusions

The characteristic features of Finnish Ni deposits can be summarized as follows:

1. The Archean ultramafic rocks (older than 2.8 Ga) in the Kuhmo–Suomussalmi schist belt include minor Ni–Cu deposits. The ultramafic rocks of Lapland, tentatively considered Archean in age, show indications of sulfide mineralization. The host rocks are chemically similar to komatiites; intense metamorphism and recrystallization have, however, obliterated the primary structures.

2. The layered intrusions of the age group 2.45 Ga do not favor the accumulation of high-grade nickel sulfides. In these rocks nickel is largely incorporated in silicates. Low-grade Ni-sulfide deposits were formed simultaneously with the crystallization of the basal contact facies of the intrusion.

3. The serpentinites of Karelidic sequence contain nickel, although mainly in silicates. In some contacts of the serpentinites, low-grade Ni ore deposits occur in skarns, particularly in places where sufficient sulfur was available from the adjacent pyrite-bearing schists.

4. Economically most important are the Proterozoic mafic to ultramafic intrusive rocks (1.9–1.85 Ga) in central and southern Finland. The distribution of rock types and sulfides in some ultramafic intrusions is complex as a result of wall-rock contamination or metamorphism (or both). This group also includes plutonic rocks that were formed by multiple intrusions resulting in a pile of layers. Here, the sulfides prefer the lower horizons.

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