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Nickel-copper deposits of the Baltic Shield and Scandinavian Caledonides

Editors H. Papunen and G. I. Gorbunov

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NICKEL-COPPER DEPOSITS OF THE BALTIC SHIELD AND SCANDINAVIAN CALEDONIDES

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H. PAPUNEN and G. I. GORBUNOV

with 165 figures and 70 tables in the text
and 2 appended maps

CONTRIBUTION TO IGCP PROJECTS 91 AND 161

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ABSTRACT

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Nickel-copper deposits of the Baltic Shield and Scandinavian Caledonides. *Geological Survey of Finland, Bulletin 333.* 394 pages, 165 figures, 70 tables and 2 appended maps.

The Precambrian Baltic Shield includes several areas with sulphide Ni-Cu deposits in mafic and ultramafic intrusive rocks. The most important of the ore-bearing areas are: Pechenga, Allarechka and Monchegorsk in the USSR, the Svecokarelian nickel belts in central Finland, the Västerbotten nickel prcvince in Sweden, the historical nickel mines in southern Norway, and the Råna intrusion in the Norwegian Caledonides. Descriptions of the Ni-Cu deposits have been compiled in the monograph, which is divided into four parts referring to the Soviet, Finnish, Swedish and Norwegian deposits of the Baltic Shield and Scandinavian Caledonides. The writers are geologists from each of the countries. A comprehensive description of the geological background of the eastern and central parts of the Shield has been included in the Soviet and Finnish parts of the monograph. A general geological map and nickel map of the Baltic Shield and Caledonides at the scale 1 : 2,500,000 have been included as an appendix.

Key words: nickel ores, copper ores, intrusive rocks, mafic composition, ultramafic composition, Baltic Shield, Caledonides, Precambrian, USSR, Finland, Sweden, Norway

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NORWEGIAN NICKEL DEPOSITS; A REVIEW

Rognvald Boyd and Frank Nixon

PREFACE

The Baltic Shield is one of the world's major nickel provinces. Numerous sulphidic nickel-copper deposits associated both spatially and genetically with Precambrian mafic-ultramafic intrusions are known in the area. Some of them have been mined out; others are at the exploration and inventory stage.

The deposits have been the subject of years of study and exploitation and hence a vast wealth of information has been accumulated on the geological structure of the ore areas, the petrology of the mafic-ultramafic massifs, the structure of the ore fields and deposits, and the composition of the ores. The most comprehensive material is held by the geologists of the Soviet Union and Finland. This explains the favourable reception given by both parties to the proposal to review the sulphidic nickel-copper deposits that was put forward at the meeting of the working group on geology of the Soviet-Finnish Commission on Scientific-Technical Cooperation in 1977. The first phase of the work comprised reciprocal visits by experts from both countries to get a first hand view of the deposits and ore showings of this type in Finland and the Soviet Union and to look the various aspects of the forthcoming collaboration. In 1980 an agreement was signed on the actual content of the collaboration.

In accordance with a joint plan, it was confirmed at the tenth meeting of the working group on geology of the Soviet-Finnish Commission on Scientific-Technical Cooperation that in 1981—1983 the existing material should be combined, that a general geological map of the Baltic Shield at a scale of 1 : 2,500,000 should be compiled and that a joint monograph should be prepared. In final phase of the work geologists from Sweden and Norway participated the preparations for the monograph and provided manuscripts on the deposits and ore showings in their countries. This material has been included in the monograph.

The monograph is to be published simultaneously in Finland in English and in Soviet Union in Russian. It is in four parts: part one deals with the nickel-copper deposits and ore showings in the Soviet Union, part two with those of Finland, part three with those of Sweden and part four with those of Norway. Each of the parts is constructed in the same way, with the numbering of tables and figures starting from one, and a list of references.

The scientific heads of the projects and the editors of the monograph were corresponding member of the USSR Ac. of Sci. G. I. Gorbunov (of the Kola Branch of the USSR Ac. of Sci. at Apatity) for the Soviet Union, and Professor H. Papunen (of the Department of Geology and Mineralogy of Turku University) for Finland, Sweden and Norway.

The encouragement and interest shown by the following people were crucial to the success of the venture: K. O. Kratz and A. I. Lisitsyn, H. Stigzelius and L. K. Kauranne, chairmen of the working group on geology for scientific-technical cooperation; I. V. Belkov and V. A. Sokolov, heads of the geological institutes of the Kola and Karelia branches of the USSR Ac. of Sci.; N. N. Hrustalev, director of »Sevzapgeologija»; and P. Isokangas and P. Rouhunkoski, directors of Outokumpu Exploration. The authors express their deep gratitude to all the above mentioned.

Apatity, May 1984

G. I. Gorbunov

EDITOR'S NOTES TO THE ENGLISH EDITION

In his review of nickel deposits Haapala (1969) maintained that Fennoscandia has a claim on the birthright of the metal nickel. The statement refers to the fact that, in the second half of the nineteenth century, Norway produced the bulk of the world's supply of nickel. Nickel mining began shortly after the discovery of pentlandite, a new Fe-Ni mineral in those days, in the Espedalen deposit in 1845 (Scheerer 1845).

But the use of nickel in Scandinavia has a longer history than that: some iron artifacts of Viking and pre-Viking days discovered in hoards in central Sweden and Norway contain appreciable amounts of nickel (Thålin 1973, Hansson & Modin 1973). Nickel tenors up to one per cent have been found in »spade-shaped bars». It has been debated as to whether the nickel originated from meteoritic iron or from nickel-bearing terrestrial iron mining. The fact is, however, that lake Kaaljärvi on Saarenmaa, an island in the northern Baltic Sea, is a meteorite impact crater dated at c. 600 B.C., which might have provided our ancestors with meteoritic iron for forging. On the other hand, nickeliferous iron implements found in central Sweden contain traces of arsenic and have a rather high tenor of cobalt. Hence Thålin (1973) concluded that the ancient iron objects with high nickel indicate that iron ores rich in nickel were exploited in some regions.

Most of the ancient nickelferous implements are from an area not far from the old Los mines, central Sweden, and it is noteworthy that »coppernickel» produced from the Los ores was the crude material from which the famous Swedish chemist A. F. Cronstedt discovered a new metal in 1751. The alloy, called »coppernickel» (copper 'devil'), was unsuitable for copper production and in his detailed description Cronstedt (1754) gives the name nickel to the new metal originally discovered in Los.

The participants from Finland, Norway and Sweden in IGCP Project 161 compiled the first generalized map of nickel deposits for the second Nickel Sulfide Field Conference (NSFC) held in the Nordic countries in 1980. The map was completed for and presented at the third NSFC in Western Australia in 1982. The map, supplemented by a corresponding geological map of Kola and Karelia, was the basis for the appended map at 1 : 2 500 000 in the present monograph. The collection of data and compilation of the manuscripts on the Swedish, Norwegian and Finnish deposits was undertaken in co-operation with IGCP Project 161.

Despite several meetings held between the authors and the editor, the descriptions in the issue at hand are not uniform in content or treatment; they reflect the variations in level of knowledge, the independence of geological thinking and the difference in exploration methods between the countries involved. Hence, in their contribution the Finnish authors often refer to the composition of mafic silicates of the host rocks because of the frequency with which they have used this geochemical parameter in exploration since the late 1960s (Häkli 1971). Despite the considerable adjustments to terminology, certain inconsistencies may have remained. The term suite is used instead of subgroup in the lithostratigraphy of the first part of the issue; the hierarchy of the units is thus: complex (e.g. Svecokarelian) — group (Pechenga) — suite (Pilgujärvi) — formation (Pilgujärvi volcanite formation) — member — bed. As a rule epithets, such as the names of rock types or minerals that are separated from each other by a hyphen, are arranged in order of decreasing abundance (for example »peridotite-pyroxenite-gabbro intrusion» means: peridotite > pyroxenite > gabbro). The reader should note that some of the manuscripts were received in revised form as early as the end of 1982 and hence the most recent references are not included.

The Academy of Finland gave financial support to the research, compilation and printing of the monograph. Special thanks are due to Outokumpu Oy and the Geological Survey of Finland for the backing they gave to the writers and for their technical assistance. Preparation of the text, figures and maps would not have been possible without the efforts of several people, including: Gillian Häkli, who translated and correction much of the text; Hanna Koskinen, Maarit Nummi and Sirkka Pasanen, who drafted the figures; Elsa Järvimäki, who drafted the appended maps; and Marjatta Jalo and Aini Roine, who typed the manuscript. Their help is gratefully acknowledged.

Turku, March 1984

Heikki Papunen

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METALLOGENY OF NICKEL OF THE EASTERN PART OF THE BALTIC SHIELD (THE TERRITORY OF THE USSR)

MAIN FEATURES OF THE GEOLOGICAL HISTORY OF THE BALTIC SHIELD AND THE EPOCHS OF ORE FORMATION

G. I. GORBUNOV, V. G. ZAGORODNY and W. I. ROBONEN

Geotectonic position, major provinces and stages of development of the Baltic Shield

The Baltic Shield is the largest occurrence of the early Precambrian crystalline basement of the East European platform. In the period preceeding the formation of the platform it was part of a vast craton whose principal structural elements outlived the geological histories differing in duration and content, and which formed a unit and consolidated at the end of the Early Proterozoic period about 1800 Ma ago. As a result of Baikalian-Caledonian reconstruction of the earth's crust the Baltic Shield became separate roughly along its current boundaries. The Riphean platform deposits that occur almost throughout the Shield periphery, and the Cambro-Silurian, Devonian and Permian outliers indicate that since consolidation, the crust of the Shield has mainly undergone uplifts, being most of the time emerged. In the west and northwest the Shield is restricted by the folded system of the Caledonides of Norway, which is composed of the Late Riphean and Cambrio-Silurian formations that are usually thrust over the Svecokarelian peneplain of the Shield. The southwestern boundary is defined by the system of the Paleozoic and younger fractures. In the south, southeast and east the Shield surface dips smoothly under the Riphean-Paleozoic deposits of the East European platform. In contrast to the southeastern boundary, a system of fractures has developed in the north along the Murmansk shoreline. The crystalline basement has been sharply and stepwise depressed and is overlain by the Riphean deposits. The latter are characterized here by rather marked thicknesses and folding and the initial metamorphism that defines them as formations of a mobile shelf.

The internal structure and tectonic zonation of the Baltic Shield have long been a subject of debate between investigators maintaining different theoretical positions. The majority of the researchers, however, attribute the main features of the Shield principally to Svecokarelian deformation, although some elements of older and younger structures also exist (Kratz *et al.* 1970, 1978, Lobach-Zhuchenko *et al.* 1972, Lazarev 1977, Shtregs *et al.* 1978, Simonen 1980). The best known is the geological and geophysical layered block model of the crust of the Baltic Shield (Kratz *et al.* 1978). This combines a general stratification of the earth's crust and structural elements such as megablocks: Murmansk, Kola-Norwegian, Belomorean, Karelian and others (Lapland), united into larger geotectonic provinces of the Shield: the west Sveconorwegian, the central Svecofennian and the east Lapland-Kola-Karelian, which differ from each other in geological history, mainly in time of consolidation and in subsequent deformation of the earth's crust.

The composition and structure of the provinces show that during the history of the Baltic Shield various types of crust and endogenic regimes coexisted. Hence in the eastern part of the Shield a continental type of crust with features of the platform regime already existed back in the Archean. Besides the Karelian-Kola region, the province probably includes Finnish and Swedish Lapland. During the Svecokarelian period it was a pericraton area that was subject to intense destructive processes, reconstruction and formation of intracontinental riftogenic, orogenic and peneplane structures. It was reconsolidated at the same time as the evolution of the adjacent Svecofennian geosynclinal region was completed. The large blocks of the earth's crust that were not involved in the reconstruction (middle and marginal massifs) preserved relict Archean structures.

The central Svecofennian part of the Shield is thought to be the most homogenous. It is a deeply denuded, epigeosynclinal folded area of Svecokarelides with its own regular tectonic zonation. The Ladoga-Bothnia miogeosyncline zone is generally distinguished as a separate unit. Some formations of western Finland and central Sweden are considered to be eugeosynclinal (Mikkola 1953, 1959, Simonen 1960, 1980). The presence of intensely reworked rheomorphosed massifs in crust of more ancient (Archean) consolidation is not excluded.

Orogenic and peneplain formations are located at the southwestern and the northeastern boundaries of the province.

The discrete western (Sveconorwegian) province is located on the slope of the Baltic Shield. It represents an area of Gothic and Baikalian regeneration superimposed on formations that might be the continuation of the Svecofennian geosynclinal area or of its western foreland including blocks of more ancient (Archean) crust. Many problems concerning the geology of the province have still to be solved.

Baikalian-Caledonian, late Caledonian and Hercynian deformations of the earth's crust have affected other regions of the Baltic Shield, too, thus activating a vast area. During the early and middle Paleozoic the crust underwent block movements along the boundaries of the old fracture systems, whose rejuvenation and position emphasize their association with the Norwegian Caledonian structures (Gorbunov *et al.* 1978). Alkaline basaltic volcanic and subvolcanic complexes were formed at that time in Oslo graben and Khibiny-Kontozero graben in the eastern part of the Shield. Paleozoic outlier deposits have been found in a number of depressions in Sweden, Finland and Karelia.

The geochronological data have recently been analyzed by a number of investigators (e.g. Lobach-Zhuchenko *et al.* 1972, Kratz *et al.* 1978, Pushkarev *et al.* 1978, Simonen 1980). They have established ages of the most important endogenic events in the Baltic Shield, which were accompanied by intrusion of magmatic masses, regional metamorphism and ultrametamorphism. In the frequency distributions they correspond to the maxima of the age determinations. The age of the formations and processes whose geological position does not correspond to the maxima is usually non-representative and sometimes, especially for the Early Archean formations, the age is completely rejuvenated by younger processes, resulting in errors of various kinds.

The geochronological data can be classified into a number of important age groups that may be interpreted geologically as follows:

Group A consists of the datings falling in the interval 2900—2600 Ma. The numerous determinations obtained by various methods include reliable isochronous Pb—Pb, Pb—U and Pb—Th ages of zircons from granodiorites, tonalites, plagiogranites and plagiomicrocline granites of the Murmansk massif, Kolmozero-Voronya zone, central Kola, Keivy, Belomorean, and west Karelia blocks, and from metamorphic supracrustal formations of the Lopian and Kola-Belomorean complexes as well. The geological data demonstrate that only the group datings obtained from granitoids that crosscut the Late Archean supracrustal formations can be considered reliable. The ages of the supracrustal rocks themselves and all the more so of their granodiorite-tonalite basement are rejuvenated. Their true age may be 3500—3700 Ma, i.e. the age that has been determined for the oldest formations of West Greenland (Moorbath *et al.* 1972). This is confirmed by the fact that some relict ages of the granite-gneisses of the oldest basement and the Archean gneisses of the Kola Peninsula and Karelia fall in the interval 3000—3500 Ma.

The set of dates considered has established the greatest endogenic events of the Late Archean: regional metamorphism, granitization, intrusion of large masses of granitoids, rheomorphism and rejuvenation of older formations common to orogenic processes, and total cratonization of the earth's crust.

Group B consists of datings in the interval 2500—2300 Ma. This group is by an order less numerous than the previous one but includes quite reliable and geologically justified data on the age (2450 ± 50 Ma) of the Early Svecokarelian (Sumian) volcanogenic formations (Kratz *et al.* 1976) and on the age (2430 ± 50 Ma) of layered massifs of peridotite-pyroxenite-gabbronorite, which seem to be comagmatic with the Sumian komatiitic lavas. The layered massifs are widely spread throughout the Kola Peninsula, North Karelia and other parts of Finland (the Monchegorsk pluton, the massifs of the Pana tundras, Kemi, Penikat, Porttivaara, Kivalo, Tsypringa and others). Their geological position has been established with some certainty. They are overlain by Sariolian conglomerates and cut the older formations.

The group also contains datings from granitoids, including that (2420 Ma) from the Topozero charnockites (Shurkin *et al.* 1974; Pushkarev 1971) and from some others, but their value as the true ages of the rocks must be taken with caution.

Group C consists of estimations falling in the interval 2200—2000 Ma, and corresponds to the Jatulian stage of the Svecokarelian history of the Baltic Shield. The group, like Group B, is not large but includes some reliable isochronous data on the Early Jatulian volcanogenic rocks of northern Finland, Karelia and the Kola Peninsula (age 2200—2100 Ma) (e.g. Kratz *et al.* 1976, Pushkarev *et al.* 1978, Lauerma 1982) that have been substantiated geologically.

Abundant recent datings on granitoids older than 2000 Ma refer to this group (Idelskie and Kachkomskie granites of Karelia, some plagio-microcline granites of Belomore, the Umba granites and granodiorites, pegmatoid granites of the northern rim of the Pechenga structure and others).

Their geological position is not quite clear, but they probably include both older and younger material.

Group D represents an age interval of 2000—1800 Ma and exhibits in histograms the maximum analogous to that of group A. The group comprises numbers of determinations carried out with various methods including reliable isochronous Rb — Sr, Pb — Pb and Pb — U ages of metamorphic supracrustal strata and of the granitoids, pegmatites and veins of sulphide ores that crosscut them: 2050, 2055 Ma for the complex ores of Vihanti; 1950 Ma for granulitic metamorphism of the Lapland type; 1940 Ma for the Lovnoozero pegmatite; 1900 Ma for the Tampere granodiorite; 1900—1880 Ma for granitoids of the Central Finland massif; 1885 ± 30, 1870 ± 30 Ma for metamorphic zoning of the Ladoga zone; 1880 ± 30 Ma for the Pechenga Ni-Cu ores; 1900 ± 70 Ma for syenites of the Soustov massif; 1845—50 Ma for granitoids of the Litsa-Araguba complex; 1900—1810 Ma for alkaline granites and syenites of western Keivy; 1840—1810 Ma for the Pitkäranta ores; 1810 ± 25 Ma for a vein cutting the Pilgujärvi massif; 1800 Ma for the Lina-granites of Swedish Lapland; and 1750 Ma for the Pechenga plagioporphyrites. The list illustrates that powerful endogenic processes took place at this stage of the geological history of the Baltic Shield: the intrusion of various magmatic masses of ultrabasic to acid composition, regional metamorphism at high pressures with high-gradient zoning, and intensive ultrametamorphism in some regions. All these processes then brought about the Pre-Riphean cratonization of the crust of the Shield.

Group E represents an age interval of 1700—1500 Ma and includes data on rapakivi-like and rapakivi granites and on related gabbro-anorthosites and diabases. Also included are some metamorphic rocks of the Sveconorwegian and Svecofennian provinces. These formations presumably mark a subplatform stage of the Late or Postsvecokarelian deformation. But they also show older ages e.g. 1900—1800 Ma for rapakivi granites. This group must therefore be treated with caution, allowing for rejuvenation during subsequent endogenic processes.

Group F is the youngest for the Precambrian of the Baltic Shield and is represented by only a few determinations from the Jotnian, Early and Middle Riphean sedimentary rocks and the dolerites and diabases (1400—1200 Ma), that crosscut them, and from the upper Riphean and Vendian sediments (800—650 Ma) in the periphery of the Shield that constitute the lower parts of the platform cover.

Group G consists of the datings in the interval 450—350 Ma, obtained mainly from the Caledonian-Hercynian magmatic formations. Also included are recent datings on various hydrothermal and metasomatic formations, which indicate that the impact of Paleozoic activation on the Precambrian structure of the Shield was more significant than has been suggested by structural and petrological investigations.

The traces of the younger geological events in the Baltic Shield are reflected in the presence of shallow Pleistocene glacial and interglacial deposits and in the current morphological relief caused by Neogen-Quaternary block movements of the earth's crust.

Stratigraphic units and main features of the geological evolution of the eastern part of the Baltic Shield

The Baltic Shield is composed of crystalline rocks of sedimentary, volcanogenic and intrusive origin that have undergone repeated metamorphism, ultrametamorphism and structural deformations. Their age ranges from 3.7—3.5 to 1.5 Ga. Ultrametamorphic formations and granitoids are especially widespread. Supracrustal rocks or their fragments, which have survived erosion, are encountered in the formations that often show separate synclinal structures.

The composition and structure of the geological sections in the eastern part of the Shield show more or less clearly the conditions of formation indicating that, from the earliest stages, an essential part was played by platform regimes in the history of the crust. In the more mobile central and western parts of the Shield subgeosynclinical conditions continued until the end of the Early Proterozoic and partly (in Sveconorwegian province) until the Late Proterozoic. Subplatform and platform formations of the Late Proterozoic and Phanerozoic developed in restricted areas, predominantly in the periphery of the Baltic Shield, which had become independent by then.

Modern conceptions of the stratigraphy and geohistorical periodicity of the Precambrian of the Baltic Shield are based on complex lithological, stratigraphic, petrological, geochemical, geochronological and geotectonic investigations. Analysis of the whole body of data shows that the Precambrian formations can be didived into four major units, or structural-stratigraphic complexes: the most ancient or the Saamian — the lower Archean; the Lopian (Kola-Belomorean) — the upper Archean; the Svecokarelian — the lower Proterozoic; and the Riphean — the upper Proterozoic. Each of them is separated from the others by major tectonic unconformities. Excluding the first they lasted for about one b.y. The formation sequence reveals the following periods of evolution: initial, corresponding to events during the initial stages and development of the mobile areas; and orogenic and subplatform periods encompassing megacycles in the history of the earth's crust.

The most ancient complex or the Saamian complex — the lower Archean, is also known in the literature as a granite-gneissic complex of the most ancient basement (Bel'kov *et al.* 1971, Goryainov 1971, Makiyevsky 1973, Predovsky *et al.* 1973, Sviridenko 1974). This complex has not been easy to distinguish and right at the beginning of the present century it occupied the attention of J. Sederholm, P. Eskola, H. Väyrynen and other Finnish geologists. The shortage of data on the Kola peninsula and Karelia, both of which are ancient formations, made it difficult for A. A. Polkanov (1936) and his followers to understand the stratigraphy in these areas. It was only at the end of the sixties that collective efforts by investigators proved that the Kola gneiss complex, considered earlier as the oldest, is stratigraphically and tectonically heterogeneous. Part of it, composed of plagiogneisses and associated diorite-granodiorite-gneisses and plagiogranites, reveals features of a closely related volcano-plutonic association (Batiyeva and Bel'kov 1968, 1979) the formation of which was followed by a long and important interval. The overlying gneisses and amphibolites, which are the main constituents of the Kola gneiss complex as interpreted earlier, contain products of disintegration and redeposition of underlying rocks (Predovsky 1970, Predovsky *et al.* 1973, Bel'kov and Zagorodny 1977). Study of the structural interrelation of these formations has demonstrated that they formed at different stages and may be interpreted as a basement with a sedimentary-volcanogenic folded complex overlying it unconformably (e.g. Bel'kov *et al.* 1971, Belyaev and Zagorodny 1974, Goryainov 1976). Thus the most ancient, or the Saamian granitogneissic complex, has been established as a distinct unit even though many of its features are still not clear and deserve special attention.

The formations of the most ancient complex are widely distributed in the eastern part of the Baltic Shield. Since the shield is a substratum, in which many especially ultrametamorphic processes developed, the oldest formations predominate in geotectonic regions such as the Murmansk massif, the Ust'-Ponoy and Tersk blocks, the Notozero and Ponoy blocks, western Belomore, eastern Finland and the Karelian massif. In other regions, mainly within the Karelian structures and their periphery, they constitute separate oval blocks, 5—7 km to 30—50 km across, which are projections of the basement between the younger folded supracrustal rocks. As has been mentioned, diorites, enderbites, granodiorites, tonalites, plagiogranites, biotite and amphibole plagiogneisses and seldom crystalline amphibole schists are encountered in the oldest complex. The location of these rocks in the Kola peninsula, for example, is characterized by a definite zonation (Zagorodny 1980) that is probably due to the depth of the erosion of the basement blocks. As shown in some regions, this peneplain preceded the formation of the supracrustal complex. More often, however, it includes smoothing surfaces of different ages up to the most recent ones. This phenomenon is consistent with I. V. Bel'kov's (1976) concepts of the presence of facies of different depths in the most ancient complex, and of the spatial location and interrelations between the facies.

Plagiogneisses and crystalline schists with stratiform features can be distinguished among the complex rocks as supracrustal formations. They are considered to be xenoliths or relict members of layers among granodiorites and plagiogranites. They occur more frequently in the southeastern and southern parts of the Kola peninsula, and probably in Belomore, where they occasionally cover vast areas. They do not exhibit bedding. Coarse sheet jointing is observed, and gentle brachyform granitogneiss block-domes and ovals have been mapped based on the orientation of the jointing. The important geochemical relation of plagiogneisses to the plagiogranites, tonalites and granodiorites of the complex, together with the volcanogenic texture relicts found in them, explains why they are referred to as a primary, crustal, volcano-plutonic association (e.g. Batiyeva and Bel'kov 1968).

Study of the textures, structures and petrography of plagiogneisses shows that they lack features of exogenic processes, whereas geochemical investigations, including those on the gaseous component of an organic substance (Belyayev 1980), indicate that they are magmatic in origin. Thus the data accumulated corroborate the notion that plagiogneisses are an effusive facies of plagiogranite-granodiorites and should be treated as formations of the oldest sialic layer of the earth's crust only together with deeper rocks of the complex. However, it should be noted that the genesis of the most ancient supracrustal formations should be interpreted with caution, as most of the formations have been intensely reworked by younger tectonic and ultrametamorphic processes, making their diagnosis difficult and often impossible.

Their location in the upper parts of the sections of the basement complex, their distribution in the periphery of the block structure close to the overlapping younger series, and their occurrence, sometimes as beds with features of unconformity on deeper complex facies, all suggest the presence of rocks that are the products of exogenetic destruction of the basement. In other words, the rocks are relicts of the most ancient sedimentary cover occupying, as has been inferred for the Canadian Shield (Markov and Shcherbak 1979), an intermediate position between the plagiogranite-tonalite basement and the greenstone belt of the upper Archean.

Summarising what is known about the most ancient formations of the eastern part of the Baltic Shield we can draw a number of conclusions not unlike those formulated earlier by I. V. Bel'kov (1976). Formations similar to those under consideration are evidently not known from the younger geological complexes. Hence, we must postulate that they were formed under the geotectonic and thermodynamic conditions that prevailed only during the early stages of differentiation of planet matter and the formation of the primordial earth's crust. The mechanism of »zone melting» (Vinogradov 1962) seems to be acceptable in this case. Keeping in mind the heterogeneities caused primarily by convectional processes in the earth's depths, one might suppose that protocrust of some other type might have formed along with the sial. No traces, however, have been revealed in the area studied. The specificity of the formation of the primary sial crust is expressed by the fact that its consolidation, which took place about 4—3.7 Ga ago, was evidently the result of a change in thermodynamic conditions without orogenic processes, as no characteristic features of the latter have yet been discovered.

Note also that the period of formation of the earth's crust, often called nucleation because of its singularity, and the subsequent break are an important stage in the history of the earth. It was only after this that the cycle of geological factors broadened essentially, i.e., the atmosphere and hydrosphere appeared, exogenetic and tectonic factors began to play a key role in the differentiation of the planet matter, magmatic differentiation increased substantially and so on. All these factors were in full action in the next megacycle.

The Lopian or Kola-Belomorean complex (the Late Archean) comprises amphibolites, gneisses, crystalline schists representing metamorphosed mafic and felsic volcanites and the products of disintegration an redeposition of the most ancient granitoids. The complex was formed about 3.5—3 Ga ago and emplaced by granitoids of 2.7 Ga (e.g. Lobach-Zhuchenko *et al.* 1972, 1978, Pushkarev *et al.* 1978). The stratigraphic boundary between it and the formation of the oldest basement is inferred to be in the places where the monotonous granitoids and plagiogneisses pass into a layered complex rock sequence with distinct features of sedimentary-volcanogenic origin. The relative position of the upper Archean complex subdivisions and the stratigraphic correlation between them are rather problematic. In our opinion this is due to the essential difference in composition between various structural-facial zones of the complex, to the ambiguity of the marker beds, intense structural and ultrametamorphic reworking and the absence of age data.

Three suites have been distinguished in the Archean formations in the Belomore: the Keret', mainly composed of granito-gneisses; the Khetolambin, composed of amphibolites and amphibole-bearing gneisses; and the Chupa, mainly composed of aluminiferous gneisses and to a lesser extent of amphibolites (Misharev *et al.* 1960). The nature of the primary rocks is not clear enough, owing to the absence of primary textural-structural features. Petrochemical data suggest that the main mass of the amphibolites is part of the magmatic formations of tholeiitic series (Sokolov and Stenar 1980). There are reasons to suppose that sections in the various regions of the Belomore are very different from each other. Thus, in the northwestern parts, the Khetolambin suite is either very incomplete or altogether absent.

Studies on the major regions of development of the Lopian formations in Karelia, which form the Archean greenstone belts (Lobach-Zhuchenko *et al.* 1978, Robonen *et al.* 1976), have made it possible to establish their stratigraphical sections and, with the aid of certain features (lithological, petrological, isotope geochemical and others), to correlate the sections. Three types of section have been outlined: Hautavaara, Kostamuksha and Pebozero.

From base to top, the section of the Hautavaara type is composed of andesite-dacitic (Vietukkalampi suite), basalt-komatiitic (Louhivaara suite), dacite-liparite (Kalajärvi suite), basaltic (Kuljun suite) volcanogenic and volcanogenic sedimentary formations with a total thickness of 5—6 km (Robonen and Chernov 1974). They constitute two nearly comtemporaneous and interbanded volcanogenic formations: an unfractionated komatiite-basaltic one and a successively differentiated andesite-dacitic one. Some parts of both are cut by granitoids 2.7 Ga in age. Relicts of sedimentary-volcanogenic formations are encountered in the granitoid fields. The Hautavaara-type section of the Lopian complex in Karelia has been established by lithological, paleovolcanological, radiological and geophysical investigations.

In a section of the Kostamuksha type sedimentary and volcanogenic rocks of basaltic composition alternate with terrigenous rocks in the lower part, and ferruginous quartzites alternate with volcanogenic rocks of dacitic composition in the upper part (Chernov 1964, Gor'kovetz *et al.* 1981). The total thickness is about 6 km. The age of the croscutting granites is 2710 Ma.

In the section of the Pebozero type the lowermost strata are composed of aluminiferous gneisses with conglomerates that correspond to the Tikshozero suite (Bogdanov, Voinov 1966, Robonen *et al.* 1974). They are overlain by volcanites of andesite-basalt composition. In this combination it is possible to compare deposits of the Tikshozero suite represented by aluminiferous gneisses with similar formations in the Louhi (Chupa) suite of the Belomore. But the texture, succession and stratigraphic position of rocks in the regions have not yet been studied enough to warrent unambiguous correlation.

There is one more region in Karelia in which it might be possible to distinguish a specific type section for the Lopian complex. The region is in the Vetreny Belt (Kairyak *et al.* 1978) and new data on it (Kulikov, Kulikova 1979) permit a reliable correlation to be made between its sections and those of the Hautvaara type. Here the inferred granite-gneiss basement (Vodlozero block and smaller occurrences) is overlain by basaltic volcanites with thin interbeds of tuffites and sedimentary rocks, and with felsic volcanites with pyrite mineralization in the upper part. Komatiitic basaltic volcanites overlie the latter and still higher up in the sequence felsic volcanites are interbedded with sedimentary rocks. The total thickness of the Lopian sedimentary volcanogenic deposits of the Vetreny Belt is 2000—3000 m.

In their resemblance to each other, the above types of the Lopian complex sections suggest the existence of various structural-facies zones in the upper Archean in the territory of Karelia. For more detailed stratigraphic description and correlation, however, further attention must be paid to a number of problems. These are:

1. The location of the lower boundary of the Lopian complex and, hence, its basement and the basal parts of the section. Currently the plagiogranite-enderbite complex is considered as the Lopian basement and no reliable Lopian basal formations have been established. Greenstone belts developed adjacent to the contact zones of the Lopian. Structural-metamorphic analysis of the young granites or intense granitization suggests that the greenstones deposited while the lower parts of the section of the Lopian complex were developing. It is noteworthy that long ago metamorphosed sedimentary formations (Robonen and Korosov 1966) that may be interpreted as Lopian basal layers (Gor'kovets *et al.* 1981) were supposed to exist in the Kostamuksha region between the basement granitoids and mafic volcanites that underlie the ore deposit.

2. The second important issue in the Lopian stratigraphy concerns the relation with the Belomore formations. It is currently widely held that Lopian deposits occur on the Belomorean formations (Kratz 1963, Bogdanov *et al.* 1968, Stenar' 1973 and others). These concepts are based mainly on material from the Pebozero region but also on some from Tikshozero-Notozero. However, owing to the lack of geological data on the regions mentioned, we have no definite data on the lower parts of the Lopian section.

More attention should be paid to the correlation between the Lopian volcanogenic-sedimentary deposits and the formations of the Belomorean series (of the Ketolambi and Chupa suites) or of the Chupa suite alone and to the presence of a basement common to both of them, i.e. the Keret' suite (Gorlov 1967). They share many features in rock composition and section structure. The same is true of the stages of tectonic and metamorphic evolution. The possible correlation of some of the deposits of the Belomorean series with not only the Lopian formations but also the younger Karelian ones should not be excluded. Special detailed investigations will have to be carried out to solve these problems.

3. The correlation of Lopian sections, excluding the isotope geochemical data, is based on the composition of volcanogenic and sedimentary rocks. Of good correlation are the mafic and ultramafic volcanites with tuffite interbeds and thin sediment horizons (Louhivaara and Kul'jun suites of the Hautavaara-type section) and the felsic volcanites with pyrite and iron ore horizons. The horizons of sedimentary rocks, especially conglomerates, play a key role in correlation. The correlation of the lower, andesitic part of the Lopian volcanite section is not distinct because andesites have not been found in all regions. The mafic and ultramafic volcanites, which make up the higher part of the Lopian complex section, often occur on the basement granitoids. It is still not known whether the andesitic parts of the section were absent here initially or whether they have been so intensely reworked (granitized) that it is difficult to distinguish them from the basement.

4. The upper parts of the Lopian complex section require more investigation. Sedimentary rocks of the greywacke type interbedded with felsic volcanites have recently been reported from the upper sections of a number of structures

(Kostamuksha, Oster, Semch, Padany and others). Their stratigraphic position, however, has not always been well established, especially where no reliable data are available on the facing of the sedimentary horizons and lava streams. The uncertainty as to whether the structures are synclinal or anticlinal makes interpretation more difficult. If the sedimentary formations are anticlinal, they will be considerably lowered in the section. It is in this sense that the structure of the zone of the Kostamuksha deposit should be further investigated. Here the sedimentary rocks of the Surlampi suite to the east of the main orebody may constitute the lowermost strata of the section and correlate with the rocks underlying the orebody, as suggested by V. M. Chernov (1964).

Moreover it may be possible to correlate the basic volcanites of the western region (Niemijärvi suite) with similar volcanites underlying the sedimentary rocks, felsic volcanites and the main orebody (Ruvinvaara suite). With such an approach, it will also be possible to correlate the sedimentary-volcanogenic (felsic) rocks with the orebodies of Shurlovaara and Kostamuksha suites (Chernov 1964). The above shows that more investigation is required on the Kostamuksha-type section of the Lopian complex and on the structure of the Kostamuksha deposit.

Considerable progress has been made towards solving some of the controversial issues in Karelian Archean stratigraphy. It has recently been established that chiefly volcanogenic and volcanogenic-sedimentary rocks developed in the Lopian structures of the upper Archean and that these rocks form greenstone belts on the granitoid basement. The stratigraphic succession of the Lopian deposits and the section types have been established in a number of regions. Their correlation has been outlined fairly reliably within blocks but less definitely between blocks (e.g. Karelian and Belomorean blocks). It has been established throughout Karelia that the Lopian formations are overlain by the lower Proterozoic Karelian complex with the intervening structural unconformity.

In the Kola peninsula the Kola-Belomorean complex is an analogue of the Lopian formations of Karelia. It comprises all the formations located between the oldest plagiogranite-gneiss basement and the overlapping Karelian complex (Bel'kov *et al.* 1971, Zagorodny 1980). An important datum marking the upper boundary of the complex formations is provided by the crosscutting granitoids of about 2.7 b.y. (Pushkarev *et al.* 1978).

The generalized section of the complex begins with the strata of gneisses and crystalline schists, 100 to 600—800 m thick, represented mainly by the products of weathering and redeposition of the basement plagiogranitoids. Greywackes containing beds of clay and tuffogenic shales, more seldom of quartzites, carbonate-bearing rocks, amphibolites, lenses of coarse gravel stones, pebble and boulder conglomerates have been reconstructed within it (Predovsky 1970). The main specific features of the conglomerates are: 1) the absence of a detrital microline or pebbles and boulders of microline-bearing rocks in accordance with the basement rocks, which also lack the primary rock-forming microline; 2) the regressive character of the section as shown by the increasing amount of rudaceous rocks higher in the section; 3) a parallel increase in the mafic volcanogenic material, which often marks the upper boundary of the strata.

The variegated sedimentary-tuffogenic section passes over into fairly homogenous amphibole gneisses and schists, granite and plagioclase-banded schistose and massive amphibolites, and into mafic granulites that are volcanites of basalt-andesite, sometimes of picrite (komatiite)-basalt-andesite composition with a total thickness of hundreds of metres to 2—3 km. The upper parts of this section usually exhibit andesitic rocks, lenses of felsic dacite and dacite-rhyolite metaporphyries and quartz and carbonate-bearing schists. The same levels are characterized by magnetite-amphibole schists and sections evidently formed under specific facies conditions and by ore-bearing highly differentiated iron quartzites. Upwards the complex section becomes more complicated once again and evidently facially inconsistent in character. Angular and stratigraphic unconformities with conglomerates containing pebbles of all the underlying rocks are sometimes met with in the basement of this part of the section. In a number of structural zones the rocks probably derived from and are mainly represented by meta-andesites, andesites-dacites and more seldom by rhyolites and their tuffs. In other regions at these levels tuffogenic and rhytmically bedded flysch-like gneiss-schists, sometimes with lenses of rudaceous rocks predominate. Terrigenous rocks of high maturity are often met with in the upper portions of the section of this part of the complex. The thickness of the formations considered varies, even within the same structures (e.g. the Kolmozero-Voron'ya zone). They are 1500—2000 m thick but along the strike they may be completely wedged out. Their composition and especially their structure may be interpreted as characteristic of inversion or orogenic development stages. The upper layers may mark the transfer to platform regimes.

Some workers consider this level to be the final one in the upper Archean section of the Kola Peninsula (Mirskaya 1975 and others). However in our opinion it is more probable that the section comes to an end with the strata of aluminiferous crystalline schists and quartzites studied in detail at the Bol'shie Keivy ridge (Bel'kov 1963). It lies subconformally on metavolcanites and terrigenous rocks of the section and continues the evolution series, constituting formations that are surely of platform origin. Its thickness is 600—650 m, and its typical rocks are staurolite-garnet, kyanite, staurolite-muscovite-quartz schists, quartzites, initially kaolinite shales and quartzites with argillaceous cement. The composition, the structure of the horizons and the fact that the formations evidently took part in the Karelian deformations and metamorphism suggest that these formations extended over a vast territory as a sedimentary cover.

The section of the Kola-Belomorean complex briefly considered above permits us to delineate the Late Archean history of the region only in general terms. In certain regions considerable deviations are observed both in quantity and in composition and structure of the sections, showing a heterogeneous development of the territory and the co-existence of various Late Archean structural-formational zones with different types of section. The summarized sections are typical of the linear synclinal zones. Intense mafic volcanism took place during the early stages but was later followed by eruptions of intermediate volcanites or mixed volcanogenic-sedimentary rock formation. Sedimentation was probably initially suppressed by volcanism but later evolution was characterized by the gradual consolidation of the earth's crust and the successive transition to the stage of orogenic and platform development. Being located between the large massifs of the oldest basement, these zones were formed under mobile and fairly mobile conditions as suggested by their thicknesses, section structure, the character of the folding and faulting and other features. These structures are encountered at Kolmozero-Voron'ya, Ponoy, Sal'nie and Kolvitsa tundras and elsewhere, and particularly in the southeastern part of the Belomore. According to the data of K. A. Shurkin (1964) M. M. Stenar (1973) and other investigators the latter may be considered as a geosynclinal structure. On the basis of the above features these formations are similar to those currently widely discussed in the literature as Archean greenstone belts.

The second type of structural-formational zone developed within the large basement massifs restricted by mobile zones. These massifs are inferred to have undergone some tectonic differentiation and to have been involved in subsidence simultaneously with the formation and development of the mobile zones. On the current erosional section the upper Archean deposits within the massifs form small asymmetrical synclines or their combinations and show complicated block-fold structures. They fill the space between the basement blocks and accentuate its primary dome-shaped and oval structures. The most typical representatives of these structures have been studied in Imandra region (Goryainov 1976): the resemblance of these with those of the Kostamuksha region in Karelia is evident. Very thick volcanogenic and tuffogene-sedimentary rock masses accumulated within the structures concurrently with the strata of linear structures. They seem to play of different role in volcanites than does the tuffogene material, and in sedimentary rocks they are more differentiated and mature in composition. The inversion processes, diapirism of the basement blocks and an increase in the consolidation of the earth's crust took place during the late stages of the structure development. All these phenomena resulted in an irregular reduction in the thicknesses of the upper parts of the sections, in displacement of the sedimentation basin, in unconformities of stratigraphic subdivisions and in the appearance of highly differentiated mature sediments. Intrusion of early granitoids, folding and metamorphism are likely to have coincided with inversion.

The third type of structure is seen mainly in andesite-dacite-rhyolite and terrigenous sections developed in vast, gentle synclinoria. A typical example is the Keivy synclinorium, whose principal structural features indicate that the linear mobile zones originated and developed along the boundaries of the synclinorium during early stages of its development, whereas in its inner parts the basement remained uplifted. During subsidence and orogenic stages, volcanism and sedimentation later covered the whole territory, but the peripheral zones seem to have preserved their more mobile state. Thus, structures of this type, like those considered above, formed within the large basement massifs but their major subsidence took place during the second part of the upper Archean evolution. During the late stages they underwent increasing stabilization, which is revealed by the formation of platform deposits.

According to their position in a region structure, composition and structure of sections, both latter types of structural-facial zone should be considered to have developed under moderately mobile conditions in episodes and not stepwise. Their deposits have a number of features that are similar to those of marginal and inner massifs in a mobile region.

Along with the above structural-facial regions where the upper Archean supracrustal formations developed, tectonic areas presumably existed that remained uplifted and were eroded throughout the Late Archean period or during some of its stages. Examples of such areas are the Murmansk massif and some smaller anticlinal block structures.

A number of controversial problems concerning the stratigraphy of the upper Archean formations in the Kola peninsula and in Karelia have not been solved. The problems deal primarily with the correlation of supracrustals. In many regions the succession and composition of the supracrustals have been studied fairly comprehensively and there is no discrepancy in the data. The general boundaries of the upper Archean complex may be considered as established. They are located on the plagio-granite-gneiss basement, intruded by granitoids of about 2.7 Ga, and along the unconformity of the overlying Karelian formations. Dispute continues on the relative position and correlation of the formations developed in various structural-formational zones. This is mainly because of the initial differences in the composition and structure of the complex sections in different regions; their fragmentary occurrence owing to later structural, ultrametamorphic reworking and erosion; and the extreme rarity of key horizons and geochronological data. A certain role is also played by the inconsistent data on the region, especially on the structures which do not provide necessary information on the position and regularities of distribution of various types of section.

The following are some of the controversial points:

1. The interrelations of the upper Archean formations of the Central Kola region, which, from the composition and structure of sections and the presence of ore-bearing ferruginous quartzites, we regard as the best analogues of the Lopian complex in Karelia (the section of Kostamuksha type) with formations of Kolmozero-Voron'ya and Keivy zones on the one hand and Vochelambi and Sal'nie and Kolvitsa zones on the other.

2. The interrelations of the formations of Sal'nie-Kolvitsa and Belomorean zones, which have several disputable variants (as in North Karelia) owing to the lack of general and, especially, of structural-historical data on the regions of their development.

In these cases of formal correlation of sections of various structural zones based on the similarity of composition and rock succession seldom gives satisfactory results and sometimes is even impossible because of the incompleteness of and differences between the sections. The differences are probably due to both the primary zonation and the relative positions of the sections in stratigraphy, where they ought to complete each other to a certain extent. That is why the primary task in correlating the formations of these zones is to establish their position in the general evolutional sequence by a complex study using structural and paleotectonic reconstructions and data on the Archean history of the region.

Generalization based on materials from upper Archean formations of Finland, Karelia and the Kola peninsula has considerably enlarged and susbtantiated our picture of the history of their formation. Most investigators interpret the late Archean tectonic megacycle with all its manifestations as protogeosynclinal. And indeed, its many features (magmatism, intense formation of structures, granitization, metamorphism and others) are similar to those in the evolution of the Phanerozoic classical geosynclines. Likewise it is obvious that the upper Archean deposits in the eastern part of the Baltic Shield were formed on the consolidated sial crust, i.e. on the most ancient basement and hence, should be compared with parageosynclinal or other structures that also have a basement.

Some specific structures were formed as a result of the upper Archean evolution, mainly at its initial stage. These structures are considered to be the oldest greenstone belts, characteristic and singular evidence of the ancient shields of the earth. The structure of the above greenstone zone is characterized by a combination of block-dome and oval structures of the granite-gneissic basement. The usually asymmetrical greenstone synclines belong to various structural-formational zones with sections that differ in a number of features including abundance and composition of volcanogenic rocks (from komatiitic basalts to andesite-dacites), maturity, differentiation degree and volume of sedimentary rocks, and intensity of structures and thermodynamic conditions of metamorphism. We believe that their dissimilarity is due mainly to the difference in mobility of structures associated in turn with the degree of destruction of the basement. Hence the most mobile zones are the sublinear and essentially volcanogenic ones located between the blocks, such as Hautavaara, Kolmozero-Voron'ya, parts of the Belomorean, and some smaller ones. These zones exhibit komatiitic basalts as well as basic and ultrabasic rocks. The other structures were formed within the large basement massifs, probably under more stable conditions.

During the second half of the Late Archean the features of inversion and orogenic processes developed in most of the structural formational zones of the eastern part of the Baltic Shield. Mafic volcanites were replaced by intermediate volcanites, and flysch-like and molasse deposits were formed. Regressive sections, unconformities and displacements of sedimentation basins occurred. Granites, granitization and regional metamorphism took place synchronously with and succeeding the acid volcanism. As a result of these processes the earth's crust in the eastern part of the Baltic Shield was reconsolidated about 2.8—2.7 Ga ago and entered the stage of platform evolution, which transformed the disjointed folded area into a peneplain. Evidence of this stage is given by the protoplatform formations of the Keivy zone.

The Svecokarelian complex — the Early Proterozoic — plays an important role in structure-formation in the Baltic Shield. It is widely spread and represented by various formational types caused by different endogenic regimes, and by paleogeographic and paleotectonic conditions both coexisting in adjacent geotectonic provinces and regions and successively changing from one to the other.

In the eastern part of the Baltic Shield the Svecokarelian complex was formed on consolidated earth's crust of continental type and occurs on folded and deeply denudated Archean formations of 2.8—2.7 Ga with a great structural unconformity and interval. In Karelia it is represented by sedimentary-volcanogenic strata of the Sumian, Sariolian, Jatulian, Zaonezhye-Suisaarian (Ljudikovian), and Ladogian (Livian) and Vepsian that correlate with formations in Finland of the Lapponian, marine Jatulian, continental Jatulian, Kalevian and Kumpu-Oraniemian, respectively; and in the Kola peninsula with deposits of the Strelnina, Pechenga, Varzuga, Tominga and South-Pechenga. The upper age limit of the complex is estimated to be at 1.7—1.6 Ga.

The Svecokarelian complex begins with basal formations represented by a crust of physical (here and there probably of chemical) weathering residual-talus breccia, which in some places are overlain by quartzite conglomerates. In Karelia the sedimentary rock members and quartzites (especially of quartzitic sandstones and quartz conglomerates) are not met with throughout the lowermost strata of the Sumian section (Okun' suite). In some places the overlying lavas discharged directly onto the ancient basement (the region of the Krasnaya river). The same happened in the Kola peninsula, but in Finland the sedimentary horizon at the base of the deposit correlated with Sumian formations is fairly common.

Lava strata up to 1000 m thick of basalts and andesite-basalts (Tunguda horizon) occur over the basal sedimentary strata within the Shuezero (Lekhtins) structure. Still higher within this structure and in the Paana-Kuolajärvi zone and Vetreny belt there are volcanites of acid composition (Ozhijärvi horizon) up to 500 m thick. The age of these strata, determined by the isochrone method on zircons from quartz porphyries, was found to be about 2450 Ma. The strata are overlain by the Paanajärvi horizon of sedimentary rocks and tuffites with a thickness of not less than 180—200 m and then by volcanites of andesitic composition (Vermas horizon), whose thickness is up to 500—550 m and which complete the Sumian section.

Higher in the section there is a Sariolian residual breccia, 2—3 m thick, that contains fragments of the rocks on which it lies; granites on granites, diabases on diabases, quartz porphyries on quartz porphyries, quartzites on quartzites, and so on. Upwards in the section the conglomerate-breccia grades into polymictic conglomerates 100 m thick, which in turn, grade over the interbedding zone 10—20 m thick into greywackes, tuffite-schists and sandstones 150—200 m thick with distinct water-slide structures. Here and there the section is topped by dolomites and limestones up to 40 m thick.

With their features similar to those of glacial formations the Sariolian deposits are tillites, as was already reported by Eskola. It is thus logical to assume that the basal level of the eluvial breccia is a result of cryogenic weathering.

The position of the horizon of residual breccia, conglomerates and sandstones on the preceding rocks of various stratigraphic levels and the fact that they are compressed into steep folds suggest that the horizon of Sariolian fragmental rocks occurs on the older formations with an important structural unconformity. This type of Sariolian-Sumian contact has been established in practically all the regions of the Baltic Shield where such formations are present and where an exposure permits them to be observed. However, note that not all parts of the Sumian section described above have been developed in each structure. Hence, in West and South Karelia acid volcanites are usually absent from the Sumian section; here and there there are no Sumian formations at all in some places, and Sariolian fragmentary rocks occur (e.g. in the region of the Luzhma river) on the Lopian phyllite-like schists. This together with the erroneous conclusion about the interbedding of fragmentary rocks of Sariolian and Sumian volcanites was why Sumian and Sariolian deposits were united into a single Sumian-Sariolian complex and the types of sections of this complex distinguished.

The absence of acid volcanites from the Sumian section in South Karelia naturally raises a question about the role the volcanites played in the main composition of the Sumian sections in East and North Karelia. One can correlate the volcanites of the same compositions in South and Central Karelia either using the chemical data on volcanites or by stating that only one stratum of volcanites of basic composition deposited here during the whole Sumian period.

The next section of the complex is represented by Jatulian deposits. The chemical weathering crust was formed at their base on the fragmentary Sariolian rocks and, where they are absent, on Sumian lava or on basement granitoids during the Prejatulian period. Crust formation indicates intense peneplanation and smoothing of the relief and establishment of humid conditions almost everywhere. These processes are presumed to have taken place about 2.3—2.2 Ga ago. Quartzitic sandstones, quartz conglomerates, gravel stones and sericitic quartz schists of the lower Jatulian occur on the chemical weathering crust. The composition, structure and thickness of Jatulian deposits change laterally, giving rise to various types of section. The lower Jatulian sedimentary rocks vary from 10—15 up to 1200 m in thickness. Here and there they pinch out completely. The lower Jatulian basaltic lavas up to 50 m thick overlie the sedimentary rocks. Although not developed everywhere, lavas have been distinguished in the Onega, Vygozero, Shuyeozero, Shambozero and Tikshozero structures.

The lower Jatulian volcanites are overlain by middle Jatulian sedimentary rocks with a weathering crust and conglomerates at the base. Where sedimentary rocks and lower Jatulian volcanites have pinched out, the middle Jatulian may also occur on older formations down to the basement granitoids with granite conglomerates at the base. As a rule the middle Jatulian sedimentary stratum is not thick (10—20 m, sometimes as much as 200—300). It is overlain by the middle Jatulian basalts that form series of lava flows up to 350 m thick. The middle Jatulian with an occasional weathering crust and a washout is overlain by upper Jatulian sedimentary rocks, represented by gravel stones, quartzites, dolomites, organic limestones and carbonaceous chlorite schists 350 m thick. The overlying volcanite series, 30—50 m thick, is represented by one or two lava flows with tuffite interbeds.

Sedimentary-volcanogenic formations with carbonaceous sediments (schungite schists) as characteristic members occur above the Jatulian deposits in this section. In the Zaonezhye peninsula of Lake Onega, where the sections are known as the Zaonezhye formation, they are stratotypes of these sediments. It has recently been suggested (Sokolov 1980) that Zaonezhye, Pitkäranta and other similar formations should be distinguished as an independent Ljudian chronostratigraphic unit.

The Zaonezhye (Ljudian) deposits are represented by carbonaceous-argillaceous sediments and schungite-bearing sedimentary volcanogenic formations: quartzite-sandstones, dolomites, carbon-bearing schists, schungite-bearing tuffs and tuffite-bearing schists, schungite-bearing tuffs and tuffites, tuffs, and tuff-conglomerates. They are characteristically impregnated with sulphides. Typical components of the section are basaltic lava flows with a total thickness of up to 300 m, individual flows being up to dozens of metres thick. Sills of gabbro-diabases with a total thickness of 600—1000 m are also characteristic. The sedimentary part of the Ljudian section attains 1000 m, and the total thickness of the Zaonezhye formations is about 2300 m.

The Suisaarian sedimentary-volcanogenic formations, which occur higher up, are 700 m thick and represented by alternating flows of plagioclase-pyroxene, pyroxene picrite porphyrites, pillow lavas and beds of tuffs, tuffites, and tuff-sandstones. Also present are volcanic and sub-volcanic pipes, volcanic necks and mafic and ultramafic intrusions comagmatic with volcanites. The Suisaarian formations have long been distinguished as a unit equal to the Ljudian, i.e. the Livian (Sokolov 1980). However, it is quite possible that the Suisaarian is only the upper part of the Ljudian formation.

The sedimentary rocks of the Besovets suite form a superstructure in the section since a horizon of the polymictic conglomerates occurs on the Suisaarian in the Onega structure. They seem to refer to the lowermost strata of the Vepsian group and correlate with the Kalevian of Finland and the Ladogian north of Lake Ladoga. This part of the Vepsian including the Besovets suite and some parts of the Petrozavodsk suite should probably be distinguished as an independent unit, i.e. Livian; for the upper part of the Vepsian (red quartzite — sandstones proper) we should preserve the present name, Vepsian, and correlate it with the Ilola suite north of Lake Ladoga and with the Kumpu suite in Finnish Lapland. If the section is separated in this way the thickness of the Livian sedimentary rocks, which consist of quartzite-sandstones and sandstones with siltstone bands and conglomerate lenses, is about 600 m.

The Shoksha suite (Vepsian proper) up to 400 m thick is separated from the underlying sedimentary rocks by conglomerates and is composed of red quartzite-sandstones and sandstones. They are characterized by horizontal bedding and oblique lamination, ripple marks and desiccation cracks. The Vepsian sedimentary rocks, together with the internal gabbro-diabase intrusion and the horizon composed of several lava flows, form a gentle asymmetrical syncline cut by faults trending northwest and northeast with a vertical displacement of tens or even hundreds of metres.

The section considered is a summarized one of the Karelian complex (the Lower Proterozoic) in the Karelian area and it occurs in more or less complete form in all structural zones.

In the Kola Peninsula the Svecokarelian sedimentary-volcanogenic complex is characterized by formations largely analogous to those considered above, but differing from them in persistency, completeness of the section and in the much higher volume of volcanogenic rocks. It has developed mainly within the Pechenga-Varzuga zone but also in a number of smaller structures or their fragments that have survived erosion and thus permit the boundaries of the Kola Karelide system to be outlined. In a generalized section (Fig. 1), the complex reaches 16—18 thousand metres in thickness and in the sections of Pechenga-Varzuga zone 10—12 thousand metres. It can thus be distinguished as one of the most representative Svecokarelian zones in the eastern part of the Baltic Shield. The complex is divided into a number of stratigraphic units, i.e. suites and groups, which correlate well enough with the Sumian, Sariolian,

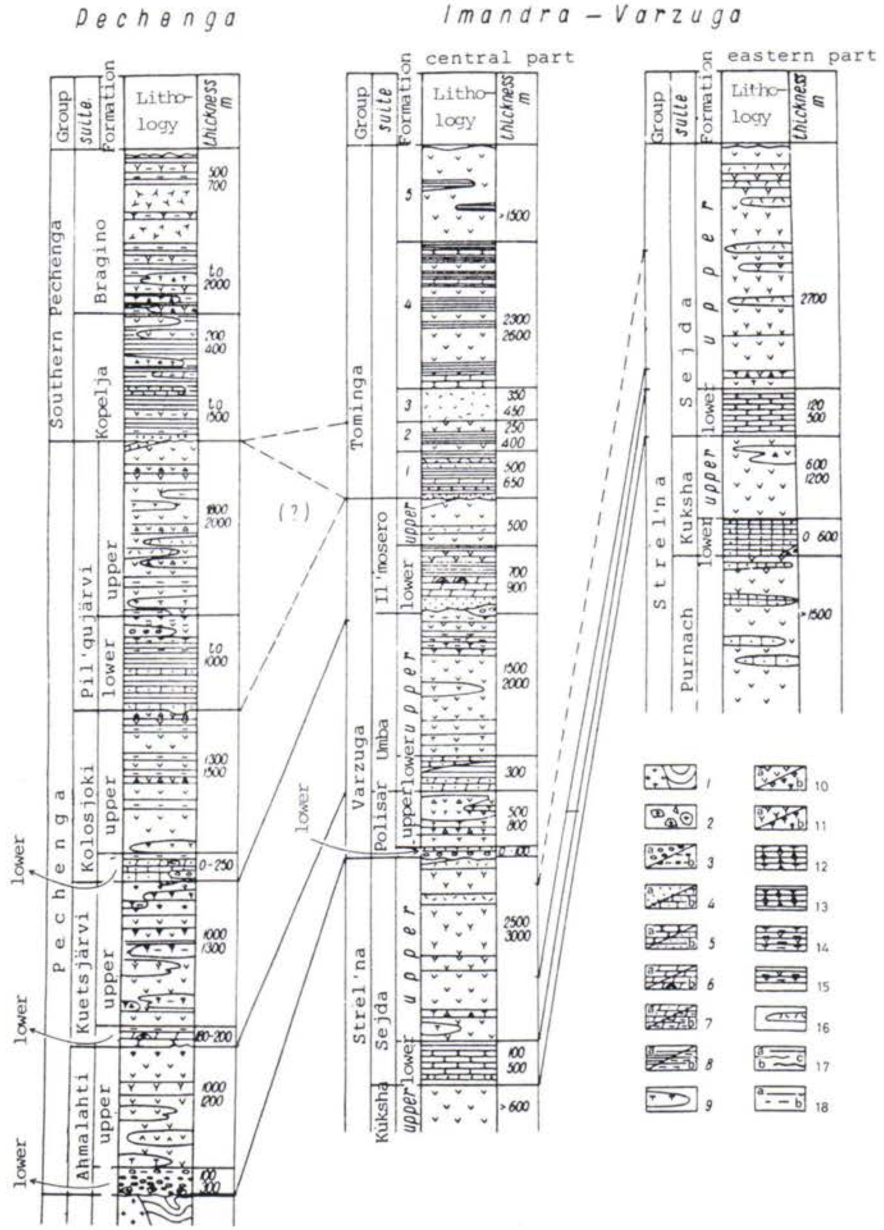


Fig. 1. Summarized stratigraphic column of the Svecokarelian complex of the Pechenga-Varzuga zone. Symbols: 1. Granites and gneisses of the basement of the Karelides; 2. Polymictic conglomerate-breccias (eluvial-diluvial); 3. a) polymictic conglomerates and gravelstones, b) conglomerates with tuffogenic cement; 4. a) volcanomictic gravelstones and sandstones, b) polymictic and arkose sandstones and siltstones; 5. a) quartzites, sericitic quartzites, feldspar-quartz sandstones and siltstones, b) thinly laminated cherts and micasiliceous schists; 6. a) dolomites, b) organogenic dolomites; 7. a) sandstone dolomites with tuffogenic material; 8. a) phyllites and siltstones and sandstone phyllite-like schists, b) tuffites and tuffogenic schists; 9. Picrites (eruptive) and closely similar melanocratic metabasalts; 10. a) diabases, porphyrites, pillow lavas of basaltic and b) trachybasaltic compositions; 11. a) porphyrites and other effusives of andesitic and b) trachyandesitic compositions; 12. Rudaceous volcanoclastic rocks, lava breccias, tuff breccias of a) picritic, b) basaltic and c) andesitic compositions; 13. The same rocks of a) trachybasaltic and b) trachyandesitic compositions; 14. Tuffs of a) picritic, b) basaltic and c) andesitic compositions; 15. Tuffs of a) trachybasaltic and b) trachyandesitic compositions; 16. Andesite-dacite and dacite porphyrites, porphyries and their lava breccias and tuffs; 17. The boundaries of stratigraphic subdivisions; a) conformable (members, formations, suites), b) with previous washout (suites, groups), c) with washout and angular unconformities (groups and complexes); 18. Correlation lines, a) established, b) inferred.

Jatulian, Ljudian and Kalevian (Ladogian) of Karelia and Finland.

The complex begins with the Strel'na group, which includes the Purnach Kuksha (Rizhguba) and Seidorechka suites. Their contacts with the Archean formations are mostly tectonic, cutting unconformably the old structures. Only in the region of the Moncha Peninsula in the basal series on the Archean gneisses and granites has a crust of physical weathering with alluvial breccia been developed that is analogous to the Sumian one in Karelia. The Kuksha and Seidorechka suites are in contact with the basement in the eastern part of the Imandra-Varzuga structure. Their contacts, although usually tectonized, are close to the normal stratigraphic ones.

The Purnach suite, which begins the Strel'na group, is composed of metavolcanites of basaltic composition including horizons of polymictic sandstones partly with a carbon-bearing cement. The Kuksha and Seidorechka suites, which are the next units of the section, are represented by an alternation of sedimentary and volcanogenic rocks repeated twice. The sedimentary rocks of the Kuksha suite are gravelstones, polymictic sandstones, more seldom sandstones with carbonaceous cement, pelite and carbon-bearing shales; those of the Seidorechka suite are predominantly quartzites that are rather homogeneous in the section and along the strike; pelitic shales or cherts are less common. The volcanites of the three suites form a series from basalts, andesite-basalts to andesites and dacites. The majority are homogeneous lavas. Also integral to the composition of the Seidorechka suite are the explosive formations: horizons of volcanic bombs, tuffobreccia and tuffs associated with komatiitic basalts in the lower part of the section; tuffs and ignimbrite-like rocks of andesite-dacite composition in the upper part. The total thickness of the sedimentary rocks of the Strel'na group reaches 1000—1200 m; the volcanogenic rocks account for 5000—6000 m. Of great importance are the sills of gabbro diabases and melanocratic komatiitic metaporphyrites of layered peridotite-pyroxenite-gabbro-norite with an age of about 2.4 Ga. The Pechenga and Varzuga groups and the formations correlated with them represent a higher part of the complex. In all cases these rocks occur on the rocks of the Strel'na group or of the Arhean basement with an angular and stratigraphic unconformity and weathering crusts and conglomerates at the base. The lower parts of The Ahmalahti suite, which begins the section of the Pechenga group, is composed of eluvial-talus breccia, poorly rounded cobbles, and rounded stones (gneiss-granite, gabbroids, gneisses) from the underlying rocks, boulder-pebbles and mainly granitic conglomerates, which alternate with gravelstones, coarse-grained psammites, sandstones and tuffites, thus forming a stratum 250—300 m thick that is discontinuous along the strike. In its upper part the interbedding of sedimentary, tuffogenic and extrusive volcanogenic rocks grades into the volcanite formation. This formation is represented mainly by andesite-basalt metaporphyrites. Beds of picrite metaporphyrites are present in the lower part, and beds and lenses of andesite porphyrites, volcanic breccia and tuffs higher up, whereas andesite vesicular lavas and meta-amygdaloids predominate in the top part. The total thickness of the volcanogenic formation is 1100—1300 m.

A shallow weathering crust developed on the metaamygdaloids of the Ahmalahti suite. Rocks of the Kuetsjärvi suite occur subconformably on them. The lower parts of the Kuetsjärvi suite are made up of chlorite schists, grey sandstones, quartzitic sandstones, brown hematite cherts, light quartzites with lenses of fine-pebbled quartz conglomerates, sandstones and organogenic dolomites, dolomitic autobreccia cemented by tuffogenic material, tuff schists and tuffs to a total thickness of 250 m. Higher up there is a formation of volcanogenic rocks characterised by a section up to 800—1100 m thick of picrite-basalt, trachyandesite-basalt, trachyandesite porphyrites, albitophyres, ignimbrite, welded tuffs, volcanic breccia, tuffs and tuff schists often with features of discontinuous sub-aerial volcanism.

The section continues with the Kolosjoki suite, which occurs with a washout and an angular disconformity on the Kuetsjärvi volcanites. The sedimentary formation 100—200 m thick or even up to 300 m is made up of polymictic gravelstones and sandstones filling paleofluvial cuttings; of deltaic and near-shore arkose gravelstones and sandstones with interbeds and lenses of conglomerates that include the weathering products of underlying volcanites with appreciable magnetite and hematite, sometimes hematite oölites, lenses and fragments of jasper-like cherts; of well-graded sandstones, siltstones and diverse hematite-bearing and silicified dolomites containing stromatolith inclusions; and of tuff schists and tuffs of intermediate and picritic composition. Volcanogenic formations of the Kolosjoki suite are represented by homogeneous tholeiitic andesite-basaltic porphyrites and pillow lavas. Horizons of tuff schists, tuff, tuff-breccia and agglomerate lavas 50—100 m thick have been observed in the middle and upper part of the sections. The total thickness of the volcanogenic formation is 1500—1800 m.

The Pil'gujärvi suite lies on the volcanogenic rocks of the Kolosjoki suite without a visible disconformity but with some features of an interval. Its lower part consists of thick (800—1000 m) strata of tuffogene-sedimentary rocks: serictic schists and chlorite-pelite shales (phyllites), siltstones, arkose sandstones, sometimes containing current-bedded lenses of fluvial gravelstones and polymictic conglomerates, beds of carbonaceus and sulphide-bearing black schists, tuffogene schists and tuffs, and more rarely (in the upper parts of the section) lenses of coarse basic tuffs and picritic flows of extrusive lavas. Layered bodies of gabbro diabase and gabbro wehrlite intrusions constitute a considerable volume of the strata. The volcanogenic formation, which is the upper part of the suite, grades into the sedimentary strata. It is composed mainly of pillow lavas of tholeiitic-basaltic composition and to a lesser extent of tholeiitic and picritic porphyrites. There are numerous beds of tuff-breccia, tuffs and tuff-schists, more rarely beds of andesitic porphyrites, quartz-porphyries and their tuffs. Geological data indicate that the volcanogenic section is up to 2000—2500 m thick, but geophysical data imply that is is 4000 m thick (Litvinenko, Lenina 1968).

The Varzuga group, which is correlated with the Pechenga group, is represented by the Palisar, Umba and Il'mozero suites and has a section which may be compared with that of Pechenga. Details of the sections point to essential differences, however. First, the Varzuga group occurs on the volcanites of the Strel'na group but not on the Prekarelian granite-gneiss basement as does the Pechenga group; this is also apparent in the composition of its terrigenous rocks, especially in that of the basal conglomerates. Second, during the formation of the Varzuga group the volcanic process often coincided with sedimentation and so the volcanite beds are observed in sedimentary strata at different levels, and the relations between the sedimentary and volcanogenic formations are less well defined. Finally, the upper part of the Varzuga group (the Il'mozero suite) is considerably reduced, especially in its volcanogenic part. It is less developed than the Kolosjoki suite and its analogy with the Pilgujärvi volcanogenic formation is still not clear.

The possibility of distinguishing the upper group of the Karelian complex in the Kola peninsula has only recently been suggested (Zagorodny *et al.* 1978), which is why not enough attention has been paid to subject as yet. The South Pechenga and Tominga groups, situated in the southwestern zones of the Pechenga and Imandra-Varzuga graben-synclinoria, respectively, are inferred to be upper Karelian. The South Pechenga group occurs subconformably on the volcanites of the Pilgujärvi suite and two suites can be distinguished in it, the Kaplya and the Bragino. The Kaplya suite is composed of rhythmically bedded terrigenous and tuffogene phyllite-like schists containing variable and sometimes large amounts (up to 12—15 %) of carbonaceous substances: siltstones and sandy shales with carbonaceous cement, and carbonaceous cherts, and in the upper part of the section beds of porphyrites, pillow lavas and tuff-breccia of tholeiitic basalt composition. These deposits are a few hundreds of metres thick. The total thickness of the Kaplya suite is 1550 m. The Bragino suite consists mainly of tuffogene and extrusive andesite-like rocks: terrigenous schists, picritic tuffogene material, lenses of picrite tuff breccia and single beds of picritic basalts. All the rocks are intensely mylonitized along the system of longitudinal faults and thrusts. Tentative estimates place the thickness at 1500—2000 m.

The section of the Tominga group is similar in composition. Various schists predominate. Carbonaceous rocks and cherts are present. Intermediate volcanites up to rhyolites and trachytes play an important role and there are some basaltic and picrite-basaltic beds. Comagmatism of the trachytes with the alkaline granite syenite has been established and the age is estimated to be about 1900 Ma (Batiyeva *et al.* 1983). Some compositional and structural features and the age indicate that the formations of the South Pechenga and Tominga groups are comparable with the Kalevian of Finland. An age close to that given above (1900—1800 Ma) is a feature of a number of granitoids and metamorphic parageneses widely spread throughout the territory studied and it very likely represents the Late Karelian cratonization of the earth's crust.

No discussion of the Svecokarelian geological history of the eastern Baltic Shield should omit the continental earth's crust, which formed here and already proceded to the platform evolution stage in the Late Archean about 2.7—2.8 Ga ago. This and the singularities in the composition, structure, sedimentation conditions, magmatism, and regional metamorphism of the Svecokarelian sedimentary-volcanogenic complex, which was formed during the next geotectonic megacycle, permit this period to be interpreted as one of the development of the intracontinental platform-riftogenic system (Zagorodny 1975, 1980). We must therefore distinguish a number of lengthy stages in its history.

The first stage, say the Sumian, included singling a riftogenic region out of the platform and the initial development of the riftogenic zones. It comprised mainly destructive processes: nonuniform uplifting of the territory, crushing (thinning) of the lithospheric plates, formation of the fracture system and development of the fracture depressions during extension of the earth's crust. The intense denudation of the ancient folded structures and the emplacement of some intrusions of basic rocks and granitoids are probably related to the singling out and uplifting of the region.

The formation of the fracture systems and fracture depressions was followed by an intense andesite-basalt, komatiite-basalt and, in the final phases of the stage, andesite-dacite volcanism, giving rise mainly to fissure eruptions and, to a lesser extent, explosions. The total thickness of the volcanites in the Imandra-Varzuga structure was 5000—6000 m, in the structures of the North Karelia zone 2000—2500 m, and on the Fenno-Karelian massif tens to hundreds of metres. The formation of some intrusions is related to the phase of komatiite-basalt volcanism, best represented in the lower parts of the Seidorechka suite. These intrusions include important layered massifs of periodotite-pyroxenite-gabbronorites such as the Monchegorsk, Pana and Fedorova tundras in the Kola peninsula; the Kivakka, Tsypringa and possibly the Burakov massifs in Karelia; Porttivaara, Koitelainen and Kemi in northern Finland and others. The isochronous age, measured for a number of massifs, is 2400—2450 Ma, which proves that they belong to Sumi. It should also be noted that the location of the intrusive massifs and some of the volcanogenic formations is controlled by structures that are not only sublatitudinal with a north-west trend, as is typical of volcanotectonic depressions, but also by transversal structures, that is, with a northeast trend.

The sedimentary formations are very informative about the characteristics of the state of the earth's crust during the Sumian stage. The formations indicate that the Prekarelian basement blocks that separated the near-fault depressions were affected by non-uniform tectonic movements only during their formation, when their relief was rugged as is reflected in their rudaceous and poorly sorted sediments. Later they were stabilized and levelled and become overlain by mature and well-differentiated sediments. The shallow and compensated sedimentation and, finally, the great thicknesses of the sedimentary rocks undoubtedly indicate prolonged and rather retarded formation of rift valleys and intermittent volcanism. Some data show that the Sumian stage was completed during irregular, crustal shortening. Some parts of the rift valleys completed their development then (Radchenko 1971) and the formations that followed overlapped them with an angular unconformity. Some activation of plutonic and metamorphic processes may have taken place at this time.

The second stage of Svecokarelian evolution should evidently be designated Jatuli. It includes Sariolan, Lower, Middle, Upper Jatulian and Zaonezhje-Suisaarian suites of Karelia and their analogues in northern Finland and in the Kola peninsula, and is characterized by displacement, significant expansion and formation of new sedimentation basins and volcanic zones (Pechenga, Onega and other structures) throughout the eastern Baltic Shield. It was during this stage that the basins underwent their principal structural changes — from linear to gentle troughlike ones belonged to the same fault systems. The volcanism of that time was of andesite-basalt, trachybasalt-trachyandesite-dacite, and picrite-tholeiite-basalt composition. Significant fissure eruptions were accompanied by eruptions of a central type, and often of a surface type. The total thickness of the volcanites in the Pechenga-Varzuga zone is 4000—6000 m; in the North Karelian zone it is 2000—3000 m, in the northeast and east around the Fennokarelian massif 1500—2000 m, and on the massif less than 1000 m. The combination of longitudinal (northwest, here and there sublatitudinal) and transversal (northeast) faults is an important structural feature that has a marked impact on the location of the volcanites as it had during the previous stage.

The sedimentary formation sections demonstrate clearly the main evolutional feature, i.e. recurrence (rhythm). The formation and suites usually begin with coarse-grained rocks indicating active tectonic processes. Later, movements gradually calmed down both in the sedimentation basins and in the washout areas. Mature highly differentiated rocks were formed, and local washouts are seen in the sections as are consedimentation breccias, desiccation fissures and other features of shallow-water compensated sedimentation. The appearance of the first volcanogenic rocks signals the revival of movements, but these are of a more local character and possibly closely connected with the volcanogenic apparatus. Four to five such cycles can be distinguished in the Jatulian history of the eastern Baltic Shield with different degrees of completeness and uniformity. These data together with the peculiarities of the structures, migrations of the sedimentation basins, and thicknesses of the sedimentary and volcanogenic formations indicate tectonic zonation in which it is possible to single out the most active zones (riftogenic) and those developed under more stable conditions (up to platform ones). The zone with the marine Jatulian deposits framing the Fenno-Karelian massif in the west should probably be referred to as a special type, that is, as a zone of a mobile shelf.

The third Kalevian stage is the most completely developed and comprehensively studied in the Svecofennian province. It is represented by typical miogeosynclinal strata unconformably overlying the platform Jatulian. In the eastern part of the Baltic Shield sedimentary and sedimentary-volcanogenic formations of the Oraniemi-Kumpu zone and the south Pechenga, Tominga and Besovets groups are probably analogues of the Kalevian rocks, and the Vepsi of South Karelia is probably its uppermost unit. They occur on the volcanites of the previous stage without any significant interval but always with an angular unconformity due to a shift of the sedimentations basins. These basins were probably residual troughs in which highly differentiated sedimentary rocks accumulated interbedded with tuffogene, sometimes rudaceous and volcanogenic rocks mainly andesite and andesite-dacite in composition. The instability of the facies condition at that period is shown by the lens-shaped structure of the sections and by the presence of diverse rocks, from picrites to rhyolites, among the volcanites.

There are grounds for supposing that the formations of this stage, which were similar to orogenic and platform ones, were formed during increasing crustal contraction and gradual reduction of sedimentation basins. In the Kola peninsula they indicate the termination of the riftogenic system under conditions typical of this process. These conditions gave rise to isoclinal folding and horizontal movements of the crustal plates, especially in the marginal parts of the Karelian structures, and to intesive reconstruction of the ancient Archean structures conformably with the Karelian deformations throughout practically the whole region. Associated with the initial stages of the progressing crustal contraction are the emplacement of gabbroid and gabbro-wehrlite intrusions, and with later stages the emplacement of granitoids and the high-gradient regional metamorphism. As already mentioned, this regional metamorphism was connected genetically and temporally with the final stage of the development of the geosynclinal area in Central Fennoscandia, i.e. with its orogeny. It covered a long period (from 1.9 to 1.7—1.6 Ga) and resulted finally in complete consolidation of the earth's crust throughout the Baltic Shield.

The Riphean complex (Middle and Late Proterozoic) is represented by sedimentary and to a lesser extent by magmatic formations and does not play an essential role in the structure of the Baltic Shield. It has developed in the Shield periphery and in some inner depressions. The formations of the middle and the upper Riphean and Vendian are distinguished by their composition. The Riphean complex is a sparagmite group at the base of Caledonides in Norway; the Rybachy, Kil'din and Volok suites on the Murmansk sea coast of the Kola peninsula; the Tersk and Chapoma suites on the southern and southeastern coast of the Kola Peninsula; the Riphean and Vendian deposits of Onega-guba and the Vetreny Belt; the Salmi suite in the northern Ladoga area; Jotnian and Subjotnian grabens in Muhos and Satakunta in Finland and others. Independent of their location, composition and structure, the formations of the Riphean complex always occur stratigraphically and structurally unconformably on the deeply denudated Svecokarelian crystalline basement. The interval indicated by the unconformity is estimated to be at least 200—300 Ma. No crusts of deep chemical weathering are known to exist in the basement of the Riphean complex, which indicates a high uplifted position of the earth's crust until the beginning of the Riphean sedimentation and continuous removal of weathering products. The section and the interrelations between the subdivisions of the Riphean complex and their relative stratigraphic position have been discussed by many authors (Keller, Sokolov 1960, Sergeyeva 1964, Becker *et al.* 1974 and others). Therefore we shall not analyse them in detail, merely mention that the composition and thickness of the deposits permit us to distinguish formation of shallow basins (the Tersk and Chapoma suites; the Salmi suite; the

Jotnian and Subjotnian grabens in Muhos and Satakunta) and of the mobile shelf (the Rybachie, Kildin and Volok suites, and the sparagmite group). From the point of view of geotectonics, the Tersk, Chapoma, Kild'in and Volok suites, the Salmi suite and the graben deposits in Muhos and Satakunta are formations of the epikarelian platform mantle; the Rybachine suite adjacent to the Kola peninsula in the north is probably part of the folded Ripheide-Tiemanide system as suggested by its fracture system; and the sparagmite group is related to the formation and development of the Riphean-Caledonian Grampian geosynclinal area.

The character and distribution of the Riphean deposits indicate that the Riphean Baltic Shield represented a passive peneplain that had a tectonically active boundary only in the north.

Although less common than the deposits of the Riphean complex, the Paleozoic deposits of the Baltic Shield are very important to our understanding of some structural features and the history of the Shield. The Paleozoic formations are composed of the deposits of the Oslo graben in the west, the Lovozero suite xenoliths of the sedimentary and volcanogenic rocks in the Lovozero and Khibiny plutons of nepheline syenites, the Kontozero volcanogenic-sedimentary series of the caldera-like depression of the Kontozero alkaline massif in the Kola peninsula and Cambro-Silurian deposits, which are part of the platform mantle framing the Baltic Shield in the south.

The age of the formation of the Lovozero suite and Kontozero series has been established by the relics of Devonian and Carboniferous flora in sedimentary and tuffogene rocks. Volcanogenic rocks represented by picrite-basalts, alkaline basaltoids and others indicate a gentic relation between the volcanite association, the Caledonian-Hercynic massifs of alkaline ultrabasic rocks and the massifs of agpaitic nepheline syenites. The geotectonic location of all the formations is defined by the fracture system and graben-like depressions, which were formed during the Caledonian-Hercynic activation of the earth's crust of the Baltic Shield (Gorbunov *et al.* 1978). The concept is corroborated by data collected by Afanas'yev (1977) demonstrating that during the period preceding the graben formation, partly synchronously with it and later, during the Mesozoic, the Shield territory as a whole was an area of active washout in contrast to the southern slopes, where crusts of deep chemical weathering were formed and products of their rewashing accumulated.

Epochs and structural-formational zones of nickel-copper ores of the eastern Baltic Shield

The review of the geology and history of formation of the major provinces and structural zones of the Baltic Shield given in the previous chapters throws light on some regional aspects of nickel metallogeny, primarily the problem of the historical and structural position of nickel-bearing and potentially nickel-bearing mafic and ultramafic intrusions and the features of magmatism of some structural zones. Our data may be of great importance in further attempts to solve the problem as, in our opinion, although the relation between sulphide nickel-copper ores and basic and ultrabasic magmas is well established, at the same time it is also known that not all the undoubtedly nickel-bearing mafic and ultramafic intrusions exhibit mineralization of any kind, let alone on an economic scale. The problem extends to the neighbouring massifs with a similar postformational history. Hence their mineralization may be attributed to processes or conditions that took place before or during their separation from the parental magma.

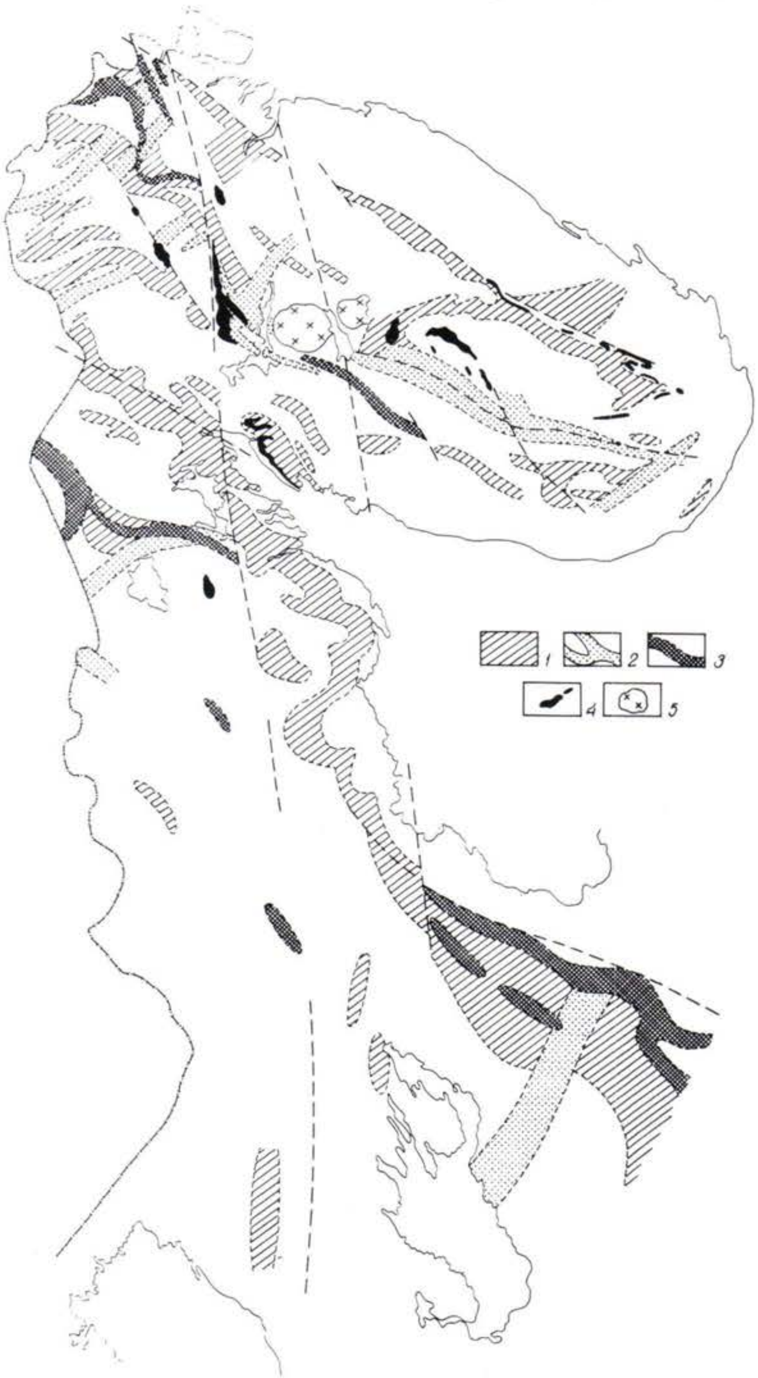


Fig. 2. Areas of occurrence of nickel-bearing and promising nickel-bearing mafic and ultramafic rocks in the eastern part of the Baltic Shield. 1 — areas of mafic-ultramafic intrusions of the Archean and non-established ages; 2 — areas of the Early Svecokarelian (Sumi) mafic-ultramafic intrusions; 3 — areas of the Late Svecokarelian (Kaleva) mafic-ultramafic intrusions; 4 — large massifs of gabbroids and gabbro-anorthosites; 5 — massifs of alkali nepheline syenites.

Regional factors are likely to play an important role in governing these processes.

In the long and varied history of the eastern part of the Baltic Shield several periods of intense basic and ultrabasic magmatism can be distinguished when thick volcanogenic series accumulated and intrusive mafic and ultramafic rocks formed (Fig. 2). The first indications of their ore content has usually been obtained during prospecting. Follow-up geological, petrological and geochemical investigations have then aimed at establishing their formational relationships and metallogenic specialization as well as their characteristic and distinguishing features.

The oldest intrusions with a promising nickel content crosscut the Upper Archean gneissic amphibolite strata of the Lopian and Kola-Belomorean complexes. These include ultramafic massifs of the Vetreny Belt, the Hautavaara zone and the Kolmozero-Voronja zone, the massfis of gabbro-norites and gabbro-websterites, clinopyroxenites and wehrlites and gabbros, lherzolites and websterites of the Lotta-Sal'nye tundras and Kolvitsa zones, and those of smaller structures. Effusive bodies may also be among them. All these formations require more comprehensive studies. Some of them have been shown to be comagmatic with the metamorphosed effusives of basalt and basaltic komatiite composition met with in sections of the Upper Archean supracrustal strata. For a number of others the structural relation has been determined. There is a lack of reliable data on the age and structural position of these massifs. Since the zones, within which they developed have mostly undergone intense Karelian deformations, it has been proposed that the massifs may have a younger, Karelian age.

A low-grade nickel-copper mineralization has been established in the ultrabasites of the Vetreny Belt and Hautavaara zone and in the websteritic gabbro-norites and gabbroic lherzolitic websterites of the Lotta Sal'nye tundras and Kolvitsa zones. Studies on the potential ore content of the massifs of other zones (Kolmozero-Voronja, Belomore, etc) continue.

The next group of nickel-bearing formations includes the ultrabasites and gabbro-ultrabasites along the southern rim of the Pechenga-Varzuga zone of Karelides (Allarechka, Annama, Strel'na regions) and in the block-anticline uplift that divides it (Titovka region). Their age is a subject of controversy. Since these formations have not been found inside the Karelian supracrustal complexes a number of investigators consider them to be Archean (Zak *et al.* 1972). They occur, however, only within the sphere of influence of the Karelian structures and are geochemically related to the Karelian mafic and ultramafic intrusives. Low-grade nickel-copper mineralization is in most cases associated with them, but small deposits of high-grade ores of the Allarechka type are also known.

During the Early Karelian period (the Sumian stage) large layered massifs of gabbro-noritic peridotite-pyroxenites were formed in the area under consideration. These are the massifs of the Fedorova and Pana tundras and the Monchegorsk pluton, the massifs of Mount Luostari, Tsypringa and Kivakka, probably the Burakov massif and a number of others. Their analogues in Finland are the intrusions in the regions of Kemi and Koillismaa and some others. The nickel content of most of them has been established by explorational measures. Low-grade disseminated ores are usually associated with them but high-grade veined ores of the Monchegorsk type are also known. Abundant small intrusivens, sometimes with a poor disseminated mineralization, together with the above ultrabasites and gabbro-ultrabasites in the rim of the Pechenga-Varzuga zone of Karelides, may be included in this age group. They are all supposed to derive from related magmas emplaced under various structural-facial conditions. Certain features favour their common parentage. First, their location is controlled by the system of longitudinal and transversal faults of the formation period and the initial development of the Karelian riftogenic system (Fig. 2); the crossings of faults are especially favourable. Second, the geochemical relationship between the intrusions and comagmaticity with the komatiitic basalts of the Strel'na series of the Karelian complex has been established. Their geological position and isochronic age data (about 2450 Ma) are consistent with these conclusions.

The last and the most productive epoch of nickel-copper ore formation in the eastern part of the Baltic Shield is related to Late Svecokarelian ultramafic magmatism, when nickel-bearing intrusives of gabbro-wehrlites and peridotites of the Pechenga-Varzuga zone, the Vetreny belt, the Kuolajärvi zone, the Kotalahti zone and others were formed. Their age is about 1900 Ma, and their location is controlled by a fracture system and fold structures of the Late Svecokarelian period. Picritic lavas of the Pechenga-Suisaarian and Kalevian supracrustal strata are comagmatic. The location of mafic and ultramafic rocks (and in the Pechenga-Varzuga zone that of nickel-copper mineralization) is evidently closely related to the intensity, character and composition of the volcanism.

A brief look at the epochs and structural-formational zones of nickel-copper ore formation in the eastern part of the Baltic Shield shows that this type of mineralization is always closely related to parent mafic-ultramafic massifs whose age is mainly Svecokarelian and whose distribution is controlled by folds and fractures of Karelides. The age of other promising, nickel-bearing mafic-ultramafic formations, which are conventionally referred to as Archean, has not been established, and their location, also controlled by the Karelian structures, wholly contradicts this concept. Thus, it is evident that during the Precambrian of the eastern part of the Baltic Shield Ni-Cu ore formation was confined to the Svecokarelian period. Two epochs were productive: the early Sumian and the Late Svecokarelian.

These concepts also agree with the geotectonic viewpoints. During Svecokarelian time various endogenic regimes and conditions, including those characteristic of the Ni-bearing provinces of the world, existed and evolved in the Baltic Shield. These are the regimes that gave rise to the intense intracratonal epiplatform volcano-tectonical system that we consider to be riftogenic. The tectonic zoning formed during the development of the regimes evidently controlled the intensity and type of volcanism, the location of mafic-ultramafic formations and their metallogenic specialization.

THE NICKEL AREAS OF THE KOLA PENINSULA

G. I. GORBUNOV, YU. N. YAKOVLEV, YU. V. GONCHAROV, V. A. GORELOV and V. A. TEL'NOV

There are six areas of Cu-Ni mineralization in the Kola Peninsula: Pechenga, Allarechka, Monchegorsk, Imandra-Varzuga, East Pechenga and Lovnoozero (Fig. 3). Some small ore showings have been found in the Salny and Kolvitsa tundras, the South Kola structural zone.

The majority of the deposits are confined to the Pechenga-Varzuga structure-facial and metallogenic zone composed of early Proterozoic effusive rocks of andesite-basalt, subalkali-basalt and picrite-basalt formations and tuffogenic-sedimentary rocks. The nickel-bearing intru-

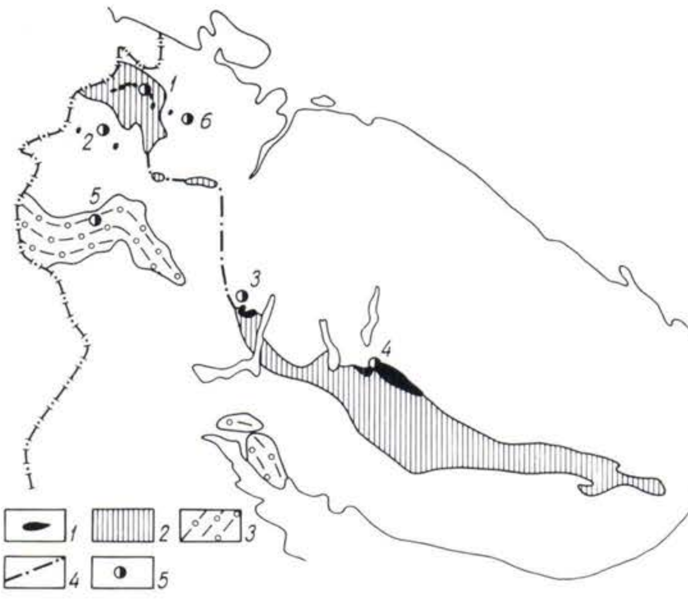


Fig. 3. Major nickel areas of the Kola peninsula. 1 — Pechenga, 2 — Allarechka, 3 — Monchegorsk, 4 — Imandra-Varzuga, 5 — Lovnoozero, 6 — East Pechenga. Symbols: 1 — mafic and ultramafic intrusions, 2 — Pechenga-Imandra-Varzuga supracrustals, 3 — granulite, 4 — fault, 5 — nickel area.

sives, which occur as phacoliths, are located mainly along exfoliation and foliation surfaces within faulted tuffogenic-sedimentary strata (Pechenga) or along faults at their contact with the Kola-Belomorian gneisses (Monchegorsk pluton, Fedorova and Pana tundras, Mount Luostari).

Less frequently the nickel-bearing intrusives are confined to faults within the gneisses and amphibolites underlying the Pechenga-Varzuga zone at sites that have undergone structural reworking, viz. Allarechka and East Pechenga areas, and individual ore showings in the Monchegorsk (Priozernoye) and Imandra Varzuga (Lastyavr) areas. The deposits and ore showings in the Lovnoozero area are located within the rocks of granulite formations at some distance from this zone but they exhibit a number of structural features resembling those of the deposits and ore showings in the other nickel areas.

The formation of the Ni-Cu sulphide deposits of the Kola region is related to the Kola-Belomorean (2800—2600 Ma) and Karelian (2600—1700 Ma) metallogenic stages.

The nickel-bearing massifs are classified into five magmatic series: gabbro-noritic websterites, pyroxenitic gabbro-lherzolites, noritic pyroxenite-peridotites, ultrabasites and gabbroic-wehrlites. The first series belongs to the Kola-Belomorean stage, the remainder to various periods of the Karelian stage.

Only one of the above types of massif predominates in each nickel area. The gabbroic wehrlite series is most productive in terms of Ni-Cu mineralization, the ultrabasite and noritic pyroxenite-peridotite series being somewhat inferior in this respect. One deposit and a number of ore showings are related to the massifs of the gabbro-noritic-websterite series, and individual ore showings are associated with the massifs of the pyroxenitic gabbro-lherzolite series.

The Pechenga area

The Pechenga area is located in the extreme northwest of the Murmansk region. Nickel-bearing rocks were first discovered there by S.A. Konradi (1913), a Russian geologist who was searching for a continuation of the Sydvaranger iron ores (Norway). During the period 1920—1960 when the Pechenga district belonged to Finland under the peace treaty of Tartu, it was studied by Finnish geologists Hausen (1925, 1926), Tanner (1928, 1929), Wegmann (1929a, b) and Väyrynen (1938). In 1921 H. Törnqvist discovered nickel pyrrhotite on a slope of the Kotseljoki river valley. The finding encouraged a further search for Ni-Cu sulphide ore. The Pechenga deposits were first described in a monograph by Väyrynen (1938).

Since 1944 the Pechenga district has been studied by Soviet geologists. Significant contributions to our knowledge of the Ni-Cu deposits have been made by numerous authors, including G. I. Gorbunov, M. A. Yeliseev, D. F. Murashov, G. V. Kholnov, E. N. Yeliseev, V. G. Zagorodny, Yu. A. A. Astaf'yev, Yu. N. Neradovsky and V. A. Gorlov. Results of investigations of paramount interest have been published in the monographs »Ultramafic and mafic intrusions of Pechenga (Yeliseev, Gorbunov *et al.* 1961), »Geology and genesis of Ni-Cu sulphide deposits of Pechenga» (Gorbunov 1968), »Textures of Ni-Cu ore fields and deposits of the Kola Peninsula» (Gorbunov *et al.* 1978), and »Mineral deposits of the Kola Peninsula» (Gorbunov *et al.* 1981).

Geology of the area and the ore field

The Pechenga nickel area is located within the graben synclinorium of the same name covering the marginal NW part of the Pechenga-Varzuga structure-facial zone of the Karelides. The graben-synclinorium is about 70 km long and up to 35 km wide (Fig. 4). Its northeastern and central parts are made up of volcanogenic and sedimentary rocks of the Pechenga group with a total thickness of over 10,000 m. Its southwestern part is composed of rocks of the South Pechenga group. Granite-gneisses, gneisses and amphibolites of the Kola-Belomorean complex occur in its basement.

The Pechenga group consists of four suites (Fig. 1). Sedimentary formations occur in the basal parts of the suites, and volcanite formations in their upper parts. The first three sedimentary tuffogenic formations are shallow (up to 250—300 m), and are often discontinuous along the strike and dip. They are composed of conglomerates, sandstones, gravelstones (the first sedimentary formation), schists, quartzites, dolomites (the second one), and arkoses, gravelstones, conglomerates, jaspers, tuffs and schists (the third one). The fourth sedimentary formation, which is up to 1000 m thick, is composed of phyllites, sandstones, siltstones, tuffites and tuffs with individual layers and beds of pyrite mineralization. It is penetrated by numerous intrusives of gabbro-diabases and nickel-bearing mafic-ultramafic rocks of the gabbro-wehrlite association. All the known Ni-Cu deposits and ore showings are within this productive set of strata. Individual ore showings confined to the NW-trending dislocations occur within the volcanites of the third formation. The volcanite formations are 100—4000 m thick and consist of porphyrites of various compositions (andesite-basalt, trachyandesite-basalt, tholeiite and picrite). The strata are composed of albitophyres, spherulitic lavas of tholeiite-basalt composition and tuffs. The fourth volcanite formation is the thickest and most composite one and covers up to 40 %, of the graben-synclinorium area.

A wide trough is conspicuous in the central part of the NE-trending limb of the graben synclinorium. It is oriented across the general strike of the graben synclinorium and causes the arched shape of the limb (in plan). The sedimentary-volcanogenic rocks have attained their maximum thickness in this »structural trench». What is more, all the rocks of the NE limb are compressed into longitudinal and transversal folds, the latter plunging southwards along the dip of the rocks.

The NW-trending, deep-seated Poritash fault marking the axial part of the graben-synclinorium

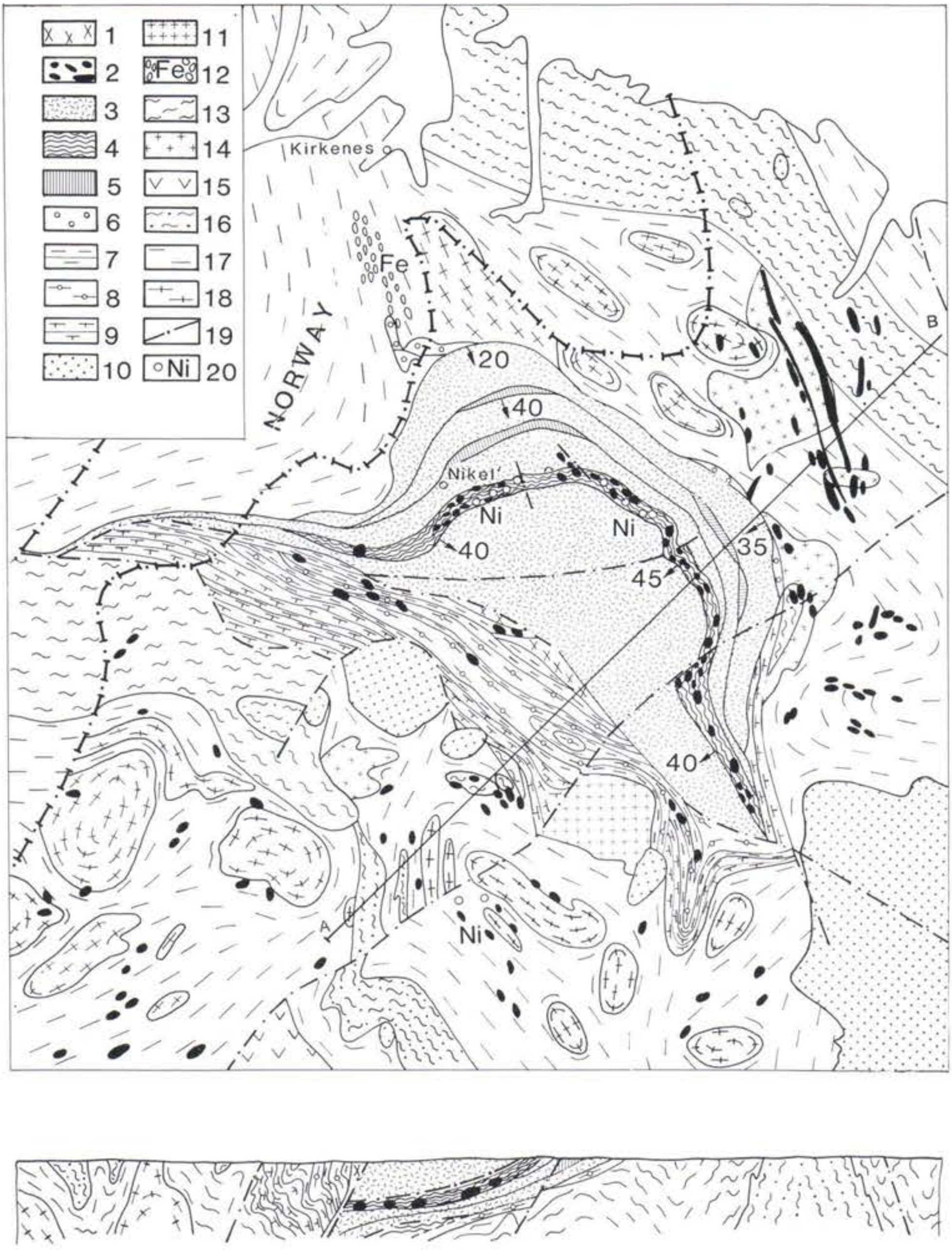


Fig. 4. Schematic geological map and the Pechenga area. Compiled by G. I. Gorbunov on the basis of data from K. D. Belyaev, V. G. Zagorodny, N. A. Kuryleva, V. F. Stupitsky, A. A. Polkanov, O. Holtedahl and the author. Proterozoic: 1 — plagioporphyrite; 2 — ultramafic and mafic rocks; the Pechenga suite; 3 — effusive diabase, metadiabase, amygdaloidal rock and tuff; 4 — phyllite and tuffite; 5 — dolomite, quartzite and arkose; 6 — basal conglomerate; the Upper Pechenga suite; 7 — quartz-biotite, quartz-biotite-amphibole, quartz-carbonate and carbonaceous schists; 8 — schistose metadiabase; 9 — schistose amphibolite, amphibolite, amphibole and mica schists and quartzites; 10 — microcline and plagio-microline granite; 11 — granodiorite. Archean: 12 — iron ore formation (conglomerate, mica schist and ferruginous quartzite); 13 — bimica and garnet-amphibole-gneiss; 14 — oligoclase gneiss-granite; 15 — hypersthene gneiss-granite; 16 — garnet-biotite gneiss; 17 — mica gneiss complex; 18 — complex of the most ancient gneissic granodiorite; 19 — faults; 20 — nickel-copper deposits.

and feathering its sublatitudinal Luotn fault, the interstratal overthrust zones along the lower boundaries of all four volcanogenic sheets and the numerous faults and upthrows of different trends can be distinguished among the faults. The whole structure of the graben-synclinorium has affected that of the Pechenga ore-field, in which there are numerous dislocations caused by folding and faulting.

Transversal folds with their axes plunging southwards are the most pronounced. Folds plunging SE at 40°—45° are intensely developed in the western and central parts of the ore field. The large synclinal folds of this group are characterized by a short, steep SE limb and a long, gentle NE limb. The amplitude is 1000 to 1800 m. Many of them are distinguished by a complex deformed crest and can be traced through the whole productive set of strata. It is to such folds that the nickel-bearing massifs and Ni-Cu deposits are confined. The wide Kaula synclinal trough, which is clearly seen on the western flank of the ore field, encloses the richest Ni-Cu deposits in its crest.

The folds plunging SW at 30°—40° extend over the eastern part of the ore field. They are slightly asymmetrical, the NW limbs being somewhat longer than the SE limbs in the synclinal structures; the amplitude is up to 1000 m and more. The ore-bearing massifs are likewise confined to the large synclinal folds of this group.

As well as transversal folds, the productive strata include longitudinal sublatitudinal folds striking over hundreds of metres and lying en echelon.

The NW and NE-trending faults developed in the limbs of large synclinal structures with the same orientation, and longitudinal, interstratal tectonic zones that can be traced throughout the ore field are typical types of fault. On the western flank these zones (or a branched zone) have developed in the upper parts of the productive strata, but in the centre of the ore field and on the eastern flank they occur in both the lower and upper parts of its section. The tectonic zones are the most important structural elements controlling the emplacement of the nickel-bearing massifs and the location of the high-grade massive and breccia ores. They are attributed to the long multistage development of the oldest faults. The orientation of tectonic furrows on the gliding planes, the rock and ore fragments, and the deformation traces within the sulphide matrix of breccias define these zones as shift-overthrust structures. The transversal faults have cut and displaced them over a distance of up to hundreds of metres.

Intrusives of mafic and ultramafic rocks in the form of bed-like bodies within the productive strata outline the shape of large folds and plunge SE, S or SW at 30°—60° in conformity with the general trend of the rocks. Their dimensions range widely: the thickness varies from several to hundreds of metres, the strike length from 100—6000 m and their depth extends to 500—1000 m or more.

The spatial distribution of the intrusive in the productive strata is not uniform, about three-quarters of their total volume being concentrated in the central part of the ore field, in the area of the structural trench mentioned above. All the known economic Ni-Cu deposits are in the same place. The intrusive bodies on both flanks are few and small.

The gabbro-diabase intrusives and the nickel-bearing mafic-ultramafic intrusives can be distinguished from each other. The gabbro-diabases that intruded during the earlier phase of intrusive magmatic activity account for about one third of all the intrusive bodies discovered in the ore field. Their mineral composition is pyroxene (augite), plagioclase (albite), chlorite, leucoxene, epidote.

The nickel-bearing intrusives are divided into differentiated and undifferentiated intrusives. Age differences have not been established between them. The larger, differentiated massifs are of asymmetrical, coarse-banded structure. From bottom to top they are made up of altered wehrlite (serpentinite), pyroxenite and gabbro. Monzonite gabbro is occasionally encountered in the uppermost parts. Serpentinites and serpentinized peridotites account for up to 70 % of the volume of the massif and contain an ubiquitous sulphide dissemination. The undifferentiated massifs are commonly thin and composed of serpentinite and, less frequently, gabbro.

The mineral composition of the altered peridotite is serpentine, olivine (chrysolite), monoclinic pyroxene (titanaugite), chlorite, kaersutite, biotite, altered plagioclase, magnetite and sulphides. The olivine is usually wholly serpentinized. Judging from the pseudomorphs, it accounts for 45—60 % to 80 % of the rocks. The pyroxenites are composed of augite (up to 80 %), plagioclase (up to 10 %) and chlorite (up to 8 %). Actinolite, ilmenomagnetite, sphene and leucoxene are present in small amounts. The gabbro constituents are plagioclase (up to 30 %), monoclinic pyroxene (up to 30 %), chlorite (up to 20 %), amphibole, carbonate, ilmenomagnetite, apatite, sphene, epidote.

The diverse petrographic compositions of the intrusive bodies, and the presence of discrete peridotite and gabbro bodies together with the differentiated peridotite-pyroxenite-gabbro massifs indicate the heterogeneous composition of nickel-bearing magma brought about by the differentiation that took place before it intruded into the upper levels of the earth's crust.

The rocks of the dyke complex are widely developed. The dykes, which occur mainly among the differentiated intrusives, strike submeridionally and dip steeply. Their thickness ranges from fractions of a metre to several metres, less frequently to tens of metres, and their length from tens to hundreds of metres. In composition the dykes are diabase, gabbro-diabase, gabbro-porphyrite, fourchite, monchikite, metamorphosed olivine pyroxenite, picrite porphyrite and rarely syenite. The chemical compositions of the most abundant intrusive rocks of the ore field are given in Table I.

Regularities of deposit emplacement

The emplacement of the deposits in the Pechenga ore field is controlled by a whole complex of magmatic, lithostratigraphical and structural factors.

The bulk of the Ni-Cu ores occurs in the serpentinites and serpentinized peridotites: only a minor portion occurs in faults and extends to the enclosing schists beyond the host massifs as injected layers, small stringers and dissemination. Consequently, the formation of the deposits was totally influenced by the emplacement of the nickel-bearing intrusives.

Practically all the nickel-bearing intrusives are located in the ore field within the fourth set of sedimentary tuffogenic strata and their number increases proportionally to the increase in its thickness. Only a few small fissured bodies occur within te underlying volcanogenic rocks of the third sheet.

The location of the nickel-bearing massifs within the productive formation is controlled by folded and ruptured structures. All the economically important intrusives and the deposits related to them are confined to large transversal synclincal folds trending NW and NE. The large massifs exhibit a thickening in the crests of the folds, and the smallest massifs occur wholly within. The emplacement of the ore-bearing massifs is controlled by the interstratal tectonic zones along or close to the lower contact of the massifs with the enclosing schists. The longitudinal tectonic zones along the contact or within the ore-bearing massifs are also the main ore enclosing structures for the high-grade epigenetic ores.

The zone offsets are also important controlling factors for the emplacement of ore-bearing intrusives. The largest NW-trending offsets have been found in the area of the maximum trough of the structural trench, where they stretch beyond the sedimentary tuffogenic formation and penetrate far into the underlying effusive diabases (the Pahtajärvi suite). Smaller

Table 1. Chemical composition of ultramafic and mafic rocks of the Pechenga ore field.

	Samples								
	1	2	3(6)	4	5	6	7	8	9
SiO_2	34.97	35.85	34.92	35.93	35.68	35.42	35.33	34.46	35.88
TiO_2	1.08	0.66	0.85	0.94	0.95	0.76	0.78	0.70	0.84
Al_2O_3	2.03	2.24	2.58	4.72	3.20	2.42	2.52	2.33	2.22
Cr_2O_3	0.53	0.48	0.42	—	0.52	0.49	0.53	0.43	0.32
Fe_2O_3	11.91	9.54	9.33	7.12	9.20	10.19	9.11	9.55	10.00
FeO	11.90	8.35	9.27	8.75	9.62	7.54	8.54	7.77	8.70
MnO	0.20	0.21	0.14	0.15	0.18	0.19	0.22	0.20	0.25
MgO	29.32	33.21	31.54	29.36	27.98	30.66	30.04	32.01	29.82
CaO	1.81	2.00	1.28	0.66	2.07	0.59	2.49	1.76	3.00
Na_2O	0.11	0.04	0.09	0.20	0.22	0.03	0.08	0.11	0.20
K_2O	0.10	0.18	0.16	traces	0.20	0.08	0.12	0.20	0.14
P_2O_5	0.04	—	—	—	—	0.08	0.07	—	—
S	0.46	0.62	1.27	—	1.86	0.71	0.50	1.76	0.95
V_2O_5	0.15	0.01	0.03	—	0.02	0.01	0.05	0.02	0.02
CO_2	0.19	0.22	0.44	0.44	0.13	0.12	0.05	0.10	0.22
H_2O^-	—	—	—	—	—	—	—	—	—
H_2O^+	5.19	6.67	7.15	11.22	6.40	9.96	9.02	8.57	6.88
	—	—	—	—	—	Zn = 0.01	BaO = 0.29	—	—
Ni	0.16	0.34	0.51	—	0.78	0.46	0.10	0.63	0.39
Cu	0.02	0.03	0.14	—	0.35	0.10	0.02	0.26	0.04
Co	0.013	0.02	0.01	—	0.02	0.01	0.02	0.02	0.02
—O = S	—0.23	—0.31	—0.63		—0.93	—0.35	—0.25	—0.88	—0.42
Total	99.95	100.36	99.50	99.49	98.45	99.48	99.63	100.00	99.47

	Samples							
	10	11	12	13	14	15	16	17
SiO_2	32.56	35.50	36.42	46.40	41.51	47.09	52.80	36.47
TiO_2	1.10	0.74	5.81	1.58	3.23	2.68	1.50	4.21
Al_2O_3	2.04	2.30	5.64	8.27	9.28	13.96	13.68	4.26
Cr_2O_3	0.43	0.64	0.02	0.18	0.07	0.01	no	0.01
Fe_2O_3	14.00	8.75	8.32	3.23	6.14	6.07	2.27	9.95
FeO	8.58	10.43	16.55	10.95	12.86	10.88	9.15	16.76
MnO	0.32	0.21	0.23	0.15	0.252	0.209	0.19	0.18
MgO	27.28	31.57	9.61	16.31	8.52	3.54	1.99	10.62
CaO	1.46	1.93	13.92	7.52	9.62	4.70	4.94	13.66
Na_2O	0.15	0.06	0.25	0.44	1.16	3.12	4.45	0.21
K_2O	0.10	0.16	0.08	1.32	0.44	2.64	2.76	0.11
P_2O_5	0.08	—	0.05	—	0.20	0.46	0.45	0.14
S	3.02	1.30	0.40	1.44	0.02	0.13	—	0.67
V_2O_5	0.04	0.01	0.23	0.03	0.03	0.02	—	0.34
CO_2	0.02	0.44	0.04	—	1.23	0.02	2.33	0.04
H_2O^-	—	—	0.09	—	0.38	0.32	0.28	—
H_2O^+	8.98	6.15	2.35	3.84	5.36	4.28	3.17	1.93
Ni	0.69	0.58	0.014	0.12	0.011	0.009	—	—
Cu	0.24	0.08	0.008	0.04	0.006	0.002	—	—
Co	0.016	0.02	0.007	0.01	0.008	0.005	—	0.01
—O = S	—1.51	—0.65	—0.20	—0.72	—0.01	—0.06	—	—0.34
Total	99.60	100.22	99.84	101.11	100.32	100.09	99.96	99.23

1 — serpentinous olivinite, Pilgujärvi; 2 — serpentinous olivinite with weak mineralization, Pilgujärvi; 3 — mineralized serpentinous olivinite, Pilgujärvi; group sample (in brackets — number of samples); 4 — serpentinite, Kaula; 5 — mineralized actinolite-chlorite-serpentine rock, Pilgujärvi; 6 — ore-free serpentinite, Pilgujärvi; 7 — serpentinous peridotite, Souker; 8 — mineralized serpentinous peridotite, Pilgujärvi; 9 — poorly mineralized serpentinous peridotite, Pilgujärvi; 10 — mineralized serpentinous wehrlite, Pilgujärvi; 11 — coarse-grained pyroxenite, Kaula; 12 — plagiopyroxenite, Pilgujärvi; 13 — actinolitized pyroxenite with biotite and chlorite, mineralized, Flangovoe; 14 — mesocratic amphibolized and chloritized gabbro, Flangovoe; 15 — leucocratic gabbro, Flangovoe; 16 — essexitic gabbro pegmatoid, Pilgujärvi; 17 — chloritized pyroxenite with titanomagnetite, Pilgujärvi. (— = not detected or not determined)

The rock analyses are from the summary of Tkachenko K. N. and Yudin B. A. (1982).

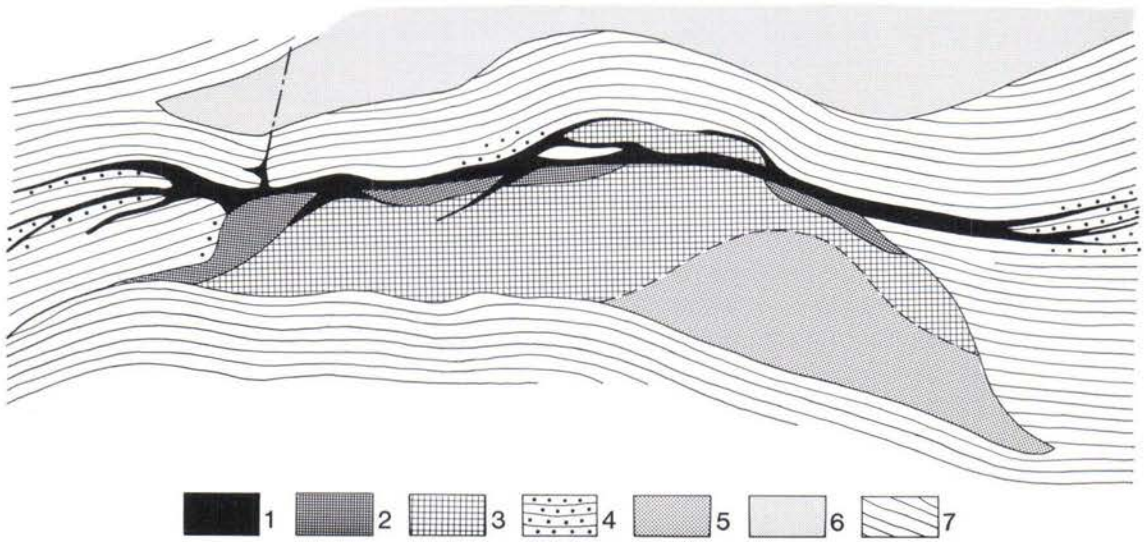


Fig. 5. Schematic geological plan of one of the upper horizons of the Kaula deposit. 1 — massive and breccia ores; 2 — high-grade disseminated ores in serpentinite; 3 — low-grade disseminated ore in serpentinite; 4 — mineralized phyllite; 5 — serpentinite; 6 — gabbro; 7 — tuffogenic sedimentary rocks.

offsets have been established at the sites of sharp bends in the sedimentary tuffogenic rocks. Small bodies of intensely mineralized serpentinites are commonly encountered in them.

Most of the ore-bearing intrusives are concentrated in the central part of the ore field, at the site extending from Kaula to Onki, north of the Luotn fault. Hence the Luotn fault is the most probable feeder for a gabbroic peridotite magma.

The Ni-Cu deposits are grouped into two ore plexuses. In the western part of the ore field the Kaula, Promezhutochnoye, Flangovoye, Verkhneye and Semiletka deposits form a linearly elongated Western ore plexus in the upper parts of the productive sedimentary tuffogenic formation. In the eastern part the major ore-bearing massifs and deposits that form the Eastern ore plexus occur in the lower parts of the sedimentary tuffogenic strata. Several small ore-bearing massifs are met with in the uppermost part of the productive strata.

In the central part the nickel-bearing massifs occur as three band-like belts. The first belt is in the lower parts of the sedimentary tuffogenic formation (North Soukerjoki, North Mirona, Kierdzhipor), and the second one is in the upper and central part (East Ortoaivi, Souker, Raisoaivi, South Mirona). A number of small ore-bearing ultramafic bodies (the so-called upper nickel-bearing geological layer) have also been found in the uppermost part of the productive formation. They seem to mark the third interstratal tectonic zone controlling the ore. The small ore-bearing intrusives of the Eastern ore plexus are located at the continuation of this belt. At the North Soukerjoki site there is the Pahtajärvi ore showing, whose small intrusive bodies occur within the diabases of the third volcanogenic formation and are confined to the zone of steeply dipping dislocations trending NW.

Morphology and geological setting of the ore bodies

The ore bodies are for the most part sheet-like and slab-like in shape. They are commonly

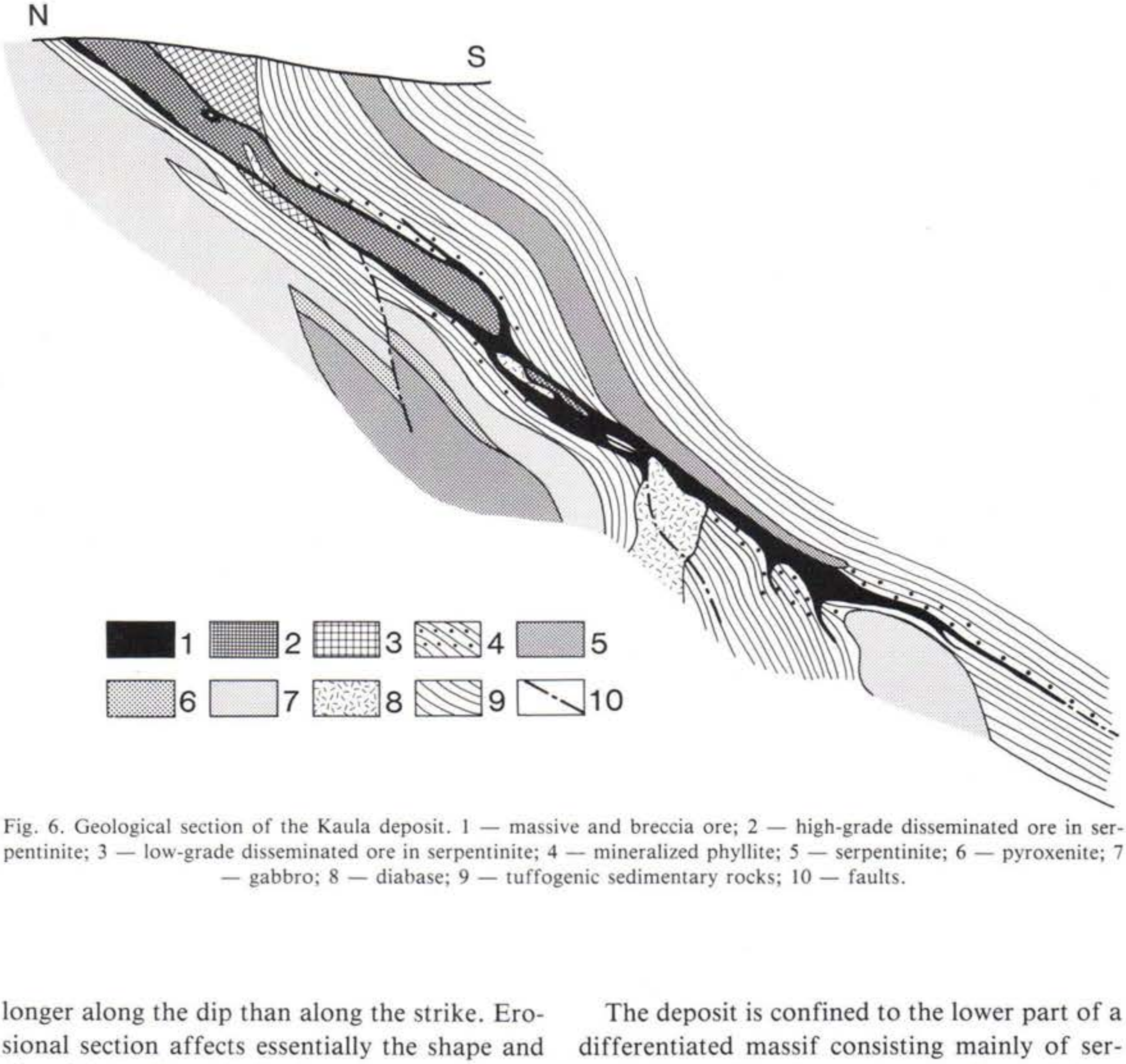


Fig. 6. Geological section of the Kaula deposit. 1 — massive and breccia ore; 2 — high-grade disseminated ore in serpentinite; 3 — low-grade disseminated ore in serpentinite; 4 — mineralized phyllite; 5 — serpentinite; 6 — pyroxenite; 7 — gabbro; 8 — diabase; 9 — tuffogenic sedimentary rocks; 10 — faults.

longer along the dip than along the strike. Erosional section affects essentially the shape and size of the bodies. All the deposits of the Western ore plexus are considerably eroded and represent the lower parts of the nickel-bearing massifs, whereas the deposits of the Eastern ore plexus are better preserved. They have not been fully established at depth.

The Kaula deposit is a typical deposit of the Western ore plexus and has been the subject of many investigations. Discovered in 1925, it was studied by the Geological Survey of Finland until 1934. It was first described by the Finnish geologists Hausen, Tanner and Väyrynen. In 1968 G. I. Gorbunov published a detailed report on the deposit.

The deposit is confined to the lower part of a differentiated massif consisting mainly of serpentinites; gabbro has only been observed close to the surface, within its hanging wall. The crescent-shaped massif strikes W-E and dips S at 40°—50° in conformity with the enclosing phyllite strata (Fig. 5). With increasing depth, it is first reduced in thickness and then, repeatedly branching, it gradually pinches out (Fig. 6). The main tectonic zone filled with breccia and massive sulphide ores is the hanging wall of the massif. Dipping 35°—40° the zone cuts the strongly dislocated tuffogenic sedimentary strata with small bodies of altered ultramafic rocks at a very acute angle. The deposit is represented by two orebodies, Osnovnoye and Otdelnoye. Os-

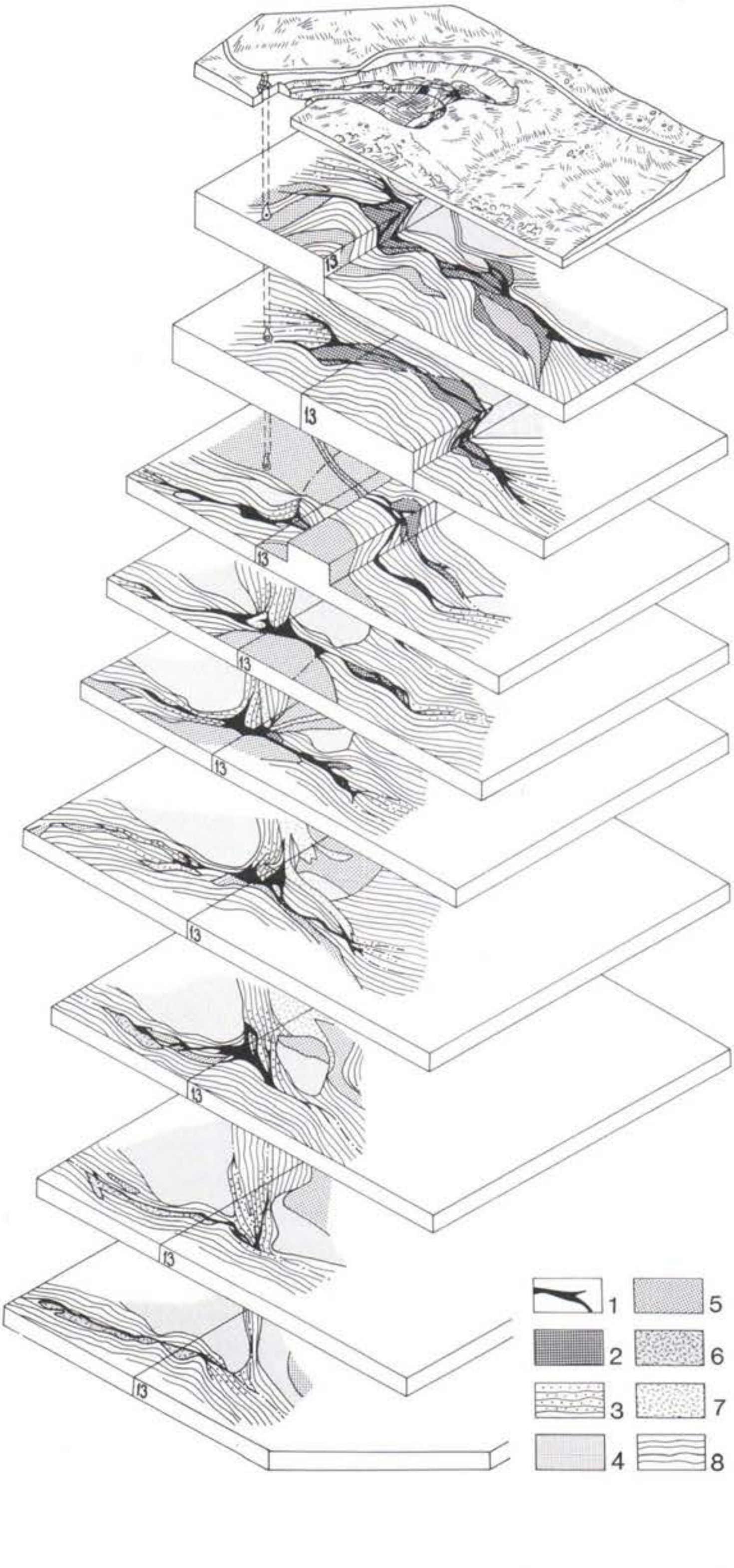


Fig. 7. Block diagram of the Kaula deposit. 1 — massive and breccia ore; 2 — high-grade disseminated ore in serpentinite; 3 — mineralized phyllites; 4 — gabbro; 5 — serpentinite; 6 — gabbro-diabase; 7 — dyke diabase; 8 — tuffogenic sedimentary rocks.

novnoye is an irregular sheet-like orebody that follows the shape of the host intrusive and runs outside its lower part. Its extension down the dip is longer than that along the strike. There are several pinches and swells that can be traced over a long distance down the dip. The orebody has a SW pitch.

Osnovnoye is composed of high-grade disseminated ores in serpentinites, high-grade breccia and massive ores and mineralized phyllites. As the depth of the orebody increases, the mineralized serpentinites gradually pinch out with a more or less constant volume of breccia ores. When the tectonic zone runs outside the ore-bearing massif the massive ores, breccia ores and accompanying mineralized wall rocks gradually become thinner. At the same time there is a decrease in Ni and Cu content up to complete replacement of the common Cu-Ni ores by pure pyrrhotite ores.

At deep levels the thickness of the orebody varies, the maximum being in steep depressions or in the footwall. It gradually pinches out on the flanks accompanied by numerous apophyses of rich sulphide ores within the sedimentary tuffogenic rocks. In many cross sections the lower boundary of the orebody is nearly rectilineal, accentuated by the Main mineralized tectonic zone. At the same time sinusoidal bends reflecting the fold pattern of the host strata are clearly visible along the strike. In these bends the orebody is commonly accompanied by apophyses in the footwall, predominantly composed of mineralized serpentinites at the upper levels and of massive sulphide ores on the deep levels. The apophyses extend along the dip and strike for up to 100 m, rarely more, and range in thickness from some decimetres to several metres. There are from five to six of them at different sites, and so the orebody is strongly branched in shape (Fig. 7). The apophyses were formed at the suite where the Main mineralized tectonic zone forks into a fan of steeply dipping feathering fractures deviating to the NE within the footwall and to the SW within the hanging wall (see Fig. 5).

The Otdelnoye orebody is the largest of the steeply dipping apophyses within the footwall of the Osnovnoye orebody. It extends for over more than 200 m along the strike.

Several of the diabase dykes occurring in the ultramafic tuffogenic and sedimentary rocks have been found within the deposit; some of them are crosscut by breccia ores. In addition, diabase bodies of irregular shape and size seemed to be fragments dragged from one of the dykes.

The structure of the deposit is defined by a combination of the synclinal fold and the Main tectonic zone plunging SW. The Main tectonic zone runs along the lower contact of the massif; in the central part it cuts off a block of the mineralized ultramafic rocks, which has been displaced eastwards. On the flanks of the massif the zone branches in a complicated manner and, being conspicuously reduced in thickness, continues farther into sedimentary tuffogenic strata. It has wave-like, curved features along the strike outlining the shape of the large folds and crosscutting the smaller ones. The zone is filled with high-grade Ni-Cu ores within the deposit and is accompanied by veins of massive ores along the exfoliation fractures in folded phyllites throughout its extension. A transversal (meridional) upthrow filled with massive ores on the western flank had a marked impact on the structure of the deposit.

The Promezhutochnoye deposit was discovered in 1950 in accordance with predictions by G. I. Gorbunov. It is located east of Kaula at a continuation of the Main tectonic zone and structurally in the SW limb of fairly large synclinal NE-trending fold complicated by upthrow-dislocation with the same orientation (Fig. 8). The deposit consists of four small interstratal bodies of talcose serpentinites with a composite curved form containing an economic mineralization. The morphology of the orebodies is characterized mainly by the shape and size of the intrusives; down the dip the orebodies ex-

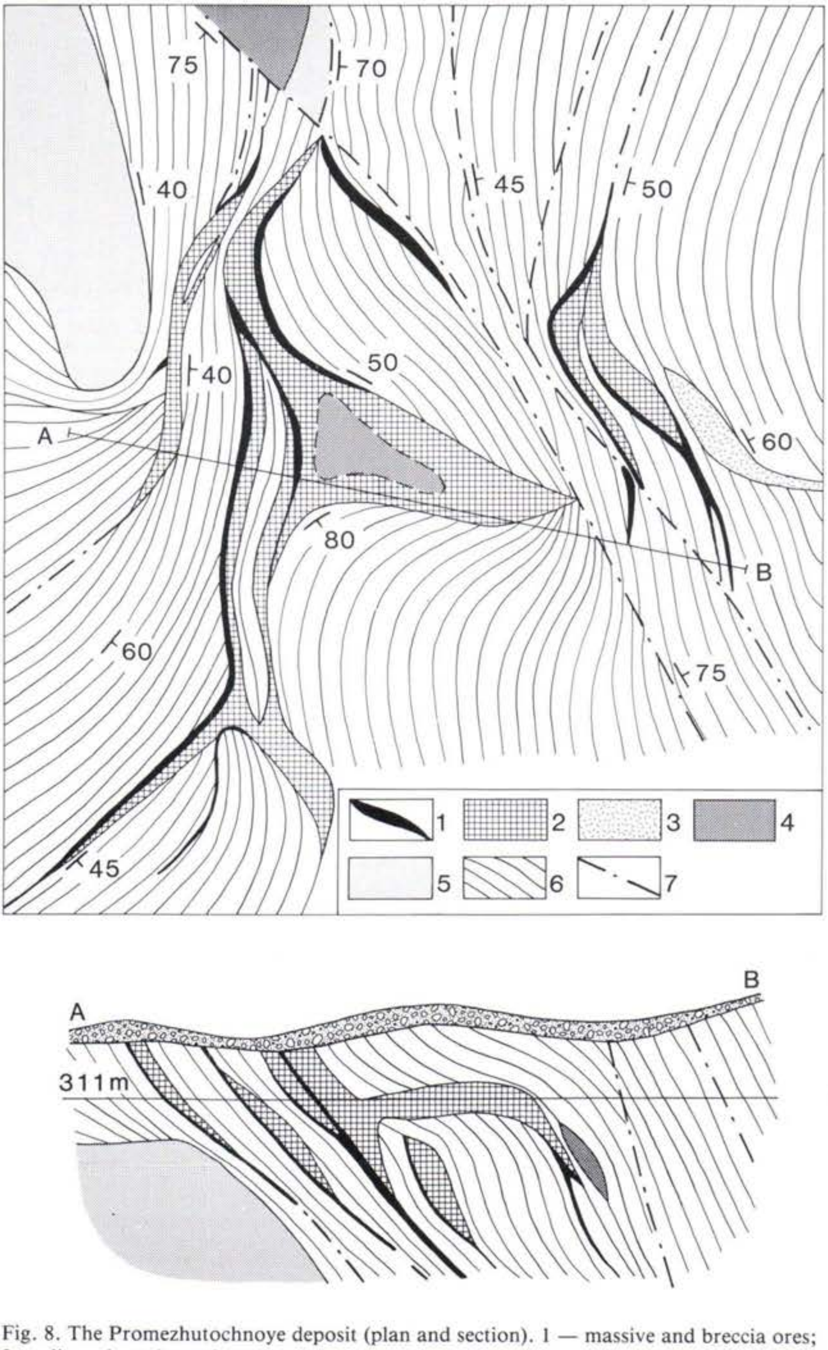


Fig. 8. The Promezhutochnoye deposit (plan and section). 1 — massive and breccia ores; 2 — disseminated ores in serpentinite; 3 — diabase dykes; 4 — serpentinite; 5 — gabbro; 6 — tuffogenic sedimentary rocks; 7 — faults.

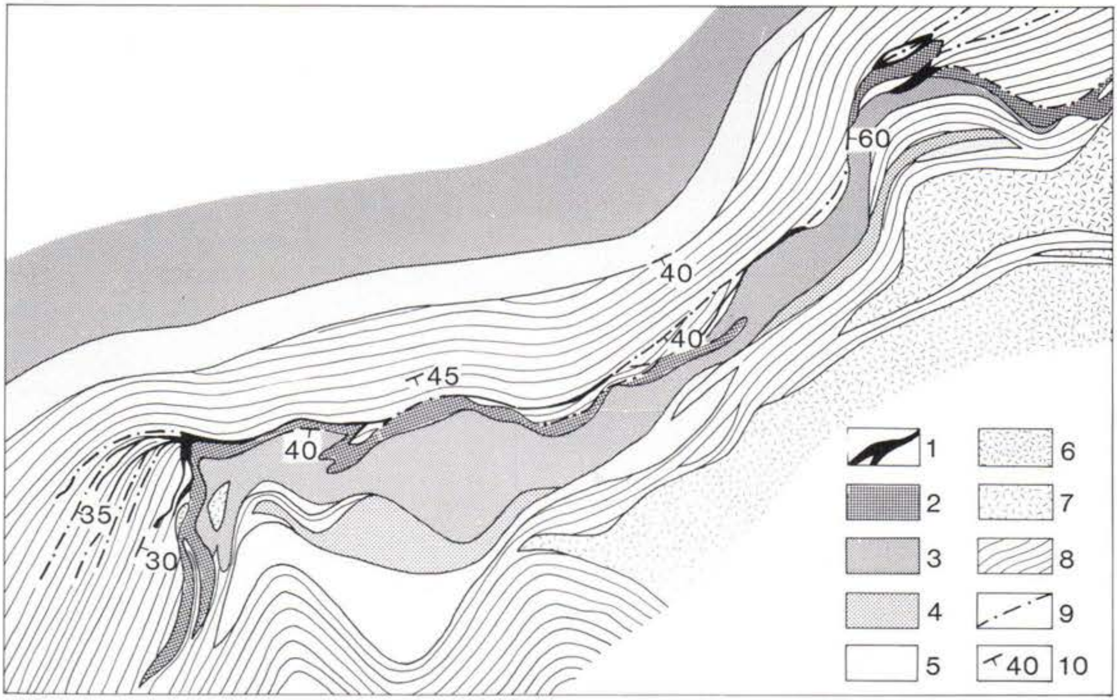


Fig. 9. Geological plan of the Flangovoye deposit. 1 — massive and breccia ore; 2 — disseminated ore in serpentinite; 3 — serpentinite; 4 — pyroxenite; 5 — gabbro; 6 — diabase dykes; 7 — effusive diabase; 8 — tuffogenic sedimentary rocks; 9 — faults; 10 — strike and dip of a planar element.

tend along the tectonic zones for tens of metres beyond the intrusives. Low-grade disseminated ores predominate. One of the small orebodies with the massive sulphide ore occurs within the upthrow.

The depositional site is of interest on account of the relations between the longitudinal and transversal dislocations. The transversal upthrow-displacement trends 315°—320° and has a steep, variable dip. The rocks of the eastern limb have been upthrown and displaced southwards at the level of the current erosional section. The vertical amplitude of the displacement is about 40 m. The interstratal tectonic zones, accompanied by feathering fractures, occur along the lower contacts of the nickel-bearing intrusives with phyllites. The longitudinal interstratal tectonic zones do not crosscut the upthrow when joining it but meet it at an acute angle and smoothly merge with it.

The Flangovoye deposit has been known since studies of the Pechenga nickel area began but the presence of only a weak sulphide mineralization near the surface made it non-prospective. Detailed structural studies by G. I. Gorbunov in 1945—1950, however, indicated the possibility of deep high-grade Ni-Cu sulphide ores. The prediction was later fully confirmed.

The deposit is related to a differentiated mafic-ultramafic massif curved in a complicated manner. It has numerous pinches and swells and outlines a large asymmetrical synclinal fold trending NW (Fig. 9). On the western flank the massif pinches out sharply and forks into several elongated bodies. The tectonic zone controlling the ore at the upper levels runs almost exactly along the lower contact of the massif. At the lower levels it diverges from the contact in places, but to a considerable extent only in the underlying phyllites.

As a curved sheet-like deposit the orebody is confined to the lower serpentinitic part of the massif dipping SW at 20°—60°. Its thickness near the surface is some decimetres, but at deep levels it increases to tens of metres. Local swells have been noted wherever the strike or dip change sharply. Ore accumulations are most frequently encountered within the troughs at the base of the massif, where the thickness of the disseminated and breccia ores increases and the ores are of higher grade.

On the western flank and in the central part of the deposit the orebody forms several offsets extending into the phyllites of the footwall. They follow the sharp rock bends and forking of the Main mineralized tectonic zone and are filled with breccia and massive ores. Called the Northern orebody the largest offset deviates from the intrusive at the site of the transversal flexure-like turn in the middle of the deposit, where the massit conforms with the turn. Keeping its trend the mineralized tectonic zone extends over hundreds of metres farther eastwards into the phyllites.

Higher sulphide contents have been found close to the intrusive and at the intersections of small ultramafic bodies. The sulphide mineralization gradually pinches out as the distacne from the ore-bearing zone increases.

Disseminated ores predominate in the deposit but there are some breccia ores as well. Massive ores and mineralized phyllites are not very abundant; disseminated ores occur at the base of the nickel-bearing intrusives and have been traced almost throughout the extension. The low-grade disseminated ores often border directly the mineralized tectonic zone. The boundaries of high-grade disseminated ores with overlying low-grade disseminated ores tend to be sharp accentuated by thin stringers of sulphide and non-metalliferous minerals. The high-grade disseminated ores are commonly observed within the weakly mineralized serpentinites as small lens-shaped bodies.

The Verkhneye deposit is a continuation of the Flangovoye deposit. The ore-bearing intrusive occurs in the crest of a synclinal fold trending NE that passes into a steep anticlinal fold on the eastern flank. At the site of transition its thickness decreases sharply and it divides into a number of small, lens-shaped bodies. A branched tectonic zone extends along the base of the massif.

The orebody at the base of the massif is slightly curved and sheet-like near the surface. Its shape becomes very complicated at deep levels owing to repeated ramification of the massif and the mineralized tectonic zone; it is particularly complicated in the core of the anticlinal fold (Fig. 10).

The largest offset of the orebody has been established in the trough where the mineralized tectonic zone diverges into phyllites and locally forms branches. The breccia ores gradually pinch out and only a thin fracture zone with no sulphides can be traced farther within the phyllites. The zone then intersects a small lens of altered nickel-bearing ultramafic rocks, and high-grade mineralization related to them, reappears.

Disseminated ores within the serpentinites predominate in the deposit (over 70 % of total volume). Massive and breccia ores make up the strongly branched tectonic zone in the lower parts of the massif, the breccia ores predominating at depth and the massive ores near the surface.

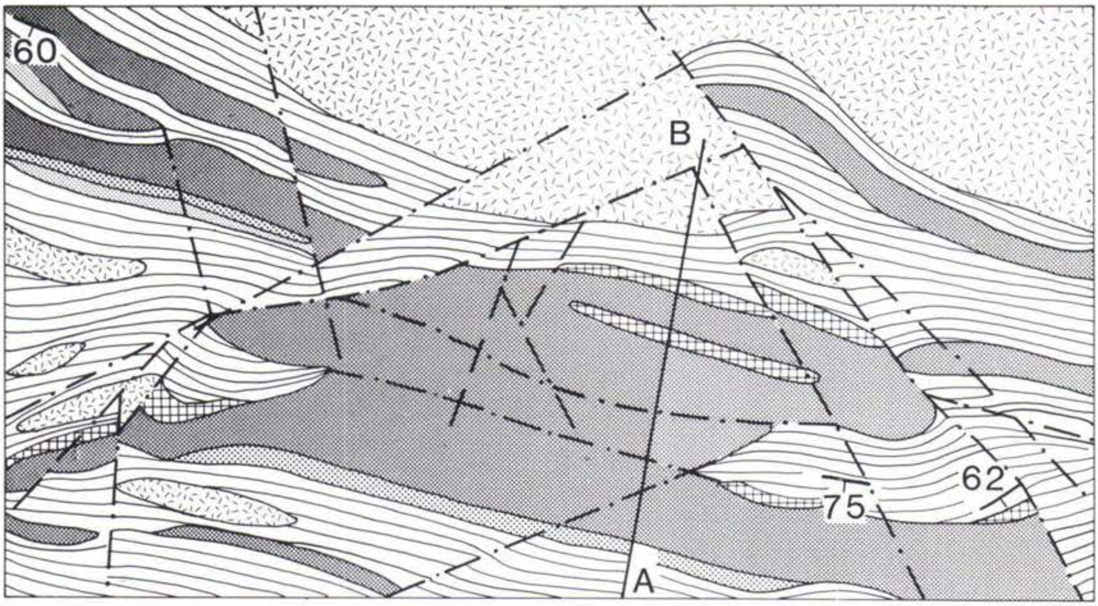
The Semiletka deposit. The orebodies are confined to the parts near the footwall of several nickel-bearing differentiated intrusives shaped like a strongly curved lens that occur in the limbs and core of the NE-trending fold. Dislocations in the footwall of the intrusives, continuing within the phyllites, link separate intrusives and related orebodies into a conspicuously branched structural plexus. Massive and breccia ores occur within the dislocations at the sites of conjunction with the ore-bearing intrusives. The small, thin lenses of the breccia ores are also confined to some transversal faults cutting

Fig. 10. Geological plan of the Verkhneye-Semiletka deposits. 1 — massive and breccia ore; 2 — disseminated ore in serpentinite; 3 — serpentinite; 4 — pyroxenite; 5 — gabbro; 6 — gabbro-diabase; 7 — effusive diabase; 8 — tuffogenic sedimentary rocks; 9 — faults; 10 strike and dip of planar element.

the ore-bearing intrusives. Most of the orebodies are composed of disseminated sulphides in the serpentinites.

The occurrences in the middle of the ore-field are related to the large differentiated gabbro-pyroxenite-peridotite massifs and small bodies of overlying and underlying altered ultramafic rocks (Fig. 11). Both occurrences are confined to the synclinal folds in the NW and close to the eastern flank in the NE; they are located in several layers in the interstratal faults.

The mineralizations is related to the lower serpentinites of the differentiated massifs at the Souker, Raisoaivi, Mirona and Kierdzhipor sites, in which a thickening of sulphide dissemination is confined to the depressions at the base of the massifs. The abundance of disseminated sulphides occasionally decreases between the depressions, and the whole occurrence is then divided into a number of small orebodies. Several of these are not exposed. The orebodies (up to three or four) are separated from each other by bodies of the same mineralized rocks but with a lower abundance of dis-



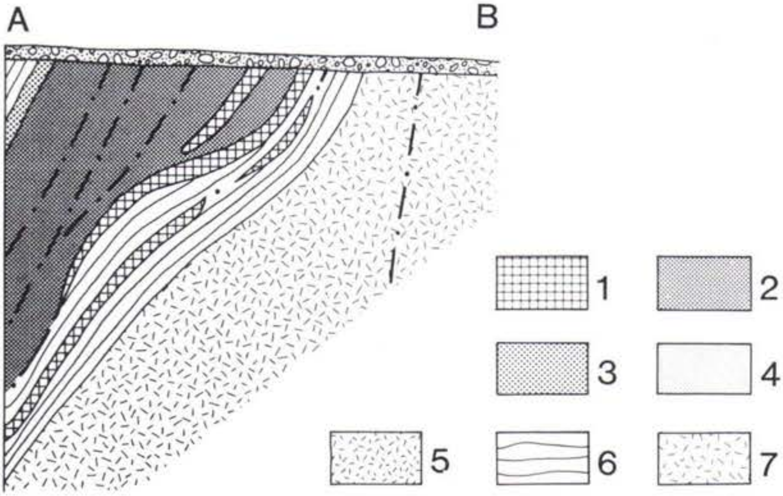


Fig. 11. Schematic geological map and section of the Kierdzhipor site. 1 — disseminated ore in serpentinite; 2 — serpentinized peridotite; 3 — pyroxenite; 4 — gabbro; 5 — gabbro-diabase; 6 — tuffogenic sedimentary rocks; 7 — effusive diabase.

seminated sulphides. Dissemination is irregular in all the orebodies. High-grade disseminated ores are also met with. Breccia and massive ores aré occasionally encountered in the faults at the base of the massifs.

The orebodies related to the small intrusives are known at all the above sites. At Kierdzhipor a »blind» non-exposed orebody composed of intensely altered and mineralized serpentinites occurs beneath the ore-bearing differentiated massif and within the sedimentary-tuffogenic rocks that separate the massif from the diabases of the third formation (Fig. 11). Extending along its lower contact is a fault marked by

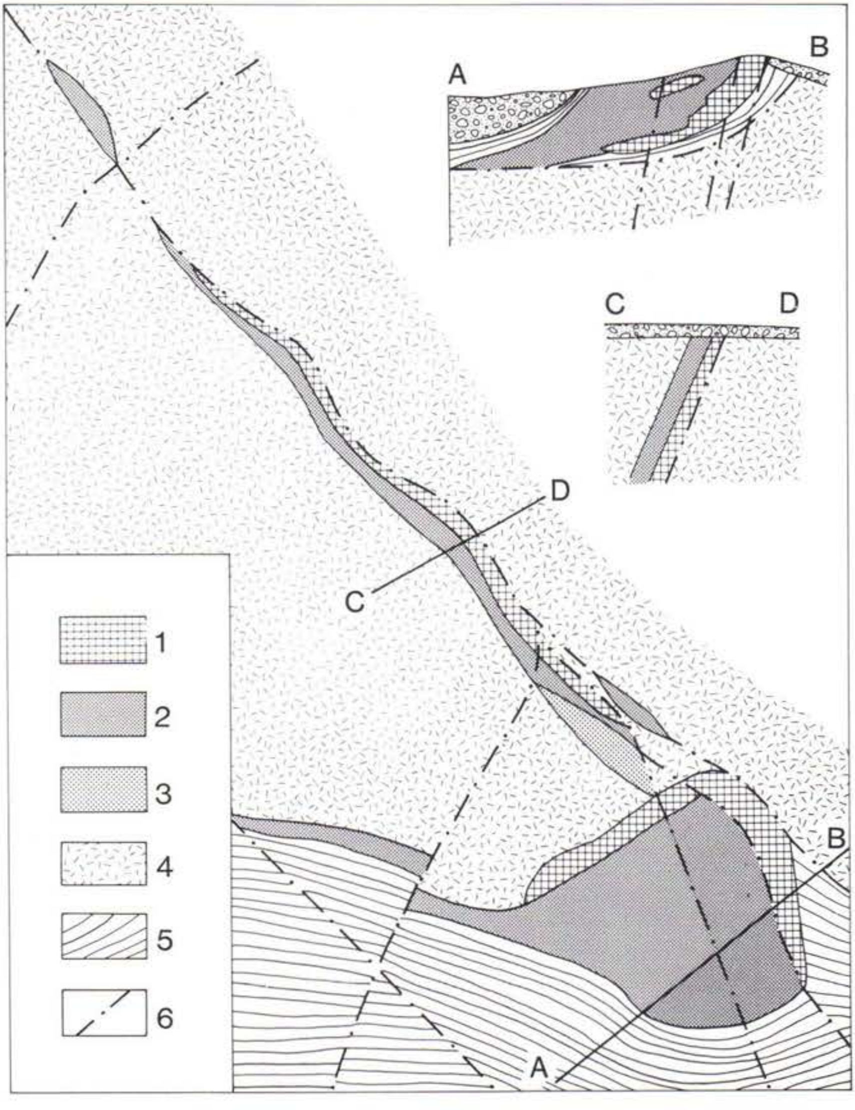


Fig. 12. Geological map and sections of the Northern Soukerjoki and Pahtajärvi ore showings. 1 — disseminated ore in serpentinite; 2 — serpentinized peridotite; 3 — pyroxenite; 4 — effusive diabase of the third sheet; 5 — tuffogenic sedimentary rocks of the fourth (productive) strata; 6 — faults.

veins of Ni-Cu breccia ores accompanied by a stringer-disseminated mineralization within sandstones and phyllites.

Several thinner sheet-like ultramafic bodies confined to another interstratal tectonic zone (termed Upper nickeliferous stage) are known to occur within the productive strata above the Kierdzhipor massif. In the east some of these Ni-Cu disseminated mineralizations have been noted to increase with depth.

The intrusives themselves trend SE to the eastern ore plexus. The tectonic zone, together with the bodies of ultramafic rocks, has been traced down the dip over a considerable distance.

The Northern Soukerjoki-Pahtajärvi ore showing includes two orebodies.

The northern Soukerjoki orebody is confined to the lower part of the serpentinite massif located in the core of the synclinal fold at the contact of the sedimentary-tuffogenic rocks with the diabases of the third volcanogenic formation (Fig. 12). It is a trough-like deposit dipping southwards at an angle of 30°—60° and having a general SE pitch. It is composed of disseminated ore.

The Pahtajärvi orebody occurs in an intrusive body with a steep SW dip; it is located in the effusives of the third volcanogenic formation along the NW-trending fault that at one of the sites is adjacent to the footwall of the nickel-bearing Northern Soukerjoki massif. The intrusive has been traced along the strike for some hundreds of metres. Farther to the NE and with depth only individual, small and usually barren intrusive bodies are met with in the fractured zones.

The Pahtajärvi intrusive is made up of serpentinized, chloritized and talcose peridotites, the margins being composed of amphibolized pyroxenites. The orebody extends along the footwall of the intrusive for its whole length along the strike and down the dip. It has a number of bends, pinches and swells and does not extend beyond the intrusive. Only the amphibole-pyroxene rocks near the contact are practically non-mineralized.

The Eastern ore plexus consists of a series of mutually related lens-like and sheet like orebodies that occur close to the footwall of the large, strongly dislocated Main massif, and of some small intrusives (Fig. 13). The Main massif is a layered body with a swell in the centre due to a steep and deep trough-like depression. The massif trends to the SE and dips SW at 55°—75°. Mineralized serpentinized peridotites and pyroxene olivinites (disseminated sulphide ores) occur in its footwall and are overlain by barren serpentinized peridotites, pyroxenites and finally gabbros, which account for up to 65 % of the total volume of the massif.

The ore horizon and the peridotites pinch out on steep slopes of the deep trough-like depression but reappear smaller in size in the side depressions. The great majority of the ore-bearing peridotite layers are confined to the footwall depressions of the intrusive. An almost direct relationship has been noted between the dimensions of the peridotite layer and the thickness of the orebodies; the relationship between the total thickness of the massif and that of the orebodies is less pronounced. A tectonic zone filled with breccia ore runs along the footwall of the massif.

A number of mineralized offsets deviate from the orebody and run into the underlying schists.

In the far western part of the ore plexus a complexly curved mineralized intrusive in the core of an asymmetrical synclinal fold was opened by mining. The ore deposit plunges SW at an angle of 30° in its central part and at as much as 70°—80° on the flanks; at the deep levels if flattens out with a decrease in thickness. It is composed predominantly of disseminated ores in altered peridotites. The zone of dislocations partly filled with breccia ores can be traced throughout the footwall of the intrusive. In the lower crest of the synclinal fold a number of faults diverge to the ESE and extend into the underlying phyllites. The dislocations are adjecent to the Western and Southwestern orebodies. They host veins of massive and breccia ores and thus of all the orebodies form a single structural group.

The Southwestern orebody trends to the EW and dips southwards at an angle of 40°, usually with a gentle E pitch. It is composed mainly of low-grade ores in altered peridotites. Numerous offsets of mineralized peridotites, and veins of massive and breccia ores occasionally accompanied by mineralized host rocks have been noted on both flanks. The offsets extend within the schists for hundreds of metres and occasionally run along the contact with the gabbro-diabase intrusives.

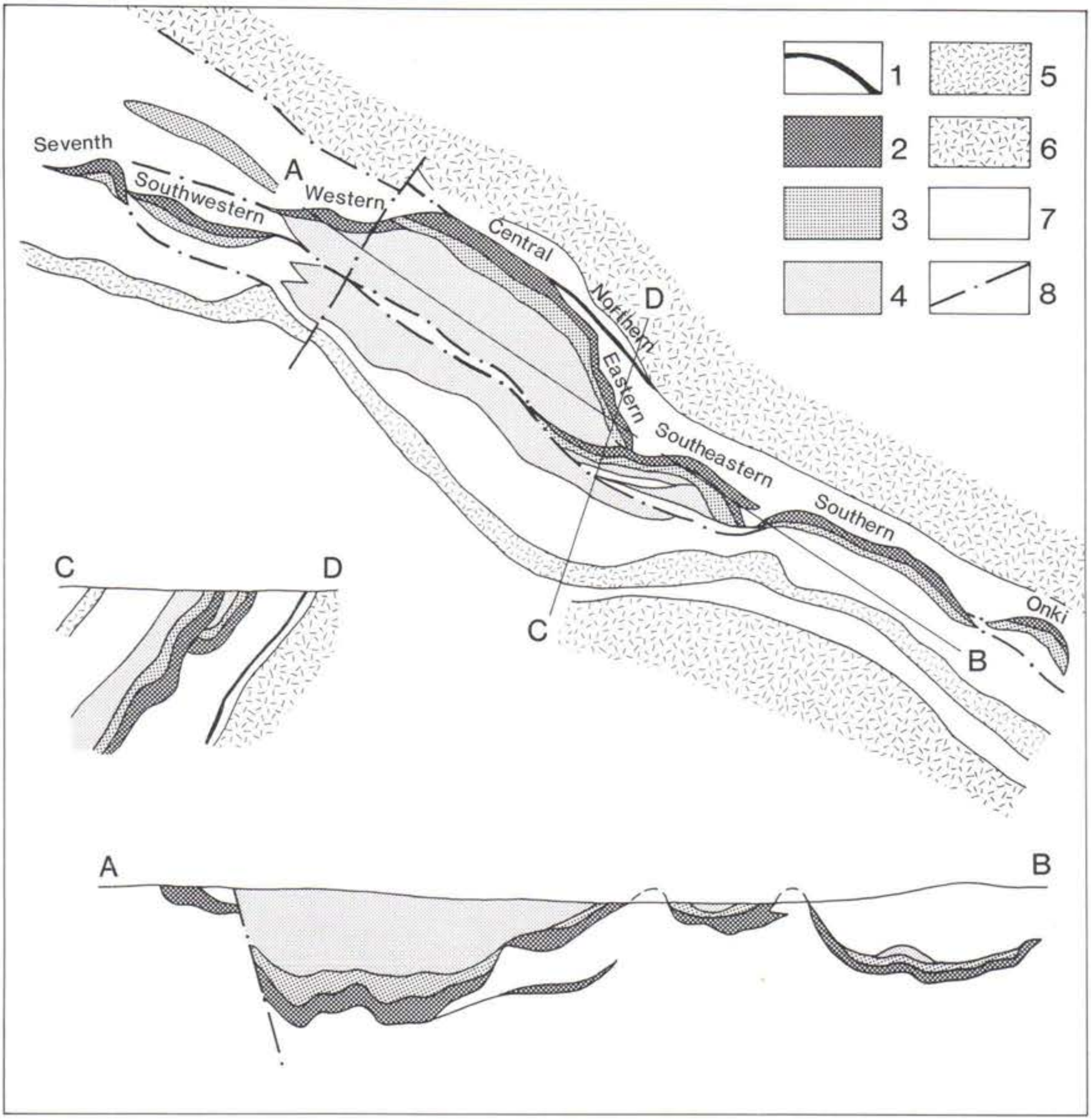


Fig. 13. Schematic geological map and sections of the Eastern ore plexus. 1 — mineralized tectonic zone; 2 — disseminated Ni-Cu ore in altered peridotites; 3 — serpentinized peridotite; 4 — gabbro; 5 — gabbro-diabase; 6 — effusive diabase; 7 — tuffogenic-sedimentary rocks; 8 — faults.

Western orebody is at the western end of the Main massif. Near the footwall it is composed of low-grade ores that form »hanging» levels in places. Lenses of breccia ores have been noted along the contact of the intrusive with the underlying schists.

The Central orebody is confined to the area of a maximum trough at the base of the Main massif. Undulating bends occur in it along the strike and down the dip. Its thickness increases in the large depressions, but decreases sharply and even pinches out completely on the steep slopes of the trough. It is composed primarily of weakly minerlized peridotites; high-grade ores are confined to the troughs at the base of the massif.

The Eastern orebody is confined to a flexure-shaped turn at the continuation of the Central body and dips WSW at 45°—75°. It flattens out gradually at depth and assumes a reverse dip at about 40° NNE (see section in Fig 13). Further it is truncated by a steeply dipping fault, along which the southern block of the ore-bearing massif together with the Southeastern orebody at its base is overthrust. For a considerable distance, the footwall of the Main massif within the Eastern orebody has a cross-cutting contact with the underlying sedimentary-tuffogenic rocks and gabbro-diabase bodies in them and is accompanied into the host schists by a number of ultramafic apophyses.

The orebody is composed mainly of mineralized peridotites whose thickness increases with depth. High-grade disseminated and, at some sites, massive and breccia ores occur at the footwall as lenses, wedge-shaped bodies and embayments along the fractures in the host rocks.

The Southeastern orebody is confined to the intrusive that occurs within the asymmetrical synclinal fold with a gentle W and a steep E limb. On the western flank the intrusive and the orebody are thin and they gradually pinch out between the large gabbro blocks. On the eastern flank obtuse pinching out is accompanied by dismembering of the intrusive and the formation of several ore offsets that extend into the underlying rocks.

The eastern flank is characterized by increased thickness of the mineralized peridotitic part of the intrusive and reduced thickness of the gabbro. Massive sulphide and breccia ores are encountered as thin veins, lenses and nests in the footwall.

The Southern orebody is confined to a comparatively thin but lengthy differentiated intrusive composed predominantly of peridotites. On the western flank the orebody pinches out at an anticlinal turn. On the eastern flank it extends up to the Onki deposit. The mineralization, which is located within the lower parts of the intrusive, is a low-grade dissemination in the peridotites. The interstratal tectonic zone enclosing massive and breccia ores at various sites extends along the footwall.

The Onki deposit is confined to the two differentiated gabbroic peridotite intrusives of which the northern one is exposed and the southern one has been established by drill holes at deep levels. The intrusives occur in the core of a large synclinal fold plunging SW at 50°C. The bulk of the mineralization, which includes disseminated, massive and breccia ores is concentrated at the base of the intrusives; it is less common in their internal parts. The mineralization of the disseminated sulphides in the serpentinites reaches its maximum thickness in the depressions at the base of the intrusives; the massive and breccia ores are located at the same sites as the separate lenses, and they occasionally fill shear fractures in the ultramafic rocks. The orebodies of both intrusives are structurally confined to the Main ore-controlling tectonic zone.

The Northern orebody, located in an offset of the Main ore-controlling tectonic zone at the site of the maximum depression of the trough, holds a special place in the eastern ore plexus. The ore zone extends within sandstones and phyllites along the contact with the underlying effusive of the third suite (see Fig. 13). Lenses of intensely schistose and mineralized serpentinites are met with together with breccia ore at some sites in the zone; at depth the zone joins the intrusive of intensely mineralized serpentinites of considerable thickness. Unlike the others, the Northern body has a SE pitch and is therefore linked with the Central orebody only at the upper levels.

The steep synclinal folds that host the nickel-bearing intrusives and the strongly branched interstratal tectonic zone have had a marked impact on the overall structure of the Eastern ore plexus. Two distinct branches of the zone merge on the flanks. The northern branch with its offsets extends along the footwall of the Main massif and is morphologically expressed by brecciation and foliation of the mineralized peridotites and schists. It is filled with massive sulphide ores at various sites. The southern branch dips steeply SE at 50°—70° and occurs between two gabbro blocks at a considerable distance south of the Central orebodies. Sulphide mineralization has been established only in the ultramafic rocks.

Common features in the structures of the orebodies

The orebodies of the Pechenga deposits are characterized by their asymmetrical banded structure. Their bases throughout the deposits are composed of syngenetic disseminated ore that occurs as curved sheet-like deposits within the lower peridotitic parts of the intrusives, and in which the sulphide content gradually increases towards the footwall. Transition from barren peridotites to disseminated ores is usually gradual whereas that from disseminated to high-grade ores tends to be sharp. Yu. N. Neradovsky, however, established a sharp transition from disseminated sulphides to barren peridotites in one of the largest orebodies in the Western plexus. Fewer thickenings have been observed in the portions of the disseminated sulphides in the middle of the peridotite layer of the massifs, where they form hanging horizons.

Epigenetic massive and breccia sulphide ores occur at the base of the intrusives along the faults and mainly along the contact with the host rocks.

Fold structures greatly affected the development of dissemination. The thickness of the orebodies markedly increases in the crests of synclinal folds and in the depressions at the base of the intrusives; the intensity of sulphide dissemination increases simultaneously as does the proportion of massive and breccia ores. An important regularity shown by the development of sulphide mineralization is a gradual thickening of the dissemination and an increase in the total amount of sulphide ore down the dip of the intrusives, i.e. zonal development of mineralization (down the dip) (Fig. 14).

The emplacement of massive and breccia ores is controlled by the faults, mainly by the interdisplacement-overthrusts that are well developed along the lower contacts of the intrusives but also to a lesser extent by transversal upthrows where they join the longitudinal zones. The veins of massive and breccia ores extend outside the intrusive bodies over a distance of up to 400 m along the strike and 200—250 m down the dip.

Stringer-disseminated Ni-Cu mineralization in the sedimentary-tuffogenic rocks is confined to a narrow zone of the exocontact of the ore-bearing intrusives and extends some way along the mineralized interstratal faults outside the intrusives.

Thus the localization of sulphide ores in separate deposits is due, on the one hand, to elements of the internal structure and shape of a parental intrusive and especially the pattern of its base and, on the other hand, to post-magmatic superimposed structural elements. In this very case the ore is controlled and enclosed by a fault.

The structural features of the orebody are principally attributable to post-ore dislocations. They displaced parts of the orebodies over a considerable distance; at the same time some of the ores underwent intensive dynamic metamorphism that left traces in crushed, compressed and recrystallized mineral aggregates.

Structural types and mineral composition of the ore

On the basis of their structural features and composition the Ni-Cu ores have divided into four principal types (Gorbunov 1968, Gorbu-

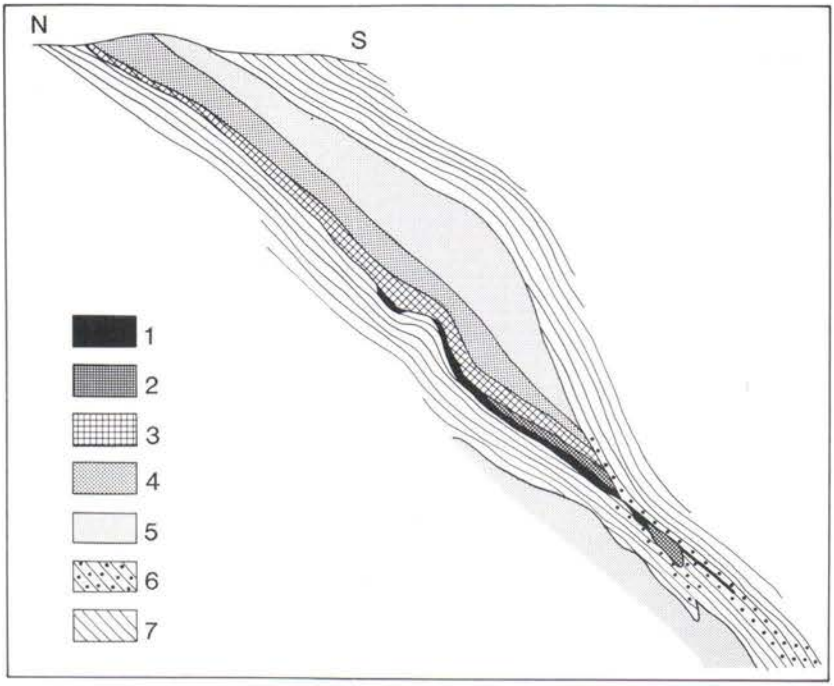


Fig. 14. Scheme of vertical zonation of Ni-Cu mineralization of the ultramafic Pechenga massifs. 1 — massive and breccia ore; 2 — intensely mineralized serpentinite; 3 — mineralized serpentinite; 4 — serpentinite; 5 — gabbro; 6 — mineralized phyllites; 7 — tuffogenic sedimentary rocks.

nov *et al.* 1973): 1. disseminated ore in serpentinites (altered peridotites); 2. breccia ore; 3. massive sulphide ore; 4. stringer-disseminated ore in schists. The disseminated ores in serpentinites are subdivided into high-grade ore and low-grade ore in terms of their Ni content.

The major minerals in all the ore types of the Pechenga deposits and the other Ni-Cu deposits are pyrrhotite, pentlandite and chalcopyrite. Magnetite is included in the mineralized serpentinites, and pyrite is abundant in some parts of the orebodies. Accessories are violarite, sphalerite, bornite, cubanite, mackinawite and valleriite. Chloanthite, niccolite, cobaltite, millerite and galena are comparatively rare. Nonmetalliferous minerals, viz. olivine, monoclinic pyroxene(titanaugite), serpentine, chlorite, amphibole and talc, are met with in disseminated ore. Biotite and carbonates are present in minor amounts. Neogenic carbonates, viz. calcite, dolomite and siderite, and quartz, occur in the breccia ore and in the massive sulphide ore.

The disseminated ore is the most abundant ore type in the parental ultramafic rocks. The low-grade ore and the high-grade ore are distinguished by the intensity of mineralization. The abundance of sulphides in the disseminated ore does not exceed 25—30 %. In slightly altered peridotites the sulphides are mainly in the interstices between the grains of serpentinized olivine and pyroxene. They represent typical sideronitic dissemination and form impregnation and bleb-like inclusions in primary silicates. In the wholly serpentinized peridotites sulphides also occur between the former olivine grains but always as intimate intergrowths with tabular serpentine and chlorite, which increase in abundance with the rise in the degree of rock alteration. Disseminated, spotted nest-structured and, less frequently, banded and foliated ores are characteristic of this type.

The sulphide content in the high-grade ores reaches 60—70 %. Intergrowths of sulphides and serpentine replacing olivine grains and

Fig. 15 a. Text on page 65.

forming peculiar ore-silicate pseudomorphs are widely developed together with a primary matrix ore in interstices between serpentine, chlorite and talc pseudomorphs after olivine (Fig. 15a). Such pseudomorphs accentuate the relict poikilitic structure of the mineralized serpentinites. The sideronitic sulphide matrix was replaced by antigorite and chlorite with the formation of felt-like growths simultaneously with sulphide pseudomorphs after olivine. Peculiar negative textures are formed when sulphides and silicates exchange place. The above textural features of the disseminated ores indicate an intensive metamorphism in association with the mass serpentinization of the parent massif.

As further hydrothermal alterations took place in the mineralized ultramafic rocks (amphibolization, chloritization, talcification, carbonatization) the sulphides redeposited with a rearrangement of elements. As a result, sulphide-chrysotile-asbestos, sulphide-carbon-bearing and pure sulphide stringers were formed.

Disseminated, stringer-disseminated and netlike structures are most common in the ore type described. Pyrrhotite is present as granular aggregates within the major ore minerals and commonly contains rounded corroded grains of early magnetite. A characteristic feature of the pyrrhotite is the presence of tabular and flamelike exsolution bodies of pentlandite. In the serpentinized peridotites, the pyrrhotite of the matrix ore is largely replaced by secondary

Fig. 15 b

magnetite. Pentlandite, the main nickel mineral, occurs as idiomorphic grains, aggregates and small inclusions regularly arranged in the pyrrhotite. It is commonly replaced by violarite and mackinawite. Chalcopyrite is predominantly in the interstices between pyrrhotite and pentlandite grains but it also occurs as thin stringers. Magnetite forms idiomorphic grains and sponge aggregates at the expense of pyrrhotite, and stringers along the peripheral margins of sulpide phenocrysts.

Breccia ores which are included in the high-grade economic ore-types, consists of fragments of talcose serpentinites, phyllites and tuffites cemented by sulphides (Fig. 15b). Apart from sulphides, minor amounts of carbonates, quartz and chlorite occur. The fragments of silicate rocks are lenticular, elongated, ellipsoidal and irregular measuring 1—2 mm to 10—20 cm.

The sulphide content in the ore may reach 80 %, with pyrrhotite, pentlandite and chalcopyrite predominating. On the flanks of the ore-bodies, at the continuation of the tectonic zones in the phyllites, the sulphide cement gradually becomes pyritic and pyrrhotitic and the proportion of fragments and veined minerals rises until they predominate over the sulphides. Although breccia-like in structure the ore is seldom a breccia.

Massive ores are spatially related to the breccia ores and have, as a matter of fact, a negligible amount of silicate rock fragments. Economically the most important ores, they consist predominantly of pyrrhotite (60—80 %), pentlandite and chalcopyrite. Pentlandite commonly forms rounded porphyritic grains 1—10 mm in size scattered uniformly or arranged as small chains and bands along the vein margins (Fig. 15c). The ore varieties are singled out on the basis of the predominant ore mineral.

The primary sulphides were intensely desulphidized and oxidized during metamorphism. As a result of metasomatosis, pyrite, magnetite, often violarite and siderite with chlo-

Fig. 15 c

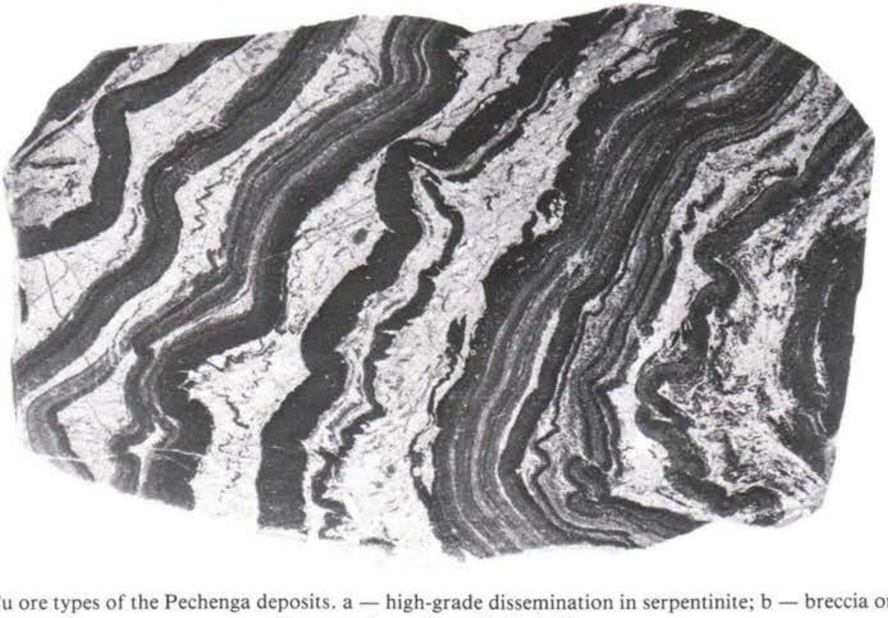


Fig. 15. Ni-Cu ore types of the Pechenga deposits. a — high-grade dissemination in serpentinite; b — breccia ore, c — massive ore; d — mineralized phyllites.

rite, talc and dolomite were formed. Intensely pyritized, »matt» ores were generated at the sites of the post-ore deformations. Massive ores underwent dynamic metamorphism in the tectonic zones in the course of which the fine-grained pyrrhotite, pentlandite and chalcopyrite bands obtained characteristic stress twins in pyrrhotite. Massive, spotted and banded structures abound in the massive ores.

Stringer disseminated ores in schists are abundant only at the Kaula deposit; in other deposits they form a thin aureole along mineralized tectonic zones. The sulphides occur either as a weak dissemination and stringers or they are arranged as lens-shaped isolated portions. In the minor puckering of phyllites the sulphide accumulations are conformable with the bends in layering and fill the fractures (Fig. 15d). The sulphide content may reach 70 % in places. The sulphides are mainly pyrrhotite, chalcopyrite, pyrite and pentlandite. The ores are characterized by disseminated, banded, puckered, stringer-like, net-like and combined structures.

Chemical composition of the ores

The Pechenga Ni-Cu ores, like the Ni-Cu ores in deposits elsewhere in the world, are complex. Apart from the main ore-forming elements, Fe, Ni, Cu, Co and S, they contain numerous trace elements in comparatively low concentrations.

The Ni content is highest in the massive and breccia ores, where it reaches 10—12 %. In intensely mineralized serpentinites it is as much as 6 %, in the low-grade disseminated ores 1—1.5 % and in mineralized phyllites it ranges from traces to 2 %. The Cu content varies widely in all ore types: from tenths of a per cent to 13 % in the massive ores and from 4 to 6 % in the breccia and high-grade disseminated ores. The Cu content in the low grade disseminated ores ranges from hundredths to tenths of a per cent. The Cu content in the mineralized phyllites ranges from traces to 8—10 %; this is an economic type of ore and the richest in Cu.

The Co content is highest, up to 0.25 %, in the massive ores. Its content in the low-grade disseminated ores has been estimated to range from a thousandth to a hundredth of a per cent.

The Ni, Cu, Co ratios in the Pechenga ores are:

1) massive sulphide ores — 48:19:1
2) breccia ores — 56:22:1
3) disseminated sulphides in serpentinites — 55:24:1
4) stringer-disseminated ores in schists — 47:48:1.

The precious metal content tends to increase as the proportion of the main components increases. The Se content regularly decreases (0.0079—0.002 %) from massive to disseminated ores (e.g. Yushko-Zakharova 1964, Yakovlev *et al.* 1968). A direct relationship has been observed between the Se content and the Ni and S contents. The main Se carriers are pentlandite, pyrrhotite and chalcopyrite. The Te content is constantly very low in all the ore types (traces —0.001 %).

In addition, Zn, Pb, As, Sb, Bi, Cr, V and other trace elements were analysed spectrographically. Zn and Pb are related to the presence of sphalerite and galenia in ores. As is incorporated in cobaltite, niccolite and arsenopyrite, and Cr in magnetite. These elements occur partly in ore minerals and rock-forming minerals as solid solutions.

The chemical composition of the main minerals of the Ni-Cu ores is shown in Table 2.

The Allarechka area

The Allarechka area is located to the south of the Pechenga area. The nickel-copper deposits were discovered in the course of geological surveys in the area. Important contributors to our

Table 2. Chemical composition of major ore minerals of the Pechenga region.

	Samples								
	1	2	3	4	5	6	7	8	9
Fe	60.14	57.78	60.00	59.55	60.41	60.00	30.80	30.60	33.15
Ni	0.39	0.66	0.70	0.39	0.56	0.19	36.59	36.00	33.72
Cu	0.00	0.00	0.00	0.01	0.00	0.00			
Co	0.01	0.00	0.00	0.02	0.02	0.00	1.39	0.18	1.47
S	40.02	39.31	39.00	38.95	38.32	38.90	30.91	32.80	31.26
Total	100.56	97.75	99.70	98.92	99.31	99.09	99.69	99.58	99.60

	Samples								
	10	11	12	13	14	15	16	17	18
Fe	32.00	31.45	31.00	30.44	30.09	30.44	30.50	30.30	30.39
Ni	35.13	34.92	36.40	35.09	35.67	0.00	0.00	0.01	—
Cu						33.38	33.80	34.48	34.77
Co	0.44	0.74	0.52	0.90	0.07				
S	32.01	33.71	33.00	33.69	33.90	35.41	35.50	34.92	33.82
Total	99.58	100.82	100.92	100.12	99.73	99.23	99.80	99.71	98.98

1—6 — pyrrhotite, 7—14 — pentlandite, 15—18 — chalcopyrite; 1 — from poorly mineralized amphibole-chlorite endocontact rock, Kaula; 2 — from weakly disseminated ore in serpentinite, Flangovoe; 3 — from heavily disseminated ore in serpentinite, Pilgujärvi; 4 — from breccia-like ore, Flangovoe; 5 — from massive ore, Flangovoe; 6 — from mineralized phyllite, Pilgujärvi; 7 — from serpentinite with poor mineralization, Kaula; 8 — from weakly disseminated ore, Pilgujärvi; 9 — from weakly disseminated ore Souker; 10 — from heavily disseminated ore, Pilgujärvi; 11 — from breccia-like ore, Flangovoe; 12 — from breccia-like ore, Pilgujärvi; 13 — from massive ore, Flangovoe; 14 — from mineralized phyllite, Flangovoe; 15 — from serpentinite with poor mineralization, Souker; 16 — from heavily disseminated ore, Flangovoe; 17 — from breccia-like ore, Flangovoe; 18 — from massive ore, Flangovoe.

The mineral analyses are from the summary of Yakovlev Yu. N. *et al.* (1983).

understanding of the geology of the area include L. S. Kossovoi, E. M. Mikhailyuk, K. D. Belyaev, V. F. Stupitsky, A. I. Bogatchov, V. V. Proskuryakov, V. S. Tikhonov, V. G. Zagorodny and O. A. Belyayev. The deposits have been studied by G. I. Gorbunov, E. K. Kozlov, Yu. V. Gonocharov, N. A. Kornilov, Yu. N. Yakovlev and A. K. Yakovleva.

General geological characteristics of the area and the ore field

The Allarechka nickel area is located in the western part of the Tersk-Notozero anticlinorium zone, which is characterized by blocks and pronounced development of dome-like structures (Fig. 16). The area is composed of rocks of the oldest crystalline basement, biotite, garnet-biotite and amphibole-biotite gneisses, and feldspathic amphibolites, all of which have been intensely migmatized by plagiomicrocline granites. Dipping gently, the most granitized rocks form the central parts of the dome-shaped structures. Steeply dipping and folded gneisses and amphibolites predominate in the marginal parts of and between the domes. The first investigators included these formations in the Archean Kola group, associating the formation of the domes with manifestations of granite diapirism. In recent works on the geology of the area, V. G. Zagorodny, V. A. Gorelov, O. A. Belyayev and E. A. Polyak consider the dome-like structures to be blocks of the Archean basement surrounded by the Lower Proterozoic

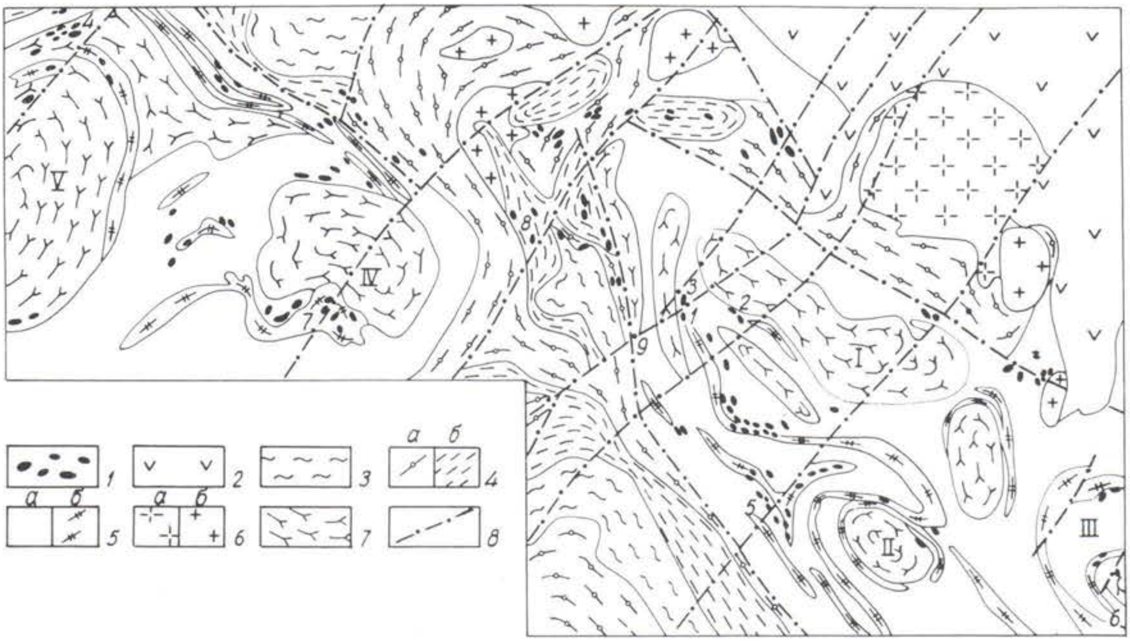


Fig. 16. Schematic geological map of the Allarechka area (according to V. G. Zagorodny et al.). 1 — intrusives of ultramafic rocks — Karelian complex; 2 — Pechenga group (phyllite, sandstone, tuffaceous schists, metadiabase) — Kola-Belomorien complex; 3 — Virnim formations (garnet-biotite gneiss); 4 — Kaskam formations (a — biotite-garnet-amphibole gneiss, b — schistose amphibolite); 5 — Annam formations (a — biotite gneiss, b — feldspathic amphibolite); 6 — diorite, granodiorite (a), plagio-microclinic granite (b); 7 — granite-gneiss of the oldest basement; 8 — dislocations. Dome-like structures: I — Allarechka, II — Koposovo, III — Annama, IV — Hihnajärvi. Ni-Cu sulphide deposits (1 — Allarechka, 2 — Vostok) and ore showings (3 — Northern deposit, 4 — Runnijoki, 5 — Akkim, 6 — Annama, 7 — Hihnajärvi, 8 — Veshjävr, 9 — Yuzhny) are marked on the map with numbers.

rocks of the gneiss amphibolite complex.

As for tectonics, two large structural block anticlinoria can be singled out in the region: the Allarechka (in the east) and Hihnajärvi (in the west), which are divided by the Veshnyar zone of compression. The Allarechka block anticlinorium, in which these deposits are located, has been studied in more detail. Some large regional fractures with northwestern and northeastern strikes have been discovered by aerial photograph interpretation and by geological and geophysical exploration.

The northeastern faults cut across the strike of the basic geological structures. Among them and along the boundaries of the block anticlinoria there are large faults that extend beyond the area proper, and smaller ones that occur in the marginal parts of the domes and are represented by steeply dipping zones of brecciation and mylonization.

Regional faults trending northwest are encountered along the borders of the Notozero anticlinorium.

About 300 mafic-ultramafic intrusives have been found in the area, either in groups or individually. They are lenses and curved beds in shape, 30-50 m to 1000—2000 m long and 5—10 m to 150—200 m thick. The nickel and copper contents of most of the intrusives are insignificantly low. Sulphide copper-nickel mineralization has been established only in some of the intrusives.

The main tectonic components controlling the distribution of nickel-bearing intrusives in the area are regional faults striking northeast, the marginal zones of gneiss-granitic domes, the

Table 3. Chemical composition of ultrabasites of the Allarechka region.

	Samples								
	1	2	3	4	5	6	7	8	9
SiO_2	37.26	40.38	38.56	41.14	46.82	35.48	42.43	41.79	47.68
TiO_2	1.44	1.52	0.98	1.69	1.22	1.30	1.50	1.54	0.14
Al_2O_3	5.14	5.50	6.39	5.87	5.08	3.51	5.19	5.31	4.95
Cr_2O_3	0.80	0.41	0.31	0.36	0.40	0.31	0.50	0.37	0.61
Fe_2O_3	7.73	6.49	13.19	6.36	3.60	23.09	7.02	6.46	3.16
FeO	9.76	9.84		9.63	10.58		11.65	11.53	6.91
MnO	0.23	0.21	0.25	0.25	0.19	0.11	0.23	0.14	0.20
MgO	23.54	24.50	16.56	22.59	21.02	15.49	20.22	21.27	26.19
CaO	4.98	4.99	5.78	4.50	5.46	6.11	7.39	6.22	4.66
Na_2O	0.75	0.45	0.71	0.64	0.65	0.24	0.62	0.27	0.43
K_2O	0.36	0.11	0.63	0.18	0.80	0.17	0.84	0.08	0.58
P_2O_5	0.03	0.17	—	—	—	0.14	—	0.09	0.06
S	0.43	0.24	7.60	0.27	0.80	13.35	0.46	0.36	0.15
V_2O_5	—	—	—	—	—	0.04	—	—	—
CO_2	—	0.15	—	—	—	—	—	0.38	0.79
H_2O^-	0.37	0.12	0.30	1.17	0.50	1.14	0.16	0.32	0.20
H_2O^+	—	4.50	2.55	5.75	2.89	—	—	2.99	2.47
losses	6.95	—	—	—	—	2.17	2.04	—	—
Ni	0.22	—	0.22	0.18	0.09	2.60	0.14	0.26	0.091
Cu	—	—	6.30	—	—	0.44	—	0.06	0.013
Co	0.02	—	0.01	0.05	trace	0.04	0.016	0.02	0.005
—O=S	—0.22	—0.12		—0.13	—0.40	—6.68	—0.23	—0.18	—0.07
Total	99.79	99.46	100.34	100.50	99.70	100.05	100.18	99.98	99.22

	Samples								
	10	11	12	13	14	15	16	17	18
SiO_2	40.00	38.27	39.02	44.74	42.95	36.72	44.25	48.56	38.66
TiO_2	1.46	1.40	0.52	1.47	2.67	0.56	1.08	0.46	0.84
Al_2O_3	5.30	4.47	4.72	4.77	6.01	2.50	4.81	2.71	3.22
Cr_2O_3	0.16	0.37	0.35	0.30	0.11	0.24	0.17	0.44	0.46
Fe_2O_3	7.00	6.50	10.80	4.92	6.95	5.05	5.98	2.79	5.32
FeO	13.98	11.61	15.03	10.22	8.80	8.63	7.06	9.84	12.05
MnO	0.17	0.20	0.20	0.18	0.20	0.21	0.18	0.19	0.19
MgO	19.36	24.37	16.10	19.67	17.43	28.61	25.17	26.13	30.75
CaO	5.86	4.70	—	6.70	10.20	6.90	5.21	3.74	2.86
Na_2O	0.49	0.16	0.03	0.21	1.72	0.64	0.65	0.47	0.09
K_2O	0.11	0.05	0.64	2.18	0.37	0.22	1.25	0.17	0.04
P_2O_5	0.13	0.35	0.04	0.19	0.24	0.02	0.11	0.03	0.08
S	1.89	1.12	8.33	0.86	0.07	0.26	0.00	1.56	0.35
V_2O_5	—	—	—	—	0.01	0.01	0.14	0.15	0.02
CO_2	0.95	—	0.21	1.06	0.40	5.00	0.10	0.12	0.80
H_2O^-	0.08	0.52	0.94	0.32	0.03	0.16	0.04	0.26	0.29
H_2O^+	3.15	5.92	3.26	2.53	1.34	3.73	3.72	3.02	3.73
losses	—	—	—	—	—	—	—	—	—
Ni	0.706	0.29	3.17	0.15	0.10	0.20	0.14	0.29	0.27
Cu	0.266	0.16	0.92	0.06	0.06	0.003	0.009	0.25	0.08
Co	0.0195	0.02	0.033	0.004	0.009	0.009	0.009	0.01	0.01
—O=S	—0.94	—0.56	—4.16	—0.43	—0.03	—0.13		—0.78	—0.17
Total	100.14	99.22	100.15	100.10	99.28	99.54	100.09	100.43	99.94

1 — peridotite, Allarechka; 2 — amphibolized and chloritized peridotite, Allarechka; 3 — mineralized actinolite rock, Allarechka; 4 — serpentine-actinolite rock, Severny; 5 — biotite-actinolite rock, Allarechka; 6 — mineralized biotite-cummingtonite-actinolite rock, Allarechka; 7 — amphibolitized peridotite, Vostok; 8 — amphibolitized and talcificated peridotite, Vostok; 9 — actinolitized pyroxenite, Vostok; 10 — mineralized actinolite rock, Vostok; 11 — mineralized amphibole-serpentine apopyroxenite rock, Vostok; 12 — mineralized biotite-cummingtonite rock, Vostok; 13 — carbonate-biotite-actinolite rock with poor mineralization, Vostok; 14 — amphibolitized pyroxenite, Runnijoki; 15 — serpentinous and carboned olivinite, Runnijoki; 16 — amphibolized and biotitized peridotite, Runnijoki; 17 — amphibolitized and serpentinous pyroxenite with poor mineralization, Akkim; 18 — serpentinous and carbonated olivinite with poor mineralization, Annama. (— = not detected or not determined)

flexure-like folds and bends, and the contact of the amphibolites and gneisses, which differ markedly in physical properties. The location of the intrusives is associated with a multi-branching controlling faults. The zones of folding, which have frequently resulted in pinches of intrusives and sometimes in discontinuities, had a marked impact on the shape, extension and mode of occurrence of the intrusive.

The lithological-stratigraphical factor, manifesting itself in some areas as the confinement of intrusives to essentially amphibolite rock, is of some importance in the distribution of the nickel-bearing bodies.

Allarechka, including the Allarechka and Vostok nickel-copper deposits, is the most thoroughly studied ore field in the area. It is located in the southwestern part of a dome-shaped structure of the same name. Gneisses with beds of amphibolites and granite-gneisses predominate in the western part of the ore field, and granite-gneisses and amphibolites form the main part of the section in the eastern part. The central part of the ore field is composed mainly of plagioclase granite gneisses. Veined granites with pegmatoidal structure are of insignificant abundance in the ore field. The strike of the rocks varies in accordance with the outlines of the Allarechka dome. Most rocks dip southwest.

The wide Alla-Akkajärvi fault in the northwestern part of the ore strikes northeast, and the Vostok fault in the southeastern part strikes parallel to it. Intrusives of ultramafic rocks are located along the margins of the ore field. On its western flank they form a submeridional zone, 1.5—2 km long, within which the ore-bearing intrusives of the Allarechka deposit and of the North site occur near the Alla-Akkajärvi fault. On the eastern flank the intrusives form the Verkhnyaya and the Nizhnyaya zones, both of which strike northwest over a distance exceeding 2 km. The Vostok deposit is located in their southeastern part, near the Vostok fault.

The intrusives are mainly composed of meta-

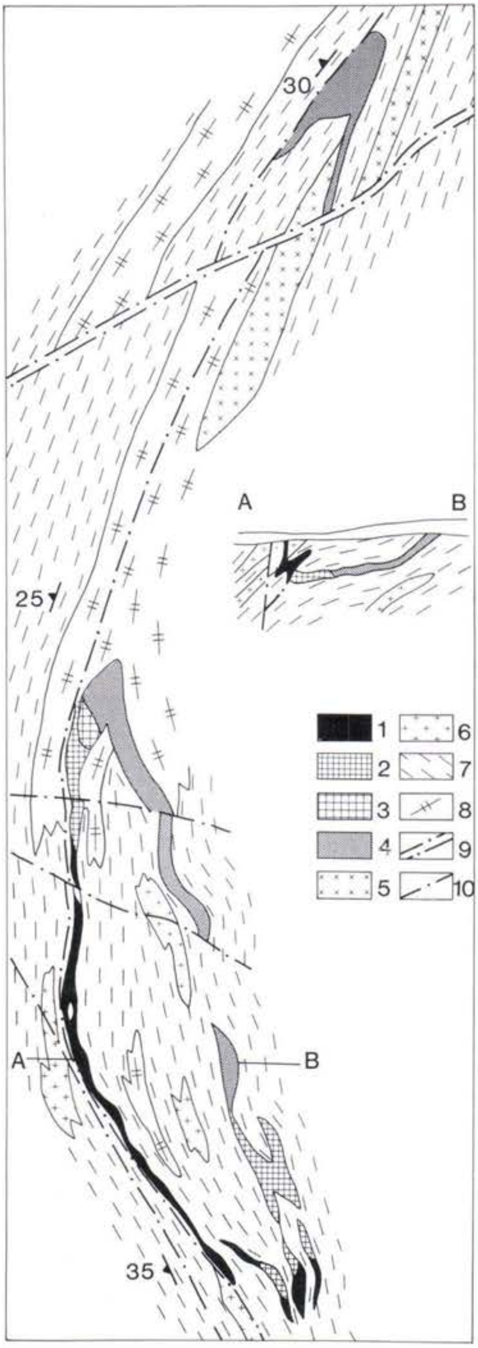


Fig. 17. Geological scheme of the Allarechka deposit. According to material of the Murmansk Exploration Expedition and the Kola Branch of the USSR Ac. of Sci. 1 — Massive sulphide ore; 2 — intensely mineralized ultramafic rocks; 3 — low-grade disseminated ore; 4 — ultramafic rocks; 5 — plagio-microclinic and microclinic granite-gneiss; 6 — plagioclase granite-gneiss; 7 — biotite gneiss; 8 — feldspathic amphibolite; 9 — regional fault; 10 — other faults.

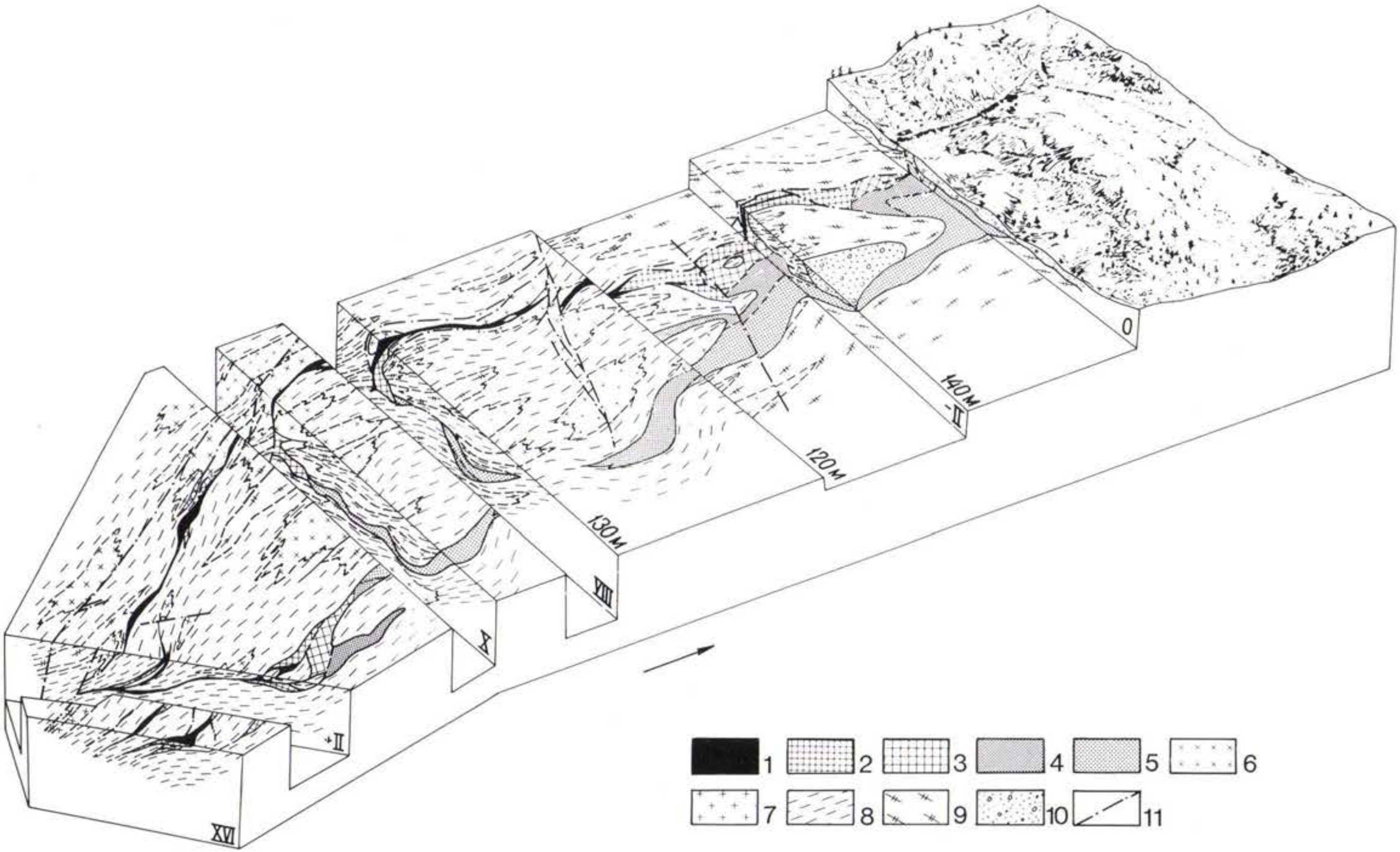


Fig. 18. Block-diagram of the Allarechka deposit. 1 — massive sulphide ore; 2 — high-grade disseminated ore; 3 — low-grade disseminated ore; 4 — ultramafic rocks with weak sulphide dissemination; 5 — ultramafic rocks; 6 — plagio-microclinic and microclinic granite-gneiss; 7 — plagioclase granite gneiss; 8 — biotite gneiss; 9 — feldspathic amphibolite; 10 — Quaternary sediments; 11 — faults.

peridotites (metaharzburgites) and to a lesser extent of metaolivinites. Metapyroxenites are encountered only in a very minor amount. The degree of alteration of ultramafic rocks differs and reaches its maximum in the marginal parts of the intrusives and in the zones of schistosity, where the ultramafites are chlorite-talc and biotite-carbonate rocks. The composition of nickeliferous ultramafic rocks is shown in Table 3.

Morphology, mode of occurrence and structure of the orebodies

The Allarechka deposit, discovered by K.D. Belyayev in 1957, has been completely mined out.

The deposit is confined to a small intrusive of ultramafics that bends in complicated fashion and is elongated in a meridional direction (Fig. 17). It is composed of two branches: a western one that dips steeply and an eastern one that, being more gentle, dips towards the west. Both branches are of a bed-like bent form with offsets and pinches. The western branch crops out totally under glacial deposits, whereas the eastern one is exposed only on the northern and southern flanks. The branches are generally as much as 200 m apart and reach their maximum depth in the centre. Towards north and south the branches gradually converge; on the northern flank they are closed: but on the southern flank they are repeatedly split and reduced in thickness until they pinch out.

At depth the branches converge and form a single body that varies considerably in shape from one section to another (Fig. 18). In the northern part, where the branches dip to meet each other, it is like a shallow trough, becoming more complicated towards the centre. The western branch is steeper, then it assumes a vertical position and finally, its eastern dip turns towards the west. In contrast, the eastern branch preserves its shape and location along its whole length.

Significant pinches and swells are observed along the strike and down the dip. In places the orebody is divided into blocks, from 5—10 m to 100—200 m in size, displaced against each other. On the northern flank the displacements are insignificant and do not break the continuity of the body, but in the central and southern parts they reach 10—15 m which has led to the detachment of some blocks. In places, therefore the western branch of the intrusive looks like a gigantic breccia with blocks of mineralized ultrabasic rocks cemented by sulphides.

Although more or less ubiquitous in the intrusive, disseminated sulphides are distributed extremely nonuniformly. The intensity of the dissemination increases towards the west and south. The economic mineralization on the northern flank of the intrusive occurs only within the western branch. In the centre, the western and lower parts of the eastern branch are mineralized, whereas at the southern edge the whole intrusive is mineralized. High-grade massive sulphide ores are located in the extreme western part of the orebody, where they fill the meridional tectonic zone passing along the contact of the intrusive and its branch. Sulphide veins are widely developed in gneisses on the central and southern flanks of the deposit. The greatest distance of the sulphide veins from the intrusive is no more than 150 m. The total thickness of the orebody varies from 4 to 20 m. The contacts of mineralized metaperidotites and sulphide veins with country rocks are mainly tectonic.

Although the orebody is concordant in plan, crosscutting contacts are observed in vertical sections. The conformable features of gneisses are manifest only at a distance of 2—3 m and sometimes only of some centimetres from the contact. On the scale of the whole deposit the lack of conformity between the orebody and the host rocks is distinct enough. Hence, in the western part of the deposit amphibolites, gneisses and granite-gneisses dip west at 25°—30° to 40° whereas the orebody shows a steeper and vertical dip; on the northern flank the orebody even dips east. In the NS direction the orebody and the intrusive occur first in amphibolites and then in gneisses and granite-gneisses.

The rocks of a gneissic complex at the site of the deposit have a meridional strike that gradually shifts southwards to the northwest. The rocks dip west and southwest. The dips are mainly gentle, 25°—40°; only in the western part, where the western branch in the nickel-bearing intrusive is located, is a flexure-like bend with a steep dip of 80°—90° distinguishable.

Folds with three main trends; longitudinal, diagonal and transversal, in relation to the strike of the rocks occur extensively in the rocks of the gneissic complex. Where intensely developed, they form zones of strongly compressed rocks.

The most important structural element in the deposit is the submeridional tectonic zone running along the western branch of the intrusive and in which the massive and high grade disseminated ores are confined. In the north the zone is adjacent to the regional Alla-Akkajärvi fault.

The nickel-bearing intrusive crosscuts the longitudinal and diagonal folds, causing it to bend some more, to branch and decrease in thickness. It is conformable in relation to the transversal folds. The intrusive was apparently emplaced during a period when the deformation plane sharply changed from longitudinal (and diagonal) to transversal, i.e. when the previously formed faults started to extend.

The morphology of the intrusive and the orebody is defined, in general, by the combination of a cross-cutting submeridional tectonic zone with an adjacent interbedded exfoliation in the gneiss strata.

The orebody is composed mainly of intensely mineralized peridotites and massive sulphide ores. Breccia ores are encountered in insignificant amounts. In the northern part the orebody is composed entirely of mineralized metaperidotites, and there are practically no massive ores. Nearer to the centre and farther towards the south they gradually increase in number until they predominate on the southern flank. The correlation between the ores of the two main types changes in the same direction, as does their position in the orebody. While on the northern flank the disseminated ores are completely concentrated in the western branch; in the centre they spread towards the east, and on the extreme southern flank they are mainly restricted to the eastern branch of the orebody. The degree of intensity of sulphide dissemination in ultramafic rocks is gradually reduced when the distance from the tectonic zone increases eastwards and high-grade heavily disseminated ores grade into low-grade ores. The overwhelming majority of the massive ores is confined to the extreme west of the orebody.

The Vostok deposit. The site of the deposit is composed mainly of granite-gneisses and amphibolites; biotite- and amphibole-biotite gneisses and granitic pegmatites are not abundant. The amphibolites and gneisses are intensely migmatized. The rocks strike mainly northwest but in places the strike turns latitudinal and towards the northeast (Fig. 19). The angle of dip varies from 15° to 40° towards the southwest and south. In the lower part of the section there is a member of the pyroxene-bearing amphibolites with a thickness of 50 to 150 m. Higher in the sequence there is a »variegated» member of similar thickness in which different rock types vary at random and are followed by the upper »light» member with a thickness of 200—250 m and composed mainly of granite-gneisses and gneisses (Yakovlev and Yakovleva 1974).

The copper-nickel mineralization is related to some small intrusives of ultrabasic rocks located in the two structural zones of Verkhnyaya and Nizhnyaya. The greatest distance between them is 140—180 m; in a north-western direction the zones approach each other. On the western flank they are confined to the regional fault of the northeastern strike. The ultramafic bodies of the Verkhnyaya zone are confined to the

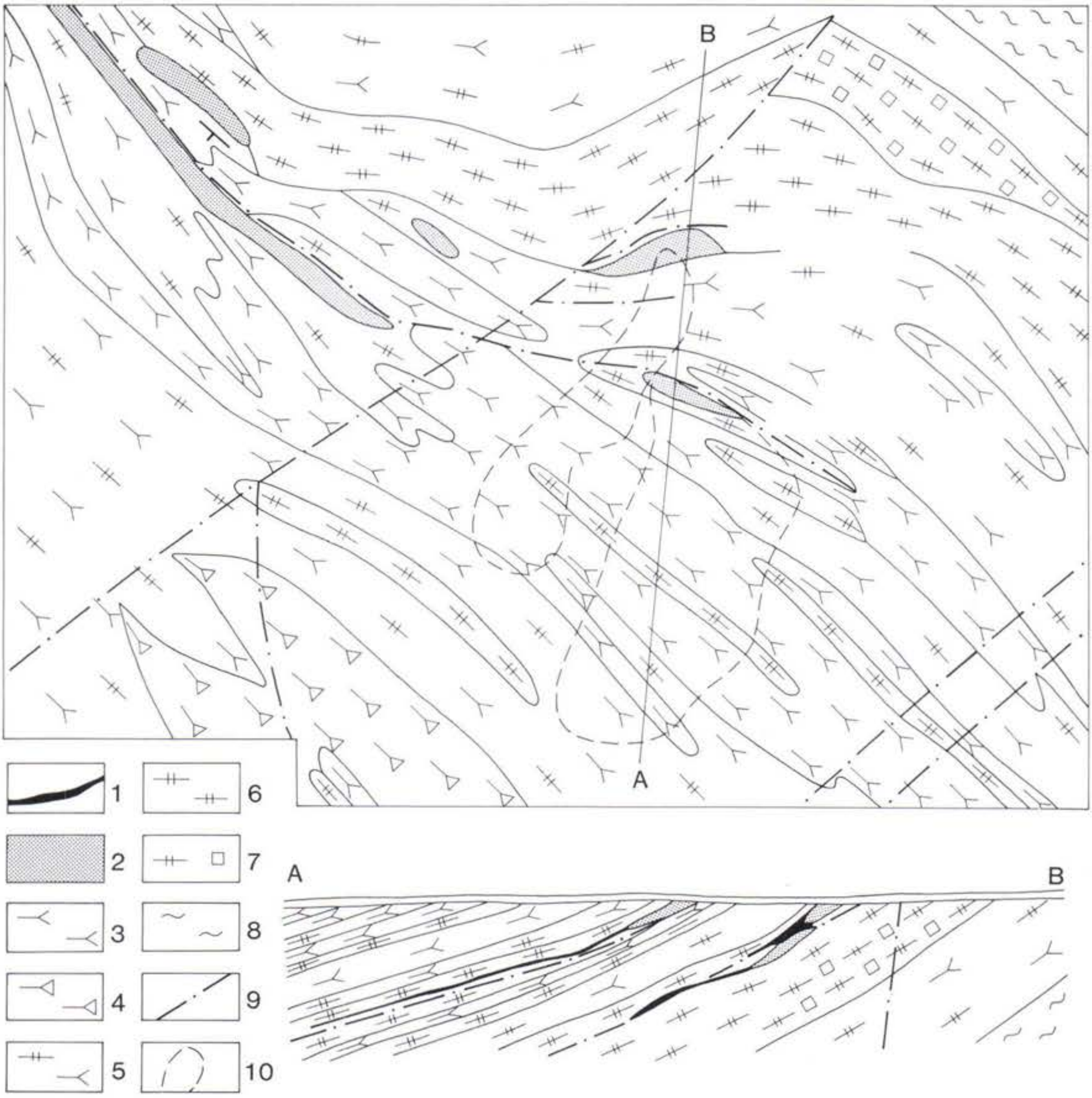


Fig. 19. Schematic geological map of the Vostok deposit. According to material of the Murmansk Exploration Expedition. 1 — breccia ore; 2 — ultramafic rock; 3 — plagiomicrocline granite-gneiss; 4 — plagioclase granite-gneiss; 5 — migmatite of plagio-microline granite formed at the expense of amphibolite; 6 — feldspathic amphibolite; 7 — pyroxene-feldspar-amphibolite; 8 — biotite-amphibole gneiss; 9 — faults; 10 — outlines of ore deposits down the dip.

member of alternating granite-gneisses, amphibolites and gneisses; the intrusives of the Nizhnyaya zone are confined to the tops of the lower member of the pyroxene-bearing amphibolites.

The ultramafic bodies are irregular lenses and beds in form. Several features distinguish them: the many times greater dimensions of the bodies down the dip than along the strike, the considerable variation in thickness, the frequent branching and pinching, and the faults. There are various intrusive bodies within the limits of each zone. All the bodies are conformable with

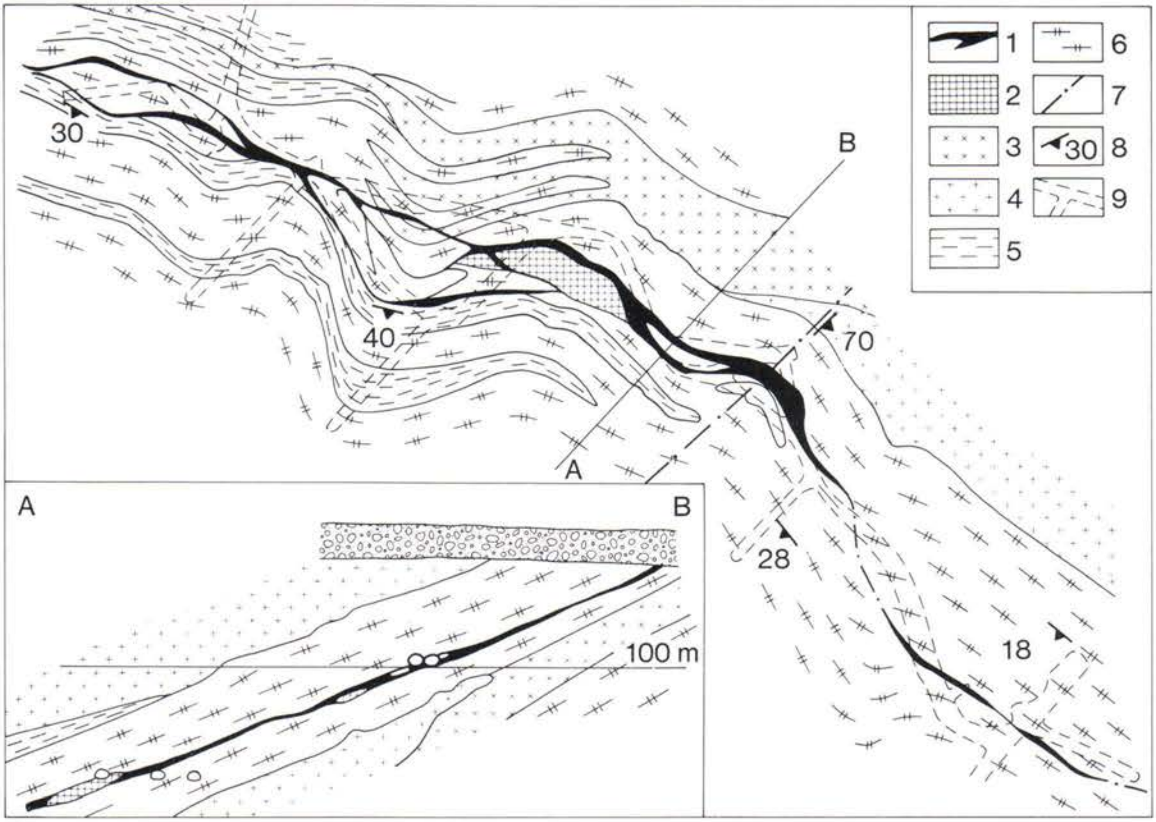


Fig. 20. Geological plan of the Verhnaya ore showing of the Vostok deposit at the + 100 m level. 1 — breccia ore; 2 — intensely mineralized metaperidotite; 3 — plagiomicrocline granite-gneiss; 4 — plagioclase granite-gneiss; 5 — biotite gneiss; 6 — felspathic amphibolite; 7 — faults; 8 — strike and dip of a planar element; 9 — mine workings.

the host rocks and bend in harmony with them along the strike and down the dip.

The footwall on the intrusive bodies of the Verkhnyaya and Nizhnyaya zone exhibits tectonic dislocations.

A characteristic feature of the Vostok deposit is the development of veined pegmatites, quartz, plagioclase and microline in composition, that dissect the mineralized and altered ultramafic rocks. The veins, which dip steeply at an angle of 70°—75° to meet the intrusives, are not persistent along the strike, and down the dip they form knee-like bends and branches. They are from 3—10 cm to 10—12 cm thick. Amphibole-chlorite reaction margins are met with in ultramafic rocks along either side of the veins. The intensity of the sulphide dissemination in ultramafic rocks does not change near the pegmatite veins, and disseminated sulphides are observed in the pegmatites themselves. The mineralized faults in the footwall of the nickel-bearing intrusives cut the pegmatite veins, and fragments of pegmatites are met with in the breccia ore.

Two ore zones, Verkhnyaya and Nizhnyaya can be defined on the basis of the two structural zones. The Verkhnyaya ore zone, represented by one ore deposit is located mainly in the upper parts of amphibole beds, but in some places it extends into gneisses and granite-gneisses along the strike (Fig. 20). That is where the main ore reserves are located. The zone strikes northwest and dips southwest at 25°—30°. It is composed of three ultrabasic bodies located along the mineralized tectonic zone. The first body, which forms the extreme western part of the deposit, is a narrow ribbon in form with uneven edges; it is 100 m wide and plunges to a considerable depth. The intrusive contains low-grade disseminated mineralization that eastwards increases somewhat in intensity.

The second intrusive body of high-grade disseminated ores is separated from the first one by a narrow zone of pronounced development of folds. At the upper levels the second intrusive body shows an arch shape in the section because of its location in the axial part of a small transversal synclinal fold. It is complicated in pattern with extra bends and branches that increase with depth. The third intrusive body of disseminated ores is thin and divided into several blocks.

The mineralized tectonic zone is thickest at the second intrusive body. It stretches conformably with the host rocks along the strike, but branches at transversal bends. One branch repeats the outlines of the folds, the other bends a little and cuts them. Down the dip the mineralized zone also cuts the gentle folds of the rocks, which is why in some places it is located within or outside the intrusives. This zone mainly consists of breccia ores with fragments of ultramafic and host rocks. The amount of sulphides increases eastwards, reaching a maximum in the area of the second intrusive body. Farther eastwards the breccia ores are replaced by stringer ores, then by rare, disseminated and more cuprous ores.

The lower ore deposit is confined to a member of the pyroxene-bearing amphibolites whose strike shifts from northeast in the west to southeast in the east (Fig. 21); the dip shifts likewise from southeast at 30°—40° in the west to southwest at 20°—30° in the east. The rocks nearer the eastern flank occupy the core of the transversal synclinal fold with an axis trending in sub-meridional direction and plunging south-southwest.

In the western limb and at the crest of the fold there are three orebodies in an echelon array divided by amphibolite interlayers 20—30 m thick. The lowest orebody (N1) is composed of lenses of mineralized ultramafics, located along the mineralized tectonic zone, with a strike length of 40—50 m and a thickness of up to 10 m. The mineralized tectonic zone is from some centimetres to 0.5 m thick and comprises high-grade breccia ores mainly along the intrusive bodies.

Orebody N2 is composed of two small lenses of ultramafics associated with the faults. One of them extends for 100 m and contains rare sulphide dissemination. The other is thinner and extends for 50 m with rich sulphide dissemination mainly of chalcopyrite, and accompanied by the mineralized tectonic breccia along the footwall. Sulphide mineralization is weak in the tectonic dislocations that connect both lenses.

Orebody N3, located above and to the east, is an intrusive, 100 m long, with poor, disseminated mineralization.

Down the dip the orebodies extend for a considerable distance with swells, pinches and breaks. At depth the mineralization is rather weak and thin.

The structure of the Vostok deposit is characterized mainly by a large submeridional fold, which complicates the general northwestern trend of the amphibolite and granite-gneiss horizons, and by the northwestern tectonic zones conformable with the general trend of the rocks. They are the major structural elements controlling the distribution of nickel-bearing intrusives. In the western limb of the fold and at its crest the orebodies are located in the Nizhnyaya tectonic zone; in the eastern limb they only occur in the Verkhnyaya zone.

The morphology of the nickel-bearing intrusives and the structure of the deposits were much affected by extra folds. Wherever the folds are cut by the tectonic zones controlling the ores, the orebodies decrease in thickness until they pinch out completely. This explain

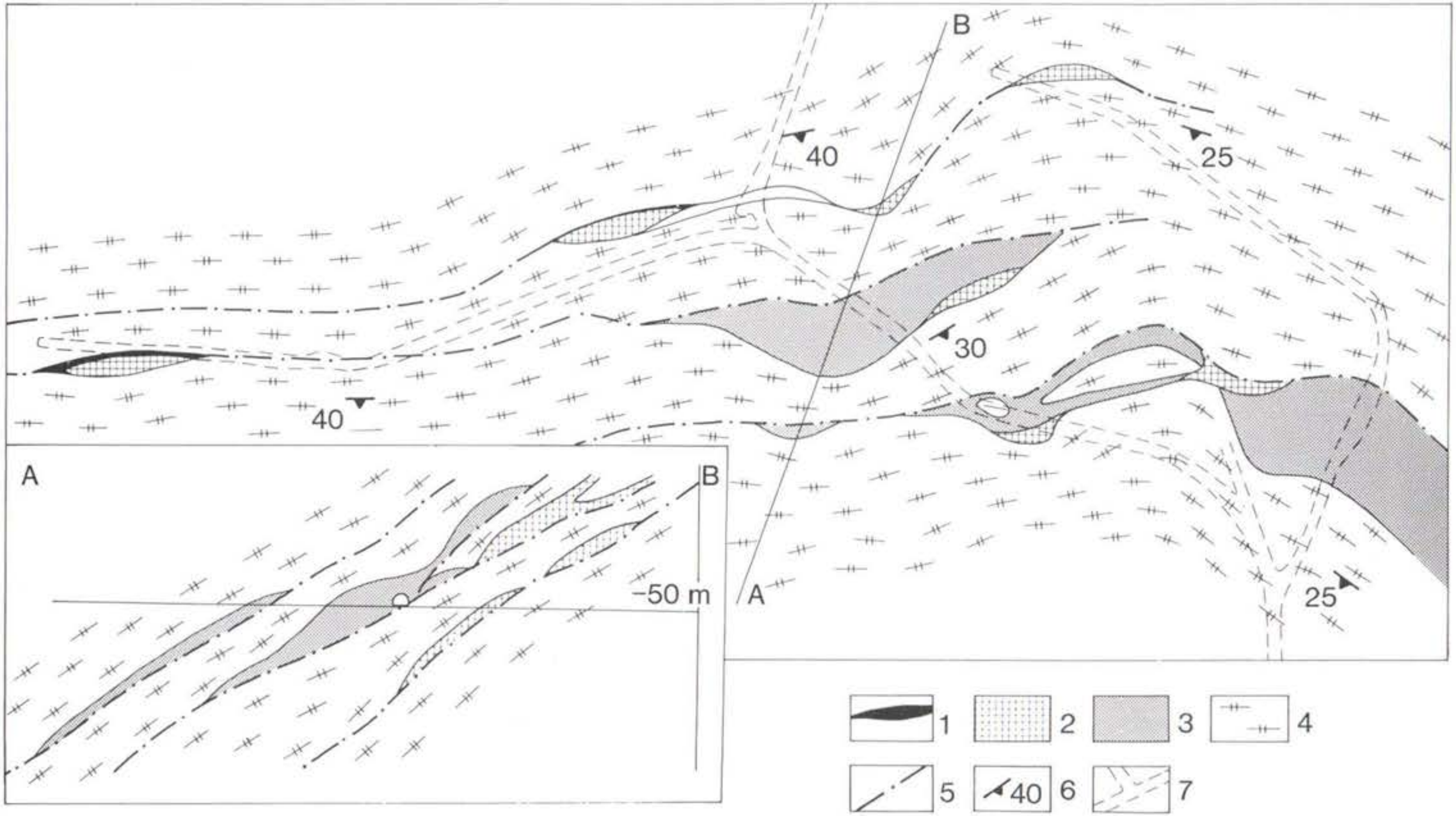
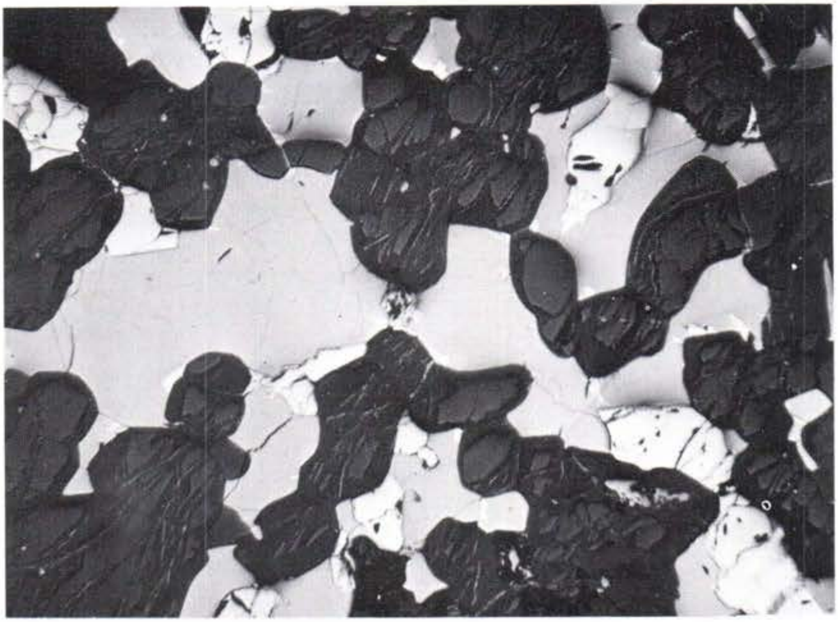


Fig. 21. Geological plan of the Nizhnyaya ore showing of the Vostok deposit at the -50 m level. 1 — breccia ore; 2 — intensely mineralized metaperidotite; 3 — metaperidotite with a weak sulphide dissemination; 4 — feldspathic amphibolite; 5 — faults; 6 — strike and dip of a planar element; 7 — mine workings.



a

Fig. 22. Structural features of the major types of Allarechka Ni-Cu ore. a — »ore» olivinite with sideronitic ore structure. The sulphides are concentrated in the intersticies between grains and aggregates of partly serpentinized olivine. Grey streaks in olivine are magnetite. The Allarechka deposit, heavily disseminated ore, polished section, × 70; b — massive ores with large porphyric portions of pentlandite often exhibiting distinct shape of a hexahedron.

why the intrusives and the orebodies have a column-like elongation down the dip and why they usually plunge southwest, parallel to the bends of the fold structures.

Ore showings. The Severnaya orebody and Runnijoki are the most interesting of the well-known oreshowings in the area.

The Severnaya orebody, which is located near the Allarechka deposit, is a small bed-like body of mineralized ultramafic rocks, elongated in a northeastern direction parallel to the strike of a gneissic series. In shape and mode of occurrence it is analogous to the Allarechka intrusive. On the southern flank the deposit comes near the regional Alla-Akkajärvi fault.

The Runnijoki ore showing is located in the northwest of the Allarechka nickel area, at the margin of the dome of the same name. The country rock is composed mainly of biotite gneisses and granite-gneisses, having a northeastern strike and a northwestern dip at an angle of 30°—40°. Among them there are rows of lenses and bed-like intrusives of ultramafic rocks in several stages. The intrusives vary in dimensions and thickness and are composed mainly of altered peridotites and pyroxene-bearing olivinites. They are frequently barren and contain scarce and fine-grained dissemination of sulphides. Associated with one of these lower-grade intrusives is an economic nickel-copper mineralization. The low-grade disseminated ores occupy the basal part of the intrusive; the richer disseminated and massive ores are some metres from it in the underlying granite-gneisses. They apparently represent one of the tongues of the ore-bearing intrusive analogously to the well-known orebodies of other deposits. The smaller ore showings of Akkim, Annama and Hihnajärvi are in the same area.

b

Textural-structural types and mineral composition of ores

The sulphide nickel-copper ores are divided, as in the Pechenga deposit, into four types: 1) disseminated ores in metaperidotite; 2) massive ores; 3) breccia ores; and 4) disseminated and stringer-disseminated ores in gneisses and amphibolites.

The disseminated ores in metaperidotites predominate; they are divided into weakly disseminated (low-grade) ores and heavily disseminated (high-grade) ores on the basis of their sulphide and nickel content. Typical of them are disseminated, spotted, nest-like, banded and stringer-disseminated structures. The sulphide content in the heavily disseminated ores reaches 60—70 %. The major ore minerals are pyrrhotite, pentlandite, chalcopyrite and magnetite (ilmenomagnetite). Ilmenite, mackinawite, pyrite, violarite, some cubanite, sphalerite, bornite, and galenia occur in smaller amounts. Depending on the predominant ore mineral the varieties of disseminated ores can be subdivided into pyrrhotite-predominant and chalcopyrite-predominant ores.

The non-metalliferous part is composed of olivine, orthorhombic bronzitic pyroxene (up to 10 %), secondary actinolite, cummingtonite, serpentine, chlorite and to a lesser extent of biotite, phlogopite, talc and carbonates.

In the low-grade disseminated ores the sulphides mainly form interstitial (sideronitic) dissemination. The grains of olivine in contact with the sulphides are usually rimmed by a thin serpentine margin; secondary magnetite has frequently developed at the expense of pyrrhotite and pentlandite.

In the high-grade dissemination the most abundant ores are: 1) a heavy interstitial dissemination in »ore» olivinites and harzburgites (fine grains of olivine appear to »swim» in the sulphide mass (Fig. 22a); 2) interstitial dissemination transfigured to a variable extent by metasomatic features; 3) impregnation and bleb-like sulphide portions in primary magmatic silicates: in olivine and pyroxene, frequently segregated into two or three phases: pyrrhotite, pentlandite and chalcopyrite ones.

Massive nickel-copper ores form a considerable part of the Allarechka ores, although in the Vostok deposit they are encountered only in places. They are composed of the same minerals as the dissemination in ultramafic rocks. The proportions of the sulphides vary widely from pure chalcopyrite to essentially pyrrhotitic and pentlanditic varieties. Rounded debris of wall-rock and inclusions of non-metalliferous minerals (amphibole, biotite, carbonate, quartz, garnet, apatite and others) frequently occur in the sulphide veins near the contacts. Massive, spotted and banded structures are most typical.

The ores are usually coarse-grained, with a high nickel content. The main nickel-bearing mineral is pentlandite, which accounts for almost 80 % of the volume of the massive ores. It forms coarse porphyritic grains with distinct crystallographic outlines up to 7 cm in diameter (Fig. 22b) and stringers up to 10—20 cm thick.

Magnetite occurs fairly uniformly in the ores as idiomorphic crystals, 2—4 mm in diameter. Its abundance is 6—10 %, rarely less. In some places the ores show intense pyritization, with the result that pyrite is often closely intergrown with chalcopyrite and pyrrhotite, forming symplectites.

The ores have numerous accessory minerals including sphalerite, galenia, marcasite, molybdenite, arsenides and tellurides.

The breccia ores are encountered mainly in the Vostok deposit. Sulphides form up to 50—80 % of the volume of the ore. On the flanks of the ore zones chalcopyrite is the predominant mineral in the sulphide matrix. Where the ore zones run along the contacts of intrusives, the sulphide matrix is composed of pentlandite and pyrrhotite with some chalcopyrite. Accessories include pyrite, sphalerite, galena, bornite, nickel arsenides and tellurides.

The breccia ore is distinguished by fine debris of non-metalliferous minerals densely scattered throughout the sulphide matrix.

The disseminated and stringer-disseminated ores in the host rocks are of no importance. Their sulphide content is up to 15 %; it may reach 30 % only in the exocontact with biotite-amphibole and garnet-quartz rocks.

The major mineral of the ores is chalcopyrite. Minerals present to a lesser extent include bornite, pyrrhotite, pentlandite, millerite, pyrite, violarite, molybdenite, chalcocite, siegenite, covellite, graphite, native copper, altaite and hessite (Yakovlev *et al.* 1981). The compositions of the major minerals of the ores are given in Table 4.

The chemical composition of the ores

The nickel-copper ores of the Allarechka area have no equal in the Kola peninsula and considerably exceed the ores of the Pechenga in major mineral abundances and nickel content.

The ores of the Allarechka deposit are of particular interest. The nickel content in massive ores reaches 28 %, in high-grade, heavily disseminated ores 10 %, and in low-grade disseminated ores 2 %. The copper content in massive and high-grade disseminated ores varies within almost equal limits, from 0.2 to 12 %. The cobalt content is highest in the massive ores and varies from 0.1 to 0.7 %; in high-grade disseminated ores its value is a hundredth, in low-grade disseminated ones a thousandth of a per cent.

The ratios between nickel, copper and cobalt are 82:25:1 in massive ores, 68:25:1 in high-grade disseminated ores, 52:23:1 in low-grade disseminated ores and 51:55:1 in mineralized host and exocontact rocks.

The major mineral abundances of the high-grade ores of the Vostok deposit (breccia and

Table 4. Chemical composition of ore minerals of the Allarechka region.

	Samples								
	1	2	3	4	5	6	7	8	9
Fe	61.18	59.88	61.60	57.95	38.37	34.82	35.45	30.68	28.04
Ni	0.02	0.29	0.09	0.83	27.04	32.65	31.41	34.77	38.61
Cu	0.00	0.01	0.00	0.00					
Co	0.00	0.00	0.00	0.02	0.58	0.31	0.87	0.27	1.33
S	38.44	39.97	37.84	41.68	32.79	31.90	32.07	34.52	32.03
Total	99.64	100.15	99.53	100.48	98.99	99.68	99.80	100.24	100.25

	Samples								
	10	11	12	13	14	15	16	17	18
Fe	24.69	29.93	29.92	30.50	29.91	40.26	40.74	56.60	59.70
Ni	41.70	0.02		—	0.37			7.79	3.50
Cu		34.23	34.41	34.96	34.91	24.35	24.73	0.39	0.21
Co	0.66		0.03		0.04			0.02	0.43
S	32.62	35.15	33.44	34.58	33.98	35.00	34.10	35.60	36.60
Total	99.73	99.34	97.80	100.04	99.21	99.62	99.58	100.40	100.44

1—4 — pyrrhotite, 5—10 — pentlandite, 11—14 — chalcopyrite, 15—16 — cubanite, 17—18 — mackinawite, 1 — from poor mineralization in serpentinous peridotite, Vostok; 2 — from weakly disseminated ore in endocontact of amphibole rock, Allarechka; 5 — from metaperidotite with poor mineralization, Vostok; 6 — from heavily disseminated ore in metaperidotite, Allarechka; 7 — from weakly disseminated ore in metaperidotite, Vostok; 8 — from massive ore, Allarechka; 9 — from mineralized granite pegmatite, Vostok; 10 — from mineralized exocontact of a biotite-amphibole rock, Allarechka; 11 — from the same sample as analysis No. 2; 12 — from massive ore, Allarechka; 13—14 — from mineralized granite pegmatite, Vostok; 15—16 — from metapyroxenite with poor mineralization, Akkim; 17—18 — from mineralized metaperidotite, Allarechka (17), Vostok (18).

heavily disseminated ores) are about 1.5—2 times less than those of the Allarechka ores; in the low grade disseminated ores, in contrast, the values exceed those in the latter by a factor of 1.3—1.5. The minor elements in the nickel-copper ores of the area include the precious metals, selenium and tellurium. The ores of the area have no equal in the selenium content in the sulphide fraction. The concentration of selenium regularly increases from low-grade disseminated ores (0.0056 %) to massive sulphides (0.0210 %). Bismuth, tin, chromium, vanadium, lead, zinc and molybdenum occur as trace elements.

The Monchegorsk area

Geological characteristics of the area

In the Monchegorsk nickel-bearing area, including the Chuna-Moncha, Volcji and Losevye tundras and their foothills, practically all the known nickel-copper occurrences are related to the Monchegorsk pluton of mafic and ultramafic rocks. Only one small Priozero deposit and some showings have been found outside it. The Monchegorsk pluton located at the meridional curve of the Pechenga-Varzuga structural-metallogenic zone occurs between the greenstone volcanogenic sedimentary rocks of the Imandra-Varzuga and the underlying Kola-Belomorian complex gneisses. In the southwest its convex part is in direct contact with the gabbro-labradoritite massif of the Main ridge of the Chuna-Moncha Volch'i tundras.

The geological structure of the Monchegorsk region has been described in detail in a number of monographs (e.g. USSR Geology 1958, Kozlov *et al.* 1967, Kozlov 1973). Three stages are clearly distinguishable in its structure. The lower (Lower Archean) stage exposed on the section northeast of the pluton is composed of oligoclase gneiss-granites, plagiogranites and diorites. The middle (Upper Archean) structural stage framing the Main ridge massif on both sides is composed of biotite and amphibole-biotite gneisses with ferruginous quartzite interbeds, sillimanite-garnet-biotite, garnet-feldspathic and other gneisses of the Kola Belomorian complex. In a structural tectonic sense the area represents a synclinorium 30—40 km wide elongated in the meridional direction for more than 100 km and with the axis lying somewhat to the east of the Main ridge. It is complicated by folds 5—10 km wide and less whose axes also strike in the meridional direction. In the southern part of the area the synclinorium suddenly turns to the southeast and gradually dips beneath the formations of the upper (Proterozoic) structural stage composed of volcanogenic sedimentary rocks of the Imandra-Varzuga group.

The Monchegorsk differentiated pluton lopolith consists of two branches: submeridional, ie. the Nittis-Kumuzh'ya-Travyanaya massif, and sublatitudinal, ie. the Sopcha and Nyud-Poaz massif (Fig. 23). The Nittis-Kumuzh'ya-Travyanaya and Sopcha massifs are mainly composed of ultramafic rocks, from top to bottom as follows:

1. Pyroxenites (bronzitites) with a well expressed trachytoid texture, rarely with lineation Their thickness measures 300—700 m.

2. Interbedding pyroxenites, olivine pyroxenites and peridotites 400 m thick. Pyroxene increases in the upper part of the zone and olivine in the lower part.

3. Peridotites, with a gradual transition to the overlying complex enriched in plagioclase down the section. Their thickness is 100—200 m.

4. Ultramafic feldspathic and mafic rocks 10 m thick at the margins, and up to 100 m thick in the centre with abundant, coarse-grained pegmatoid rocks.

A thin (8—10 m) interbed of quartz-biotite-norite and gabbro-norites occurs in the zone of a direct contact between the massifs and the host rocks.

The base of the Nittis-Kumuzh'ya-Travyanaya massif is a symmetrical trough, dipping southwest at 5°. Its limbs are inclined to the centre at 30°—40°. The base of the Sopcha massif is also in the form of a trough; it dips gently west-southwest and its limbs are inclined to the centre at 40°—45° in the west and at 20°—25° in the east.

The Nyud-Poaz massif is composed of mafic rocks and represents a layered bedded intrusion with a gentle dip to southwest of primary banding and lineation. At its western end the upper part of the section is composed of interbanded plagioclase pyroxenites and melanocratic norites among which there are some interbeds, up to 100 m thick, enriched in olivine. The »critical horizon» of Nyud is confined to a transitional zone between olivine and olivine-free rocks. In the lower part of the section the abundance of plagioclase (up to 35—40 %) increases in norites and they become mesocratic. A narrow interbed of quartz and quartz-biotite norites can be seen at the contact with the host gneiss. The intrusive is 600—650 m thick in the east and 350—400 m thick in the west.

In and around the Monchegorsk pluton the host gneisses have dykes of olivine and olivine-free diabases, labradorite porphyrites, quartz diabases, lamprophyres, camptonites, spessartites and quartz porphyries. Table 5 gives the compositions of the most common mafic and ultramafic rocks of the pluton.

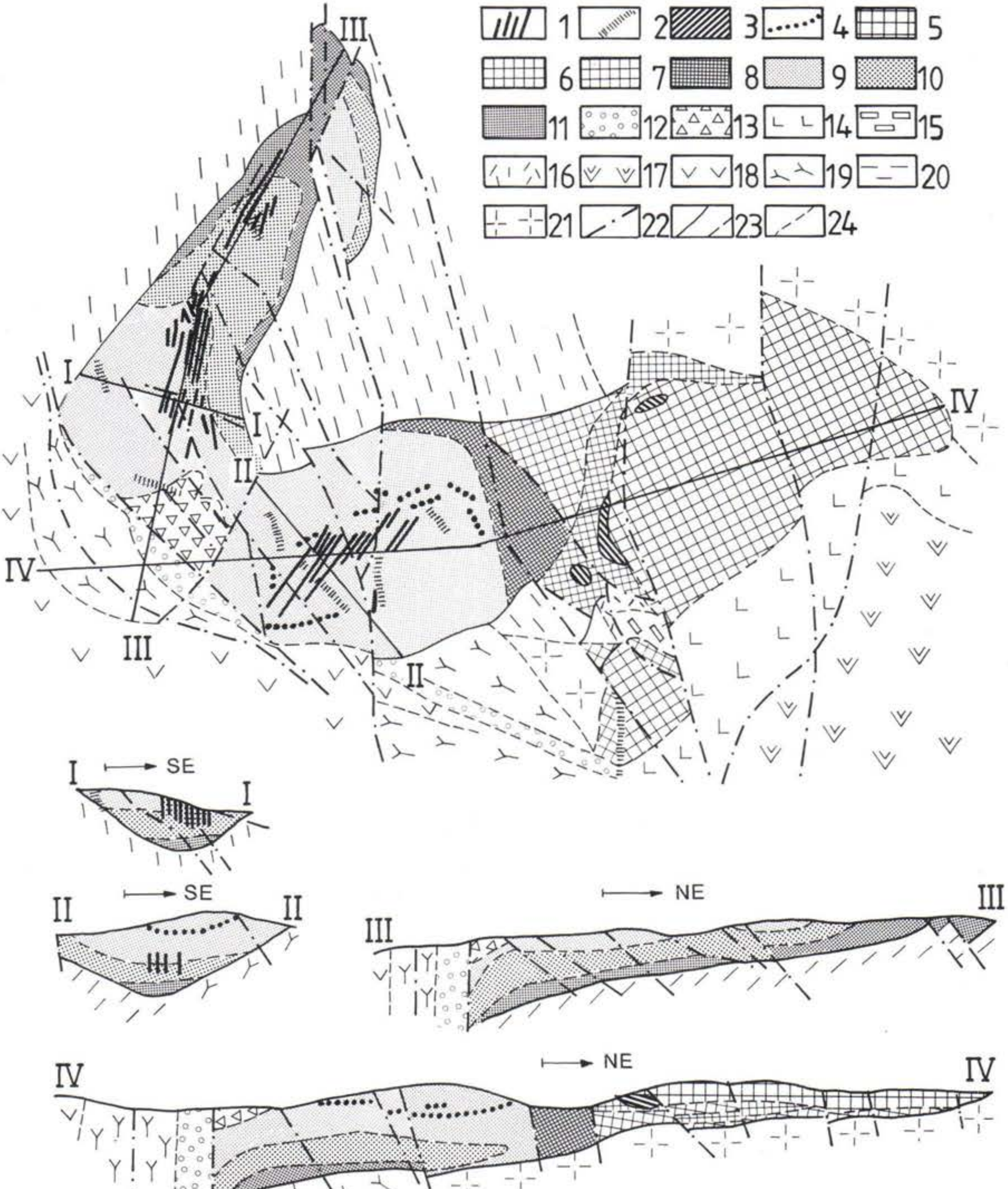


Fig. 23. Schematic geological map of the Monchegorsk pluton, compiled from data collected by the Murmansk Exploration Expedition and the Kola Branch of the USSR Ac. of Sci. 1 — sulphide Ni-Cu veins; 2 — dykes of diabase and lamprophyre; 3 — rocks of the »critical» horizon, 4 — Sopcha ore beds; 5 — leucomesocratic norite; 6 — melanocratic norite; 7 — olivine norite; 8 — plagioclase pyroxenite; 9 — pyroxenite (bronzitite); 10 — an alternation zone of pyroxenite, olivine pyroxenite and peridotite; 11 — peridotite (harzburgite); 12 — an alternation zone of pyroxenite, peridotite and norite, penetrated by numerous veins of mafic and felsic rocks; 13 — olivinite; 14 — metamorphosed norite and gabbro-norite in foothills of the Byruchuaiven; 15 — quartz gabbro and diorite; 16 — andesite, dacite and their tuffs; 17 — metadiabase and metaamygdaloid of the Imandra-Varzuga group; 18 — massive gabbronorite and gabbro of the Main ridge of the Moncha; 19 — the same rocks but metamorphosed and schistose; 20 — gneisses of the Kola-Belomorean complex; 21 — diorite; granodiorite; 22 — dislocations; 23 — intrusive contacts (a — established, b — inferred); 24 — the boundaries of the rocks.

Table 5. Chemical composition of mafic and ultramafic rocks of the Monchegorsk region.

	Samples							
	1	2	3	4	5	6	7	8
SiO_2	40.21	41.70	43.08	45.85	47.25	46.18	46.10	44.19
TiO_2	0.24	0.24	0.23	0.26	0.25	0.16	0.25	0.24
Al_2O_3	1.64	5.66	4.98	6.89	6.24	5.92	5.04	15.35
Cr_2O_3	0.49	—	0.23	—	0.40	0.47	—	0.02
Fe_2O_3	1.13	5.55	2.20	1.51	3.63	3.58	4.78	3.74
FeO	11.53	7.72	10.60	11.73	8.34	7.70	7.51	7.27
MnO	0.18	0.15	0.14	0.21	0.17	0.17	0.13	0.16
MgO	42.58	30.15	31.80	26.36	26.04	28.14	29.09	6.27
CaO	0.63	3.31	3.12	4.50	4.73	4.41	3.61	11.43
Na_2O	0.20	0.74	0.66	0.60	0.92	0.78	0.46	3.32
K_2O	0.06	0.36	0.12	0.02	0.17	0.11	0.15	0.11
P_2O_5	0.02	0.03	0.03	—	0.03	0.02	0.04	0.02
S	—	1.00	0.05	—	0.47	0.50	—	2.06
V_2O_5	0.02	—	0.01	—	0.02	0.02	—	0.09
CO_2	0.11	—	0.29	—	0.19	0.17	—	4.61
H_2O^-	0.08	0.31	0.14	0.16	0.15	0.09	0.37	0.16
H_2O^+	0.96	1.73	1.88	—	0.76	1.82	—	1.87
losses	—	—	—	1.92	—	—	3.01	—
Ni	0.23	0.46	0.175	—	0.180	0.170	—	0.016
Cu	0.006	0.22	0.024	—	0.074	0.079	—	0.08
CO	0.014	—	0.014	—	0.012	0.013	—	0.07
—O=S	—	0.50	—	—	0.23	0.25	—	1.03
Total	100.33	98.83	99.77	100.01	99.79	100.25	100.54	100.05

	Samples							
	9	10	11	12	13	14	15	16
SiO_2	47.72	47.79	48.48	48.52	49.15	51.66	53.02	54.59
TiO_2	0.18	0.27	0.29	0.43	0.22	0.33	0.48	0.05
Al_2O_3	16.33	8.60	15.96	14.02	8.04	16.52	16.98	21.03
Cr_2O_3	—	0.86	0.20	0.08	0.30	—	—	—
Fe_2O_3	1.01	4.96	1.81	7.96	6.89	1.91	0.65	1.09
FeO	8.04	11.71	7.02	6.12	8.20	4.97	4.28	3.10
MnO	0.16	0.20	0.13	0.12	0.32	0.19	0.12	0.06
MgO	11.79	15.80	9.12	6.93	18.40	9.53	7.80	4.90
CaO	9.09	4.36	12.20	10.14	4.12	12.38	10.81	7.98
Na_2O	1.57	1.10	1.54	2.08	0.64	1.66	3.02	5.24
K_2O	0.71	0.15	0.07	0.50	0.11	0.32	0.22	0.34
P_2O_5	—	0.02	—	0.05	0.02	—	—	—
S	—	2.65	1.46	2.67	2.03	—	—	—
V_2O_5	—	—	—	0.02	0.02	—	—	—
CO_2	—	0.29	—	0.57	0.65	—	—	—
H_2O^-	0.05	0.04	0.31	0.07	0.39	0.20	0.24	—
H_2O^+	0.06	0.96	—	0.17	1.13	—	—	0.23
losses	3.01	—	2.03	—	—	1.00	2.42	1.16
Ni	—	0.37	0.28	0.600	0.24	—	—	—
Cu	—	0.91	—	0.051	0.16	—	—	—
CO	—	0.016	—	0.021	0.016	—	—	—
—O=S	—	1.33	0.73	1.33	1.01			
Total	99.72	99.73	100.17	99.79	100.04	100.67	100.04	99.77

1 — peridotite with casual dissemination of sulphides, Sopcha; 2 — feldspathic peridotite with weak dissemination of sulphides, Travyanaya; 3 — feldspathic peridotite Pojkiäntov, Nittis-Kumuzhje-Travyanaya; 4 — feldspathic pyroxenite with olivine, Kumuzhje; 5 — olivine pyroxenite with casual dissemination of sulphides, Nittis-Kumuzhje-Travyanaya; 6 — olivine norite with casual dissemination of sulphides, Nittis-Kumuzhje-Travyanaya; 7 — ore-free norite, Travyanaya; 8 — mesocratic to leucocratic, fine-grained mineralized gabbro-norite, Njud-II, 9 — ore-free gabbro-pegmatite, Njud-Poaz; 10 — mesocratic, fine-grained mineralized norite, Njud-II; 11 — ophitic gabbro-norite with casual dissemination of sulphides, Kumuzhje; 12 — medium-grained mineralized gabbro-norite, Nittis-Kumuzhje-Travyanaya; 13 — mineralized, melonocratic norite with olivine, Njud-II; 14 — ore-free olivine, gabbro-norite, Nittis; 15 — ore-free gabbro-pegmatite, Nittis; 16 — diorite-pegmatite, Nittis-Kumuzhje-Travyanaya.

The Monchegorsk pluton is cut by a series of shear faults that break it up into big tectonic blocks displaced in relation to each other (Fig. 23). They are represented by zones of schistose cataclastic rocks 0.5 to 2—3 m thick (sometimes even up to 7—8 m thick). The bulk of the tectonic dislocation is outside the pluton, continuing in underlying gneisses.

Localization of the Ni-Cu mineralizations

Sulphide nickel-copper ore occurrences have been studied at different times by several geologists, including V. K. Kotul'sky, N. A. Yeliseyev, I. V. Galkin, P. V. Lyalin, G. V. Kholmov, E. K. Kozlov, V. A. Maslenikov, T. N. Ivanova, V. S. Dokuchaeva and I. S. Bartenev.

All the occurrences of sulphide Ni-Cu mineralization in the area are spatially related to the intrusives of mafic-ultramafic rocks. Exploitable deposits are related to the Monchegorsk pluton.

The occurrences of syngenetic disseminated ores are of bed form and are usually spatially confined to the layers of olivine-bearing rocks. Their location is controlled by the primary structural elements of massifs, the form of the base, the degree of differentiation, the presence of flow layers, etc. In intrusives they may occur in upper and basal parts. Mineralization is related to the coarse-grained pegmatoid rocks.

The ore occurrences of syngenetic and nested disseminated ores with bedded, lens-shaped and stock-like forms are locally confined to the parts of the massifs where fine-grained and irregular-grained rocks, pegmatoids and rocks allogenic for the massif (»critical horizon») are widely developed. The distribution of the latter two rock varieties may be used as ore-controlling zones in some cases.

The deposits of veined epigenetic sulphide ores in the Monchegorsk pluton are confined to the systems of steeply dipping shear fractures trending north-northeast and dipping south southeast closely related to the primary structural elements of the massif (the geometry of the intrusive blocks, primary jointing).

The main ore-controlling elements in the occurrences of epigenetic stringer-disseminated ores are the zones of tectonic dislocations marked by schistose and blastomylonitized rocks. Most favourable for the concentration of injected stringer-disseminated ores are the places where the tectonic zones pass along the bend of the contact between rocks sharply different in physico-mechanical properties, e.g. between ultramafic rocks and diorite-gneisses.

All the occurrences of epigenetic sulphide Ni-Cu ores in the region are characterized by orebodies with a mainly meridional, northeast strike, most of which exhibit a southwest plunge.

The disseminated ore deposits of the Monchegorsk pluton

The basal deposit of the Nittis-Kumuzh'ya-Travyanaya massif is confined to the horizon of essentially feldspathic rocks that represents a transitional zone from ultramafic rocks of the massif to gabbro-norites. The deposit is distinguished by isometric portions, up to 10—15 m across, of coarse-grained pyroxenites, feldspathic pyroxenites, rare peridotites and norites in the host rocks. The disseminated ore mineralization is concentrated within a zone 5—10 m above the base (Fig. 23).

In cross section the deposit is a crescent in shape. Its thickness increases towards the axial part of the massif, where it is 40—50 m. Within the deposit the mineralized and barren portions alternate randomly, the most pronounced sulphide dissemination being confined to the middle of the ore bed.

The basal deposit of disseminated nickel-copper ores in the Sopcha massif is analogous in structure.

The Sopcha and Nyud ore beds are best studied among the ore occurrence confined to the upper parts of the massifs.

The ore bed of the Sopcha massif or »bed

330» is spatially confined to the discontinuous layers of olivine-bearing flows: peridotites, olivine pyroxenites and feldspathic olivine pyroxenite occurring in a pyroxenite layer, where they form a bed-shaped ore deposit that crops out in the upper part of the massif at the 330 m mark (Fig. 23). The deposit is 1—5 m thick and the peridotite layers are usually enriched in sulphides.

The boundaries of the disseminated mineralization do not usually coincide with the boundaries of the olivine-bearing layers as sulphides appear somewhat higher in their roof and disappear lower down in the footwall. Sulphide dissemination is spread uniformly throughout the mineralized layer. In some places ore-bearing layers occur at two or three levels.

The Nyud ore beds are confined to olivine-norite horizons 50—80 m thick and plagioclase peridotites 150—200 m thick. A disseminated mineralization bed within them measures 30—50 m, its upper boundary approximately coinciding with the hanging wall of olivine-bearing ores. Mineralized ores are characterized by a medium-grained, in places pegmatoidal texture.

Analogous horizons of disseminated mineralization in olivine-bearing rocks are also met with outside the Monchegorsk pluton (Pentlandite gorge and others).

Nickel-copper ores in deposits of this type are syngenetic with the enclosing host rocks. Sulphides, which tend to occur in the interstices between primary silicates, and not infrequently to substitute for them, are intergrown with secondary silicates. The average size of the disseminations does not exceed 0.5 cm although individual nest-like sulphide accumulations are 15—20 m across. The major ore minerals are pyrrhotite (up to 60 %), pentlandite, chalcopyrite, ilmenomagnetite and magnetite; accessories include ilmenite, chromite and pyrite.

A distinctive feature of the ore of the basal deposit is the presence of cubanite, sphalerite, some generations of magnetite and a regular increase in pyrite towards the base of the deposit. The metal content of the ore is not high, the nickel-copper ratio being 1.5—2 : 1. The ore regularly contains cobalt, selenium and tellurium. Primary silicates (olivine, pyroxene, plagioclase) have undergone insignificant alterations.

The ores of the Sopcha peridotite bed are characterized by their high content of sulphides, including pentlandite. Their metal content is 1.5 times higher than that in the basal deposit. Chromite is invariably present. The rock-forming minerals in ores have altered considerably more than in the wall rocks of the massif.

Nested-disseminated ore deposits

The group comprises the Nyud-2 deposit, the »Terrasa» ore showing and »Anomaliya S-38» of the Monchegorsk pluton.

The Nyud-2 deposit is confined to the upper part of the Nyud-Poaz massif, where melanocratic norites with interbeds of olivine-bearing rocks predominate. The »critical horizon», which hosts the orebody, occurs in the transitional zone between normal and olivine-bearing norites (Kotul'sky 1947, Ivanova 1953, Kozlov 1973, Maslenikov 1969, Bartenev, Dokuchaeva 1975 *et al.*). Mineralized rocks up to 40 m thick extend in a longitudinal direction. Mesocratic and leucocratic norites and gabbro-norites predominate in the »critical horizon», where they form a row of alternating interbeds that grade one into the other. The hypersthenic cordierite rocks, often with spinel and not infrequently resembling hornfels, are less well developed. They form lenses, interbeds and isolated, irregular portions among fine-grained norites and gabbro-norites. Their boundaries with other rocks are distinct.

Some morphological types of sulphide mineralization can be distinguished: disseminated, stringer-disseminated, stringer-like and nested (schlieren) types. The disseminated ores predominate. The sulphide dissemination has been encountered in all the rocks within the orebody excluding the isolated central parts of spinel-cordierite-hypersthenic portions. Substantial accumulations of sulphides forming massive ores in places were found in the base of the ore-body.

The major one minerals are pyrrhotite (up to 90 %), pentlandite, chalcopyrite and magnetite. Pyrite, mackinawite, violarite and molybdenite are also present. The nickel content is highest in the massive (schlieren) ores, where it predominates markedly over Cu (up to 50:1); in the other types of ore, copper often predominates. Amphibole, biotite, chlorite and talc are closely associated with sulphides.

Deposits of ore veins

Two deposits, Nittis-Kumuzh'ya-Travyanaya (completely mined out) and Sopcha, can be distinguished in the veined field of the Monchegorsk pluton.

In the Nittis-Kumuzh'ya-Travyanaya deposit the Ni-Cu sulphide veins are confined to steeply dipping longitudinal fissures in the axial part of the massif. The attitude of the ore veins (only 51 veins have been studied) is partly similar to that of the primary jointing in the rocks of the massif. The veins have a strike length of 100—1400 m, and a thickness of 5—50 cm increasing up to 2—3 m in swells.

The deposit is broken into three blocks (See Fig. 23) by two pre-ore faults. In the central part the sulphide veins have a meridional strike; in the north and south, they trend northeast (5°—20°). The veins dip steeply (85°—90°), usually towards the axis of a trough-shaped depression at the base of the massif. Horizontal and very short transversal ore veins connecting the adjacent basic veins are also met with.

The thickest and most persistent veins have been encountered in the central part. The veins in the south are »blind» and not exposed; they pinch out gradually southwards. With depth, the veins decrease consistently in thickness and they pinch out completely within the range of 500—600 m above the base of the intrusive. None of the veins reaches the basal deposit of disseminated ores.

Platy and often complex ore veins are characterized by bench-like changes in thickness, thickenings when passing from one fracture to another, joints and forkings, and offsets as thin apophyses. When crossing dykes the sulphide veins often extend or branch into a network of thin intersecting stringers (Fig. 24). Xenoliths of dyke rocks have been noted where the veins thicken.

Irregular thickening and pinching are observed when large faults are crossed by sulphide veins, and sometimes the veins branch when the angle between the fault and the vein is 30° or more. If the angles are smaller the sulphides form embayments in the fault zone.

The contacts between the sulphide veins and the host rocks are sharp. Hydrothermal alterations near the ores are insignificant; when present they are manifested by the formation of amphibole (anthophyllite) and a thin network of stringers of talc and breunnerite.

The lode nickel-copper deposit of the Monchegorsk pluton is characterized by the close relation between the sulphide mineralization and the pegmatite veins of diorite composition. Upwards and southwards in the southern limb of the Nittis-Kumuzh'ya-Travyanaya deposit the sulphide nickel-copper veins grade into coarse-grained gabbro-pegmatites and further into gabbro-norites. The sulphide veins change gradually into silicate veins within a range of 1—3 m in a vertical direction, the thickness of the veins usually remaining constant. A change in sulphide and silicate compositions is sometimes observed along the strike of the veins. Large plagioclase and pyroxene crystals are met with in ore veins far away from the pegmatites. Some pegmatite veins are parallel to the ore veins.

Chalcopyrite-predominant sulphide nickel-copper veins are encountered 100—150 m deeper in the axial part of the Nittis-Kumuzh'ya-Travyanaya massif. They are confined to the pla-

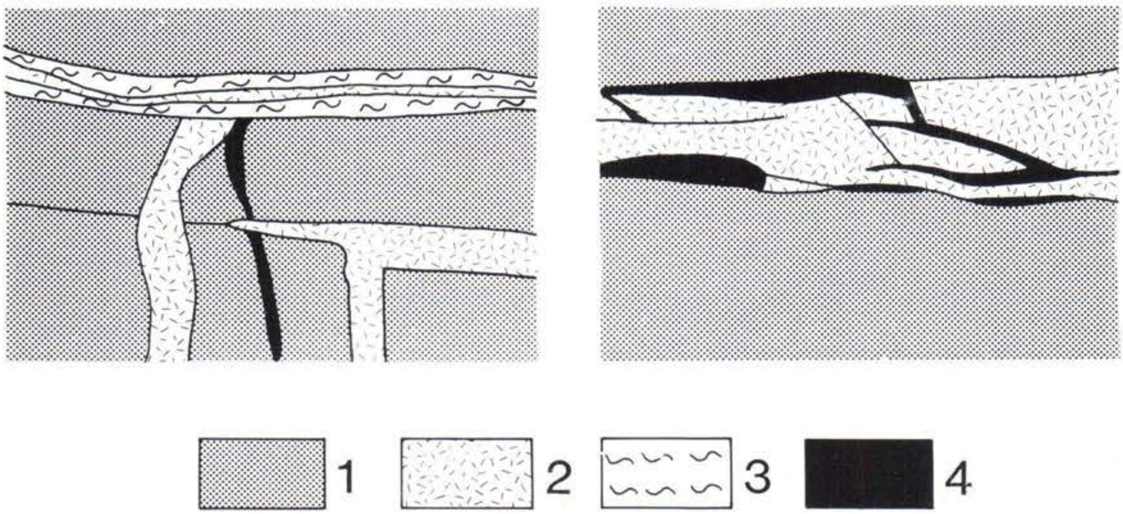


Fig. 24. Interrelation of ore veins and diabase dykes. Sketches of a drift roof. According to P. V. Lyalin. 1 — pyroxenite; 2 — diabase; 3 — schistose pyroxenite; 4 — sulphide veins.

gioclase peridotite horizon and do not extend into the norites in the footwall of the massif. The strike length of the veins does not exceed 150 m. The veins fill steep fractures of the northwestern strike and are closely related to diorite-pegmatites.

The Sopcha deposit has much in common with the Nittis-Kumuzh'ya-Travyanaya deposit. The main characteristic features of the sulphide veins are:

1) northeast trend (35°—45°); 2) location mainly in schist formation zones; 3) mostly lens-form with frequent undular pinches; 4) lesser and non-persistent thickness; and 5) absence of vein exposures. Endomorphic parts of the ore veins exhibit pegmatoid formations as elongated lenses and irregular isolated portions. Veins of pegmatite composition are usually parallel to the ore veins. In this deposit the diorite-pegmatites exhibit fairly high abundances of ore minerals xenomorphic in relation to the silicates.

The nickel-copper ores of lode deposits are epigenetic, and their mineral composition varies substantially. The major minerals are pyrrhotite, magnetite, chalcopyrite, pentlandite and pyrite. Accessories and rarely encountered constituents include ilmenite, cubanite, mackinawite, sphalerite, millerite, molybdenite, galena, tellurobismuthite, minerals of the melonite group and altaite. The compositions of the most abundant minerals of the nickel-copper ores of the Monchegorsk pluton are given in Table 6.

The pyrrhotite-pentlandite-chalcopyrite ores predominate, although there are some portions and stringers that are composed almost completely of chalcopyrite and cubanite. Magnetite-predominant ores are sometimes observed in zones of compression and in near-contact parts of veins. Mutual transitions between ores of different types may be sharp or gradual. There is no obvious regularity in the distribution of mineral types and in that of nickel and copper in the veins. The vein ores are characterized by massive, spotted, banded, corrosive and clastic textures.

Deposits of stringer-disseminated ores in the massif contact

The »Moroshkovoe ozero» is a typical representative of the group. It is located at the southwestern end of the Nyud massif but is se-

Table 6. Chemical composition of ore minerals of the Monchegorsk region.

	Samples								
	1	2	3	4	5	6	7	8	9
Fe	60.88	58.99	62.82	58.76	60.09	59.92	31.20	31.88	31.21
Ni	0.00	0.50	0.02	0.43	0.13	0.37	34.01	34.03	35.14
Co	0.00	0.00	0.00	0.00	0.06	0.00	1.44	0.89	0.79
Cu	0.00	0.02	0.00	0.02	0.03	0.02	—		
S	37.64	39.39	36.28	40.15	37.89	40.17	33.41	32.76	32.89
Total	98.52	98.84	99.12	99.36	98.20	100.48	100.06	99.56	100.03

	Samples								
	10	11	12	13	14	15	16	17	18
Fe	31.96	31.33	30.32	30.67	29.97	30.54	30.34	47.69	44.76
Ni	33.68	33.45	32.49	0.16	0.00	0.05	0.05	0.05	0.60
Co	1.38	1.66	3.39					2.21	2.50
Cu	0.07		0.82	34.64	34.64	34.84	34.55	0.05	0.19
S	32.63	33.06	34.23	34.44	36.04	34.36	35.17	51.64	53.63
Total	99.72	99.50	101.25	99.91	100.65	99.79	100.11	100.64	101.68

1—2, 4—6 — pyrrhotite; 3 — troilite, 7—12 — pentlandite, 13—16 — chalcopyrite, 17—18 — pyrite. 1 — from basal deposit of Nittis-Kumuzhje-Travyanaya; 2 — from poorly disseminated mineralization in norite, Njud-II; 3 from weakly disseminated ore in peridotite, Sopcha; 4 — from weak dissemination in norite, Njud; 5 — from heavily disseminated ore, Nittis-Kumuzhje-Travyanaya; 6 — from heavily disseminated ore, Njud-II; 7 — from poor mineralization in norite, Njud-II; 8 — from poor mineralization in gabbro-norite, Nittis-Kumuzhje-Travyanaya; 9 — from weakly disseminated ore, Sopcha; 10 — from heavily disseminated ore, Nittis-Kumuzhje-Travyanaya; 11 — from nest-disseminated ore, Njud-II; 12 — from massive ore, Sopcha; 13 — from poor dissemination in olivine pyroxenite, Nittis-Kumuzhje-Travyanaya; 14 — from weakly disseminated ore, Sopcha; 15 — from weakly disseminated ore, Njud-II; 16 — from massive ore, Sopcha; 17 — from basal deposit, Nittis-Kumuzhje-Travyanaya; 18 — from heavily disseminated ore, Njud-II.

parated from it by a latitudinal anticlinal bend in the base of the massif. The Ni-Cu mineralization is confined to the schist zone along the contact between norites and underlying diorite-gneisses (Fig. 25). The rocks of the zone are represented by actinolite-chlorite, actinolite and quartz-chlorite schists, which are alteration products of the near-contact norites. A band of schists 50—60 m thick has been traced in a northwest along the strike direction for up to 550 m with a dip northwest at 55°—65°.

The orebody is a lens pitching southeast in the plane of the dip. Its strike length is about 280 m, and the thickness varies from some centimetres up to 6 m. The sulphide mineralization consists of thin branched stringers, lenses and nests 20 cm thick that include rock debris (breccia-like ores) and dissemination oriented parallel to the schist formation (Fig. 25). The wavy bends in the base of the massif and the places in the base crossed by a tectonic zone at an acute angle favour stringer-disseminated ores.

The ores of the deposit are classified as sulphidic and essentially magnetitic ores with magnetite abundances up to 70—90 %. The major minerals of the sulphide ores are the same as those of the other types of deposit. They are all characterized by the presence of nickel-bearing pyrite (up to 0.9 % nickel). Silicates are commonly replaced by sulphides and early oxides.

The ore showings near the base of the western and central parts of the Nyud massif are of analogous structure.

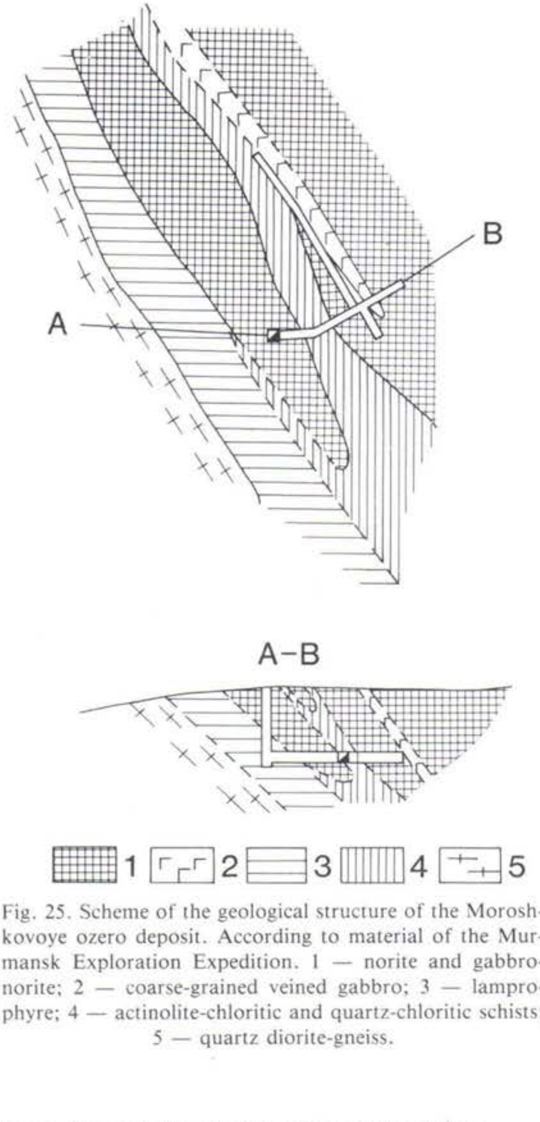


Fig. 25. Scheme of the geological structure of the Moroshkovoye ozero deposit. According to material of the Murmansk Exploration Expedition. 1 — norite and gabbronorite; 2 — coarse-grained veined gabbro; 3 — lamprophyre; 4 — actinolite-chloritic and quartz-chloritic schists; 5 — quartz diorite-gneiss.

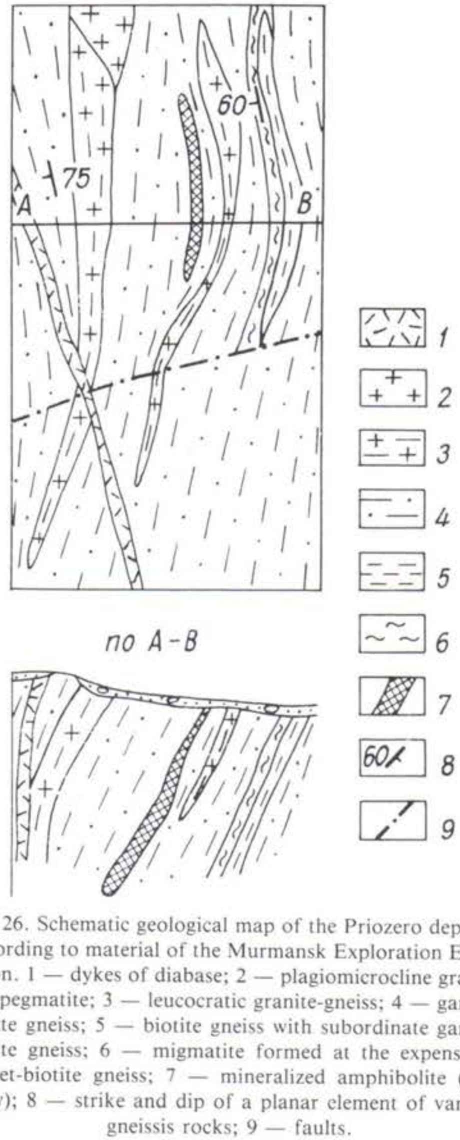


Fig. 26. Schematic geological map of the Priozero deposit. According to material of the Murmansk Exploration Expedition. 1 — dykes of diabase; 2 — plagiomicrocline granite and pegmatite; 3 — leucocratic granite-gneiss; 4 — garnet-biotite gneiss; 5 — biotite gneiss with subordinate garnet-biotite gneiss; 6 — migmatite formed at the expense of garnet-biotite gneiss; 7 — mineralized amphibolite (ore-body); 8 — strike and dip of a planar element of various gneissis rocks; 9 — faults.

Deposits outside the Monchegorsk pluton

The Priozyornoe deposit, discovered to the north of the Monchegorsk pluton in 1968, is confined to the lens-shaped body of amphibolites (meta-ultramafites) embedded in the rocks of the gneiss complex.

The environment of the deposit is composed of biotite and garnet-biotite gneisses with conformable bodies of schistose amphibolites up to 30 m thick (Fig. 26). In composition the amphibolite bodies are cummingtonite (meta-ultramafites) plagioclase-hornblende rocks (metabasites) occurring both separately and together. The host rocks are compressed into linear, wide submeridional folds with a gentle southward dip. Complicated by smaller folds, the eastern limb of the big syncline crops out at the site. A characteristic feature of the gneiss complex is the development of the submeridional cataclastic zone up to 1200 m wide together with mylonitization of the rocks. Gneisses and mylonites have undergone intense migmatization within the zone, and the amphibolite bodies are cut by numerous veins of granite pegmatites.

The ultramafites with associated sulphide nickel-copper mineralization are almost totally metamorphosed into ultramafic, nearly monomineral amphibolites (the amphibole is of the cummingtonite-grunerite series) with medium-grained texture. Their bodies extend 200—300 m along the strike and 400—500 m along the dip.

Metabasites (feldspathic amphibolites) are met with both as ore-free and as mineralized varieties. The latter have sulphide nickel-copper stringers along joints in the zones of fracturing and foliation.

Along the mylonite zone the deposit has abundant dykes of diabases, gabbro-norites, olivine gabbros and gabbro-norites, websterites and lherzolites. Sporadic pyrrhotite-pentlandite-chalcopyrite dissemination has been encountered in the olivine-bearing rocks of the dyke complex.

The orebody is related to the lens of spatially united metaultramafites and metabasites and is confined to the tectonic zone along the contact with gneisses. Pitching southwest it has been traced along the strike for 200 m and it is 4—5 m, in places up to 16 m, thick.

Both petrographical ore varieties are encountered, together and separately, in the drill hole sections. The meta-ultramafites are much thicker than the metabasites and they occur mainly at depth. The lens-shaped amphibolite body is much larger than the ore deposit.

The meta-ultramafites are characterized by ores varying in texture (disseminated stringer-disseminated, breccia-shaped), but metabasites

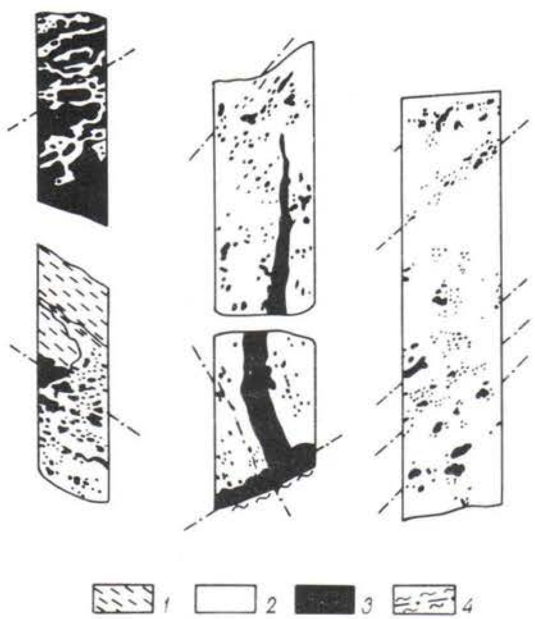


Fig. 27. Morphology of separated portions of sulphide mineralization in the orebody of the Priozero deposit. Sketches of drill core. According to I. S. Bartenev. 1 — mylonite formed at the expense of gneiss; 2 — plagioamphibolite; 3 — sulphides; 4 — tectonic fractures and zones of schistosity.

by stringer and breccia ores only (Fig. 27). In the direction of the tectonic zone the intensity of mineralization increases: disseminated ores grade into stringer-disseminated ores (with distinct orientation of stringers normal to the zone) and breccia ores. Minor stringers and sulphide dissemination are met with in mylonites formed at the expense of the host gneisses. At some sites the orebody is cut by plagioclase-microcline pegmatite veins.

The major ore minerals are pyrrhotite, pentlandite and chalcopyrite; pyrite and magnetite are developed to a lesser extent. Near the surface violarite has been observed in pentlandite.

The Imandra-Varzuga area

The Imandra-Varzuga area is located on the extension of the Pechenga-Varzuga structural-metallogenic zone between Lake Imandra in the west and the eastern extremity of Kola peninsula.

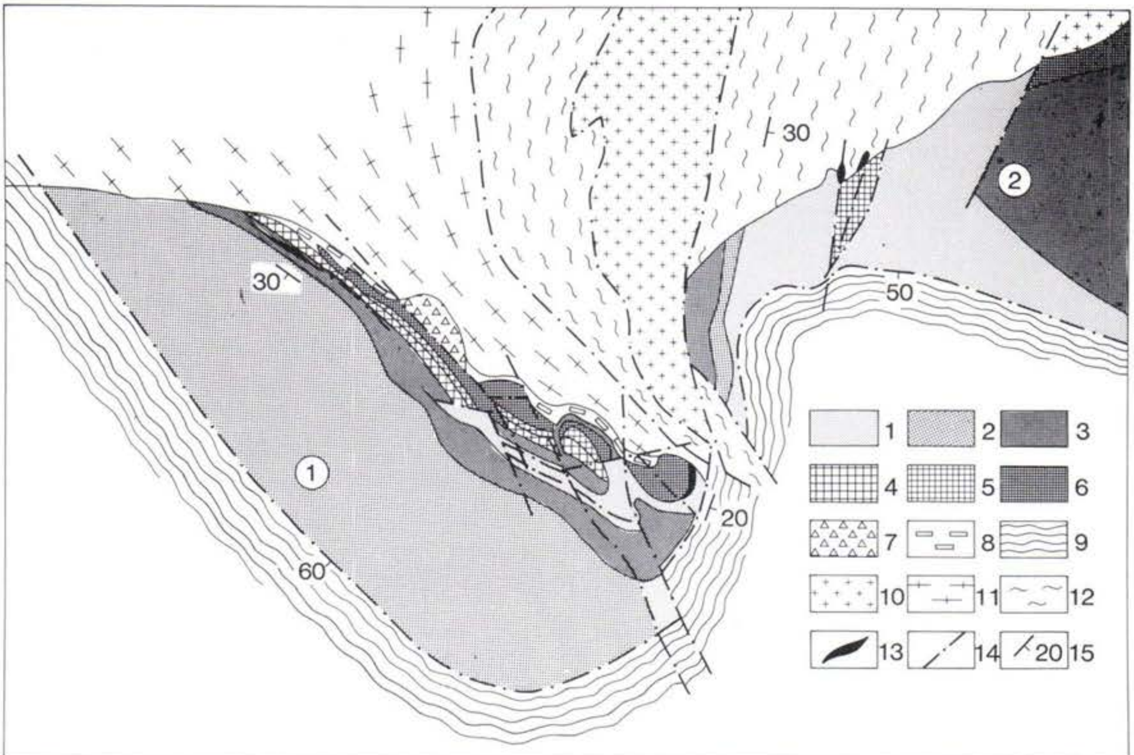


Fig. 28. Schematic geological map of the area of the Fedorova (1) and Pana (2) tundras. According to material of the Murmansk GS. 1 — gabbro-amphibolite, green schist, amphibolite formed at the expense of ultramafic rocks; 2 — coarse-grained leucomesocratic gabbro; 3 — medium-grained gabbro-norite with equal abundances of ortho and clinopyroxenes; 4 — fine- and medium-grained norite and gabbro-norite with predominant orthopyroxene; 5 — melanocratic norite, plagiopyroxenite, pyroxenite and their olivine-bearing varieties; 6 — non-unformly-grained, partly porphyritic gabbro-norite, massive, rarely trachytoid (taxitic horizon); 7 — the same rocks with xenoliths of ultrabasite; 8 — rocks of the exocontact; quartz and hypersthene diorite, chlorite-albite schists and others; 9 — sedimentary-volcanogenic formations of the Imandra-Varzuga group; 10 — plagio-microclinic and microclinic granite; 11 — plagio-granite-gneiss, gneiss migmatite; 12 — gneiss-schist, quartz-micaceuous schist; 13 — tectonic zones among basite with sulphide mineralization; 14 — faults; 15 — strike and dip of a planar element.

Like the Pechenga area this zone represents a graben-synclinorium composed of a complex of metamorphosed volcanogenic sedimentary rocks that can be classified into three groups: Strelna, Varzuga and Tominga. The latter two are largely analogous to the Pechenga and South Pechenga series, showing, however, a less definite relationship between volcanogenic and sedimentary strata than that in Pechenga. The Strelna group is composed mainly of volcanites (total thickness 5000—6000 m), representing a series from komatiitic basalts and basalts to andesites and dacites. The majority are lavas with horizons of bombs, tuff-breccia and tuffs. The sedimentary rocks with a total thickness of 1000—1200 m are represented by polymictic sandstones, gravelstones, quartzites and schists.

Regional faults are clearly distinguished along both margins of this zone with the Archean basement. Large massifs of basic rocks of Fedorova and Pana tundras and the Lastyavr occurrence are located at the northern contact (Fig. 28).

The opinion has recently been expressed by

V. N. Sokolova *et al.* that all the massifs intially constituted a united gabbro-norite massif, which was then divided along the zone of the South-Lovozero fault. The analysis of an enormous amount of data performed under the leadership of V. G. Zagorodny (Zagorodny *et al.* 1982), however, showed that there is no complete analogy in composition between the massifs. Hence it can only be suggested that the intruded magma was injected into independent chambers and formed genetically related, but spatially separated, massifs.

Numerous massifs of gabbro-norite (e.g. Umbarechka, Ozero Peschanoye. the south of the Moncha peninsula, Devichja and Yagelnaya mountains), peridotite-pyroxenite (e.g. Strelna group, Podzemelny, Lake Voche-Lambina, the Chornaya and Chapoma rivers) and ultramafite (the Falalei site) have been found along the southern and southwestern contacts in and partly inside the gneissic rim of a graben-synclinorium. Inside the graben-synclinorium itself there are small massifs of gabbro-wehrlite (e.g. Polissarka, Panarechka and the Foma creek) and gabbro-diabase formations (a great number of small bodies).

Sulphide nickel-copper mineralization has been established at the Lastyavr site in the Fedorova tundra massif and a lower grade one in Pana tundras and some other massifs.

The ore showing of the Fedorova tundra massif has been studied by many investigators (D. V. Shifrin, G. N. Staritsyna, E. K. Kozlov, V. A. Kostin, V. A. Gorelov, V. A. Tel'nov, M. K. Radchenko *et al.*). In plan the massif shows an irregular wedge-shaped form, elongated towards the southeast for 8.5 km. It is 2—5 km wide and plunges southwest at an angle of 30°—60°. Its northern contact with gneisses is conformable, rarely showing cross-cutting features.

The massif is layered, the upper part being composed of coarse-grained leucocratic to mesocratic gabbro and the lower part of fine-grained gabbro-norites and norites that grade into taxitic gabbro-norites of non-equigranular texture in the footwall. Xenoliths of ultramafic rocks such as peridotite and pyroxenites have been found throughout the section. At the base there are layered and veined bodies of diorites and quartz-diorites. The thickness of the gabbro horizon increases along the strike in a southeastern direction and down the dip; that of the gabbro-norite horizon towards the centre of the massif. Down the dip the layering in gabbronorites flattens and trachytoid structure appears. The rocks lie unconformably on the lower contact of the massif. The norite horizons, which are practically detached from the northwestern part of the massif, are a few tens of metres thick in the southwestern part. In the same direction the thickness of the plagiopyroxenites and plagioperidotites occurring as isolated portions and interlayers among the norites increases gradually. The taxitic horizon can be traced along the whole footwall of the massif, where its thickness fluctuates between several metres and 200 m.

The sulphide dissemination, more rarely nested disseminated mineralization, is present in all types of rock. In the upper part of the massif the dissemination is rare, but near the footwall some portions are enriched in sulphides (up to 5 %). The ore mineralization occurs as lenses and layers that form a sulphide-bearing zone striking along the whole base of the massif at some distance from the footwall. The thickness of the ore-bearing zone increases towards the southeast and reaches 500—600 m. The sites most enriched in sulphides have been submitted to exploration (the Maly Ihtegipahk, Pahkvaraka ore showing) at various times.

The interstitial sulphides predominante, some of them reaching 1—2 cm in diameter. The larger isolated portions of sulphides, manifest as nests and schlieren, are attributed to the widespread gabbro-pegmatites in the endomorphic zone and the zone of »autobreccia» occurring in the middle of the massif as isometric or vein-like bodies.

In the basal part of the massif the epigenetic ores occur as stringer-disseminated, massive and breccia ores. The stringer-disseminated mineralization is confined to the zones of schistosity and alteration of gabbro-norites on the northwestern and northeastern flanks of the massif. The thickest zone (in the northwestern part of the massif) extends for more than 2 km subconformably with the schistosity and intersecting it down the dip. At some sites the zone branches. In the zones of schistosity the sulphides form disseminations of various intensity, nests, lenses, discontinuous stringers conformable with or intersecting the schistosity, thin veins and isolated portions of irregular shape. The breccia ores are also encountered there.

The massive sulphide ores are exposed in the northwestern part of the massif, in the zone of contact with underlying rocks, as a vein 40 cm thick and a number of thin stringers. The vein is composed of coarse-grained euhedral magnetite that forms margins 2—3 cm wide along the selvage, and of coarse-grained pyrrhotite with pentlandite and chalcopyrite as accessories in the central part. The ores along the strike and down the dip have not been studied.

In general, the sulphide dissemination of the massif is low-grade. In ores of all types the sulphides are mainly pyrrhotite, to a lesser extent chalcopyrite and pentlandite. The minor constituents include magnetite, ilmenomagnetite, ilmenite, pyrite, violarite, sphalerite and molybdenite. The nickel and copper content increases towards the footwall of the massif, reaching in places 0.25 and 0.38 %, respectively. In veined ores the nickel content is 1.35 % and the copper content 0.76 %. The nickel-copper ratio is 2.1 : 1.

The Lastyavr ore showing is located at the joint of the South Lovozero tectonic zone with the Imandra-Varzuga graben-synclinorium.

According to the data of I. S. Bartenev, V. N. Kliment'ev, V. A. Tel'nov and M. K. Radchenko, the ore showing is associated with a series of wedge-shaped bodies of intensely altered (schistose, amphibolized, chloritized) mafic and ultramafic rocks, embedded in the biotite gneisses and mica quartz schists (Fig. 29). Two wedge-shaped bodies, the central and the eastern ones, dip east at an angle of 50°—70°; the western one dips almost vertically. Northwards the matabasite bodies pinch; southwards they increase in size and join each other and the main massif.

The sulphide mineralization is concentrated in the tectonic zones along the contacts of the intrusive bodies with the host rocks. The orebodies strike northeast, dip steeply southeast and have a southern pitch. Mineralization is epigenetic in type and is manifested as dissemination and nests, discontinuous, conformable and intersecting stringers, lenses and isolated portions irregular in shape. The orebodies are from a few metres to some tens of metres thick. The portions enriched in sulphides are 0.1—1.0 m thick, some even 2.6 m. The mineral composition of the ores is pyrrhotite, which in places amounts to 50 % of the volume of the sulphides, chalcopyrite (its content does not usually exceed 30 %, although in stringer-disseminated ores it may reach 70—80 %), pentlandite (usually from 10 to 30 % of the volume of the sulphides), pyrite, practically ubiquitous (1—3 %) in the ores and occasionally reaching 50 %, sphalerite, magnetite, mackinawite and molybdenite. The predominance of nickel over copper is typical of the ores in general: their ratio in disseminated varieties is (1—2):1, in the stringer disseminated ores (3—7):1 and in the veined ores (5—10):1, averaging 2:1.

The ore showing of the Pana tundra massif. This large massif is nearly 50 km long, 6—8 km wide in the west and 3—4 km in the east. It dips southwest at an angle of 40° and is composed mainly of gabbro-norites, the individual layers of which differ in mineralogy, texture and composition. The layers dip more gently than the contacts of the massif.

The sulphide mineralization is located in the western part of the massif, close to its northern boundary, among the banded varieties of olivine

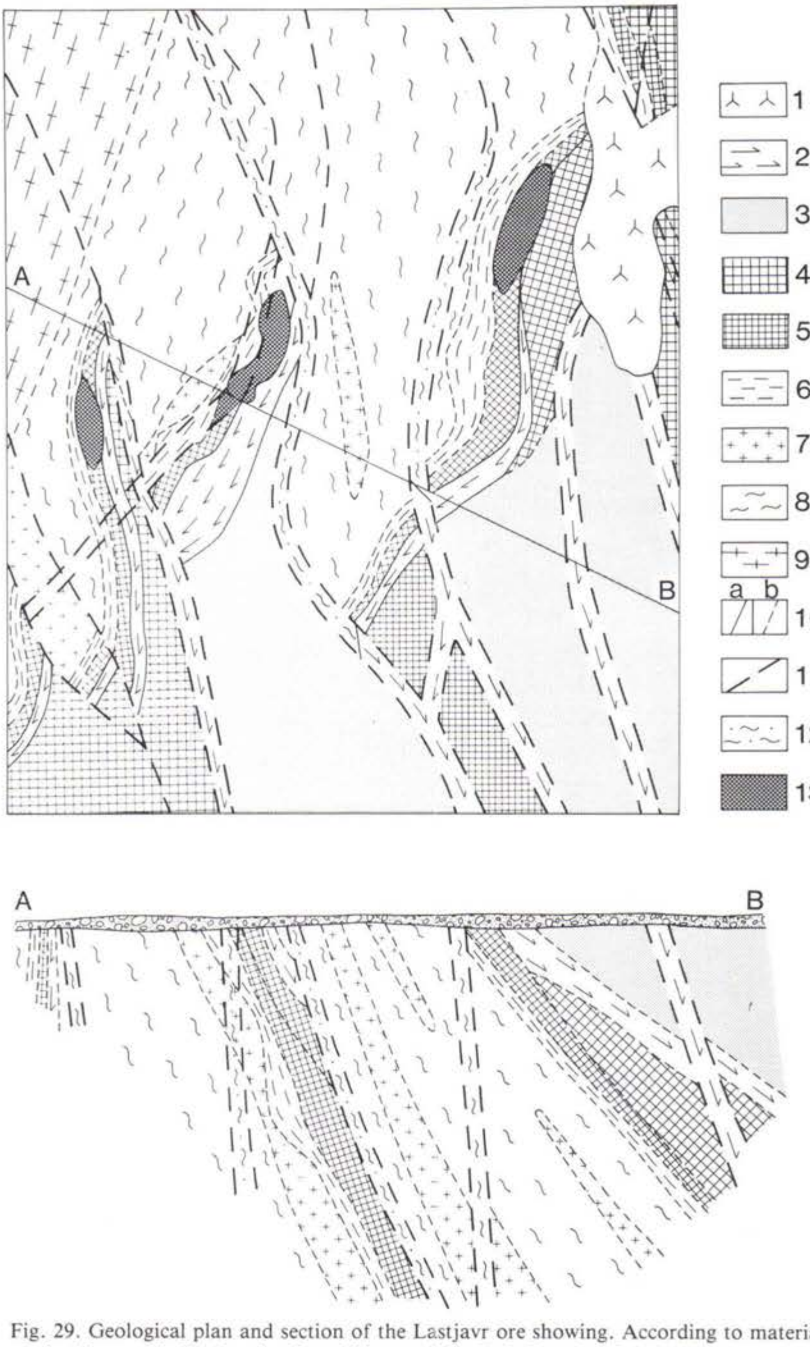


Fig. 29. Geological plan and section of the Lastjavr ore showing. According to material of the Murmansk Exploration Expedition and the Kola Branch of the USSR Ac. of Sci. 1 — granosyenite-syenite; 2 — chlorite-actinolite and chlorite-actinolite-talc schists; 3 — metagabbro; 4 — metaplagiopyroxenite; 5 — metamorphic rocks (metanorite, metagabbro-norite, plagioclasite) with non-uniform sulphide mineralization; 6 — exo-contact biotized gneiss; 7 — plagiogranite; 8 — mylonite of biotite gneiss and diorite-gneiss; 9 — diorite-gneiss; 10 — geological boundaries (a — established, b — inferred); 11 — faults; 12 — zones of foliation in gneiss; 13 — zones of the sulphide nickel-copper mineralization.

Table 7. Chemical composition of mafic and ultramafic rocks of the Imandra-Varzuga and East Pechenga regions.

	Samples								
	1	2	3	4	5	6	7	8	9
SiO_2	47.78	49.33	49.62	50.01	51.32	53.33	49.22	50.11	50.88
TiO_2	0.23	0.50	0.64	0.52	0.49	0.17	0.14	0.20	0.33
Al_2O_3	9.35	8.77	15.82	15.57	17.49	6.28	17.34	15.06	13.35
Cr_2O_3	—	—	—	—	—	—	—	0.02	—
Fe_2O_3	2.06	1.36	2.26	1.97	3.58	0.85	1.07	0.91	1.45
FeO	10.26	10.26	8.60	9.49	5.90	8.85	5.61	4.83	6.97
MnO	0.23	0.22	0.17	0.19	0.15	0.20	0.12	0.12	0.12
MgO	15.50	18.08	9.75	7.14	4.57	22.83	10.01	10.90	13.11
CaO	11.97	9.44	8.42	8.19	10.93	5.12	13.54	13.92	10.51
Na_2O	1.01	0.63	2.04	2.05	2.54	0.61	1.44	1.05	1.59
K_2O	0.06	0.11	0.24	0.33	0.60	0.05	0.07	0.15	0.08
P_2O_5	—	—	—	—	—	—	—	0.03	—
S	0.02	0.02	0.37	0.52	0.08	0.02	—	0.02	—
V_2O_5	—	—	—	—	—		—	—	—
CO_2	—	—	—	—	—		—	—	—
H_2O^-	—	—	—	—			0.22	—	0.18
H_2O^+	0.75	0.81	1.53	3.15	2.44	1.01	1.48	2.95	0.99
Ni	0.048	0.079	0.051	0.029	0.014	0.067	—	0.04	0.021
Cu	0.005	0.004	0.042	0.03	0.011	0.010	—	—	0.026
Co	0.03	0.007	—	0.008	0.005	0.008	—	0.04	0.003
—O~S	—0.01	0.01	—0.18	0.26	0.04	0.01	—	0.01	—
Total	99.29	99.61	99.37	99.19	100.12	99.41	100.26	100.35	99.61

	Samples								
	10	11	12	13	14	15	16	17	18
SiO_2	47.48	49.02	49.87	38.41	39.56	41.91	44.36	50.80	55.69
TiO_2	0.80	0.29	0.29	0.39	0.25	0.69	0.80	1.33	0.45
Al_2O_3	18.36	14.17	17.33	2.28	3.89	3.84	4.71	17.81	9.49
Cr_2O_3	—	0.01	0.02	0.83	0.42	0.81	0.72	0.05	0.10
Fe_2O_3	1.89	3.54	0.71	6.23	5.58	5.03	2.68	0.40	0.86
FeO	5.56	6.84	6.53	8.63	6.73	9.03	9.95	4.44	9.30
MnO	0.14	0.16	0.13	0.13	0.18	0.19	0.18	0.05	0.17
MgO	9.60	15.06	10.57	32.95	33.77	30.45	27.27	5.03	9.39
CaO	10.30	8.15	10.11	1.47	2.21	2.53	2.95	11.17	7.27
Na_2O	2.23	1.88	2.16	0.33	0.11	0.90	1.18	4.05	3.96
K_2O	0.69	0.50	0.36	0.31	0.03	0.40	0.52	0.56	0.36
P_2O_5	0.02	0.02	0.02	0.03	0.01	0.02	0.06	0.11	0.11
S	0.04	0.02	0.02	0.17	0.15	0.13	0.12	0.02	0.07
V_2O_5	—	0.06	0.02	0.02	0.04	0.02	0.02	0.01	0.03
CO_2	0.35	0.18	0.08	0.11	—	0.30	0.30	0.37	0.36
H_2O^-	0.17	0.20	0.04	0.24	0.19	0.22	0.46	0.10	0.14
H_2O^+	2.45	0.12	1.37	6.99	6.65	3.98	3.04	2.90	1.66
Ni	0.048	0.069	0.047	0.20	0.22	0.19	0.18	0.017	0.024
Cu	0.012	0.005	0.004	0.12	0.007	0.013	0.07	0.10	0.005
Co	0.007	0.003	0.006	0.013	0.008	0.012	0.01	—	0.005
—O~S	—0.02	—0.01	—0.01	0.08	0.07	0.07	0.06	0.01	0.03
Total	100.13	100.29	99.69	99.77	99.94	100.59	99.52	99.31	99.41

1—6 — Fedorova tundra, 7—9 — Pana tundras, 10—12 — Mount Luostari, 13—18 — Northeastern rim of Pechenga; 1 — melanocratic olivine gabbro; 2 — plagioclase peridotite; 3 — gabbro-norite; 4 — fine-grained gabbro with weak sulphide dissemination, 5 — leucocratic amphibolitized gabbro; 6 — amphibolitized plagioclase pyroxenite; 7 — medium-grained gabbro-norite with actinolite; 8 — mesocratic, medium-grained, amphibolitized gabbro-norite; 9 — olivine gabbro-norite; 10 — mesocratic, amphibolitized gabbro-norite; 11 — olivine gabbro-norite; 12 — mesocratic gabbro-norite; 13 — serpentinous pyroxene olivinite, Karikjävr; 14 — serpentinous and talcificated harzburgite, Koshka; 15 — serpentinous lherzolite, Karikjävr; 16 — serpentinous plagioherzolite, Karikjävr; 17 — amphibolitized gabbro, Karikjävr; 18 — melanocratic fine-grained gabbro, Karikjävr.

Table 8. Chemical composition of ore minerals of the Imandra-Varzuga and East-Pechenga regions.

	Samples								
	1	2	3	4	5	6	7	8	9
Fe	60.12	59.28	59.02	60.61	60.05	59.05	63.23	60.90	32.17
Ni	0.38	0.52	0.38	1.29	0.26	2.00	0.01	0.68	35.56
Cu	0.00	0.00	0.00	0.78	0.00	0.09	0.00	0.00	
Co	0.01	0.03	0.02	0.04	0.02	0.04	0.00	0.00	0.57
S	40.09	40.65	40.41	37.28	39.45	38.82	37.66	39.34	32.50
Total	100.60	100.48	99.83	100.00	99.78	100.00	100.90	100.92	100.80

	Samples								
	10	11	12	13	14	15	16	17	18
Fe	30.05	29.05	28.90	31.20	31.61	36.57	31.64	30.27	30.86
Ni	34.76	34.57	31.51	34.17	36.43	29.78	32.27	—	—
Cu								35.08	34.69
Co	2.55	4.06	6.74	2.21	0.55	1.01	3.17	—	—
S	32.49	32.47	32.70	31.75	32.17	33.03	32.85	34.17	34.08
Total	99.85	100.15	99.85	99.33	100.76	100.39	99.93	99.52	99.63

1—6, 8 — pyrrhotite, 7 — troilite, 9—16 — pentlandite, 17—18 — chalcopyrite; 1 — from weak dissemination in gabbro-norites, Panskie tundras; 2 — from poor mineralization in gabbro-norite, Fedorova tundra; 3 — from weakly disseminated ore in gabbro-norite Last-javr; 4 — from weakly disseminated ore in gabbro-norite, Fedorova tundra; 5 — from breccia ore, Last-javr; 6 — from breccia ore, Fedorova tundra; 7 — from sparsely disseminated ore in altered harzburgite, B-Karikjävr; 8 — from disseminated ore in meta-ultrabasite, Rovno; 9—10 — from weak dissemination in gabbro-norite, Panska tundra; 11 — from poor dissemination in amphibolitized gabbro, Fedorova tundra, 12 — from weakly disseminated ore in gabbro-norite, Last-javr; 13 — from nest-disseminated ore in gabbro-norite, Fedorova tundra; 14 — from breccia ore, Last-javr; 15 — from poor mineralization in peridotite, Karikjävr; 16 — from weakly disseminated ore in meta-peridotite, Rovno; 17 — from poor dissemination in peridotite, Karikjävr; 18 — from breccia ore, Fedorova tundra.

gabbro-norite. It occurs as fine and medium-grained dissemination in some beds, 0.1—6.0 m thick, which cannot be correlated to form a coherent horizon. The sulphide content amounts to 0.5—5.0 %. Small nested and isolated portions of sulphides 5 cm in size have been encoutered in the basal melanocratic norites of a borehole. Pyrrhotite and chalcopyrite are the predominant sulphides; pentlandite and pyrite are less abundant, and ilmenite and magnetite occur as casual grains. In general the mineralization is of a low grade, nickel and copper contents amounting to 0.15 and 0.22 %, respectively.

At other sites of the Imandra-Varzuga area the sulphide nickel-copper mineralization manifests itself mainly as scattered disseminated sulphides. At some of them the sulphide mineralization is essentially chalcopyrite or pyrrhotite and chalcopyrite in composition. The composition of the mafic and ultramafic rocks of the nickel-bearing complex and of the ore minerals are given in Tables 7 and 8.

The Lovnoozero area

The area is located south of the Allarechka area within the Lappish granulite belt. Tectonically this belt is considered to be a synclinorium. Several autonomous blocks can be distin-

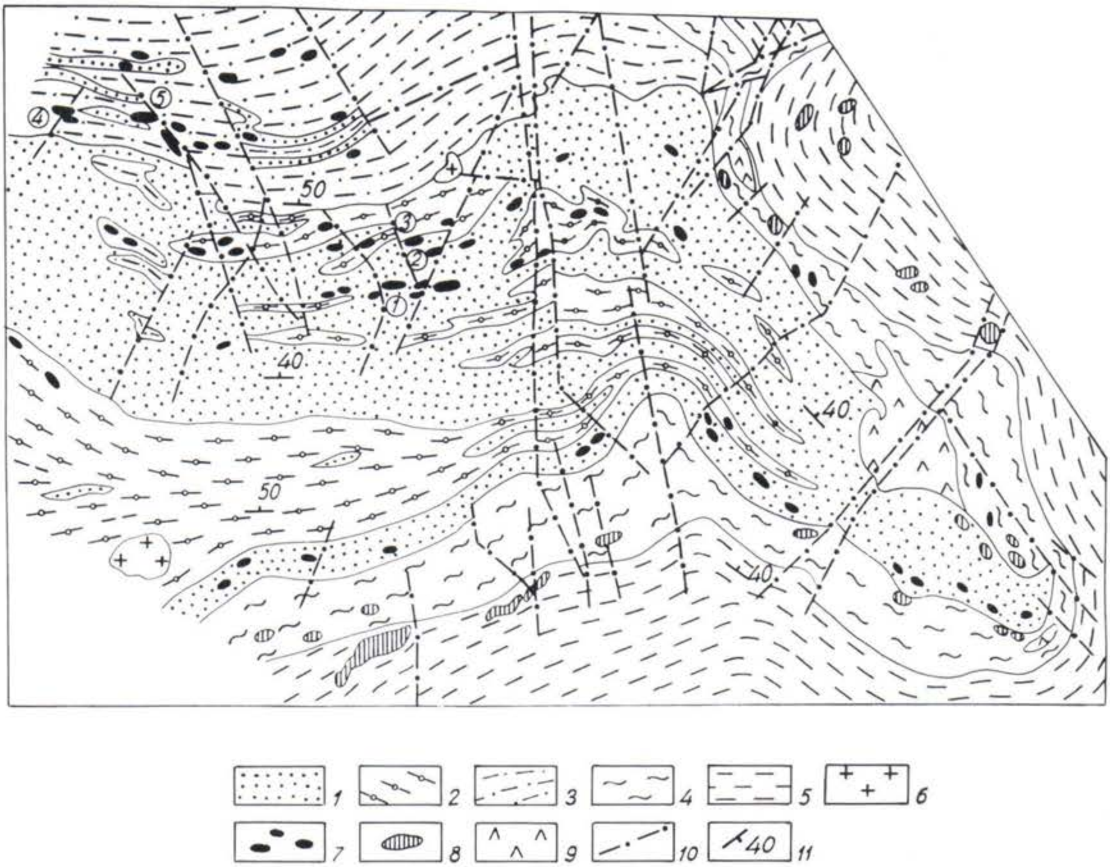


Fig. 30. Geological scheme of granulite formation in the western part of the Kola peninsula (by V. N. Spirov with additions). 1 — hypersthenic and bipyroxenic plagiogneiss; 2 — acid granulite and granulite-like rocks; 3 — garnet-biotite gneiss, sillimanite-garnet-biotite gneiss, amphibole-bearing gneiss, etc.; 4 — amphibolite and gneiss of Kola-Belomorean complex; 5 — gneiss and granite-gneiss of Kola-Belomorean complex; 6 — microclinic and plagiomicroclinic granite; 7 — mafic and ultramafic rocks of Ni complex (norite, gabbro-norite, pyroxenite, peridotite); 8 — mafic and ultramafic barren rocks (gabbro, gabbro-amphibolite, serpentinite); 9 — gabbro, gabbro-labradorite; 10 — faults; 11 — strike and dip of a planar element. Numbers in circles: 1-the Lovnoozero deposit, 2, 3, 4-Lounjoki, Sueinlagash and Laukku ore showings.

guished in it, the largest being Lovnoozero, which comprises a nickel-bearing region of the same name. The mineralized norites in the area were first mentioned in 1934, when H. Väyrynen assessed the claim of a Finnish fisherman as of no economic value. Today a nickel-copper deposit (Lovnoozero) and a number of ore showings (e.g. Laukku, Yunges, Sueinlagash, Lounjoki) are known in the area. The main results of the study of the geology and ore content of the area have been reported in works by D. F. Murashov, D. V. Polferov, Ye. K. Kozlov, V. N. Spirov, Yu. N. Yakovlev, A. K. Yakovleva and L. A. Vinogradov and others.

Major features of the geological structure of the area and of the distribution of nickel-bearing massifs

Two complexes, granulitic and gneissic, contribute to the structure of the area (Fig. 30). The granulitic complex, which comprises the central part, includes hypersthenic and bipyroxene plagiogneisses (gneiss-diorites), acid granulites and granulite-like formations. The rocks of the gneissic complex, which occupies the northern and southern parts of the area, are garnet-biotite gneisses, plagioclasites, amphibolites and diopside and amphibole-bearing gneisses. In general the rocks have a sublatitudinal trend that turns northeast and northwest in places, the dip is mainly north, more rarely south, at an angle of 30°—60°. The rocks are characterized by a distinct mineral lineation, plunging northeast (320°) (sometimes east and northwest) at an angle of 20°—35°.

Here and there the rocks are compressed into linear folds (erect, isoclinal, carinate), with an amplitude of 100—500 m, complicated by smaller folds. The fold axis coincides with the mineral lineation.

The faults include large sublatitudinal and submeridional ones that frame individual blocks and a large number of others that are small to intermediate and small in size and trending NW and NE.

About 300 massifs of mafic rocks (norites, gabbro-norites) and about ten massifs of ultramafic rocks (peridotites, pyroxenites) belonging to two associations (websterite-gabbro-norite and gabbro-lherzolite-pyroxenite) have been found in the area. The sulphide nickel-copper mineralization is related to individual massifs and the factors controlling their spatial distribution are not yet known. According to data available the massifs are situated in trains and individual groups in narrow, extensive zones conformable to the regional trend. Differing in lithology, these zones may demarcate ancient, deep faults. All the massifs are lens, cigar and ribbon-like in shape and tend to exhibit conformable, more rarely uncorformable, contacts with the host rocks. Their dip is mainly north at an angle of 30°—50°, and their pitch northeast but sometimes northwest in conformity with the mineral lineation. They are usually small, the strike length not exceeding 800—1000 m and the thickness being from 70 to 100 m. Not infrequently the mafic and ultramafic massifs are veined by granite pegmatites 0.5—10 m thick.

The sulphide nickel-copper mineralizations, which are almost completely confined to the host massifs, are of syngenetic and epigenetic types. No distinct structural and petrographic control of the mineralization has been established in the mafic massifs. In the ultramafic massifs, mineralization favours the footwall and is usually located in the olivine-free rocks. Low-grade disseminated ores are significantly less frequent; breccia and massive ores and mineralized host rocks are encountered very rarely. All the ores are characterized by a high proportion of pyrrhotite, and even higher proportion of pyrite and a comparatively low proportion of pentlandite and chalcopyrite.

Deposits and ore showings in mafic rocks

The massifs of the Lovnoozero deposit are typical of the ore-bearing mafic rocks of the area.

The deposit site is mainly composed of hypersthenic plagiogneisses (up to 70 %) and acid granulites (to 20 %); other rock varieties (e.g. granulite-like »ancient gabbroids», and a veined complex) are of secondary importance (Fig. 31). Northern, central and southern zones are visible in the areal structure. The northern and southern zones are composed of homogeneous hypersthenic plagiogneisses, whereas the central zone, which encloses the mafic rock massifs, is complex in structure. Much more important here are the granulite-like formations, the veined complex and the »ancient gabbroids». The rocks trend mainly NE and dip NW at an angle of 40°—70°.

The ten or more nickel-bearing mafic massifs are elongated lenses and ribbon-like or flat cigar-like bodies: that lie conformably with the host rocks and plunge to NE at an angle of 20°—35° in accordance with the mineral lineation. Their dimensions along the strike vary from 50 to 300 m, and their thickness from 5 to 80 m. All the massifs are characterized by elon-

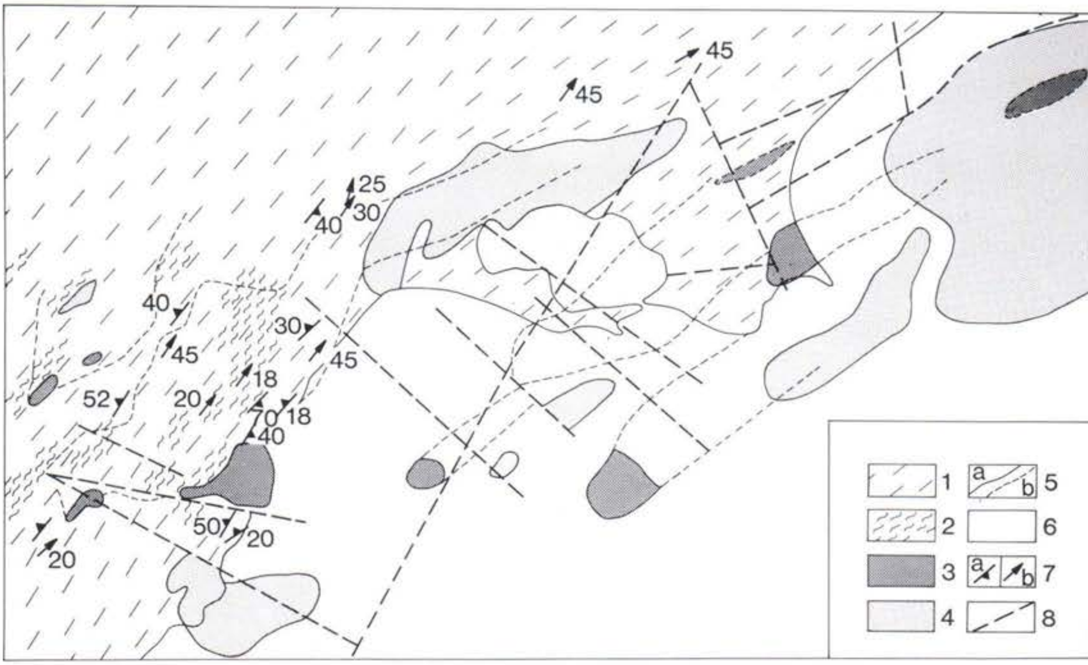


Fig. 31. Schematic geological map of the Lovnoozero deposit (by E. K. Kozlov with additions). 1 — hypersthenic plagiogneiss; 2 — granulite; 3 — ore-bearing norite and gabbro-norite; 4 — barren norite and gabbro-norite; 5 — outlines of norite bodies exposed by erosion (a), outlines of norite bodies not exposed by erosion (b); 6 — Quaternary sediments; 7 — strike and dip of a planar element (a) and lineation (b); 8 — faults.

gation along the pitch. The massifs are situated in an en echelon array in relation to each other: and some are confined to the limbs of small synclinal folds. The massifs are often broken up by tectonic dislocations into a number of blocks that have moved slightly in relation to each other.

Massifs of noritic composition predominate; besides norites the individual bodies include gabbro-norites and rare plagioclase pyroxenites. A slight differentiation is observed in the largest massifs the melanocratic norites and plagiopyroxenites that occur at the base being replaced higher up by mesocratic varieties. Gabbronorites have developed in the roof and marginal parts of the massif. Some massifs, however, exhibit a reverse succession of lithologies.

The boundaries of the mafic massifs with the host rocks are generally gradual or sharp, without any essential endomorphic or exocontact alterations. Here and there the near-contact alterations in massifs are revealed as pronounced schistosity and partial biotitization. The boundaries of the »transition zones», which are up to several metres thick, grade from leucocratic norites into plagiogneisses. Within the massifs the transitions between rock varieties may be gradual or sharp. Not infrequently the granite pegmatite bodies or other rocks of the veined complex occur in the contact zone. The contacts may be tectonic.

Nickel-copper mineralization is observed in almost all the norite bodies, but exploitable ores have only been found in some of them (Kozlov 1960, 1975, Yakovlev *et al.* 1979). Disseminated ores predominate and often form a number of »hanging» horizons 1—15 m, sometimes as much as 35 m, thick.

The degree of ore mineralization varies. In some massifs the fine-grained hypersthenites

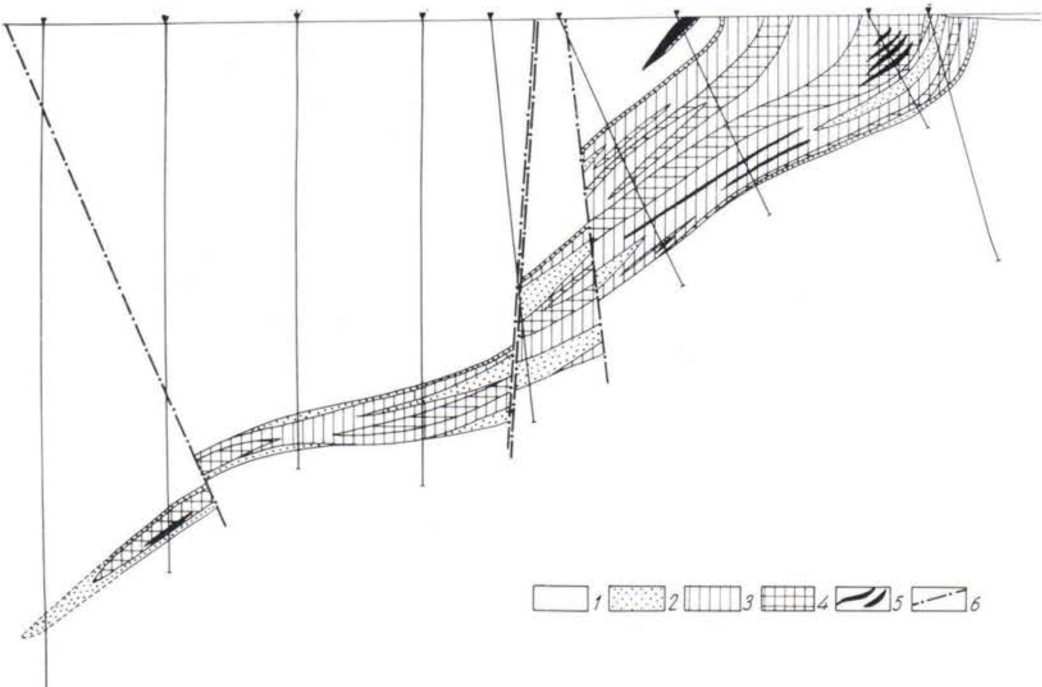


Fig. 32. Ni + Cu distribution in the central part of the Main orebody in the Lovnoozero deposit. 1 — host rocks; 2 — poorly mineralized norite; 3—5 — ore with Ni and Cu content from 0.3 to 1 %; 4 — ore with Ni and Cu content from 1 to 2.5 %; 5 — ore with Ni and Cu content exceeding 2.5 %; 6 — faults.

are more enriched in sulphides than are the enclosing norites and the gabbro-norites. Portions with high sulphide content differ from the monotonous barren sites in having coarse-grained structure, variable petrographic composition, and alternating norites of different varieties. In other massifs the mineralization is distinctly confined to norites, and even then mainly to the melanocratic varieties. The gabbro-norites only rarely contain weak dissemination near the contacts with mineralized norites.

The high-grade, heavily disseminated breccia and massive ores are of insignificant abundance. In some massifs they are spatially confined to the sublatitudinal zone of the most intensive development of granitic pegmatite veins. The breccia ores are 0.1—1.5 m thick, rarely 1.5 m. The sulphide veins are but a few centimetres thick, and although individual sulphide veins extend from the norite bodies into the granulites and diorites, they do not do so for longer than 100 m.

The largest ore body N1, or Glavnoye, has been traced along the pitch for more than 1000 m. Its thickness and extent depend on the size of the massif: the maximum thickness is observed in the swells of the massif; the minimum at pinch-out sites. The orebody is of multistage structure, demonstrated by a series of contiguous lenses of scattered and heavily disseminated ores, separated by rocks with weak sulphide dissemination and roughly conformable with the outlines of the norite massif (Fig. 32). The multistage structure of the ore body is best seen in the central part of the massif in which there is often a middle »layer» covering 60—70 % of the volume of the orebody near the footwall and a fragmentary »layer» near the hanging wall. It is noteworth that the useful major components, nickel and copper, are not distributed

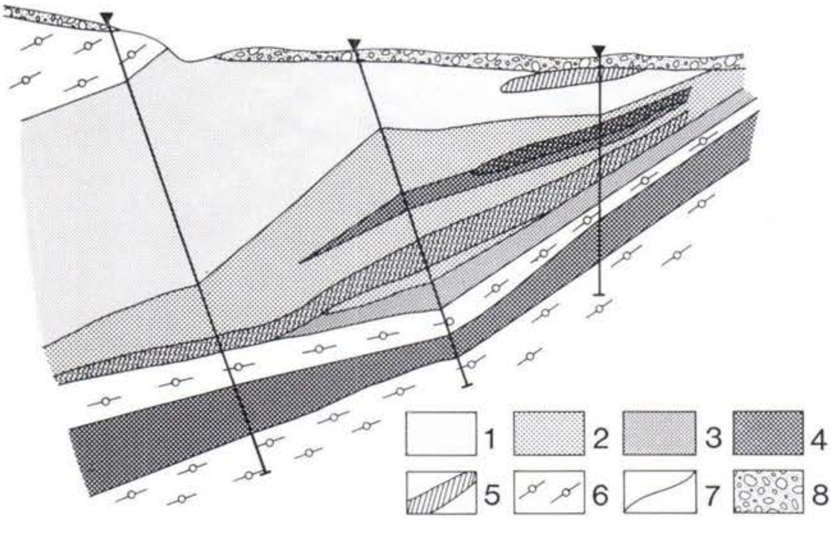


Fig. 33. Geological section of the massif at Sueinlagash. 1 — olivine pyroxenite; 2 — websterite and plagiowebsterite; 3 — gabbro-norite; 4 — norite; 5 — mineralized rocks; 6 — granulite; 7 — borders of rocks; 8 — Quaternary sediments.

in the same way: as a rule, the distribution of copper appears to be less persistent and less regular. The content of the useful components increases gradually along the pitch of the orebody.

The other orebodies of the deposit are of similar structure. The ore-showings, associated with mafic rocks (e.g. Lounjoki and Laukku) exhibit the same conditions for the ore localization, but there are no massive or breccia ores in them.

The Ni-Cu ores are mainly represented by two textural varieties: disseminated and breccia ores (Fig. 34).

Their mineral composition varies less than that of Pechenga and Allarechka. The major ore minerals are pyrrhotite, pyrite, pentlandite and chalcopyrite, the accessories are ilmenomagnetite, ilmenite, rutile, magnetite and violarite. The trace minerals include molybdenite, sphalerite, gersdorffite and millerite. According to the pentlandite-chalcopyrite ratio the majority of ores are the common pentlandite-chalcopyrite ores. The »copper» varieties are sometimes encountered in altered mafic rocks wherever the orebodies pinch out, but more often in veined hypersthenite and granite pegmatites, and also in host rocks. The latter sometimes have a higher content of iron and titanium oxides (e.g. ilmenomagnetite, rutile and ilmenite).

The ores are distinguished by extensive development of pyrite and relatively weak development of secondary magnetite. Ores of the Lovnoozero deposit and the Laukku site have the highest content of pyrite, accounting for 30—40 % of the total amount of sulphides. Heavily disseminated and breccia ores essentially pyrite in composition (up to 80—95 %) are also met with. The disseminated ores have the highest relative pentlandite abundance; in the massive and breccia ores the abundance is much lower.

In terms of the content of useful major components the Lovnoozero ores are equal to those of Pechenga and Allarechka. The nickel to copper ratio in the Lovnoozero ores is (2—5):1; increasing from disseminated ores to breccia and massive ores. The nickel to cobalt ratio is (25—40):1, being highest in the heavily disseminated ores.

Ore showings in ultramafic rocks

Massifs of ultramafites have been found mainly in the northern part of the granulite for-

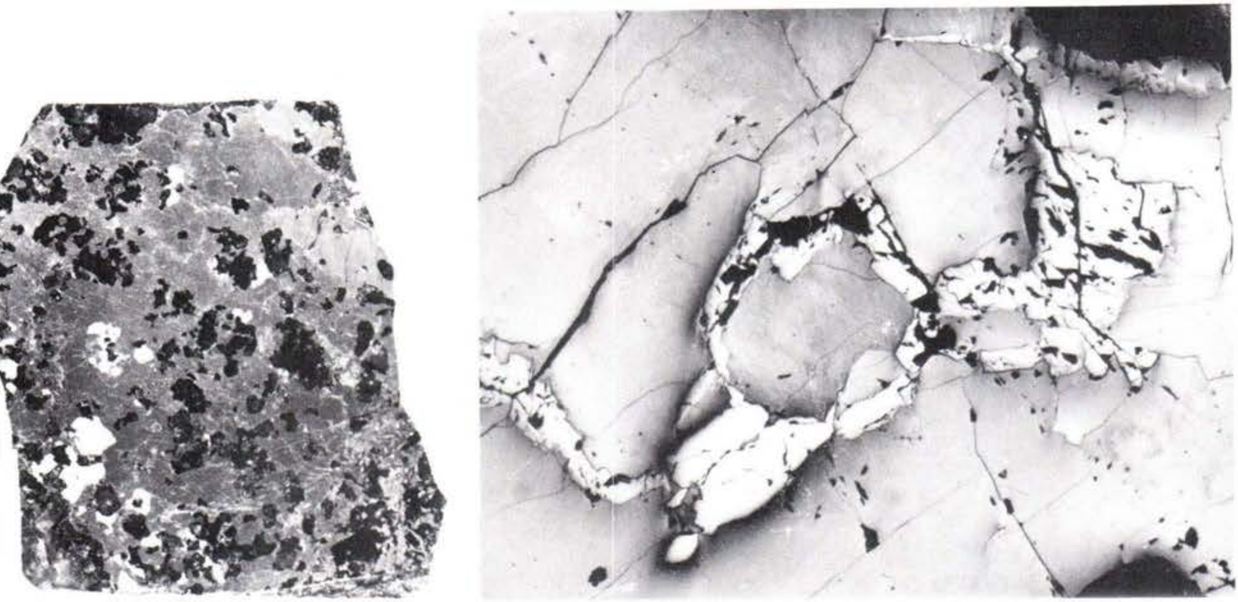


Fig. 34. Textures of the Lovnoozero ores. a — breccia ore; plagioclase, pyroxene and biotite fragments in the sulphidic groundmass; b — segregated pentlandite in the pyrrhotite aggregate; polished section, ×60.

mation, where they sometimes occur together with massifs of mafic rocks of the nickel-bearing complex (Spiroc 1975, Yakovlev *et al.* 1979). They are lenses in form and 200—600 m long, although some massifs are larger (e.g. Sueinlagash, Yunges). They have a latitudinal trend and dip north at an angle of 30°—80°. The bodies are mainly conformable with the strata of the metamorphic rocks but sometimes they cut them obliquely. The ultramafic massifs occasionally cut the lineation and small folds of the metamorphic rocks. The contacts of the ultramafites are distinct, sometimes tectonic.

The small massifs are usually composed of pyroxenites, whereas large ones are distinctly differentiated from peridotites to gabbro-norites. In some massifs the rocks are practically non-metamorphosed, in others they are altered to a considerable extent (serpentinized, amphibolitized), especially in contact with the granite pegmatite veins.

The sulphide nickel copper mineralization is not uniform and occurs in different parts of the ultrabasite massifs. As a rule, it favours pyroxenites; peridotites usually show a weak sulphide dissemination.

The sulphide nickel mineralization of the Sueinlagash massif deserves attention. It is composed of bipyroxene pyroxenites-websterites with olivine pyroxenites, websterites proper and plagioclase websterites. The latter two varieties are predominant. The massif is differentiated but the position of the differentiates in the massif is unusual (Fig. 33): the olivine pyroxenites lie in the upper part, and the websterites and plagioclase websterites in the middle and lower parts; the transitions between them bein gradual. In near-contact parts the pyroxenites are so altered that their composition is that of melano-mesocratic norites and gabbro-norites, the latter being met with inside the massif, too. In the contacts, especially on the footwall side, the pyroxenites are layered, amphibolized and injected with quartz-feldspathic material. The massif is also cut by individual veins of granite pegmatites 1.0—1.5 m thick.

Table 9. Chemical composition of mafic and ultramafic rocks of the Lovnoozero region.

	Samples								
	1	2	3	4	5	6	7	8	9
SiO_2	25.12	30.96	36.31	45.61	46.18	50.92	50.97	51.01	43.58
TiO_2	0.14	1.02	0.25	0.56	2.25	0.98	0.74	0.43	0.27
Al_2O_3	6.68	12.55	5.66	17.30	16.87	17.77	20.66	17.46	6.03
Cr_2O_3	0.08	0.04	0.14	0.05	0.05	0.01	0.03	0.02	0.14
Fe_2O_3	43.93	36.67	33.47	6.69	5.56	3.21	1.60	1.73	19.39
FeO				7.91	9.81	5.72	4.44	5.45	8.34
MnO	0.10	0.10	0.21	0.10	0.14	0.13	0.09	0.10	0.13
MgO	5.24	3.56	13.55	5.52	6.17	6.64	5.11	7.50	10.90
CaO	4.45	4.74	2.68	7.34	6.60	9.71	10.62	11.46	1.38
Na_2O	0.92	2.01	0.68	2.93	2.74	3.07	3.20	2.99	0.92
K_2O	0.18	0.21	0.13	0.35	0.38	0.67	0.43	0.44	1.43
P_2O_5	—	0.06	0.02	0.16	0.17	0.30	0.24	0.48	0.06
S	19.42	13.59	10.55	3.64	1.97	0.26	0.27	0.11	10.48
V_2O_5	0.01	0.06	0.03	0.01	0.05	0.03	0.01	0.02	—
CO_2	—	0.08	0.34	0.30	0.26	0.10	0.49	0.17	0.06
H_2O^-	0.12	—	—	0.14	0.06	0.06	0.20	0.05	0.12
H_2O^+	0.65	0.57	1.30	2.57	0.71	0.61	0.77	0.80	0.86
Ni	1.96	2.03	1.58	0.38	0.29	0.009	0.01	0.015	1.47
Cu	1.79	0.43	0.90	0.35	0.15	0.004	0.006	0.005	0.10
Co	0.08	0.01	0.03	0.01	0.03	0.004	0.004	0.005	0.04
$-O \sim S$	9.71	6.79	5.28	1.87	0.98	0.13	0.14	0.05	5.24
Total	101.16	101.95	102.55	100.05	99.46	100.08	99.76	100.20	100.46

	Samples								
	10	11	12	13	14	15	16	17	18
SiO_2	51.70	45.98	48.26	52.91	39.45	41.86	42.12	46.74	49.66
TiO_2	0.37	0.53	0.18	0.60	0.17	0.52	0.82	0.40	0.68
Al_2O_3	12.76	6.92	21.55	7.52	3.21	4.49	5.52	5.26	6.63
Cr_2O_3	—	0.23	0.04	0.30	—	0.68	0.22	0.30	0.29
Fe_2O_3	1.08	5.36	1.01	0.23	6.45	4.78	3.67	2.54	1.21
FeO	7.56	14.07	6.77	10.37	5.11	7.78	12.41	6.55	7.49
MnO	0.14	0.16	0.07	0.18	0.13	0.14	0.12	0.16	0.16
MgO	15.47	19.01	8.86	21.85	30.98	32.40	15.26	20.98	17.95
CaO	5.82	2.59	9.23	3.04	3.22	1.87	11.46	12.48	11.86
Na_2O	2.13	0.59	1.62	0.70	0.52	0.48	0.65	0.76	0.60
K_2O	1.00	0.47	0.45	0.74	0.21	1.12	0.45	0.78	0.45
P_2O_5	0.06	0.06	0.02	0.10	0.10	0.17	0.10	0.17	0.14
S	0.34	4.08	0.44	0.15	0.10	0.47	4.59	0.08	0.05
V_2O_5	—	0.03	—	0.03	—	—	0.02	0.04	0.02
CO_2	0.42	0.14	0.34	0.19	0.43	0.28	2.67	0.74	1.23
H_2O^-	0.24	0.02	0.25	0.02	0.81	0.18	0.29	0.34	0.18
H_2O^+	1.32	0.51	0.69	0.88	9.15	2.54	1.13	1.98	1.42
Ni	0.051	0.92	0.018	0.068	0.174	0.21	0.44	0.06	0.041
Cu	0.017	0.15	0.014	0.008	0.008	0.07	0.54	0.01	0.004
Co	0.007	—	0.008	0.005	0.010	0.01	0.02	0.01	0.01
$-O \sim S$	0.17	2.04	0.22	0.08	0.05	0.24	2.30	0.04	0.02
Total	100.32	99.78	99.60	99.82	100.18	99.81	100.21	100.34	100.05

1—8 — the Lovnoozero deposit, 9—10 — Lounjoki; 11—13 — Laukku, 14—15 — Junges, 16—18 — Sueinlagash.

1 — mesocratic norite with rich nest-disseminated mineralization; 2 — leucocratic norite with rich nest mineralization; 3 — melanocratic amphibolitized norite with rich disseminated mineralization; 4 — mesocratic intensely amphibolitized norite with sulphide dissemination; 5 — leucocratic norite with weak sulphide dissemination; 6 — mesocratic ore-free norite; 7 — mesocratic, ore-free gabbro-norite, Ozero massif; 8 — mesocratic, ore-free, amphibolitized gabbro-norite (South massif); 9 — melanocratic norites with heavy dissemination and sulphide stringers; 10 — melanocratic norite with casual dissemination sulphids; 11 — melanocratic norite with heavy dissemination of sulphides; 12 — leucocratic norite with weak dissemination of sulphides; 13 — mesocratic ore-free, biotitized norite; 14 — ore-free, serpentinous lherzolite; 15 — biotitized and amphibolitized websterite with weak dissemination of sulphides; 16— carbonated and amphibolitized websterite with heavy dissemination of sulphides; 17 — olivine websterite, biotitized and amphibolitized, ore-free; 18 — amphibolitized and carbonated, ore-free plagiowebsterite.

Table 10. Chemical composition of ore minerals of the Lovnoozero region.

	Samples								
	1	2	3	4	5	6	7	8	9
Fe	59.98	59.10	58.89	60.09	60.15	26.48	31.27	28.86	28.57
Ni	0.08	0.38	0.41	0.46	0.49	41.70	35.95	34.70	37.02
Cu	0.26	0.00	0.04	0.00	0.00	—	—	0.02	0.01
Co	0.01	0.00	0.01	0.01	0.00	0.01	0.72	3.75	2.20
S	38.86	40.28	41.04	40.24	40.13	31.45	33.04	32.47	32.38
Total	99.19	99.76	100.39	100.80	100.77	99.64	100.98	99.80	100.18

	Samples								
	10	11	12	13	14	15	16	17	18
Fe	26.40	30.91	30.18	30.50	46.54	46.20	48.54	2.58	0.62
Ni	41.28	0.00	0.02	0.00	0.95	0.00	0.00	31.92	35.01
Cu	—	35.32	34.43	34.43	0.00	0.00	0.00	As = 43.80	45.78
Co	0.02	—	—		0.23	0.61	1.40	3.13	0.01
S	32.49	33.09	34.75	35.56	53.24	53.44	53.35	19.57	18.97
Total	100.19	99.32	99.38	100.49	100.96	100.25	103.29	101.00	100.39

1—5 — pyrrhotite; 6—10 — pentlandite, 11—13 — chalcopyrite; 14—16 — pyrite; 17—18 — gersdorffite; 1 — from weakly disseminated ore, Lovnoozero; 2 — from heavily disseminated ore, Lovnoozero; 3 — from breccia ore, Lovnoozero; 4 — from weakly disseminated ore, Laukku; 5 — from weakly disseminated ore, Sueinlagash; 6 — from weak dissemination in norite, Lovnoozero; 7 — the same; 8 — from weakly disseminated ore, Lovnoozero; 9 — from weakly disseminated ore, Sueinlagash; 10 — from a tectonic zone with gersdorffite-pyrite mineralization, Lovnoozero; 11 — from weakly disseminated ore, Lovnoozero; 12 — from weakly disseminated ore, Lounjoki; 13 — from weakly, disseminated ore, Sueinlagash; 14 — from weak dissemination in norite, Lovnoozero; 15 — from weakly disseminated ore, Lovnoozero; 16 — from a sulphide stringer in norite, Laukku; 17—18 — from a tectonic zone with gersdorffite-pyrite mineralization.

The nickel-copper mineralization, which is distributed non-uniformly, is composed of a fine to medium-grained dissemination, small nests, stringers and also of small accumulations of breccia-like and massive ores. It forms several »hanging» horizons and irregular zones in the near-contact and central parts of the massif favouring the footwall in general. The sulphide content varies from 5 to 30 % in the disseminated ores and from 70 to 80 % in the breccia and massive ores. In mineral composition and structural types, the nickel-copper ores are similar to those in the mafic massifs, except that the abundance of chalcopyrite is higher and that of pyrite lower. In chemical composition they differ from ores of the same type in mafic rocks in having lower nickel-copper ratios (1—3.5):1 and a nickel cobalt ratio of (15—17):1.

The composition of the mafic and ultramafic rocks in the area and that of the major minerals of the ores are shown in Tables 9 and 10.

The East Pechenga Area

Intrusives of mafic and ultramafic rocks of various composition (see Fig. 4) are widely spread throughout the gneisses of the Kola series NE of the Pechenga synclinorium. The

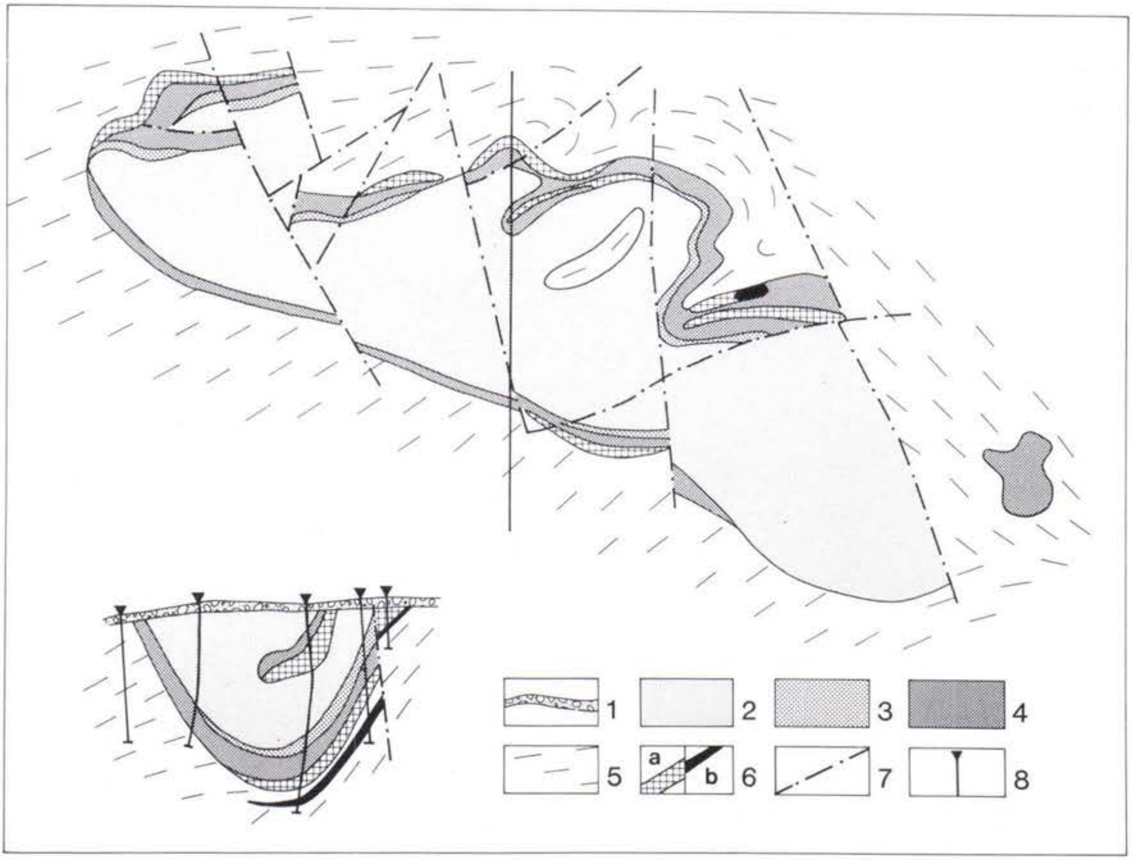


Fig. 35. Schematic geological map and section of the Karikyavr site. According to material of the Murmansk Exploration Expedition. 1 — Quarternary deposits; 2 — gabbro-norite; 3 — pyroxenite; 4 — peridotite, olivinite; 5 — the rocks of the gneiss complex; 6 — Ni-Cu ores: a) disseminated ores, b) breccia ores; 7 — faults; 8 — bore holes.

complexes in them are: the ultrabasite complex of the Rovno type, the peridotite-pyroxenite-gabbro-norite of the Karikyavr type, the gabbro-norite of the Mount Luostari type, and the gabbro-peridotite of the Nyasyukka type. The complexes have been investigated chiefly by E. M. Bakushkin, Zh. A. Fedotov, I. A. Yakovlev, A. S. Osokin and B. G. Kopyt'ko.

The Karikyavr type intrusives are of particular interest for their nickel content. Their locatión is considered to be controlled by zones of deep faults and by associated feathering faults with sub-meridional and sub-latitudinal trends. This type of intrusive was only recently singled out from a group ultrabasite bodies of the Rovno type after of detailed prospecting permitting the two intrusives of ultramafic and mafic composition, earlier considered as discrete to be united spatially. These two bodies are now considered to be a single mafic-ultramafic massif (N1), differentiated from gabbronorites to olivinites (Fig. 35).

The Karikyavr nickel-bearing massif occurs among biotite, biotite-garnet and biotite cordierite-sillimanite-gneisses migmatized by plagiomicrocline granites. It strikes sublatitudinally, here and there turning SW; the dip is mainly north at an angle of 50°—80°. In plan the massif is of irregular-oval form, extending in a sublatitudinal direction for nearly 2000 m. In cross section it is a funnel-shaped trough where north and south contacts meet along the dip. The bulk of the massif occurs unconformably among gneisses.

The massif is broken up by a series of submeridional faults into blocks overthrust one over the other from east to west. The depth of its footwall therefore decreases in the same direction from 700 to 50—100 m.

The massif exhibits distinct layering caused by the alternation of mafic and ultramafic rocks confined to the marginal and lower parts. The mafic to ultramafic ratio is approximately 3:1 in volume, and the contacts between them are conformable with the outer boundaries of the massif. Thinner layering is seen.

The massif is composed of gabbro-norites, plagioclase pyroxenites, harzburgites, plagiolherzolites and plagioclase-bearing pyroxene olivinites. Gabbro-norites form the upper horizon of the massif, and plagioclase pyroxenites the narrow intermediate »layer» (5—8 m) between gabbro-norites and peridotites. Peridotites and olivinites are located in the steeply dipping northern side and in the lower basal part, which pinches out progressively southwards. Plagiolherzolites predominate among the two types of peridotite; olivinites are less frequent. The transition between differentiates is usually gradual. Kelyphitic rims around olivine are features peculiar to ultramafic rocks.

Narrow chilled zones (not more than 1—2 m) are seen almost universally in the endocontact of the massif. They are composed of fine-grained pyroxenites with sharp borders against gneisses and gradual ones against the massif rocks. The gneisses in the contact zone are slightly altered.

The massif rocks are metamorphosed. Amphibolization increases gradually towards the marginal parts of the massif. This major process of the secondary alterations was most intensive in gabbro-norites, where 50—90 % of pyroxenites have been replaced by green hornblende and actinolite. The endocontact pyroxenites have been practically totally amphibolitized. The serpentinization and talcification of ultramafic rocks in the fault zones are of subordinate importance.

The sulphide Ni-Cu mineralization is mainly concentrated in the lower part of the peridotite »layer», principally in plagiolherzolites and more seldom in olivinites. »Hanging» lenses of sulphide mineralization have been observed in the middle and upper parts of some of the peridotites. The ores are mainly disseminated, and more seldom massive. Some of the Cu-Ni ores occur in the exocontact gneisses as veins, zones of sulphide breccia and as a scattered dissemination.

The disseminated mineralization in peridotites is mainly syngenetic and shows rather regular in distribution. Sulphide disseminations are of angular, polygonal form with distinct boundaries and are up to 5—7 mm across. The sulphides often show complex reticulate structures in heavily disseminated ores. Nests of massive ores and veins of irregular form are encountered in the lower portions of the heavily mineralized zones; these units measure up to 20—30 cm.

The ores are characterized by various mineral compositions; most minerals, however, are accessories and rare. The data obtained by V. V. Distler, I. P. Laputina, A. A. Philimonova, A. S. Osokin and Yu. N. Neradovsky, who studied the mineralogy and chemistry of the Karikyavr ores, demonstrate that the major ore-forming sulphides include minerals of the pyrrhotite group (troilite, monoclinic and hexagonal pyrrhotites), minerals of the chalcopyrite group (tetragonal chalcopyrite, ferruginous chalcopyrite and talnakhite) and pentlandite of variable composition. The group sometimes includes cubanite, although generally this mineral occurs as an accessory.

The accessories and rare minerals include magnetite, mackinawite, violarite, argentopentlandite, galena, sphalerite, bornite, ilmenite, chrome-spinels, sperrylite, merenskyite and michenerite.

The Ni content in disseminated ores is 3.5 % and in massive ores 11 %. Cu concentrations are highest (up to 13 %) in the breccia ores in the endocontact of the massif. The mean nickel copper cobalt ratio in ores in 35:30:1.

The large Rovno group of intensely altered ultrabasite bodies was discovered somewhat southeast of the Pechenga area. The location is considered to be controlled by faults of two systems: submeridional faults framing the Pechenga synclinorium and sublongitudinal feathering faults of the Titovka fault. Intrusives, which occur conformably with gneisses, amphibolites and migmatites, are met with in groups of 5—10 bodies as beds and lenses. Most of the intrusives are small, measuring 100—300 m along the strike and from a few metres to 50 m in thickness, although some larger ones are known as well.

The ultramafic rocks include intensely altered olivine pyroxenites, harzburgites and pyroxene olivinites. The metamorphic alterations are expressed in amphibolitization, chloritization, serpentinization and talcification. The narrow bodies often grade into chlorite-amphibolite and serpentine-talc-chlorite schists. Most intrusives are ore-free or contain a fine-grained and scattered sulphide dissemination. Near the footwall and in the central parts some of them exhibit horizons (or zones) with a high content of sulphides (up to 10—15 %, but seldom more). The mineralization is mainly epigenetic. The bulk of the sulphides occur as metasomatic dissemination, nests and silicate-sulphide intergrowths.

The Ni-bearing intrusives of the Rovno type and the Allarečhka ultrabasites are analogous in morphology, mode of occurrence, mineral composition and chemistry.

The Mount Luostari massif occurs non-conformably in the gneisses of the Kola series near the contact with the Pechenga synclinorium. In plan massif is of irregular wedge-shaped form, extending for 3 km in a meridional direction. Its thickness increases from north to south and reaches some hundreds of metres. The massif plunges gently (30°—35°) below the formations of the Pechenga series, its west and east contacts meeting each other at angles of 40°—50° and 60°—65°, respectively.

The massif is mainly made up of meta-gabbronorites that contain weakly altered rocks i.e. norites and olivine gabbro-norites. Weak layering is seen here and there. Secondary alterations are manifested in amphibolization, chloritization and epidotization.

The sulphide mineralization occurs in linear zones running parallel to the NW and NE-striking faults and to the contact of the massif. The zones are 300 m long and up to a few metres thick. The sulphides within the zones are distributed non-uniformly. Disseminated mineralization predominates; the nested and stringer-disseminated ores are less common and the sulphide content does not usually exceed 15—20 %. Chalcopyrite prevails over pentlandite.

The Nyasyukka intrusive group, which is located north of Mount Luostari, is represented by steeply dipping dykes of olivine gabbro, kaersutite plagioperidotites, olivine plagiopyroxenites and gabbro-diabases. The dykes 15—26 km long and 400 m thick, strike mainly NW, seldom NE, and sublatitudinally. They form two subparallel branches striking NW. One of the branches (SW) is composed of a large central dyke (length 26 km, thickness 40—250 m) of kaersutite plagioperidotites and abundant, narrow dykes of the olivine gabbro that accompany the central dyke. The other branch is made up of a dyke of olivine gabbro 15 km long and 50—150 m thick. Smaller dykes (2 km long), which usually consist of quartz gabbro-diabases, predominate in the southern part of the zone. The largest dykes are differentiated, and the feldspar content in them gradually increases towards the western contacts.

All the dyke rocks are amphibolitized, the alteration degree increasing from north to south towards the Pechenga synclinorium. The mineralization revealed in the dykes is of a syngenetic type and is represented by scattered dissemination in all the rocks but quartz gabbro-diabases. Higher concentrations of sulphide (Ni value up to 0.7 %) are observed in some small portions.

The compositions of mafic and ultramafic rocks of the nickel-bearing complex and those of the major minerals of the ores are shown in Tables 7 and 8.

THE NI AREA OF THE VETRENY BELT OF KARELIA

A. I. KAYRYAK and S. A. MOROZOV

The Vetreny Belt synclinorium borders on the Lower Archean formations of the Belomorean block in the northeast and on Archean granitoids, gneisses, migmatites and amphibolites of the Vodlozero block in the southwest. The Lopian, Sumian, Karelian and Riphean formations are all involved in the structure of the synclinorium zone. The Sumozero-Kenozer greenstone belt is 300 km long and composed of a number of smaller structures mainly with a northwest and submeridional strike. They seem to surround the granite-gneiss block-domes and are clearly associated with the Lopian structural stage. The structures are composed of basic, intermediate and acid volcanites alternating with tuffogene sedimentary and carbonaceous rocks; they contain numerous mafic and ultramafic intrusions.

The Karelian Lower Proterozoic structural stage is represented by sedimentary, sedimentary-volcanogenic, effusive and intrusive complexes, which constitute the 250 km long paleorift or paleoaulacogene type of structure (Kayryak A. I., Grib V. P. *et al.* 1978). The extrusion of picrite-basalts and the emplacement of gabbro-peridotite intrusions are conspicuous features of the Suisaari.

Locally, the Vendian deposits overlap the Archean and Lower Proterozoic formations, which, in the east and south, plunge below the Paleozoic rocks of the Russian platform.

Lower Proterozoic and Upper Archean magmatism was very widely developed in the region. The magmatic formations are represented by a great diversity of rocks — from felsic varieties to ultramafics. Effusive and intrusive complexes of mafic to ultramafic rocks developed in the suture structures and greenstone troughs. The ultramafites contain the following complexes: in the Upper Archean, olivine peridotite and peridotite-gabbro complexes in the greenstone belt, and in the Proterozoic, the Suisaarian peridotite-gabbro complex, which is generally related to the picrite-basaltic complex in the riftogenic structure of the Vetreny belt.

The promising showings of Ni-Cu ores occur within the Kamennoozero structural zone and at Voloshov, where they are associated with ultramafic intrusives.

The Kamennoozero structural zone

Situated in the northwestern part of the Vetreny Belt synclinorium the zone is confined to the system of suture structures developed along deep faults trending NW (Kumbuksa) and NE

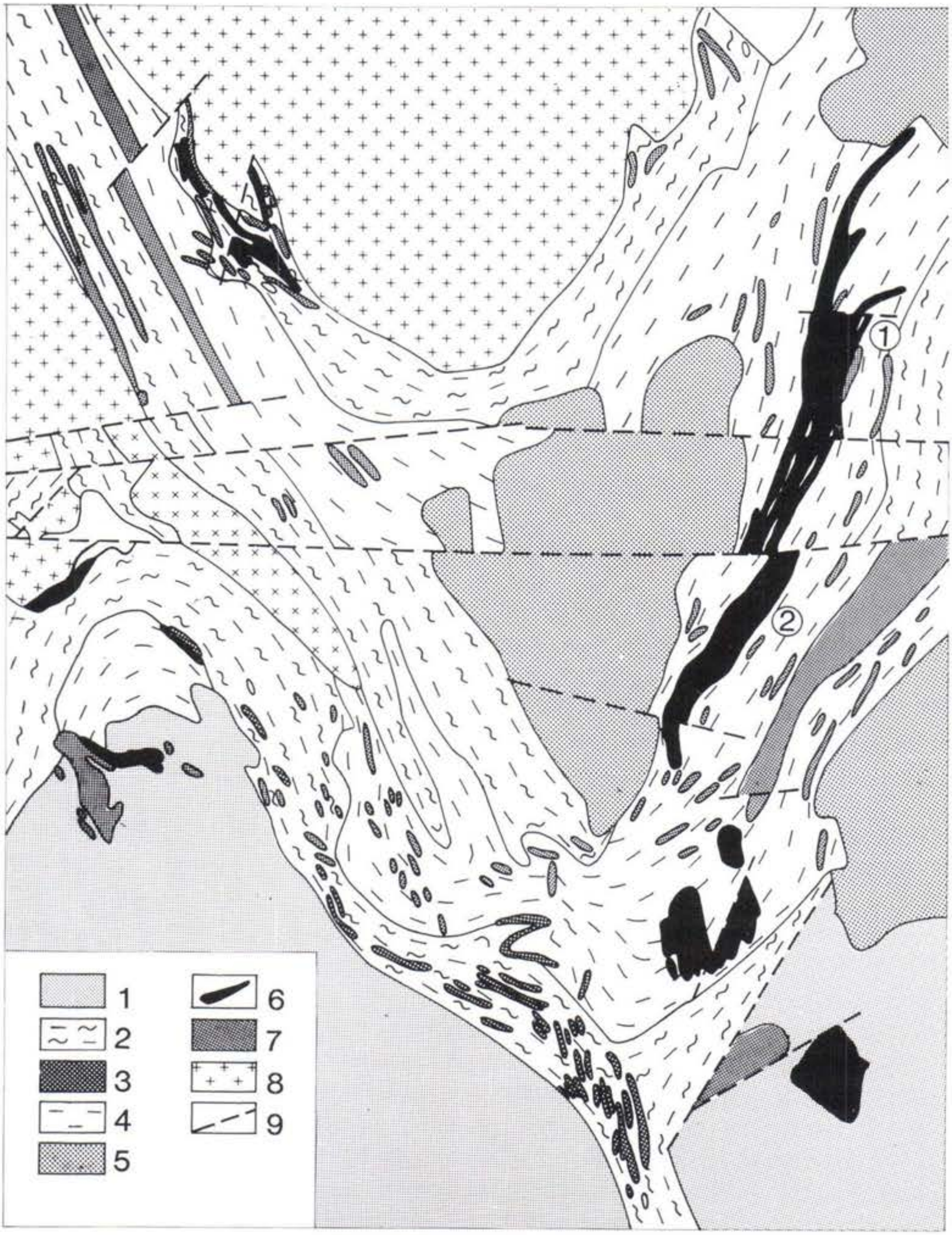


Fig. 36. Scheme of the geological structure of the Kamennoozero structure. According to material of the Karelian Exploration Expedition. Sedimentary-volganogenic complexes — Archean: 1 — non-segmented lower sedimentary-volcanogenic strata of the Saamian-Lopian stage; 2.3 — middle volcanogenic strata (2 — tholeiitic basalt, 3 — komatiites, and schists formed at the expense of the komatiites with subordinate tuffogene-sedimentary rocks); 4 — upper sedimentary-volcanogenic strata (dacite-liparite, andesite, andesite-basalt, tuff-sandstone, black schists); Proterozoic: 5 — volcanogenic strata (basalts with horizons of welded tuff). Intrusive complexes; 6 — olivinites, harzburgites, wehrlites, pyroxenites; 7 — gabbro, gabbro-diabases; 8 — plagiogranites; 9 — faults. Large massifs of ultrabasites are from north to south: The Vozhma massif; the Kumbuksa massif; the Svetloozero massif; the Urosozero massif. Numbers in circles refer to the Ni-Cu ore showings (1 — East Vozhma, 2 — Lebyazh'a).

(Vozhma, Vostochno-Vozhma). It is composed of Upper Archean metamorphosed, volcanogenic and sedimentary volcanogenic formations, and of Lower Proterozoic basic volcanites (Fig. 36).

The Upper Archean rocks are the most widely spread. They are related to the Lopian structural-formation complex consisting of a number of stratified formations; quartzite-bearing komatiite-basalt, tholeitic andesite-basalt, tholeitic and carbonaceous dacite-andesite-basalt and picrite-bearing tholeiite-andesite-basalt. The earliest of the formations is of the greatest interest, i.e. the quartzite-bearing komatiite-basalt that occurs in the Lopian basement on the oldest non-separated, mainly granitoidal, basement. It has developed principally within the Kumbuksa. Lezhchevsko-Kamennoozero, Eastern Vozhma and Sinego-ozero synclinal structures.

Flows of schistose metabasalts with subordinate horizons of komatiitic peridotites and interbeds of sulphide-bearing quartzites predominate in the lower part of the quartzite-bearing komatiite-basalt formation (50—250 m thick). Komatiitic peridotites, quartzites and schists of tuffogenic-sedimentary origin alternate in the middle of the section of the formation, forming a member of interstratification 50—500 m thick. The lower part of the member is usually represented by one or several comparatively thick (30—50 m) flows of komatiitic peridotite, which are considerably thinner (to 0.2—5 m) higher up in the section, where they alternate with flows of metabasalts, interbeds of quartzites and schists of tuffogenic-sedimentary origin. The upper part of the formation is mainly composed of metabasalts with thin interbeds of tuffogenic-sedimentary rocks and single interbeds of komatiitic peridotites. The total thickness of this formation is 500—1000 m.

The komatiitic peridotites, characterized by the presence of spinifex structures, form lava flows or sills among sedimentary-volcanogenic rocks. They are usually intensely altered into talc-carbonate, chlorite-talc-carbonate, and talc-chlorite-amphibole rocks of different degrees of schistosity. There are some distinct relics of primary textures permitting individual flows to be distinguished. At one site (the Lezhensk) the flow is of a three-membered structure: its base is 1.2 m thick and it is composed of fine-grained massive and essentially actinolitic rock; the middle part is 17.4 m thick and composed of massive serpentinite-chlorite-talc rocks with relict structures resembling a porphyry in the upper part of the flow. »Porphyry» segregations exhibit hexagonal and rounded forms measuring 2—5 mm; they are composed of talc flakes that show a simultaneous extinction in crossed nicols and are rimmed with a magnetite rash. The interstities between those segregations are filled with chlorite-talc aggregates. The porphyry segregations are probably pseudomorphs of talc after olivine.

The upper part of the flow exhibits distinct 5.8 m thick spinifex structures diagnosed on cut (sawn) core surfaces as dark clusters and light band differing in orientation. The length of the clusters and bands is 5—30 mm, the width of the clusters 5—10 mm and of the bands 0.5—1 mm. The clusters are biggest in the uppermost parts of the flows. With depth they gradually decrease in size until they disappear and grade into the rocks with the relics of porphyry structures. Microscopic investigations have established that the light bands are composed of fine-grained aggregates of talc, chlorite and serpentine-chlorite. Magnetite appears in noticeable amounts together with the above minerals in the dark bands. Another flow lacks amphibolic rocks in its base.

Petrochemically the komatiitic peridotites are volcanogenic rocks with the highest magnesia content in the region (MgO contents are 21.7—36.5 %). Table 11 shows the results of silicate analyses of the komatiites and basalts.

The Lower Proterozoic formations are not abundant, and they are represented by amygloidal diabases that form a volcanic structure of a central type.

Table 11. Chemical composition of komatiitic peridotites, komatiitic metabasalts and basalts in the Kamennozero structural zone.

	1	2	3	4	5
SiO_2	36.44	42.85	38.28	41.72	48.22
TiO_2	0.15	0.30	0.18	0.41	1.88
Al_2O_3	3.18	6.53	4.74	9.45	13.91
Fe_2O_3	5.16	4.86	3.30	1.50	3.47
FeO	2.62	5.28	6.62	7.87	9.59
MnO	0.14	0.21	0.10	0.18	0.20
CaO	1.62	5.85	4.26	8.98	10.43
MgO	36.57	26.01	26.14	12.32	5.62
K_2O	0.01	0.01	0.03	0.19	0.24
Na_2O	0.01	0.02	0.09	1.20	2.82
H_2O	0.56	0.32	—	—	0.15
losses	13.07	7.27	15.52	15.84	3.80
P_2O_5	0.05	0.06	0.04	0.05	0.08
NiO	0.24	0.16	—	—	0.01
Cr_2O_3	0.27	0.27	—	—	0.02
Total	100.09	100.0	99.30	99.71	100.44

1 — Komatiitic peridotite. The Zolotye Porogi site. Average of four analyses.
2 — Komatiitic peridotite from the zone with the spinifex structure. The Zolotye Porogi site. Average of six analyses.
3 — Carbonate-talc rocks (apokomatiites). The Zolotye Porogi site. Average of nine analyses.
4 — Komatiitic-basalts. The Zolotye Porogi site. Average of nine analyses.
5 — Basalts. The Svetloozersky site. Average of six analyses.

Extensively developed within the Kamennoozero structural zone is the Upper Archean — Lower Proterozoic magmatism, which is represented by a wide range of rocks from felsic varieties to ultramafites. The granitoids occupy the central part of the area — the »Khizhozero block». Intrusive complexes of intermediate to ultramafic composition have developed in the suture structures and greenstone troughs, where they form belts of intrusions. The Vozhma and Kumbuksa belts of intrusions have been distinguished within the Kamennoozero zone. Each belt of intrusions has its own characteristic features, such as form, composition, dimensions of intrusions, texture and composition of the host rocks. On the magnetic maps the belts are distinctly associated with linear positive anomalies.

The 5—10-km-wide Vozhma belt of intrusions, which is confined to the zones of deep faults trending NE, intersects the general NW trend of the Vetreny belt synclinorium zone. It has been traced for a distance of 40 km. The largest massifs of ultramafites in this belt are Vozhma, Kumbuksa, Svetloozero and Urosozero. The belt incudes the nickel-copper showings, the largest of which are in the Vozhma and Kumbuksa massifs, 13 km and 7 km long, respectively. The thickness of the massifs in the central parts is up to 1—1.3 km but on the flanks it gradually decreases to 300—150 m. Rocks of two intrusive phases are involved in the structure of the massifs. The first phase features a direct differentiation series (dunite, olivinite, pyroxene-bearing olivinite, peridotite, pyroxenite, gabbro), which is usually represented by olivinites, pyroxene olivinites and harzburgites with a subordinate amount of peridotites (lherzolites, wehrlites). The second phase of the massifs is composed of differentiated dykes of gabbro-wehrlite, clinopyroxenite and gabbro-pyroxenites.

The largest Vozhma massif trends NNE at 10°—15° and dips NW at 70°—80°. The ultramafites are characterized by sharp, steeply dipping contacts with the host rocks. The contacts

Table 12. Chemical composition of mafic and ultramafic rocks of the Vozhma and Zolotoporozhje massifs.

	1	2	3	4	5	6
SiO_2	35.72	40.49	42.57	46.37	48.22	39.13
TiO_2	0.05	0.17	0.36	0.73	0.77	0.10
Al_2O_3	0.57	1.78	2.60	5.26	9.56	1.82
Fe_2O_3	9.40	5.70	5.33	2.89	2.79	3.55
FeO	1.61	6.84	6.96	10.03	10.24	2.56
MnO	0.08	0.20	0.25	0.23	0.22	0.07
CaO	0.24	1.87	3.50	9.80	8.63	1.38
MgO	38.43	33.74	29.52	15.77	12.75	37.88
K_2O	0.06	0.05	0.05	0.12	0.31	0.03
Na_2O	0.08	0.09	0.1	0.12	1.34	0.07
H_2O	0.5	—	0.32	0.24	—	—
losses	13.4	9.86	9.37	4.83	4.58	13.56
P_2O_5	0.03	0.02	0.025	0.05	0.04	0.02
V_2O_5	0.015	—	0.025	0.03	0.04	—
NiO	0.35	0.25	0.3	0.12	0.07	—
CoO	0.02	0.016	0.014	—	0.008	—
Cu	0.014	0.006	0.01	0.013	0.02	—
Cr_2O_3	0.58	0.44	0.47	0.27	0.16	—
S	0.26	0.14	0.40	0.35	0.11	0.19
Total	100.17	100.81	100.55	96.44	99.45	100.17

Ultramafic and mafic rocks of the Vozhma massif (the Kamennoozero area): 1 — Apo-olivinite serpentinites (average of 12 analyses); 2 — Apoperidotite serpentinites (average of 16 analyses); 3 — Metawehrlites (II phase), the eastern ore vein (average of five analyses); 4 — Metapyroxenites, ore vein (average of nine analyses); 5 — Metagabbro, ore vein (average of four analyses); 6 — Apoharzburgite serpentinites (average of 10 analyses), the Zolotoporozhje massif.

are usually tectonic. The western part of the massif is composed of serpentinites formed at the expense of pyroxene olivinites and harzburgites and their intensely carbonated and talcificated varieties. The eastern boundary is marked by the central fault. A dyke-like body, gabbro-metawehrlite-metapyroxenite in composition, occurs in the fault. The central part of the massif, to the east of the central fault, is composed of strongly asbestized meta-olivinites (serpentinites). Metaperidotites (serpentinites) have developed at the eastern side of the massif. The ultramafic rocks of the massif are cut by dykes of gabbro-diabases, augite porphyrite and subalkaline andesite-diabase porphyrites. The dykes are from 0.1—0.5 to 20 m thick and over 100 m long.

Other large massifs of the Vozhma belt of intrusions are of the same structure. Table 12 shows the chemical compositions of mafic and ultramafic rocks.

The Kumbuksa belt of intrusions is confined to the NW-trending system of faults, which can be traced for more than 100 km. It contains numerous (dozens and more seldom hundreds of metres in size) thin ultramafite bodies that are conformable with the upper Archean volcanogenic-sedimentary rocks. They are seldom any longer than 300—800 m, rarely 1—5 km. In the Zolotoporozhje intrusion, which has been studied in more detail, the ultramafites have altered into serpentinites, talc-carbonate and quartz-carbonate-chlorite rocks and schists (listvenites). The small showings of pyrite-millerite ores are associated with them.

The following sequences of metamorphic transformation (from early to late) have been established in the massifs of the Kamennoozero zone: a) pre-ore: early serpentinization, lizarditization, chrysotilization, chrysotil-asbestization, antigoritization, carbonatization, talcification; b) syn-ore: chloritization, tremolitization, pyroauritization, nemalitization, carbonatization, listvenitization and sulphidization.

A great number of ore showings confined to the linear structures have been established in the territory of the Kamennoozero zone. Within the Vozhma belt of intrusions all the known Ni-Cu ore showings are confined to two zones: the eastern and the western ones. The largest ore showings, the Vostochno-Vozhma, Lebyazh'a and Zapadno-Svetloozero, are located in the eastern zone, which runs along the basal contacts of ultramafite massifs. The central fault (the western zone) which divides all the massifs into two equal parts and is filled with dyke-like wehrlite-pyroxenite-gabbro bodies, contains the known low grade Ni ore showings of the Vozhma and Kumbuksa massifs.

The following sulphide Ni-mineralization can be distinguished:

1. The syngenetic minerlization: low-grade disseminated interstitial (sideronitic) pentlandite-pyrrhotite and chalcopyrite-pentlandite-pyrrhotite.

2. The epigenic mineralization: stringer-disseminated, nested-disseminated, disseminated, breccia-like and veined chalcopyrite-pyrite-pentlandite-pyrrhotite, disseminated millerite-pyrite, disseminated and stringer-disseminated pentlandite-heazlewoodite and haeazlewoodite.

The largest zones of syngenetic sulphide dissemination have developed among serpentinites formed at the expense of pyroxene olivinites and harzburgites in the western parts of the Vozhma and Kumbuksa massifs. A mineralized zone in the Vozhma massif has been traced with drill holes to a depth of 400—450 m. The sulphide content is 5—8 %, sometimes 10 % and the Ni value is 0.20—0.62 %. The Ni value increases somewhat wherever the epigenetic stringer-disseminated mineralization is superimposed on the interstitial one (the Kumbuksa massif). Relict syngenetic sulphide dissemination is also observed in the rocks of the Svetloozero massif. The primary minerals in the dissemination are pyrrhotite, pentlandite, chalcopyrite and chromite. The secondary minerals are violarite, millerite, magnetite, pyrite, marcasite, hematite, ilmenite and graphite. As a result of metamorphism the syngenetic sulphide disseminations have been replaced by magnetite, antigorite, radial tremolite, carbonate, millerite, violarite and pyrite. They are locally flared, recrystallized and redeposited, forming metasomatic dissemination and stringers. The pyrrhotite-violarite-magnetite ore association is the youngest.

The epigenetic pyrrhotite-pentlandite-chalcopyrite mineralization has developed in substantially altered and brecciated wehrlites and pyroxenites of the »ore dyke» of the Vozhma massif (the East Vozhma showing) and in carbonated, sometimes talcificated and more seldom chloritized, metaperidotites (serpentinites) of the footwalls of the Kumbuksa (the Lebyazhia showing) and Svetloozero (the West Svetloozero showing) massifs.

The East Vozhma showing is located in the eastern contact of the central part of the massif. The sulphide Ni-Cu mineralization is confined to the complexly differentiated dyke, gabbro-wehrlite-clinopyroxenite in composition, that cuts the ultrabasites and the host volcanogenic sedimentary rocks. The ore zone is a steeply dipping lens (Fig. 37) and its strike varies from sublatitudinal (80°—85°) to NE (30°—40°). The ore zone dips NW at an angle of 60°—70°. It is at its thickest in its central part, but towards the flank the thickness gradually decreases, and at a depth of 300—350 m the ore zone pinches out almost completely down the dip. The Ni content varies from 0.5 to 2.5 %, the Cu value from 0.1 to 0.6 % and the cobalt content from 0.02 to 0.09 %. The mineralization is mainly composed of disseminated and stringer-disseminated types. Breccia ores 5—0.8 m thick are met with as ore, sometimes as stringers of massive ore 3—5 cm thick. The breccia and massive ores cut the disseminated ores.

The Lebyazh'a showing includes a series of

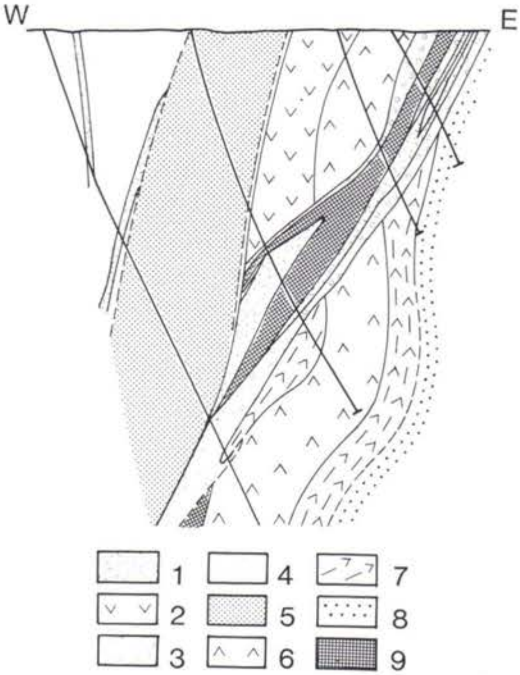


Fig. 37. Geological section of the East Vozhma ore showing. According to material of the Karelian Exploration Expedition. 1 — andesite-diabase porphyrite; 2 — metagabbro-diabase; 3 — gabbroamphibolite and apopyroxenitic amphibolite; 4 — apoperidotitic serpentinite; 5 — apoolivinitic serpentinite; 6 — metaandesite-diabase; 7 — tuff and tuffaceous schist of the andesite-diabase composition; 8 — quartzite; 9 — Ni-Cu ores.

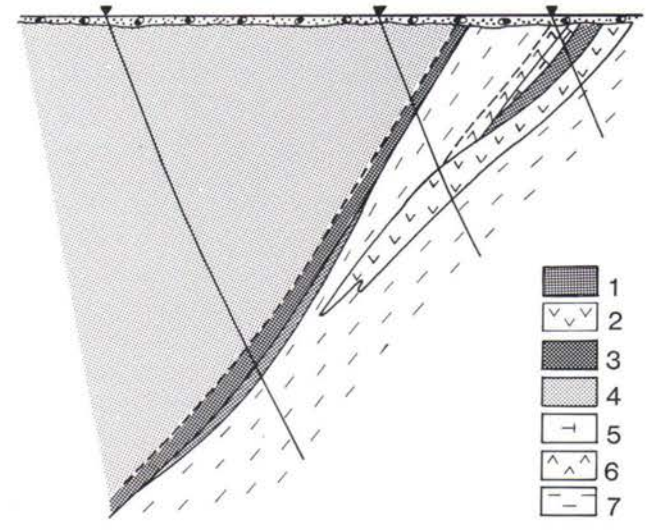


Fig. 38. Geological section of the central part of the Main orebody of the Lebyazh'a ore showing. According to material of the Karelian Exploration Expedition. 1 — nickel-copper ores; 2 — gabbro-diabase; 3 — apoperidotite, serpentinite; 4 — apoolivinite serpentinite; 5 — talc-carbonate rocks; 6 — metaandesite; 7 — sericite-quartz, albite-quartz-sericite and tuffite.

small orebodies located within the two ore-controlling zones: the Eastern and Central zones. The Eastern zone, where the highest-grade ores are encountered, is confined to the eastern contact of the Kumbuksa massif (Fig. 38). Disseminated syngenetic and epigenetic ores have developed within the zone. A specific feature of the zone is the confinement of the epigenetic orebodies to the gentle syncline-like trough of the footwall of the Kumbuksa massif. The orebodies are characterized by a small extension down the dip and by considerable dimensions along the pitch.

In mineral composition the ores of the Main orebody can be divided into two types: 1) those in which primary silicates have largely undergone talcification and carbonatization, and whose ore minerals are mainly of the chalcopyrite-pyrite-violarite association; 2) those in which silicates are made up of serpentine (antigorite) and more seldom of amphibole, and among whose sulphides chalcopyrite, pentlandite and pyrrhotite predominate.

The central controlling zone is composed of dykes of wehrlites, pyroxenites and gabbro-diabases, of veins of rodingite and of talc-carbonate rocks developed in the axial part of the massif. The mineralization in the Central zone is controlled by lithological and tectonic factors. On account of the lithological factor the low-grade syngenetic sulphide dissemination is restricted to the base of the serpentinite horizon formed at the expense of harzburgites. The epigenetic mineralization is confined to the Central tectonic zone, with which dykes of various composition were emplaced and the hydrothermal and metasomatic rock and ore transformations took place. The mineralizations are located in different rocks (I and II phases). The hydrothermal and metasomatic processes gave rise to several types of epigenetic sulphide minerlization: millerite-magnetite and magnetite-heazlewoodite mineraliztion in serpentinites formed at the expense of olivinites, and pyrrhotite-pentlandite, magnetite-pyrite-pentlandite-violarite mineralization in the serpentinites that were formed at the expense of harzburgites, but also in pyroxenites and metawehrlites of the second phase.

In the West Svetloozero ore showing the zone of epigenetic mineralization consists of a complex system of stringers of massive and breccia sulphide ores of varying thickness alternating with disseminated, nest-disseminated ores and non-mineralized rocks. The sulphide veins and zones of breccia ores crosscut the carbonated and talcificated serpentinites and the carbonate-talc rocks.

In contrast to the syngenetic dissemination, the epigenetic mineralization is not associated with the primary rock structure and it is obviously superimposed in character. The sulphides of the epigenetic ores are intimately intergrown with chlorite, radial tremolite, carbonate, secondary magnetite, serpentine that intensely corrodes and replaces augite, amphibole pseudomorphs after augite, chromite and ilmenomagnetite. The main minerals of the epigenetic mineralization are pyrrhotitc, pentlandite, chalcopyrite, chromite, galena, sphalerite, ilmenomagnetite, magnetite and valleriite. The accessories are violarite, pyrite and marcasite, pyrite and melnikovite, magnetite, ilmenite, hematite, millerite and covellite.

The metamorphogenic disseminated pyrite-magnetite-millerite mineralization is encountered in chlorite-quartz-carbonate listvenites, developed in the NE contact of the ultramafic massif (Kumbuksa, the »Zolotye porogi» region). The mineral composition of the mineralization is pyrite (25 %), millerite (up to 5 %), magnetite (5 %), chalcopyrite (1 %), pyrrhotite and violarite. The metamorphogenic heazlewoodite mineralization has developed in the serpentinites of the Vozhma, Kumbuksa and Svetloozero massifs. The mineralization occurs in two morphogolical types: 1) stringer-disseminated heazlewoodite in chrysotile-asbestos and antigorite veins; 2) fine-disseminated heazlewoodite with pentlandite, sometimes with millerite in serpentinites. The largest zone of the stringer-disseminated heazlewoodite mineralization has developed in the intensely asbestozed serpentinites of the Vozhma massif. The mineralization is usually non-uniform. Heazlewoodite mainly occurs in veins of asbestos, replaced by pyroaurite, nemalite, carbonate and magnetite. The nickel content usually ranges within 0.2 to 0.5 %: only rarely is it higher.

The Voloshov site

The Voloshov intrusions of ultrabasites are located in the southeastern part of the synclinorium and are confined to the deep Voloshov fault striking NE.

According to geological and geophysical dâta, there are more than 30 ultramafite massifs at this site, but only a few of them have been studied. The thickness of the massifs varies from tens of metres to 200—300 m, seldom to 500—700 m; along the strike they have been traced for a distance of from 1—2 km to 3—5 km. The massifs are usually conformable with the enclosing Upper Archean volganogenic-sedimentary formations.

The intrusions of the Voloshova site are composed of meta-olivinites and metaperidotite-serpentinites. The dyke complex involves diabases and porphyrites. In zones of intense jointing the serpentinites have been converted into magnetite-tremolite rocks showing elevated values of pyrite and pyrrhotite. The sulphide Ni mineralization observed in a number of massifs consists of disseminated and stringer-disseminated types with a Ni content ranging from 0.2 to 0.9 %. The higher Ni concentrations are encountered in the stringers of massive ores and in the breccia zones. Secondary superimposed magnetite-pyrite mineralization is typical of the Voloshov massifs. The magnetite of the late generation usually replaces sulphides, and, in its turn, is replaced by marcasite.

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NICKEL-COPPER DEPOSITS IN FINLAND

NICKEL DEPOSITS IN FINLAND, A REVIEW

H. PAPUNEN and A. VORMA

HISTORICAL BACKGROUND

Finnish geologists were introduced to the exploration of sulphide Ni-Cu deposits by the discovery of the Pechenga deposit in 1921. Exploration continued for more than ten years until in the mid-1930s the search for ore reserves and the planning of mining operations were transferred to a foreign company. The ore type was thus well known to the geologists of the Geological Survey when the Nivala area in western Finland became the target of exploration in 1936. It was not long before a small nickel-copper deposit was discovered at Makola. At about the same time exploration was underway for nickel ore at Parikkala in southeastern Finland, but the occurrence there was too small for mining operations. The first indications of Makola and Parikkala occurrences were given by mineralized samples sent to the Geological Survey by members of the public. This co-operation has been fairly successful and many of the Finnish deposits being mined today owe their discovery to the initiative of outsiders. Outokumpu Oy started the mining of the Makola deposit in 1941. About 415,000 tonnes of ore were mined in 1941—1948, and again in 1951—1954.

With the discovery in 1954 of the largest known Ni-Cu deposit, the Kotalahti ore, a new period of nickel production began in Finland. Explôitation started in 1959. Reserves warranted the establishment of a nickel smelter and refinery at Harjavalta that same year and another one in Pori in 1962. In the first half of the 1970s nickel ore was extracted from small mines at Telkkälä (c. 141,000 tonnes) at Kitula in Puumala (19,000 tonnes) at Kylmäkoski, southwestern Finland (c. 500,000 tonnes) and at Petolahti (c. 86,000 tonnes). A low-grade nickel ore totalling 5.5 million tonnes was mined at Vuonos in the Outokumpu area during 1972 and 1977. The Hitura deposit in the Nivala area, about 4 km north of the old Makola deposit, was discovered by the Geological Survey in 1961. After underground exploration and comprehensive process testing by Outokumpu Oy production started in 1970. At the beginning of the 1980s the capacity of the mine was c. 450,000 tonnes of ore per year. The first indication of the Vammala deposit was received in 1960 when a member of the public sent a sample to the Outokumpu Oy. After a period of laborious exploration test mining started in 1975, and full-scale exploitation by Outokumpu Oy in 1978. The present capacity of the mines is c. 330,000 tonnes of ore per year.

Nickel ore is currently produced in the Kotalahti and Vammala mines. Minor amounts of nickel concentrate are produced from the ores of Lahnaslampi and Polvijärvi talc mines treated at Lahnaslampi, Vuonos and Luikonlahti. Underground exploration in in progress at the Laukunkangas deposit is the Haukivesi area, the most promising of the nickel exploration targets in recent years.

Table 1 gives the production of nickel concentrate in Finnish mines during the last 20 years.

This review describes in detail the main nickel

Table 1. Production of nickel concentrate in Finland from 1963 to 1981.

Year	Nickel concentrate tonnes	Year	Nickel concentrate tonnes
1963	54,400	1973	122,511
1964	58,800	1974	122,252
1965	55,318	1975	116,460
1966	52,163	1976	115,595
1967	57,826	1977	81,065
1968	52,028	1978	64,152
1969	71,095	1979	87,540
1970	93,065	1980	100,471
1971	66,121	1981	90,311
1972	107,537		

deposits in Finland. Several other occurrences have also been found during the intense exploration period that started in 1960 but, with their low potential for exploitation, they are only listed in Table 3 and marked on the appended map.

The classification of Finnish nickel deposits is preceded by chapters summarizing the bedrock geology of Finland. This summary is rather detailed to enable the reader to compare the different geological environments and the various concepts held by geologists working in the Baltic Shield.

OUTLINE OF THE BEDROCK GEOLOGY IN FINLAND

Finland being in the central part of the Baltic Shield, the study of its bedrock geology is crucial to our understanding of the evolution of the Shield. The present survey describes shortly the main structural units, from oldest to youngest, major attention being paid to the latest ideas and interpretations. The metallogeny of Finland will receive only brief mention in the description of general geological features. Classification of nickel deposits and related mafic and ultramafic rocks will be discussed in the following paragraphs, and in the next chapter by Gaál. It is presumed that most of the relevant literature published more than 10 years ago is familiar to the reader and so the descriptive part of it is omitted from the references.

The traditional division of the geological evolution of Finland into the Presvecokarelian, Svecokarelian and Postsvecokarelian (Simonen 1960) is followed in the present survey. The order in which the phenomena are discussed is not quite chronological, more attention being paid to cratonic formations even though they cover a smaller area than the geosynclinal formations. This is because the cratonic rocks are ideally suited for both chronostratigraphical and lithostratigraphical correlations. The rocks of the geosynclinal formation will receive more attention in the following chapter by Gaál describing the tectonics of the metallogenic provinces of nickel. For the case of brevity the stratigraphic terminology and related metallogenic features have been collected in Table 2. Figure 1 presents the main structural units of Finland.

Presvecokarelian formations

The basement of the Proterozoic cover consists of Archean greenstone belt associations, granitoids and the granulite complex. The basement was cratonized over 2500 Ma ago. In Fin-

Table 2.

AGE (Ma)	EVENT	ORES
350—380	Crystallization of *Sokli carbonatite;* alteration of rocks in environęment	P, Nb, Fe, U in Sokli carbonatite
435	Main phase of *Caledonian* folding	
450—570	*Deposition of Cambrian and Cambro-Silurian* sediments; sandstone deposits still exist in southwestern Finland, around the Gulf of Bothnia and in the western part of Enontekiö	
1270	*Postjotnian diabases:* Basic magma erupted onto the surface along faults in the cratonized shield: the diabases of the Åland, Satakunta and Vaasa archipelagos (the Salla diabase dyke is c. 1200 Ma)	
1300—1400	*Jotnian sediments:* Sand and clay formed as weathering products of the bedrock were deposited in river deltas; preserved nowadays in rift valleys as the sandstones of Satakunta, the siltstone of Muhos and in basal formations in the Gulf of Bothnia	
1540—1700	*Rapakivis:* Formation of rapakivi massifs and the preceding gabbro-anorthosite intrusions postorogenic in relation to the Svecokarelian orogeny	Sn, Be, W (± Cu, Zn, Pb) mineralization associated with younger rapakivi intrusions in certain places, e.g. Eurajoki and Kymi
1800—1860	*Svecokarelidic late-orogenic phase:* granitic magma intruded during the final stage of folding and formed late-orogenic granite intrusions; volcanic activity in southern and southwestern Finland	— porphyry-type Cu-Mo-precious metal mineralizations associated with granitoids — tourmaline breccias with Cu and W (Ylöjärvi) — Cu ores associated with skarns (Hällinmäki) — volcanic-hydrothermal Cu and Cu-Zn-Pb ores (Orijärvi area, Haveri)
1860—1900	*Main phase of Svecokarelidic folding:* emplacement of synorogenic plutonic rocks; partial migmatization and melting of sediments undergoing folding; intrusion of ultramafic and mafic magmas before and during folding; volcanic activity particularly in the Savo schist area and in Ostrobothnia; sedimentation of turbidites in geosyncline basin	— volcanic-hydrothermal strata-bound pyrite-Cu-Zn (Pb) ores (Vihanti—Pyhäsalmi—Pielavesi area) — Ni-Cu ores in ultramafic and mafic intrusions
1900—2200	*Karelidic evolutionary phase:* Deposition of sediments of flysch type into deep parts of sedimentation basin; deposition of carbon-bearing gyttjas and carbonate sediments into shallow parts of basin; deposition of feldspathic quartz sands, pure quartz sands and basal conglomerates on the continent and along its margin; mafic volcanism on the continent and along its margin, ultramafic eruptions into the trough on the sea bottom	— massive volcanic-hydrothermal Cu-Zn-Co ores associated with ultramafic-mafic submarine extrusions, and disseminated Ni sulphides (Outokumpu area) — Ni-Cu-Zn sulphides in black schists (Sotkamo, Talvivaara) — iron deposits (Sotkamo, Puolanka) — disseminated Cu-Zn ores and breccias in arenitic metasediments (Hammaslahti) — V-bearing Ti-Fe ores (Otanmäki) — uranium ores in hiatus zone (Eno)
	Lapponium: formation of geosyncline, sedimentation and volcanic activity in central Lapland and Koillismaa	— volcanic-hydrothermal strata-bound Cu (-Zn) ores (Pahtavuoma) — iron deposits containing Mn in parts (Kittilä area) — skarn iron ores (Kolari)
2450	*Layered intrusions:* intrusion of basic magma and its solidification into layered complexes in Koillismaa and central Lapland	— V-bearing Ti-Fe ores (Mustavaara) — disseminated Cu-Ni sulphides and PGE (Porttivaara, Kuusijärvi, Konttijärvi) — chromite cumulates (Kemi, Koitelainen)
2600—2800	*Archean granitoids:* emplacement of granitoids of Archean basement complex, deformation	— Mo mineralizations associated with younger granitoid phase (2600—2700 my) and surrounding schists
2700—3000	*Archean greenstones:* volcanic activity and sedimentation in narrow zones of rift valley type that were later deformed	— iron deposits (Huhus) — pyrite and minor polymetallic sulphide deposits associated with felsic volcanics (Tipasjärvi) — Ni-Cu sulphides in ultramafic intrusions (Tainionvaara)

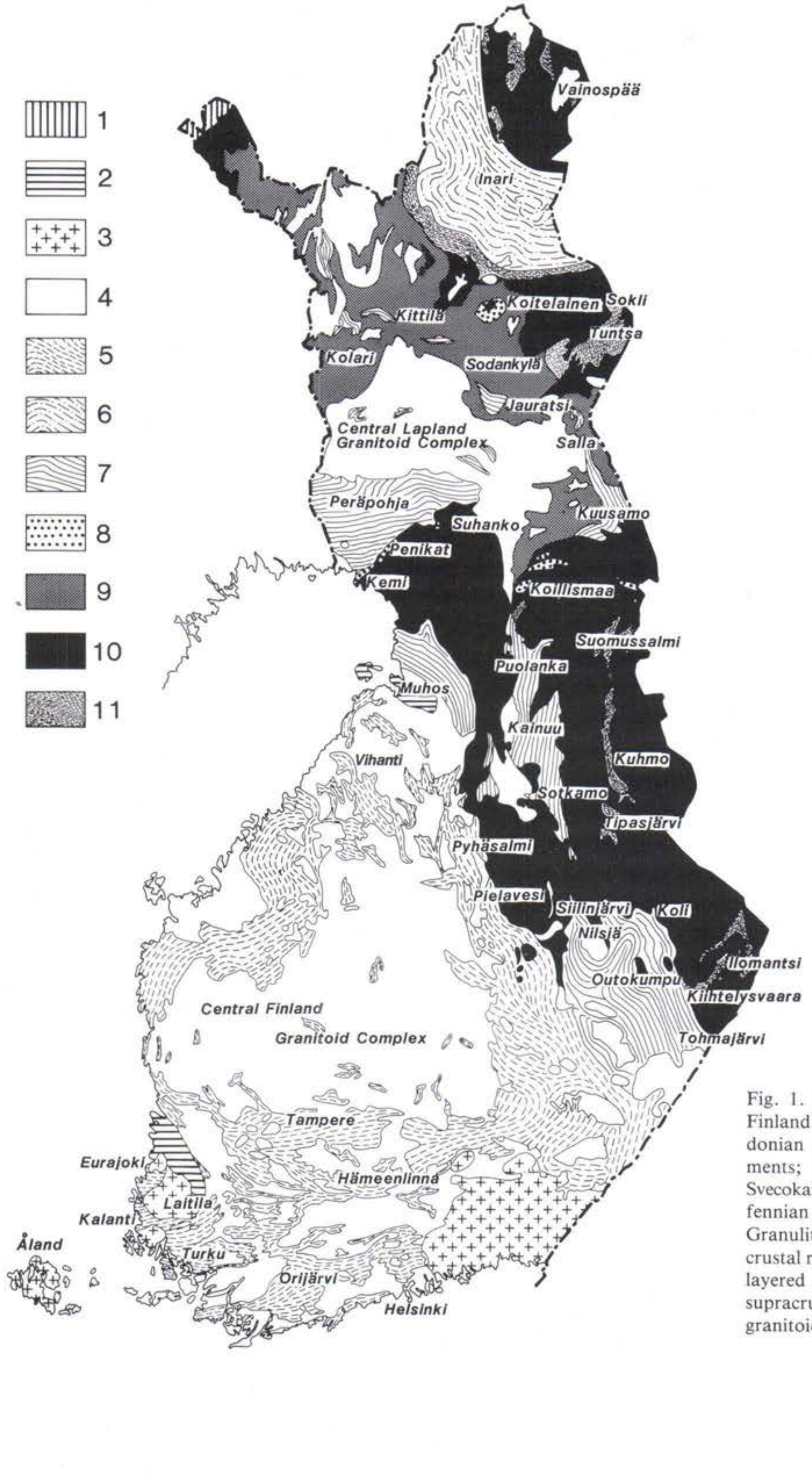

Fig. 1. Main structural units of Finland (Simonen 1980). 1. Caledonian rocks; 2. Jotnian sediments; 3. Rapakivi granites; 4. Svecokarelian granitoids; 5. Svecofennian supracrustal rocks; 6. Granulite belt; 7. Karelian supracrustal rocks; 8. Presvecokarelian layered intrusions; 9. Lapponian supracrustal rocks; 10. Archean granitoids; 11. Archean greenstone belts.

land the basement complex is called the Jatulian continent and in Soviet Karelia the Karelian massif, the name given by Soviet geologists.

Greenstone belts

Finnish geologists disagree about which of the greenstone belt associations are Archean in age and which are Early Proterozoic. In their survey of the evolution of the Archean crust in Finland, Gaál *et al.* (1978) regard the Ilomantsi (southeastern Finland), Suomussalmi-Kuhmo-Tipasjärvi (eastern Finland; here called for brevity the Kuhmo belt), Salla, Jauratsi, Kittilä and Inari greenstone belts and the Tuntsa-Savukoski formation (all in northern Finland) as Archean in age. The Kuhmo, Ilomantsi, Inari and Tuntsa-Savukoski belts are unanimously claimed to be Archean. The Inari, Kuhmo and Ilomantsi belts are correlated with the Lopian and the Tuntsa-Savukoski belt with the Belomorean in Soviet Karelia. The Archean age of the other greenstone belts is disputable (see e.g. Lauerma 1982). Silvennoinen *et al.* (1980) regard the Lapponian Kuusamo and Salla greenstone, and the Jauratsi and Kittilä greenstones as Archean.

Dated from the Paanajärvi formation in the USSR the greenstone formation of Kuusamo is 2450 Ma old (see Meriläinen and Sokolov 1981). The volcanics at Paanajärvi are included in the Sumi-Sariola. Similar controversy exists over the Salla greenstone formation, to the north of the Kuusamo belt. Silvennoinen *et al.* (1980) maintain that these Lapponian formations are Archean in age, whereas some of the Soviet Karelian parts of the formation are included in the uppermost Suisaarian group (Kulikov *et al.* 1980), i.e. Proterozoic in age. The age of the Salla formation and the correlations across the Finnish-Soviet border have recently been discussed by Lauerma (1982).

The Kuhmo belt is one of the type areas of Archean greenstone belts in Finland and in recent years it has been the subject of thorough restudy. An abundance of new data has now been collected (references to the latest works can be found in Hanski 1980; Taipale and Tuokko 1981; Taipale 1982; Auvray *et al.* 1982).

The Kuhmo greenstone belt is a narrow zone trending north-south for about 200 km. It consits of mafic and ultramafic metavolcanics with minor amounts of felsic volcanic rocks and metasediments. Both true lava beds and pyroclastics have been identified among the metavolcanics. Amygdaloid and porphyritic textures are frequently met with as an agglomeratic and pillow lava structures.

One of the thoroughly investigated type localities of the Kuhmo greenstone belt is the Siivikkovaara area in the middle of the belt (Hanski 1980). Komatiitic metavolcanics underlain by tholeiites (often pillowed and massive metalavas, low-potossium tholeiites) and intercalated banded iron-formations abound. The overlying peridotitic komatiites have structures typical of extrusive rocks: breccias, pillows, polygonal jointing and spinifex textures. These in turn are overlain by basaltic and pyroxenitic komatiites (variolitic pillow lavas), and these again by ultramafic to mafic metatuffs. A deep-sea origin is postulated for the lavas.

The metavolcanics of the Kuhmo belt are overlain by a discontinuous metasedimentary suite composed of biotite schists, black schists, meta-arkoses and conglomerate intercalations.

Only a few ore occurrence are known in the Kuhmo greenstone belt. The Ni-Cu deposits of Suomussalmi (Kojonen 1981) are associated with tholeiitic ultramafic-mafic rocks and sulphide-bearing metasediments. Low-grade Ag-Zn-Pb mineralizations have been encountered in felsic metavolcanics in the northern part of the Suomussalmi area and in Tipasjärvi.

The Kuhmo belt is surrounded by acid and intermediate granitoids. According to Taipale and Tuokko (1981), nowhere has an intermediate granitoid rock been found that can be interpreted indisputably as the basement of the belt. Granites of the other hand intersect the schists in many places.

The formations of the Lapponian stratigraphic groups in central Lapland (Kittilä, Jauratsi, Tuntsa-Savukoski and Salla) consist largely of »greenstone belt-type» volcanics, both mafic and less frequently felsic varieties, and in smaller amounts sericite quartzites and mica-rich schists (Silvennoinen *et al.* 1980). According to Silvennoinen *et al.*, the Lapponian formations, which underlie the formations of the peneplane stage of the Svecokarelian orogeny, are Archean in age. Volcanic textures and structures, similar to those in the Kuhmo belts, have been described from these greenstone belts. Komatiitic compositions of ultramafic and mafic metavolcanics have also been reported from the Sattanen area (Tyrväinen 1983).

The Kittilä greenstone area, a key area for the stratigraphy of Lapponian formations has recently been restudied (Rastas 1980). According to Rastas the stratigraphy of the area, from the lowest unit to the highest, is: the Kaukonen amygdaloid composed of basaltic lavas and intermediate to acid volcanics (Lower Lapponi); sericite quartzite and mica schist (Upper Lapponi) related to the sillimanite quartzite-mica schist zone in western Lapland; the volcanis of the Kittilä greenstone complex with acid volcanics, mafic volcanics, ultramafic komatiitic metalavas intercalated with cherts, iron-formations, tuffs and tuffites; and, uppermost in the complex black schists, mica schists, greywackes and numbers of carbonate rock horizons (Upper Lapponi). The greenstone complex is overlain, here discordantly there concordantly, by the sedimentary rocks of the Kumpu formation, regarded by Rastas as Middle Jatulian. As pointed out by Rastas (op.cit.), the sediments of the Kumpu formation have long been considered the youngest units of the Svecokarelidic orogeny, i.e. molasse sediments. However, as Rastas points out, the occurrence of albite diabases aged 2000 to 2200 Ma cutting Kumpu-type quartzites elsewhere in Lapland excludes the possibility of these quartzites being molasse sediments. The Kumpu formation, composed of polymictic conglomerate, with clasts embedded in a tuff matrix, carbonate rock, orthoquartzite, conglomerate interlayers and argillaceous layers, is overlain by rocks that Rastas regards as Kalevian (1885 Ma old), a felsic volcanic rock conglomerate and iron ore showings.

In addition to the iron ores of the Kolari district currently being mined by Rautaruukki Oy (Hiltunen 1982), the Lapponian formations contain several sub-economic occurrences of Cu and Zn and manganiferous iron-formation (Pakkola 1971). The Pahtavuoma deposit in Kittilä is the most promising of the Cu-Zn-Co-Ag sulphide occurrences discovered in the volcanic complex. The sulphides occur as breccia, matrix or strata-bound dissemination in a phyllite host rock interlayered with mafic spilitic metavolcanics (Inkinen 1979). The uranium occurrence of Pahtavuoma, which lies in the greenstone complex not far from the stratigraphically overlying Kumpu formation (Inkinen 1979), is probably a deposit of the unconformity type.

The Ilomantsi greenstone belt constitutes four narrow synforms, 1—6 km wide, in granitoids in southeastern Finland (Gaál *et al.* 1978). Metavolcanics make up only from 1/4 to 1/3 of the schists. The western part of the belt was remapped by Nykänen (1971), and the eastern part by Lavikainen (see Lavikainen 1980). In the area of the Kiihtelysvaara map sheet (Nykänen op. cit.) the belt is composed of volcanogeneous amphibolites, banded hornblende schists, chlorite schists, serpentinites and banded iron-formations overlain by quartz-feldspar schists, mica schists, black schists and metasomatically altered rocks (e.g. Otravaara pyrite ore). According to Nykänen (op. cit.), the orthogneisses of the basement gneiss complex penetrate the schists. Nykänen points out that the depositional basement of the paragneiss belt has not been established. From Ilomantsi, Lavikainen (op. cit.) has described different stratigraphic profiles through the paragneiss belt, which here consists of mica schists, basic volcanics, banded iron formations, black schists, etc. Of great interest is the Vattumökki profile, which begins with a conglomerate containing pebbles of basement complex quartz diorite. Lavikainen (personal communication 1982) does not believe that the issue of the depositional basement can be settled until the genesis of this conglomerate, which might in fact be a tectonic one, has been studied.

Orthogneisses of the granite gneiss complex of eastern Finland

In the last decade studies on the orthogneisses in the granite gneiss complex of eastern Finland have been restricted to certain key areas. Most of the area was mapped during the first half of this century.

One of the key areas in the environment of the Ilomantsi greenstone belt, viz. the map sheet areas of Tohmajärvi (Nykänen 1968), Kiihtelysvaara (Nykänen 1971), Ilomantsi (Lavikainen 1973, 1977, 1980) and Oskajärvi (Lavikainen 1975). Nykänen (1971) divided the Archean orthogneisses into three groups. From oldest to youngest there are: 1) a coarse-grained, cataclastic, often banded, migmatitic, and partly mylonitic, grey gneissose granite that is quartz dioritic or granodioritic in composition. It grades into 2) a leucogranodiorite (oligoclase granite). Considerably younger than either 1) or 2) is 3), a reddish, mostly coarse-granied but in places distinctly porphyritic, and often cataclastic granite. The Kutsu granite in the Tohmajärvi and Kiihtelysvaara map sheets is a good example of this Archean granite.

Metagabbro and metadiorite occur as inclusions in the orthogneisses; see Nykänen (1971) for paragneiss inclusions.

The division of basement gneisses in the Ilomantsi map sheet area (Lavikainen 1977) is similar to that by Nykänen. Lavikainen (op.cit.), however, tackles the problems of Archean granitoids and their division in greater detail.

Taipale and Tuokko (1981) and Taipale (1982) have divided the granitoids in the surroundings of the Kuhmo greenstone belt into trondhjemite-tonalite gneiss and (granodiorite-) granite series. The latter tend to be massive and porphyroblastic and to crosscut the rocks of the greenstone belt and the trondhjemite-tonalite series. In texture and structure, the orthogneisses bear a close resemblance to those in the surroundings of the Ilomantsi greenstone belt.

The younger granitic phase is locally characterized by Mo mineralization, the most promising occurrences being at Aittojärvi, Suomussalmi and Mätäsvaara, in Pielisjärvi. Most of the basement gneisses were metamorphosed under the conditions of epidotite-amphibolite facies, evidently during the Svecokarelidic orogeny. Basement gneiss areas metamorphosed under the conditions of granulite facies have been described recently. Paavola (1982), for example has described an orthopyroxene-bearing Archean granite gneiss block from the Nilsiä-Varpaisjärvi area.

Farther west, basement gneisses, both orthogneisses and paragneisses, occur in the Karelian schist belt as domes, a number of which are examples of the classical mantled gneiss domes of Eskola (1949). In many of the mantled gneiss domes the zircon ages are lower than those in the basement gneiss area, indicating rejuvenation of the rock during later metamorphic crystallization.

The granulite complex and associated formations

Meriläinen (1976) has divided the area north of the central Lapland greenstone complex into four subareas: 1) the granite gneiss complex; 2) the Apukasjärvi, Vätsäri and Kuorboaivi schist zones; 3) the granulite complex; and 4) the West Inari schist zone.

1) The rocks of the granite gneiss complex

were uplifted or metamorphosed about 2500 Ma ago. Ages as high as 2865 Ma (whole rock common lead method) or 2730 Ma (zircon method) have been recorded from the cores of certain blocks. The complex was remetamorphosed during the Karelian epoch, c. 1900 Ma ago. The Vainospää granite was emplaced during the postorogenic phase 1735 Ma ago, the Nattanen granite 1730 Ma ago.

The granite gneiss complex is composed mainly of granite gneisses, quartz diorites, granodiorites and granites with minor quartzfeldspar gneisses, mica gneisses, hornblende gneisses and amphibolites. Also encountered are ultramafic intrusions (Papunen *et al.* 1977; Papunen and Idman 1982) and diabase and pegmatite dykes cutting all the forementioned rocks (Meriläinen op.cit.).

2) The Apukasjärvi, Vätsäri and Kuorboaivi schist zones (Meriläinen op.cit) are synclines or synclinoriums between the dome-shaped anticlines or anticlinoriums of the granite gneiss complex. The dominant supracrustal rocks are amphibolites and hornblende gneisses, locally also quartzites and calc-silicate gneisses, quartz feldspar gneisses, mica gneisses and banded iron formations. Meriläinen regards these schist zones as Prekarelian and correlates them with the Kuhmo greenstone belt and the Ilomantsi schist complex. The Apukasjärvi and other schist zones include abundant ultramafic rocks (Meriläinen 1976; Papunen *et al.* 1977; Papunen and Idman 1982) as peridotites, serpentinites, anorthosites and hornblendites, but also gabbros, quartz diorites, granodiorites and granites.

3) According to Meriläinen (op.cit), the rocks of the granulite complex were granulitized or uplifted about 2150 Ma ago and remetamorphosed diaphthoretically c. 1900 Ma ago. The rocks of the complex derive mainly from various Prekarelian supracrustal and infracrustal rocks.

Meriläinen has divided the granulite complex into three parts: the granulite complex proper, the northeastern marginal zone and the southwestern marginal zone.

On the basis of the garnet gneisses, Meriläinen (op.cit.) has further divided the granulite complex proper into an eastern subarea with coarse-grained garnet-feldspar gneisses and garnet-cordierite gneisses and a western subarea with fine-grained garnet-quartz-feldspar gneisses, garnet biotite gneisses and garnet-biotite-plagioclase gneisses. In chemical composition the fine-grained granulites correspond to greywacke, subgreywacke and average shales, and the coarse-grained granulites to mica schists and kinzigites.

The bulk of the granulite complex proper was metamorphosed under the conditions of granulite facies, at either low or medium pressure, whereas the rocks of the marginal zone were metamorphosed under the conditions of amphibolite facies.

The granulite complex also contains some pyroxene gneisses derived from amphibolites, hornblende gneisses and mafic sills. Infracrustal rocks such as gabbros, quartz diorites, ultramafic rocks and garnet-bearing porphyritic granite are also met with.

According to Meriläinen (op.cit.), these rocks are cut by coarse-grained anatectic dykes formed during diaphthoretic granulitization.

According to the interpretation by Väyrynen (1952, p. 227), the granulite complex was thrust from the northeast over the formations lying to the south and southeast.

In one of the latest studies on granulites, Barbey (1982) maintains that the rocks of the granulite belt are metaturbidites that deposited originally on the oceanic crust in an intracratonic geosyncline. Deformation and metamorphism took plase in four phases, the second phase being characterized by an overthrust under moderate pressure and PT conditions of granulite facies. Barbey also interprets the granulite belt as a collision structure of two continental blocks.

The petrology, geochemistry, metamorphism and mineral chemistry of the granulite complex have been tackled in detail by Hörmann *et al.* (1980).

4) Meriläinen (op.cit.) divides the West Inari schist zone into three subzones: arkose gneisses; the Peltotunturi quartzites, greenschists and greenstones; and the intervening wide amphibolite zone. He dates the rocks, metamorphosed 2500 Ma ago, as Prekarelian. The infracrustal rocks of the West Inari schist zone comprise ultramafic rocks, gabbros, diorites and granites. The ultramafic rocks include extrusives of pyroxenitic composition and dunitic and peridotitic intrusives of the komatiitic rock suite. Sulphidic and calcareous metasediments interlayered with metavolcanics locally host low-grade base metal occurrences. The belt continues in Norway as the Karasjokk greenstone belt (Wennervirta 1969) and includes numerous ocurrences of banded iron-formations. The ultramafic rocks in the environment of sulphidic metasediments have recently been studied as potential host rocks for nickel deposits (Papunen *et al.* 1979).

Other Presvecokarelian formations

The high-grade metamorphic Tuntsa-Savukoski gneiss complex in northeastern Finland is regarded as the westernmost extension of the Belomorean orogenic belt. The main rock types of the complex are plagioclase-biotite gneisses, that are often rich in garnet, staurolite, kyanite and cordierite. Volcanogeneous amphibolite, glassy quartzite, and ultramafic rocks are also met with. The granite gneisses (basement gneisses) penetrate the gneisses of the complex and often form interlayers. Remapping of the complex is underway.

Svecokarelian formations

Karelian area

Layered mafic intrusions (cratonic, possibly contemporaneous with Sariolian formations)

The cratonized Presvecokarelian basement in northern Finland was intruded by tholeiitic magmas during the peneplane phase of the Svecokarelidic orogeny 2440 Ma ago.

Large layered mafic intrusions, e.g. those of Kemi, Penikat and Suhanko (Piirainen *et al.* 1974), Koillismaa (Piirainen *et al.* 1977) and Koitilainen (Mutanen 1980, 1981) were built up between the basement complex and the Proterozoic cover, and within the basement complex. All these intrusions are characterized by cryptic and rhythmic layering, and often by igneous laminations, too.

All the layered complexes mentioned are important for the associated ore deposits. Thin chromite horizons exist in basal parts of the Penikat, Kemi and Tornio intrusions (Söderholm and Inkinen 1982), and two stratigraphically different horizons of the Koitilainen intrusion contain chromite and locally PGE (Mutanen 1980, 1981). The thick accumulation of chromite ore in the basal ultramafics of the Kemi intrusion is of major economic importance (Kujanpää 1980). Sulphide disseminations are encountered close to the basal contact zone of the Koillismaa layered intrusions and in some places higher up in the sequence as well. In addition to Cu and Ni the sulphides contain appreciable PGE. The PGM occurrence of Konttijärvi has recently been studied by Vuorelainen *et al.* (1982). The ferrogabbro horizon in the upper part of the Porttivaara instrusion has been exploited as a vanadium ore (Juopperi 1977).

Sariola (cratonic graben or half graben)

Karelian formations in Finland begin with the lower portion of the Proterozoic that deposited before or about 2450—2300 Ma ago. They correspond to the Sumian-Sariolian rocks in Soviet Karelia.

Formations in Finland that are correlated with the Sariola in Soviet Karelia are numerous but small in area. Meriläinen (1980a and b) has described a complete Sariolian tripartite group from the Jaurakkajärvi area, in the northern part of the Puolanka schist belt, where a volcanic formation c. 1200 m thick (Middle Sariolian according to Meriläinen) occurs between two conglomerate-arkosite formations about 100—200 m thick. Other Sariolian occurrences have been described from the eastern margin of the Puolanka schist belt (Laajoki 1973, 1980) and from the Kemi schist belt. This group evidently includes certain formations in central Lapland and in the Kuusamo schist belt, and the sathrolithic basement breccias described by Havola (1980) from Sotkamo, by Perttunen (1980) from the Kemi-Rovaniemi (Peräpohja) schist zone, and by Pekkarinen (1979) from Kiihtelysvaara, eastern Finland. According to Pekkarinen (op.cit.), the arkosite formation is separated from the underlying breccia conglomerate formation of the Prekarelian basement by an angular uncornformity. In his opinion, the rocks of the arkosite formation are lithologically very similar to the conglomerates and associated arkoses east of Lake Seletskoje in Soviet Karelia which are included in the Sariolian formation. The formations around the mantled gneiss domes are also correlated with the Sariolian formations (Gaál *et al.* 1975). Pekkarinen considers that the Prejatulian early sedimentary sequense in the Kiihtelysvaara area, which deposited uncorformably on the basement gneiss complex, was of cratonic graben or half-graben type. This stage was followed by the deposition of cratonic shallow water and partly marine sediments, i.g. by the Jatuli.

The Sariolian quartzites host sub-economic uranium occurrences in the Koli-Kaltimo area, North Karelia. The stratabound weak dissemination of uranium oxides was locally upgraded by the action of intruding diabase dykes as at Paukkajanvaara, where a deposit was mined in the early 1960s. The mineralization bears characteristics of uranium deposits of the unconformity type (Piirainen 1968).

Jatuli (cratonic shallow water marine)

The Jatulian sediments deposited on the margins of the continental blocks during the peneplane orogenic stage. They are separated from the underlying Sariolian or Archean rocks by the weathering crust. The boundary between the Sariolian and Jatulian group has been dated by Meriläinen (1980a) at c. 2300 Ma. The Jatulian group is often divided into three subroups mainly on the basis of the transgression and regression phases of the sedimentation. Meriläinen (op.cit.) states that these phases can be traced from region to region, even though the classification — Lower, Middle and Upper Jatuli — does not apply throughout. Conglomerate, sericite quartzite, orthoquartzite and quartzite, separated by volcanic phases, predominate in the Lower and Middle Jatulian sediments, whereas quartzites, mafic volcanics, black schists, phyllites and iron-formations indicating shallow marine environments the Upper Jatuli (Marine Jatuli of Väyrynen, 1954). About 2000—2200 Ma ago the Jatulian sediments were intruded two or three times by (albite) diabase dykes and sills (Pekkarinen 1979).

Jatulian formations are well developed in southeastern Finland e.g. in the Tohmajärvi, Kiihtelysvaara, Koli areas, (Pekkarinen 1979), in the Kainuan schist belt (Laajoki 1973; Havola 1980), the North Pohjanmaa schist belt (only Upper Jatuli, according to Honkamo 1980), the Peräpohja schist belt (Perttunen 1980), the Kuusamo schist belt (e.g. Rukatunturi quartzite, Silvennoinen *et al.* 1980) and the Kittilä area (Rastas 1980). The Pyhätunturi quartzite and the Kumputunturi quartzite conglomerate formation in central Lapland and the extensive quartzite formations in western Lapland are also included in the Jatulian groups (Silvennoinen *et al.* 1980).

Kaleva (miogeosynclinal flysch)

The Kalevian sediments, i.e. sediments of the miogeosynclinal flysch type in the Karelian schist belt, are typically represented by the phyllites, mica shcists and mica gneisses of North Karelia. According to Pekkarinen (1979), this stage probably began in southeastern Finland about 2000 Ma ago. The sediments, originally sandy clays, were deposited by the action of turbulent currents. Hence, turbidite structures are common.

A continuous conglomerate bed denotes an unconformity that is often met with between the Kalevian and Jatulian formations. The conglomerate contains pebbles from various Jatulian rocks (see e.g. Pekkarinen 1979) and is overlain in southeastern Finland by a turbidite conglomerate-quartzite formation, which in turn grades upwards into mica schist (the Mica Schist Formation of Pekkarinen 1979). Westwards the rock association changes. Meriläinen (1980a and b) maintains that the oldest phyllites and mica schists in the Svecofennian region are probably of the same age as the oldest Jatulian sediments, and that the overlying volcanites are contemporaneous with the synorogenic granitoids penetrating the Karelian schists. The Karelian group in the Kainuan schist belt, which is part of the Karelian schist belt, has recently been studied by Havola (1980) in Sotkamo and by Laajoki (1973, 1980) in Puolanka. The northern Pohjanmaa schist area, studied by Honkamo (1980), is unusual in that it lacks the continental and epicontinental supracrustal rocks typical of Jatulian areas. Kalevian greywacke formations deposited directly (?) on the weathering crust of the basement gneiss complex. The lower greywacke formation, 2 to 3 km thick, is characterized by turbidite-structured greywackes. These are overlain by a complex formation of volcanites and chemical sediments overlain by another greywacke formation, mainly turbidite in structure. A black schist horizon and arkose and conglomerate deposits occur locally.

In the Peräpohja schist area the Kaleva is represented by the large Martimo Phyllite Formation over 2000 m thick. According to Perttunen (1980) the rocks are typical turbidites in structure. Black schists and oligomictic conglomerate occur as interlayers.

Apart from these, northern Finland lacks rocks typical of the Kaleva (cf. the acid volcanics and associated rocks overlying the Kittilä greenstone complex, which Rastas (1980) regards as Kaleva).

The Kalevian metasediments host the Cu deposit of Hammaslahti in North Karelia. According to Hyvärinen *et al.* (1977), the sulphides were deposited together with the sediments as a weak dissemination but were later upgraded by hydrothermal fluids during deformation and metamorphism.

The belt of serpentines and related carbonate rocks, skarns, cherty quartzites and black schists called collectively the »Outokumpu complex» from a sinuous band winding between the Kalevian metasediments. It hosts several massive Cu-Co-Zn deposits, e.g. at Outokumpu, Vunos and Luikonlahti (Peltola 1978) and low-grade nickel occurrences. The belt has been interpreted as the Precambrian counterpart of an ophiolite complex which was overthrust into its present position during Svecokarelidic deformation (Koistinen 1981). The belt probably continues in the Sotkamo schist belt, where a low-grade Cu-Zn-Ni deposit exists in the black schists of Talvivaara (Ervamaa 1980; K. Mäkelä 1981). Differences in host rock and type of mineralization are mainly due to variation in sedimentary environments during rifting and ore deposition: deep ocean floor in the Outokumpu belt, a more shallow basin and a continental environment in Sotkamo.

Svecofennian area

Svecofennian formations cover western and southern Finland. Simonen (1980) tentatively assumed that Svecofennian sedimentation took place about 2400—1900 Ma ago, for the most part immediately before the climax of orogenic movements accompanied by the emplacement of synorogenic granitoids about 1900 Ma ago. Geosynclinal volcanism took place 1920—1880 Ma ago, i.e. later than Jatulian volcanism (2200 —2000 Ma ago).

The Svecofennian formations consist of micaceous shists (slates, mica schists, mica gneisses) that were originally greywackes; quartz feldspar schists that were originally impure arkoses and acid pyroclastic rocks; and some metabasalts and amphibolites, the bulk of which were originally mafic lavas and pyroclasts. Quartzites and limestones are sparse in the Svecofennian area.

Most of the primary textures and structures have been wiped out. Graded bedding, for example, is rare in the greywacke slates, and fluidal, amygdaloidal, perlite, pillow lava, blastoporphyritic, agglomerate and volcanic conglomerate fabrics, are seldom met with in the largely basaltic and andesitic metavolcanics.

It has been possible to establish the stratigraphic sequence for some key areas only. The Svecofennian of southwestern Finland is tentatively divided by Simonen (1960a, 1980) into three subroups: Lower, Middle and Upper Svecofennian. The Lower Svecofennian comprises felsic volcanics and immature sediments (arkoses and greywackes) with interbeds of calcareous material and mature sandstones in the arkoses of some areas. The Middle Svecofennian contains mafic volcanics, both lavas and pyroclastics, with intercalated arkoses, greywackes and conglomerates. The Upper Svecofennian is composed mainly of argillaceous sediments.

The Lower and Middle Svecofennian groups occur chiefly in the classical Tampere schist zone (see e.g. Simonen and Kouvo 1951), and in the Orijärvi area (Latvalahti 1979).

The areas covered by Svecofennian volcanics, especially in the Vihanti-Pyhäsalmi-Pielavesi district in central Finland and in the Orijärvi district in the southwestern part of the country are favourable environments for stratiform hydrothermal base-metal sulphides. Although some of the deposits occur in metasediments (Huhtala 1979), the massive sulphides of the Vihanti-Pyhäsalmi district are commonly associated with felsic pyroclastics and their metasomatically altered counterparts. Lead isotope data suggest a mixed crustal-mantle origin for lead in this particular area and an age of c. 1900 Ma for both the sulphides and their host metavolcanics (Helovuori 1979). The Orijärvi leptite belt with related sulphide and oxide deposits seems to be a continuation of the leptite area of central Sweden. According to Latvalahti (1979), the felsic supracrustal rocks of Simonen's (1960a) Lower Svecofennian group in the surroundings of the base metal sulphide deposits are predominantly of volcanic origin. The lead of the Orijärvi sulphides is mainly of crustal origin (Helovuori 1979). The rocks, which are somewhat younger than the Vihanti-Pielavesi belt, yield ages of c. 1800 Ma.

Plutonic rocks

According to Simonen (1980), about 80 per cent of the Svecofennian area is occupied by plutonic rocks that are mainly quartzdioritic to granodioritic or granitic in composition. Ultramafic and mafic plutonic rocks play but a minor role in Svecofennian plutonism. About 40 per cent of the Karelian area comprises plutonic rocks, principally the granitic varieties (Simonen op.cit.). The Karelian belt, especially its Kalevian group, is characterized by ultramafics, that are often interpreted as ophiolites.

Simonen (1960b) has divided the plutonic rocks of the Svecofennian area into petrographical provinces, which he named according to the most acid end member as follows:

1. Granodiorite province, e.g. the Hämeenlinna-Loimaa area
2. Trondhjemite province, e.g. the Kalanti area in southwestern Finland (Hietanen 1943)
3. Charnockite province, e.g. West Uusimaa Complex (Parras 1958) and the Turku-

Naantali area (Hietanen 1947).

4. Granite province, i.e. plutonic rocks passing gradually from mafic members into granites: southern part of the central Finland batholith and central eastern Pohjanmaa.
5. Microcline granites, i.e. the migmatite-forming potassium-rich granites in southern Finland, which are attributed to anatexis and/or granitization (Härme 1965).

Special mention should be made of the noritic gabbros and associated rocks along the belt, that stretches from Lake Ladoga to the Bothnian Bay. Similar gabbros occur elsewhere around the composite granite massif of central Finland.

The composite granite massif of central Finland corresponds in age of the synorogenic and late-orogenic phases of Svecokarelidic orogeny. Some of the granitoids are certainly palingenetic in origin (cf. Lauerma 1982), whereas some of the magmas evidently derive from the upper mantle. The apparent equilibrium association of the minerals fayalite-eulite-quartz (-grunerite-ferrohastingsite) of certain »hypersthene granites» in this composite massif points of a very high stabilization pressure. In pressure these rocks are quite different from the surrounding supracrustal rocks, most of which were metamorphosed under the conditions of low-pressure facies.

It is tempting to interpret the weakly recrystallized and weakly migmatized greywacke shcists in the area encircling the central Finland granite batholith e.g. in the Tampere-Sysmä belt, south of Pieksämäki, in Vieremä and elsewhere as large-scale rim-syncline rocks.

The synorogenic plutonic rocks of Simonen's granodiorite, trondhjemite and charnockite provinces are characterized by marked gneissose texture, especially at the margins of the plutons. The massifs are often concordant with the enveloping rocks.

The late-orogenic, mostly migmatite-forming microcline granites are characterized by diapir structures, updoming, crossfolding, migmatization and metasomatic granitization (see Edelman 1949).

The monzonites and granodiorites of the Haaparanta series (c. 1900 Ma old according to Perttunen 1980) penetrating the Peräpohja schist belt and related rocks in western Lapland (e.g. quartz monzonite of the Kallo massif, 1885 Ma old according to Rastas 1980) evidently derived from the upper mantle.

In this context some words are called for on the origin of the late Svecokarelian granite complex of central Lapland. According to recent views (see discussion in Lauerma 1982), this complex in mainly composed of rocks produced by the melting of the Archean basement complex. Material of the Svecokarelian sedimentary pile was presumably also syntectically melted.

Encircling the central Finland granitoid area the mineralized mafic and ultramafic intrusive bodies occur mainly in strongly migmatized Svecofennian metasediments. They intruded during the early revolutionary stages of orogeny and now form clusters of intrusions that differ in certain respects from other clusters. Intrusions of this type will be discussed in more detail later.

The synorogenic granitoids at the margins of the central Finland granitoid batholith have low-grade occurrences of base and precious metals at some places, e.g. at Rautio, Haapajärvi, Viitasaari, Perho and Sääminki. According to Gaál and Isohanni (1979), they are porphyry-type copper and molybdenum deposits in origin. Close to its eastern margin the Hämeenkyrö tonalite stock has anomalously high tenors of Cu, S, As, Sn and Zn (Gaál *et al.* 1982). A tourmaline breccia pipe outside the tonalite stock proper, but genetically associated with the intrusion of tonalite, was mined for its Cu and W contents in the Ylöjärvi mine (Himmi *et al.* 1979).

The termination of the compressional phase of the Svecokarelidic orogeny is indicated by the emplacement of small stocks of granitoid rocks in various parts of Finland, e.g. in the southwestern archipelago, where they are represented by the Lemland, Mosshaga and Åva granites (1813 Ma old according to Vaasjoki 1977). The Åva ring intrusion composed of porphyritic granite, monzonite, fine-grained granite, lamprophyre, diabase and quartz porphyry dykes, has repeatedly been referred to as a classical example of these granites (Kaitaro 1953). In southeastern Finland the small Tetravaara trondhjemite stock in Tohmajärvi cutting the Kalevian mica schist, the Kitee granite (1820 Ma, Nykänen 1975) and the granodiorite stock at Luontarivesi (1820 Ma, Korsman and Lehijärvi 1973) cutting the Svecofennian mica gneiss in Anttola, SE Finland, are of the same age as those in the southwestern archipelago of Finland. The Petravaara, Kitee and Luontarivesi granitoids are regarded as late orogenic Karelian rocks.

In northern Finland the granites of the Nattanen type (1735 Ma according to Meriläinen 1976) and the Vainospää granite (1730 Ma, op.cit.) are related to the well-documented rapakivi-like granites in the Kola Peninsula. All these granite massifs are composite in structure, often with well-developed ring structure. The small granite stocks of Kittilä and nearby Tiuramatala also belong to this category of granites (1760 Ma, Rastas 1980).

There are several indications of disseminated Mo mineralization in the granites of the Nattanen type in Lapland.

Postorogenic granites

Rapakivi granites and related rocks were emplaced after the culmination of the Svecokarelidic orogeny, when the crust was denuded down to a depth of 10 to 15 kilometres (Vorma 1976) 1700—1540 Ma ago in thoroughly cratonized parts of the Svecofennian complexes at Viborg, Laitila, Vehmaa, Åland, Kökar, Obbnäs, Bodom, Suomenniemi, Mäntyharju, and elsewhere (Vaasjoki 1977). Rapakivis and postorogenic epizonal composite massifs associated with mafic rocks (e.g. anorthosite) on the one hand and porphyry dykes and volcanic equivalents, on the other. Contact breccias with the Svecofennian country rocks and chilled banded margins are often encountred. In a few places the rock shows well-developed alignment of potassium feldspar laths due to the flow of magma; otherwise flow textures are rare. Signs of the high temperature contact metamorphism can be detected in the roof pendants (Vorma 1975) and non-rapakivitic country rocks (Vorma 1972). Migmatization of the country rock by rapakivi is unknown. Gravity data suggest that the intrusions are elongate and shaped like mushrooms. The present erosion level is probably near the roofs of the massifs (Laurén 1970).

In chemistry the rapakivi granites are richer in K, F, Rb, Zr, Hf, REE, Th and U, and poorer in Ti, Al, Fe, Mn, Mg, Na, P, and Sr, than granites in general, and are thus characterized by low Mg/Fe and K/Rb ratios and a high Ca/Sr ratio (Vorma 1976).

It has been postulated that rapakivi magma was generated in the lower crust either during the Svecokarelidic orogeny or after it as an anorogenic granite.

In Eurajoki, western Finland, the youngest phase of the rapakivi intrusion is an even-grained topaz-bearing and protolithionite-bearing leucocratic microcline-albite granite that differs from normal rapakivi in its low TiO_2, FeO, MgO and K_2O/Na_2O and high F, Li, Ga, Rb, Sn and Nb. The stock contains cassiterite in pegmatite and greisen veins. Disseminated cassiterite is also encountered. Similar greisen and quartz veins with Be, Sn, W, Pb and Zn minerals have been found at Kymi in the Wiborg rapakivi area (Haapala 1977).

Diabase dyke swarms (cratonic)

The diabase and related dyke rocks, either crosscutting or as sills in the Archean and the Proterozoic complexes, have widely been used to determinate the minimum ages of the rocks they penetrate. They intruded either during the peneplane phase of the orogeny or during the graben, postogenic phase. In the former case the magma penetrated the Presvecokarelian Jatulian continent and in the latter case the cratonized and already well-eroded Svecokarelian orogenic crust as well.

Diabase dykes and sills that cut the Presvecokarelian basement and the Jatulian formations but not the Kalevian formations have been recorded from numerous localities in North Karelia (Pekkarinen 1979), the Kainuu schist belt (Havola 1980, Laajoki 1973), the Peräpohja schist belt (Perttunen 1980), the central Lapland schist belt (Rastas 1980; Silvennoinen *et al.* 1980), the Kuusamo schist belt (Silvennoinen *et al.* 1980) and the Salla greenstone complex (Lauerma 1982). The metadiabases that in many places cut the Presvecokarelian basement have also been correlated of this group of diabases (see e.g. Neuvonen *et al.* 1981 concerning the diabases in the Nilsiä-Varpaisjärvi area). The ages of these diabases vary from 2200 Ma to 1950 Ma. According to Pekkarinen (1979), the diabases in the Kiihtelysvaara-Värtsilä area intruded at two or three stages about 2000—2100 Ma ago.

The Kalevian schists around Tuusniemi-Kaavi-Nilsiä were cut 1830—1860 Ma ago by a set of microtonalite dykes (Huhma 1981; Neuvonen *et al.* 1981). About 1830—1840 Ma ago lamprophyre dykes intruded the same areas; at Niinivaara in Kaavi (Huhma 1981), and in the Haukivesi area (Neuvonen *et al.* 1981). These indicate that cratonization of the crust was already far advanced at this stage and that the climax of orogeny being part, the crust was deeply eroded.

The Subjotnian diabases, which were evidently some kind of fore-runners to rapakivi granites, were emplaced about 1700 Ma ago. The Subjotnian diabases are represented by the well-documented Häme diabase dykes (Laitakari 1969) and by the trapp diabases in the southwestern archipelago of Finland (C. and M. Ehlers 1977).

Postjotnian diabases were emplaced 1200—1300 Ma ago. Good examples of these rocks are the olivine diabases of Satakunta in southwestern Finland, the olivine diabases of Åland, especially those of Märket (Bergman 1981), the diabases in the Vaasa archipelago in western Finland and the »Tuutijärvi» diabase dyke cutting the Salla greenstone complex and the surrounding rock (1200 Ma old according to Silvennoinen *et al.* 1980). This group of diabases may already belong to the peneplane phase magmatism of the Dalslandian orogeny.

Carbonatite and alkaline rock complexes (cratonic)

Excluding diabases, which are regarded as extrusion channels for flood basalts, layered mafic complexes and rapakivi granites with associated rocks, magmatic rocks typical of the peneplane or graben phase of the orogeny are rare in Finland and include only a few carbonatite and alkaline rock occurrences.

The Siilinjärvi alkaline-carbonatite complex in eastern Finland is a tabular, subvertical body about 16 km long and up to 1.5 km wide that intrudes the surrounding Presvecokarelian granite gneiss (Puustinen 1971). It is composed of syenite, glimmerite and carbonatite, and has poorly developed fenitic margins. Puustinen (op.cit.) dates the comples at c. 2500 Ma on the basis of few K-Ar ages. Mention should be made that the complex is cut by a set of SE-NW-trending metadiabases correlated to the Jatulian diabases.

Two small occurrences of carbonatite have been reported from the Kuusamo schist belt; Kortesjärvi in Pudasjärvi (Vartiainen 1980b) and Laivajoki in Posio (Vartiainen and Woolley 1974, Vartiainen 1980b). In both places the carbonatite bodies are in mafic volcanics; Upper Archean (Lower Lapponian) according to Silvennoinen *et al.* (1980) and Proterozoic, according to Alapieti (1982). A radiometric age of 2020 Ma has been given to the Laivajoki dolomitic carbonatite (Vartiainen and Woolley 1974).

The extensive Kola Peninsula carbonatite-alkaline igneous province extends from the USSR into Finland. The Iivaara alkaline rock massive (Lehijärvi 1960) in Kuusamo, eastern Finland, was emplaced in the basement gneiss complex of Karelides c. 430 Ma ago (Doig 1970), producing a pronounced fenite aureole. The large Sokli carbonatite complex in Savukoski, northern Finland, was formed about 360 Ma ago, i.e. during the Upper Devonian (Vartiainen and Woolley 1974, 1976; Vartiainen 1980a). According to Vartiainen and Woolley (1976) the carbonatite is an ovalshaped, downward tapering plug covering some 20 km^2 and surrounded by an extensive fenite envelope. The country rocks comprise granitoids and gneisses of the basement complex. According to Vartiainen (1980a), the carbonatite massif can be divided into three parts: a transitional zone of metasomatites, a metacarbonatite area and a magmatic core. Evolution started with the production of magnetite olivinite and pyroxenite by an ultramafic intrusion. The ultramafites were slightly altered during a quiet episode that was followed by intense alkali metasomatism. Carbonatization produced metasomatic carbonatites. The multistage carbonatite intrusion completed the evolution of the complex.

Unmetamorphosed sedimentary cover and phanerozoic record

In a few scattered localities the Svecokarelian orogenic rocks and the postorogenic granitic rocks are overlain by both Middle and Late Precambrian and Phanerozoic unmetamorphosed sedimentary rocks.

Paleozoic sedimentary rocks are known to cover extensive areas on the bottom of the Bothnian Sea. The latest summary of the subject (Flodén and Winterhalter 1981) describes the distribution of Jotnian sandstone and the overlying Cambrian and Ordovician formations on the sea bottom. The downfaulted block of Satakunta, southwestern Finland, filled with Jotnian sandstone is a direct continuation of the above unmetamorphosed sedimentary rocks. The sandstone formation of Satakunta (see Simonen and Kouvo 1955) consists of stratified, arkosic red sandstone with interbeds of red and black shales. Current bedding, ripple marks and mud cracks indicate terrestrial conditions of deposition (piedmont facies). The downfaulting, indicated by drilling, extends for at least 650 m. The formation is cut by Postjotnian diabases, 1200—1300 Ma old.

The Muhos siltstone formation near Oulu likewise occurs in a downfaulted block. Drilling shows that the downfaulting extends for about one kilometre. The formation is regarded as Jotnian in age. Tynni and Donner (1980), however, have described microfossils that they regard as Vendian in age, i.e. younger than Jotnian, from Hailuoto in the western part of the formation.

Paleozoic sedimentary rocks in Finland have recently been discussed in more detail by Lehtovaara (1982). The largest formation, in which the rocks belong to the Caledonides, is in the Kilpisjärvi region, in the northwestern corner of Finland.

The Söderfjärden formation near Vaasa (Lehtovaara op.cit.) is interpreted as a crater depression with 240 m of preserved fill of Lower Cambrian claystone and sandstone. The Cambrian Lauhavuori sandstone in southwestern Finland is a minor Paleozoic occurrence (see Lehtovaara op.cit.). The Ordovician limestone of Lumparn, Åland, has been the target of enthusiastic study in recent years (see Bergman *et al.* 1982; Lehtovaara op.cit.). The Lumparn Bay occupies a depression within the Åland rapakivi massif, and Proterozoic and Lower Paleozoic sediments have been protected from denudation in a downfaulted block.

The occurrence in southwestern Finland of clastic dykes and sandstone fissure fillings in Proterozoic rocks in both the Svecofennian orogenic complex and the postorogenic rapakivi granites, suggests that at the onset of the Phanerozoic eon the erosion level of Proterozoic formations was near the present one. Microfossil studies indicate that the clastic dykes in the Åland rapakivi are Lower Cambrian and Lower Ordovician in age (Bergman *et al.* 1982). Some 300 clastic dykes are currently known in the Åland area.

According to Bergman *et al.* (op.cit.) about twenty or thirty clastic dykes have also been observed in and near the coastal area of southwestern Finland.

The impact crater of Lappajärvi (Lehtinen 1976) and the tentative impact crater of Sääksjärvi (Mutanen 1979), both in southwestern Finland, are signposts to the Phanerozoic eon in the evolution of the bedrock in Finland. Reimond and Stöffler (1979) report an $^{40}Ar/^{39}Ar$ age of 77 Ma for the Lappajärvi crater.

CLASSIFICATION OF NICKEL DEPOSITS IN FINLAND

On the basis of the age of the mafic or ultramafic host intrusion, Papunen *et al.* (1979) have proposed a tentative division of the nickel deposits into four age groups: 1) Archean (over 2.8 Ga), 2) Prekarelian layered complexes (2.45 Ga), 3) Karelian ultramafics 2.1 Ga(?) and 4) Svecokarelian ultramafic and mafic intrusions (1.9—1.86 Ga). The last group is by far the most impotant economically and all the mined deposits are included in this group. Figure 2 depicts the type localities of the various Ni-Cu deposits, and the most important occurrences are listed in Table 3.

Only a few Ni-Cu deposits have been discovered in the *Archean greenstone belts* of Finland. Arola, Hietaharju and Peura-aho are located in the Kuhmo-Suomussalmi greenstone belt, and the metaperidotite-hosted Tainionvaara occurrence (Pekkarinen 1981) seems to be a remnant of greenstone in an Archean granitoid area. The deposits of Suomussalmi (Kojonen 1981) and Arola are associated with sulphide-bearing metasediments and felsic volcanics in contact with an ultramafic intrusive body.

The greenstone belts characterised by metavolcanics and metasediments in Lapland — in western Inari, northern Kittilä and Sarvisoaivi, eastern Enontekiö — include intrusive metadunites that locally host disseminated sulphides with a high content of nickel. The sulphide-rich metasediments and cherty horizons of the belts are poor in nickel. Exploration of the occurrence is in progress. The sulphides of the intrusive metadunites display very low values (0.02 to 0.05) of the Cu/(Cu + Ni) ratio.

The *layered mafic complexes* of Koillismaa contain locally a weak sulphide dissemination in the basal marginal rocks. The sulphides com-

Table 3. Nickel d…

No in map	Name and type of deposit	Age group	M… Ni
110	Suhanko; disseminated sulphides in layered intrusion	2.45 Ga	[illegible]
111	Vaaralampi; massive Fe sulphides at the basal part of layered intrusion	2.45 Ga	1
112	Kuusijärvi; dissemination Cu-Ni sulphides and PGE in layered intrusion	2.45 Ga	4
113	Porttivaara; disseminated Cu-Ni sulphides in layered intrusion	2.45 Ga	7
114	Peura-aho; massive and disseminated sulphides associated with ultramafics and graphite schist	Archaean ?	
115	Hietaharju; lenses of disseminated sulphides in ultramafic rocks and graphite schists	Archaean ?	[illegible]
117	Talvivaara; Fe-Ni-Cu-Zn sulphide impregnation in black schist	Karelian (c. 2.1 Ga?)	78
118	Tainionvaara; mineralized ultramafic lens	Archaean	[illegible]
120	Vuonos; Fe-Ni sulphide impregnation in cherty quartzite and calc-silicate rocks	Karelian (c. 2.1 Ga?)	2
123	Kusiaiskallio; mafic-ultramafic pipe with disseminated sulphides	Svecokarelian	[illegible]
125	Makola; subvertical ultramafic pipe with massive and mainly disseminated sulphides	Svecokarelian	[illegible]
127	Pitkäneva; ultramafic body (pipe)	Svecokarelian	[illegible]
128	Hitura; ultramafic stock, massive and mainly disseminated sulphides	Svecokarelian > 1877 M.a.	17
133	Ilmolahti; gabbro-peridotite dyke	Svecokarelian	
137	Talluskanava; metaperidotite lens with sulphide dissemination	Svecokarelian	
138	Kotalahti; ultramafic-mafic intrusive complex, breccia, massive and disseminated sulphides	Svecokarelian 1883 M.a.	10
140	Sarkalahti; mainly ultramafic lens	Svecokarelian	[illegible]
151	Tienasoja; ultramafic small dyke	Svecokarelian	
152	Härmäniemi; gabbroic lens with sulphide stringers	Svecokarelian	
153	Niemilahti; mafic body with breccia sulphides	Svecokarelian	
154	Kurikkasaari; mafic lens	Svecokarelian	
156	Laukunkangas; ultramafic-mafic intrusive complex, massive, breccia and disseminated sulphides	Svecokarelian	4
158	Makkola; lens of metapyroxenite, gabbro and norite with breccia and disseminated sulphides	Svecokarelian	
159	Hälvälä; subvertical pipe, maily gabbroic in composition	Svecokarelian	
162	Ruimu; mafic to ultramafic lens in a wide gabbroic complex	Svecokarelian	1
163	Revonmäki; ultramafic lens in gabbroic complex	Svecokarelian	[illegible]
164	Kitula; gabbroic lens with breccia sulphides	Svecokarelian	
166	Telkkälä; ultramafic-mafic lens with breccia sulphides	Svecokarelian 1820 M.a.	[illegible]
169	Kylmäkoski; ultramafic lens with breccia and disseminated sulphides	Svecokarelian 1856 M.a.	[illegible]
170	Kovero-oja; ultramafic subvertical pipe with disseminated sulphides	Svecokarelian	[illegible]
171	Vammala (Stormi); layered subhorizontal metaperidotite-hornblendite intrusion	Svecokarelian 1890 M.a.	8
174	Hyvelä; ultramafic lens with breccia and disseminated sulphides	Svecokarelian	[illegible]
178	Petolahti; mafic (diabase) dyke, disseminated sulphides	Subjotnian?	
180	Oravainen; subvertical ultramafic pipe, mainly disseminated sulphides	Svecokarelian	1

monly display high values of the (Cu/(Cu + Ni) ratio (0.62 to 0.65), but the Cu and Ni values are too low to make the exploitation of the deposits economically viable. Locally the sulphide dissemination also exists higher up in the sequence of layered gabbros. The sulphide-bearing horizons have recently been explored with promising results for platinum-group elements land.

ns	Grade				Cu	Co	Pt	% Ni_S
per	% Ni	% Cu	% Co	% S	Ni + Cu	Ni + Co	Pt + Pd	
100	0.27	0.31			0.63			
000	0.31	0.20		11.20	0.39			0.96
000	0.09	0.15		0.27	0.62		0.26	12.17
000	0.11	0.20		0.3	0.65			13.38
520	0.58	0.24	0.04	7.4	0.29	0.06	0.26	2.98
075	0.86	0.43	0.05	8.5	0.32	0.05	0.28	3.84
000	0.26	0.14	0.02	8.54	0.35	0.07		1.14
120	0.5	0.03	0.01		0.06	0.02		
000	0.20	0.04	0.05	2.5	0.17	0.20		3.0
100	0.24	0.16	0.01	1.45	0.40	0.04		8.17
000	0.74	0.52	0.05	6.92	0.41	0.06		4.01
000	0.22	0.06	0.02	2.31	0.21	0.08		3.88
000	0.84	0.38	0.03	5.11	0.31	0.03	0.36	6.5
500	0.36	0.27	0.04	5.88	0.43	0.10		3.3
380	0.33	0.19	0.02	1.17	0.37	0.06		6.55
000	0.70	0.27	0.03	4.00	0.28	0.04		6.57
500	0.93	0.30		6.79	0.24			5.07
	0.90	0.32	0.03	6.13	0.26	0.03		5.43
	0.63	0.18	0.03	4.0	0.22	0.04		5.9
	1.06	0.30	0.04	7.74	0.22	0.04		5.0
	0.39	0.14	0.03	5.21	0.26	0.07		2.84
400	1.1	0.29	0.06	8.5	0.21	0.05		4.92
	0.31	0.13		5.76	0.30			1.97
	2.88	0.50	0.13	20.28	0.14	0.04		5.06
000	0.32	0.29	0.04	4.55	0.48	0.11		3.05
100	0.29	0.31	0.02	1.95	0.52	0.06		5.62
100	1.6	0.4	—	10.4	0.20			5.77
515	1.06	0.29	0.05		0.22	0.04		
400	0.55	0.48			0.47			
500	0.43	0.32			0.43			
000	0.60	0.41	0.04	3.62	0.41	0.06		6.35
250	0.52	0.26		5.65	0.34			3.45
500	0.65	0.70	0.02	3.27	0.52	0.03		7.45
080	1.2	0.21	0.05	8.21	0.14	0.04		5.5

(see Vuorelainen *et al.* 1982, Lahtinen, this issue).

The *ultramafic rocks of North Karelia* are associated with chrome-bearing calc-silicate rocks, cherty quartzites, carbonate rocks and black schists as an »Outokumpu-type rock complex», which is well known for the associated Cu-Zn-Co-pyrite deposits. In places the

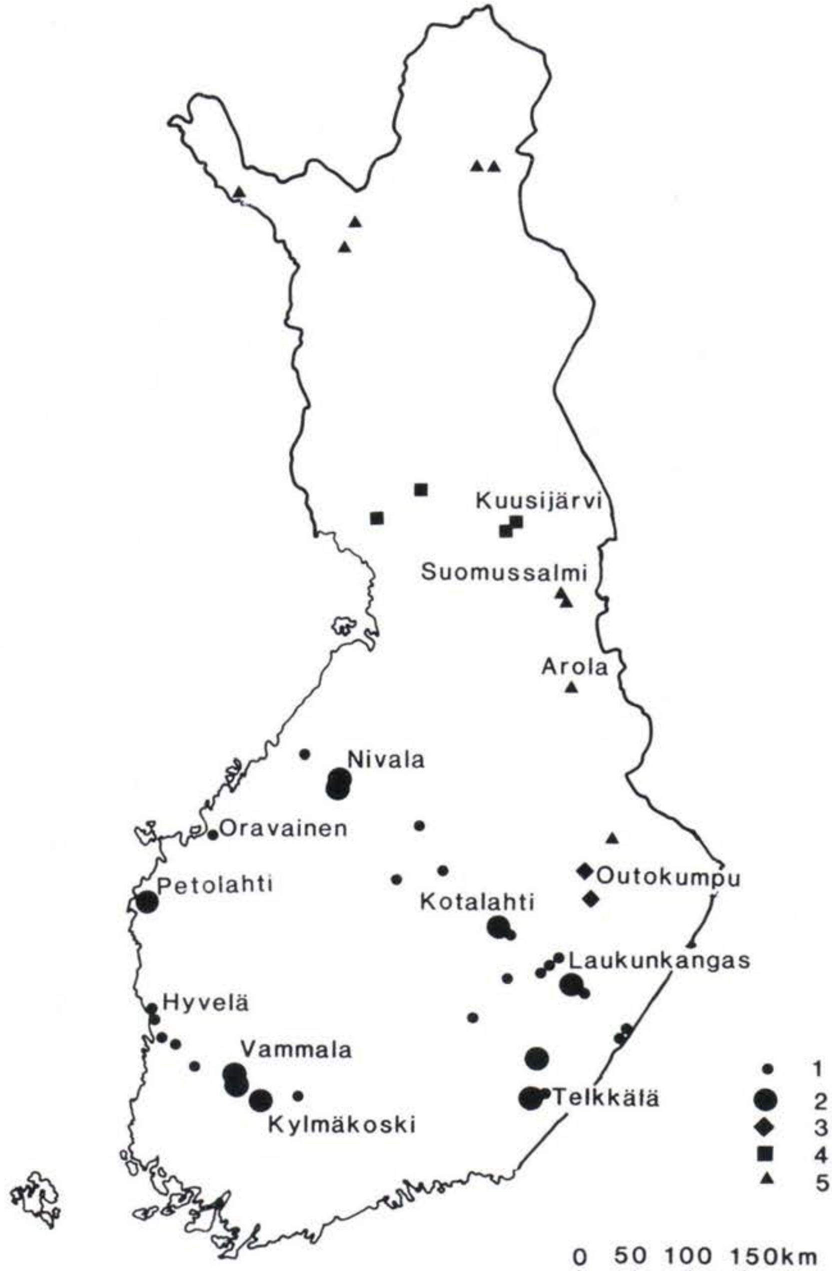

Fig. 2. Main types of nickel occurrences in Finland. 1. Svecokarelian Ni-Cu occurrence; 2. Svecokarelian Ni-Cu ore deposit; 3. Ni occurrence in the Karelian ultramafics; 4. Cu-Ni occurrence in layered intrusions; 5. Ni occurrence in Archean or undefined environment.

complex also hosts Ni-Fe sulphides (Kokka, Vuonos, Keretti), which are mined at Vuonos as a low-grade nickel ore. The disseminated sulphides exist in calc-silicate rocks and in quartzites enveloping the serpentinite bodies. The recent study by Koistinen (1981) reveals that the serpentinites and associated rocks are part of an ancient ophiolite complex, and, accordingly, that the ores formed as a result of submarine hydrothermal activity. The Vuonos and Keretti Ni occurrences will be described in this issue by Parkkinen and Reino.

The *Svecokarelian mafic and ultramafic intrusions* and the allied Ni-Cu occurrence are economically the most important. The occurrences are located in central and southern Finland, where they form a more or less circular pattern around the central Finland granitoid area. Gaál (1972) described a linear »Kotalahti nickel belt» that parallels the gravimetric trough in a SE-NW direction and tangentially touches the ring structure. Together with the Pori-Kylmäkoski nickel belt of southwestern Finland, the northeast trending linear Lappvattnet belt south of Skellefteå, Sweden (Nilsson, this issue) completes the ring pattern. The Svecokarelian Ni-Cu deposits vary widely in form and composition, but can still be divided into subgroups in which the deposits resemble each other.

The Svecokarelian subgroups are: a) the Nivala area (Hitura, Makola and Oravainen), b) the Haukivesi-Kotalahti area (Kotalahti, Laukunkangas, Parikkala, etc.), c) the Saimaa area (Telkkälä, Kitula and several small deposits farther northwest), d) the Pori-Kylmäkoski belt (Vammala, Kylmäkoski, Sääksjärvi), and e) the Lappvattnet belt in Sweden. This division does not cover all the existing types, for instance Petolahti is an individual deposit, and Hyvelä differs from Vammala and Kylmäkoski.

The next chapters include a treatise by Gaál on the structural geology around the Ni-Cu deposits followed by the description of some important type deposits.

NICKEL METALLOGENY RELATED TO TECTONICS

GABOR GAÁL

The Central Baltic Shield consists of two major geotectonic units: The Archean basement complex with continental crust formed 2500—3100 Ma ago and the Svecokarelian geosynclinal complex which evolved in a period between 1600 Ma and 2100 Ma. Within this geotectonic framework the nickel deposits can be classified into four groups as presented in foregoing chapters.

The tectonic settings of the deposits will be described and an attempt will be made to analyse the geotectonic evolution of the metallogenic provinces. Special attention will be paid to deposits associated with synorogenic intrusions, economically the most significant type in Finland. The locations of the main nickel-copper mineralizations connected with major geological and geophysical features are depicted in Figure 3.

An early version of this paper has been presented on the International Symposium on Archean and Early Proterozoic Geologic Evolution and Metallogenesis, ISAP, in Salvador Bahia, Brazil in September 1982 (Gaál 1982).

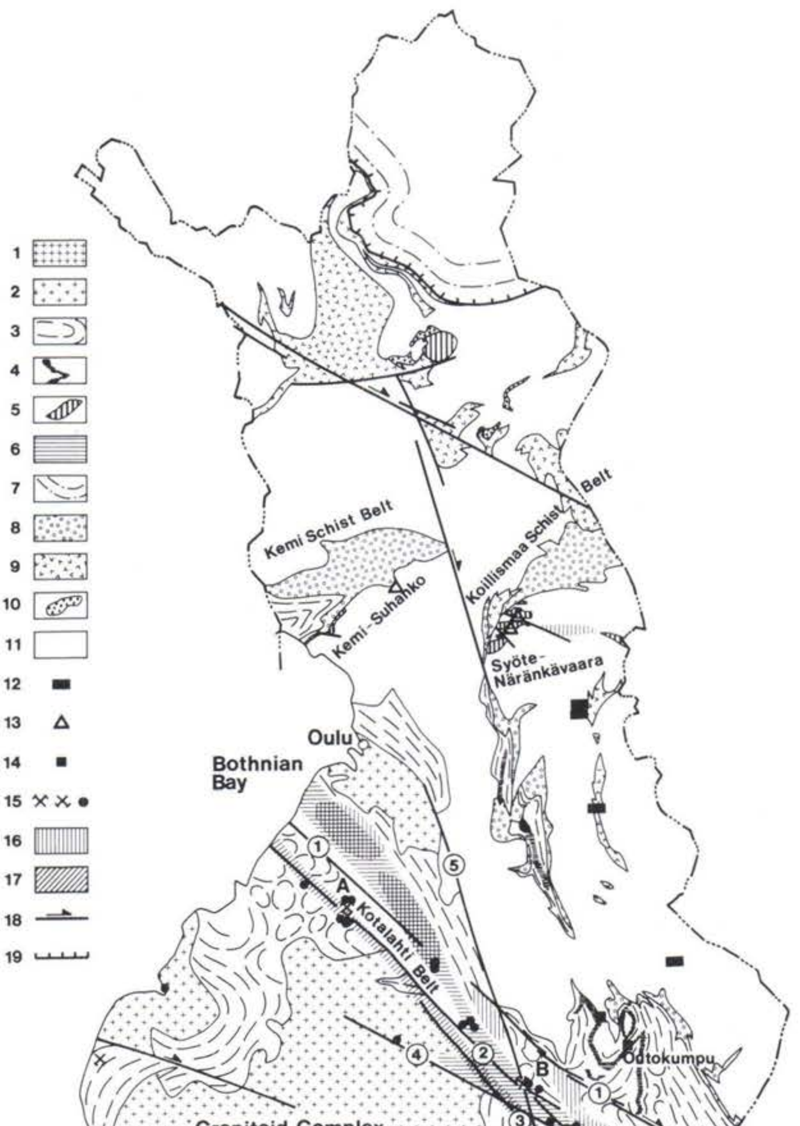

Fig. 3. Major tectonic features related to nickel metallogeny in Finland. 1. Rapakivi granites; 2. Proterozoic granitoids; 3. Rocks of the Svecokarelian geosynclinal complex; 4. Ophiolite belt; 5. Layered mafic intrusions; 6. High-grade metamorphosed zones; 7. Granulite complex of Lapland; 8. Epicontinental cover of the Archean basement complex; 9. Archean mafic volcanics; 10. Archean ultramafic volcanics; 11. Archean in general, chiefly granitoids; 12. Archean nickel-copper deposits; 13. Nickel-copper deposits in layered intrusions; 14. Nickel deposits associated with tectonically emplaced serpentinites; 15. Nickel-copper deposits associated with Svecokarelian synorogenic intrusions: mines, past producers and prospects. A = Hitura, B = Kotalahti, C = Laukunkangas, D = Vammala; 16. Gravimetric highs; 17. Gravimetric throughs; 18. Fault with sense of movement; 19. Thrust fault (saw teeth indicate dip).

ARCHEAN NICKEL-COPPER DEPOSITS

Archean nickel-copper deposits in Finland are located in typical Archean low-grade terrain, the Kuhmo and Suomussalmi greenstone belts of eastern Finland. These greenstone belts are surrounded by three generations of granitoids. The oldest generation consists of migmatitic and banded tonalitic gneisses, the second of leucogranodiorite or trondhjemite, and the third of latekinematic to postkinematic potassium granites. Granitoids of the first generation are supposed to form the ensialic basement of the greenstone belt association (Gaál *et al.* 1978). Geochronological evidence of an Early Archean basement of the greenstone belts has been found in northern Finland, where a banded tonalitic gneiss, uncorformably underlying the Sodankylä greenstone belt, yielded a U-Pb zircon age of 3100 Ma (Kröner *et al.* 1981). The granitoids of the second generation have intrusive contacts with the greenstone belt rocks. Since they yield U-Pb ages of zircon ranging from 2500 to 2800 Ma, they set the minimum age of the greenstone-belt association at 2800 Ma (Gaál *et al.* 1978). More recent Rb-Sr-determinations on the granitoids around the Suomussalmi greenstone belt indicate ages between 2510 and 2860 Ma, the first-generation grey gneiss yielding 2860 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7023 (Martin *et al.* 1983).

The greenstone-belt association consists chiefly of metavolcanics covering more than 90 per cent of the area of supracrustal rocks. According to Blais *et al.* (1978), a lower volcanic cycle, komatiitic and tholeiitic in composition, is overlain by a middle sedimentary sequence and an upper volcanic cycle, chiefly andesite-rhyodacite in composition. Komatiites abound in the lower cycle, where they exhibit spinifex structures (Hanski 1980). The nickel-copper deposits occur in serpentinites, which are intrusive bodies associated with gabbros and diorites in the lower volcanic cycle (Kojonen 1981).

The N to NW trend of the greenstone belts is indicative of deep-seated fractures, that were sites of Archean magmatism and governed the trend of the first deformational phase in the Archean supracrustals, e.g. tight to isoclinal N-S-trending folds. Current evidence implies that the magmatism of the first volcanic cycle was associated with N-S-trending subvertical tensional faults in the Archean sialic crust, developed as a result of rifting. The source of the komatiitic and tholeiitic magma was melted mantle material below the rift zone (Taipale 1983).

LAYERED INTRUSIONS IN THE ARCHEAN BASEMENT COMPLEX

The basement complex of the Central Baltic Shield, consisting of granitoids and rocks of the greenstone belt association, was cratonized 2500 Ma ago. The consolidated continental crust of Archean age was the site of deposition of epicontinental sedimentary-volcanic rocks during early Proterozoic times. Between 2300 and 2500 Ma there was a period of block faulting and erosion, and a sequence of petromictic conglomerates and mafic volcanics was deposited, forming the thin discontinous layer of the Sumi-Sariola group (Sokolov *et al.* 1976 and Laajoki, 1980). This was followed by a period of subaerial weathering and the deposition of the upto several hundred metres thick epicontinental sequence of the Jatulian group (Meriläinen 1980). The Archean craton and the Jatulian group were invaded 2000—2200 Ma ago by numerous N-NW striking diabase dykes and sills marking a period of tensional fracturing of the continental crust.

Zircons of the layered intrusions yielded a U-Pb age of 2440 Ma (Simonen 1980) implying that the layered intrusions of northern Finland were emplaced immediately after the cratonization of the late Archean crust. At that time faults tapped the upper mantle and served as conduits of partially melted mantle material of tholeiitic composition as manifested in the basaltic volcanism of the Sumi-Sariola group and in the sizeable mass of magma in the layered intrusions, estimated by Alapieti (1982) to exceed 2000 km^3 in volume.

The layered intrusions form two belts trending E-W and NE, the Kemi-Suhanko belt and the Syöte-Näränkävaara belt (Piirainen *et al.* 1974 and Piirainen 1978). Both belts consist of several elongate mafic massifs up to 30 km long, either surrounded by the granitoids of the Archean basement complex or located at the junction of the basement and the Proterozoic cover (Fig. 3). The Kemi-Suhanko belt consists of three massifs. Whereas the two western bodies are closely related and are obviously parts of the same intrusion, the eastern Suhanko massif is a separate body with different characteristics. In the Syöte-Näränkävaara belt five separate massifs show indentical or similar trends of crystallization, indicating an originally single body fragmented by later tectonic movements. Between these massifs and the easternmost Näränkävaara massif a narrow gravity high trending E-W suggests a mafic body 1 to 2 km deep (Piirainen *et al.* 1974). Alapieti (1982) therefore concludes that the Syöte-Näränkävaara belt originally consisted of two intrusion centres, about 50 km apart, connected by a dyke-like mafic body indicated by the gravity high.

It can be inferred that the layered intrusions of Finland originally formed a single belt with four individual intrusions emplaced along a deep-seated tensional fracture or fracture zone trending ENE. The mafic belt was displaced by a large fault causing a right-lateral separation of about 90 km (Fig. 3).

There is an obvious similarity between the geological environment of the layered intrusions of northern Finland and the Early Proterozoic aulacogene in the Siberian platform (Salop and Scheinmann 1969) as well as in the border zone of the Coronation geosyncline in the Slave Province, Canada (Hoffman 1973). The Kemi and Koillismaa schist belts extend, at a high angle to the general trend of the Svecokarelian geosyncline, into the Archean craton. The schist belt could be interpreted as remnants of rocks evolved on a failed arm of a plume-generated triple junction which led to the breaking up of the Archean continental crust (Burke and Dewey 1973). Rifting during the initial stage provided opening for the intrusion of tholeiitic magma. The epicontinental clastic sedimentation of the Jatulian group prevailed during the incipient rift stage while turbidites of the Kemi schist belt deposited during the sagging stage when the continental shelf of the passive plate margin in the west foundered. The sediments were thrown into folds with axes trending parallel to the rift axis. Subsequent transcurrent faulting displaced and fragmented both schists and intrusions.

NICKEL DEPOSITS ASSOCIATED WITH TECTONICALLY EMPLACED ULTRAMAFIC BODIES

Low-grade nickel mineralizations in calc-silicate rocks and cherty quartzites associated with serpentinite bodies occur in the Kalevian group of the Karelian zone at the eastern margin of the Svecokarelian geosyncline complex. The Kalevian group can be divided into two tectonic-stratigraphic units: the external zone in the east and the internal zone in the west. The external zone, which is the Kalevian group sensu stricto, is a para-autochtonous sedimentary unit consisting of metaturbidites deposited on the western margin of the Archean craton. Especially in its eastern part, this zone contains low-grade metamorphosed proximal turbidites with graded beds from a few centimetres to 10 m thick. The thick cycles are conglomeratic at the base and indicate a near-shore depositional environment. The internal zone consists chiefly of medium-grade to high-grade metamorphosed mica schists and mica gneisses in which few primary structures are preserved. These rocks are interpreted as metagreywackes with thin graded bedded cycles indicating distal turbidites. The tectonic style of the internal zone is dominated by large F_1—F_2 recumbent folds refolded in several subsequent deformational phases (Koistinen 1981).

The serpentinites occur exclusively in the internal zone of the Kalevian group as part of the Outokumpu association, a strongly deformed and cofolded sequence of serpentinite, dolomite, calc-silicate rocks, cherty quartzite with Cu-Co-Zn deposits and black schists (Huhma and Huhma 1970). Low-grade sulphide nickel deposits occur in cherty quartzite and calc-silicate rocks close to the contacts with serpentinite. The rocks of the Outokumpu association occur typically in the Outokumpu region, but it has been suggested that they continue northwards into the Kainuu schist belt (Mäkelä 1981).

Many authors accept tectonic emplacement of the ultramafic masses. As early as 1928, Wegmann suggested that the serpentinites of Finnish North Karelia are comparable to Alpine ultramafic rocks emplaced during nappe movements. This view has since been corroborated by Väyrynen (1939), Gaál *et al.* (1975) and Koistinen (1981). The lead isotopic composition of the Outokumpu Cu-Co-Zn deposit suggests that rocks of the Outokumpu association formed an oceanic crust 2100 Ma ago (Vaasjoki 1981). Evidence that the serpentinites were part of an ophiolite complex in the modern sense has been presented by Park and Bowes (1981), who described deformed pillow lavas in association with serpentinite. The occurrence of a gabbro with a U-Pb age of 1972 $\pm$ 18 Ma, predating the D_1 deformation and association with serpentinites, corroborate the concept of an ophiolite assemblage (Koistinen 1981). In his summary of the results of new structural and other investigations in the Outokumpu area, Koistinen (1981) proposes that the Outokumpu association, together with its flysch-type environment, comprises a large ophiolite nappe whose surface expression is the Outokumpu Ore District.

It is concluded that the serpentinites of North Karelia are tectonically emplaced fragments of Precambrian oceanic crust generated some 1970—2100 Ma ago. The assemblage serpentinite, chert-quartzite, pillow lava and gabbro in the fold hinges of recumbent F_1—F_2 folds indicates the presence of a deformed and dismembered ophiolite complex that was introduced into the continental crust by plate tectonic processes during a compressional event 1880—1900 Ma ago. This compressional event has been explained by Bowes (1980), Bowes and Gaál (1981) and Koistinen (1981) as a continent-continent collision of the Tibetan type. Mäkelä (1980), supported by Gaál (1982), proposed that the Kalevian group deposited in a marginal basin underlain by transitional crust and that the ophiolite thrust is the result of a collision between the Archean continent and a Svecofennian oceanic island arc system.

NICKEL-COPPER DEPOSITS ASSOCIATED WITH SYNOROGENIC MAFIC TO ULTRAMAFIC INTRUSIONS OF SVECOKARELIAN AGE

Nickel belts

Although mafic to ultramafic igneous rocks occur throughout the Svecokarelian geosynclinal complex in various geological settings, some broad patterns are recognizable in their areal distribution. The mafic-ultramafic rocks are most abundant in the Ladoga-Bothnian Bay zone, in an elongate belt 420 km long and 100—150 km wide that trends NW-SE across Central Finland. Another marked concentration of mafic-ultramafic plutonic bodies is in southwestern Finland, in a belt 280 km long and 60 km wide that trends WNW-ESE from Pori to Porvoo. The most significant nickel-copper deposits in Finland are concentrated in these two zones (Mikkola 1980). Mafic-ultramafic plutonic rocks also occur, in association with mica schists and gneisses, around the granitoid complex of central Finland.

After extensive study of the nickel contents of mafic silicates and the sulphide phase in mafic-ultramafic rocks, Häkli (1971) classified the mafic-ultramafic bodies of Finland in terms of the favourability of the occurrence of sulphidic nickel ore. He delineated two linear NW-SE-trending zones with nickel-bearing intrusions, which have since been named the Kotalahti nickel belt (Gaál 1972) and the Kylmäkoski nickel belt (Fig. 3). Häkli (1971) also noted that the two belts are connected by an ENE-trending belt resulting in a U-pattern of the nickel potential zone.

The nickel mineralizations of the Kotalahti and Kylmäkoski nickel belts are associated with NW-trending fault systems. This fault system has been studied by various methods and the great diversity of results had to be combined before a tectonic model of the nickel belt could be established. The methods used were geological mapping, remote sensing (including the study of topographic lineaments, magnetic and gravimetric maps), magma petrology, structural geology of nickel deposits and geochronology.

Surface expression of faults

The surface expression of deep-seated faults associated with nickel mineralizations was studied by methods combining geological mapping, interpretation of aeromagnetic maps and localization of major topographic lineaments (Talvitie 1971, 1975 and 1976; Gaál 1972; Parkkinen 1975 and Kuosmanen *et al.* 1981). There is consensus among these authors on the fault control of the nickel mineralization and on the identification of major faults and shear belts. Opinions differ, however, on the details of the nature and localization of individual faults. The differences stem partly from the scales of the maps analysed and partly from the disparate approaches to a complex problem. The faults of the Lake Ladoga-Bothnian Bay zone exhibit composite features, such as primary patterns of ductile shear zones; mimic fracture patterns superimposed on older fault systems and shear zones; and several generations of magmatic rocks intruding zones of local tension along the faults. The faults are generally subvertical or steeply dipping. The sense of the lateral displacements can be determined by the S or Z pattern of the vertical drag folds and by attenuation of the rock units within a shear belt. The evidence, however, is often dubious because of regional fold interference patterns in the surrounding rocks. On the other hand, clear evidence of extensive vertical displacement is given by the juxtaposition of geological units of different metamorphic grade. Figure 3 gives the present author's interpretation of the NW-trending fault system of the Lake Ladoga-Bothnian Bay zone. Only major faults relevant to the control of the Ni mineralization are shown. The NW trend is a compound pattern of mainly two directions, 300°—305° and 325°—330° (Talvitie 1971 and 1975 and Parkkinen 1975).

Fault 1 is a ductile belt with a right-lateral displacement (Gaál 1972, Talvitie 1975, Parkkinen 1975 and Halden 1982). The overall trend of the fault is 320° and it is composed of small lineaments in an treding 305° en echelon pattern. The fault is flanked on both sides by subvertical Z-shaped drag folds (Koistinen 1981). Its plane dips 70°—85° towards SW, indicating a reverse component with upthrust towards NE. The fault can be regarded as the northeastern limit of the fault system controlling the nickel occurrences. It is a relatively young structure, which deforms the S_2 foliation but is deformed by D_3 (Koistinen 1981 and Halden 1982).

Fault 2 is a fault zone 10 to 15 km wide associated with the nickel occurrences in the Kotalahti Ni belt. It has a complicated internal structure which has been described in detail in its southern part, the Haukivesi area (Gaál and Rauhamäki 1971 and Parkkinen 1975), and in the surroundings of the Kotalahti nickel mine (Gaál 1980). It is composed of several fracture sets, the major ones trending 305° and 330°, and was reactivated in at least two deformational phases. Owing to its composite patterns, the fault does not show up in detailed lineament maps as a distinct fracture direction (Talvitie 1975; Parkkinen 1975) but as a zone of high lineament density (Talvitie 1971). Is is, however, recognized as a major shear zone or fracture zone (Gaál 1972; Tuominen *et al.* 1978 and Kuosmanen *et al.* 1981). Koistinen (1981) considers approximately the same zone as a major suture. Gaál (1972) suggested that it is a wrench fault with right-lateral displacement as deduced from drag folds and en echelon fold patterns in the Haukivesi area (Gaál and Rauhamäki 1971). Dextral movements on faults trending 305° in this zone have been reported by Talvitie (1975) and Parkkinen (1975), who also observed leftlateral movements along the same zone. Gaál (1972 and 1981) explained the left-lateral movements as results of late revival during the third deformational phase.

Fault 3 runs subparallel to fault 2 as a distance of 5 to 20 km, delimiting the Kotalahti nickel belt to the southwest. Fault 3, which coincides with the southern part of the gravimetric trough to be described below, is a pronounced topographic lineament that can be seen on the aeromagnetic map as a discontinuity zone.

Fault 4 cuts the Kotalahti belt obliquely with a WNW trend. It has been described by Gaál (1972) as a younger left-lateral transcurrent fault controlling a line of nickel-bearing intrusions, e.g. the Laukunkangas deposit (Grundström 1980).

Fault 5 is a prominent lineament on the aeromagnetic map and is recognized by Kuosmanen *et al.* (1981) as a major fracture representing an important block boundary. The Kotalahti deposit is located at the intersection of fault 5 and fault 2.

Deep structures as revealed on the gravimetric map

Regional gravity-anomaly patterns are generally regarded as indicative of deep crustal structures, and Bouguer anomaly maps have a special significance in the search for the structural control of nickel-bearing mafic-ultramafic rocks. The Kotalahti nickel belt is associated with distinctive features of the Bouguer anomaly map (Honkasalo 1962). Talvitie (1971) emphasized the importance of a narrow NW-trending gravity trough transversing southern Finland, indicative of a major fracture zone separating two crustal blocks. This gravity trough runs 0—30 km southwest of the Kotalahti nickel belt (Fig. 3). Northeast of the gravity trough there is a discontinous ridge consisting of several gravity highs. The southernmost gravity high has been attributed to the marked abundance of mafic igneous rocks (Gaál and Rauhamäki 1971 and Talvitie 1971). The large areal extent of the gravity highs is, however, more probably due to the occurrence of rocks metamorphosed under conditions of granulite facies.

The nickel mineralizations, which are located on the gravity slope between the trough and the ridge, are associated with discontinuities expressed as high curvatures and embayments of the Bouguer anomaly isolines (Kuosmanen *et al.* 1981 and 1982). These areas of »maximal perturbations» can be attributed to cross-cutting structures.

Metamorphic zones

Svecokarelian metamorphism is of the high temperature — low pressure type and pT estimates for the metamorphic zones between the low amphibolite and granulite facies range between 3 kb, 600°C and 6.5 kb, 825°C (Korsman 1977; Schellekens 1980 and Campbell 1980). The corresponding metamorphic rocks were formed at crustal depths between 10 and 20 km. High-grade areas metamorphosed under conditions of granulite facies or neargranulite facies in the Svecokarelian geosynclinal complex show two trends (Fig. 3). One of them runs in a NW direction, parallel to the Ladoga-Bothnian Bay zone, and the other in an E to ENE direction in the Svecofennian zone of southern Finland. The nickel belts show a conspicuous parallelism with high-grade belts, and individual nickel deposits and occurrences are located regularly in terrains of upper amphibolite facies close to high-grade areas.

The tectonic significance of the metamorphic zonation of the Svecokarelian complex has been discussed by Campbell (1980), who maintains that the high-grade zone of the Ladoga-Bothnian Bay zone represents thickened crust exposed by later isostatic movements. The uplift of high-grade rocks obviously occurred along faults, some of which are probably related to deep-seated structures controlling the intrusion of nickel-bearing magma.

Magma generation related to tectonics

The Kotalahti and Kylmäkoski nickel belts are distinguished by the predominance of two magma types represented by a tholeiitic and a tonalitic-trondhjemitic suite. A characteristic feature seems to be the subordinate occurrence of granitic rocks.

Tholeiitic suite

Tholeiitic magma, which extruded first in an eugeosynclinal environment, is preserved as banded diopside amphibolite with pillow lava structures (Gaál and Rauhamäki 1972). The tholeiitic magma intruded for the second time during the orogenic stage in differentiated plutonic bodies associated with the nickel deposits. U-Pb ages of zircon in the intrusions vary between 1882 ± 13 and 1892 ± 14 Ma (Neuvonen *et al.* 1981). The rocks of the mineralized plutonic complexes, which range in composition from harzburgitic peridotite to quartz diorite, are regarded as a differentiation series derived from an olivine-tholeiitic magma of basaltic composition (Grundström 1980). Owing to their synkinematic nature, the mineralized plutonic bodies have diverse shapes, such as pipes plugs, lenses, ellipsoids and irregular bodies. The differentiated rocks show a zoned, layered or more or less irregular arrangement within the bodies attributed to either multiple intrusion or flowage differentiation (Häkli 1971).

There is little doubt that the source of the nickel-bearing tholeiitic magma is the upper mantle with a composition approximating the most ultramafic members of the intrusions. The tholeiitic magma was produced by partial melting of the upper mantle.

Basaltic magma is formed under high water pressure and high temperature at a depth interval of 70 to 100 km (Ringwood 1974). The water needed for this process is introduced into active continental margins by hydrated minerals in a subducting oceanic crust. The reaction amphibolite → eclogite + H_2O liberates water, thereby causing melting of the upper mantle. The result is a hydrous tholeiitic magma which ascends into higher crustal levels in rising diapirs. This stage is characterized by a minimum transfer of silicate material from the oceanic crust into the melt. The bulk of the magma is derived from the mantle. In present-day island arc environments tholeiitic magma is generated by rapid subduction (Horikoshi 1976).

Tonalitic-trondhjemitic suite

Tonalitic-trondhjemitic magma intruded the Kotalahti nickel belt in two stages (Gaál and Rauhamäki 1972). During the early stage of deformation, large conform sheets of homogeneous trondhjemite were emplaced in the course of southfacing recumbent folding. These intrusions were refolded by later deformation phases into phacolites in synforms, antiforms and domes. The first-stage trondhjemite contains some inclusions of hornblendite, diorite and hornblende gabbro. The U-Pb age of zircon of the trondhjemite is 1900 Ma (Kuusela 1982). This is in accordance with the whole-rock Rb-Sr age of trondhjemite in the Kalanti area, south of the Kylmäkoski nickel belt, with an approximate age of 1900 Ma and a low initial $^{87}Sr/^{86}Sr$ ratio (Arth *et al.* 1977). Recent geochemical studies of granitoids of southern Finland (Nurmi *et al.* 1984) show that the trondhjemites of the Ladoga-Bothnian Bay zone are high-Al_2O_3 trondhjemites as defined by Barker *et al.* (1976).

The trondhjemite of the second stage is a rock of strongly migmatitic aspect. Trondhjemite forms various migmatites along the central axis of the nickel belt. A characteristic rock is the schollenmigmatite, a breccia with angular to rounded fragments of mafic to ultramafic igneous rocks and supracrustal material in a trondhjemitic matrix (Gaál and Rauhamäki 1971, Gaál 1972 and Grundström 1980). Locally the trondhjemitic matrix has a conspicuous content of garnet, and it is often banded. Schollenmigmatites occur in narrow, discontinuous belts, 100—2000 m wide and several tens of kilometres long. Many observations indicate a close relation between schollenmigmatites and nickel-bearing rocks. The mafic-ultramafic rafts, especially the angular fragments, can often be demonstrated as broken dykes which were disrupted and intruded by several generations of trondhjemitic material. Some of the fragments are mineralized. It is obvious that both nickel-bearing magma and the trondhjemite intruded tectonic weakness zones representing deep-seated faults. The grading of migmatitic trondhjemite into veined mica gneisses led Gaál and Rauhamäki (1971) to conclude that the rocks have a palingenic origin.

Any model explaining the generation of tonalitic-trondhjemitic magma has to account for its high Na_2O and lower K_2O content compared with the calc-alkaline suite. The generation of trondhjemite has been explained either by a two-stage model involving partial melting of the mantle or tholeiite, and fractional crystallization of the melt or by a one-stage model leading directly to a plagioclase-rich melt by partial melting of amphibolite.

In the two-stage model, plagioclase plays a key role in the generation of a magma rich in Na_2O and Al_2O_3. During the partial melting of a mafic-ultramafic material, plagioclase is present at a pressure lower than 20 kbar. At 15 kbar, at an equivalent depth of 45 km, the subsolidous contains enough plagioclase to produce a Na_2O rich melt (Maaløe 1982). A diorite-gabbro magma is formed by partial melting, and trondhjemite evolves by fractional crystallization from the melt. One hundred parts of gabbro would yield 24 parts of trondhjemitic liquid through precipitation of hornblende, plagioclase and biotite (Arth *et al.* 1978). The primary reason for the remelting of tholeiitic material at a depth of 45 to 60 km could be subduction of the oceanic crust (Hietanen 1975 and Maaløe 1978).

According to the one-stage model, the partial melting of amphibolite takes place in the stability field of hornblende at depths less than 60 km (Barker and Arth 1976).

Since trondhjemites are spatially associated with cumulate diorites and gabbros in the Proterozoic nickel belts (Hietanen 1943, Gaál and Rauhamäki 1971), the application of the two-stage model seems to be more plausible. However, large homogeneous trondhjemite massifs could also have envolved by the one-stage model.

Mantled gneiss domes and Kotalahti nickel belt

Geochronological data indicate that the Kotalahti nickel belt coincides with the southwestern limit of the Archean crust of the Baltic Shield. No geochronologically defined Archean is known south and west of the Kotalahti nickel belt (Gaál *et al.* 1978). The Archean basement is covered with Proterozoic geosynclinal sediments in a 100 km broad zone north and east of the Kotalahti nickel belt. Owing to extensive Svecokarelian activation, the basement is exposed in numerous domes and brachyantiforms, known since Eskola (1949) as mantled gneiss domes. Brunn (1980), who interprets these structures as gravity-induced diapirs, pointed out that the basement domes and brachyantiforms are arranged in ridges trending N-S and at distances of 27—42 km from each other. The same pattern has been interpreted by Gaál (1972) and Koistinen (1981) as a result of fold interference.

Tontti (1981) pointed out that the intersection of the southward continuations of the dome ridges with the nickel belt coincides with clusters of nickel-copper deposits. It can be assumed that the intersection of the dome ridges with the NW-trending fault zones are sites of tectonic perturbations, which were favourable for the intrusion of nickel-bearing magma.

Integrated model

Nickel-bearing intrusions were emplaced in long, fault-controlled straight or curvilinear belts. The geology of the belts is complex and the nickel-copper deposits evolved as a result of the interplay of several factors. These factors are reviewed first by profile across the southern sector of the Kotalahti nickel belt, the area for which most data are available. After an idealized profile has been established, the model is extended to cover the tectonic relations of the nickel belts within the Svecofennian geosynclinal complex.

Magma tectonics offer a unique insight into the crustal processes leading to the formation of nickel-copper deposits. The plutonic rock associations evolved in two stages giving rise to a tholeiitic suite and trondhjemitic suite. A model with subduction of a hypothetical oceanic crust and with successive stages of partial melting of the oceanic crust and the overlying mantle wedge could explain the spatial and chronological overlap of the trondhjemitic and tholeiitic suites.

The Archean craton northeast of the Kotalahti nickel belt is an important factor in localizing the hypothetical subduction zone. Hietanen (1975), Mäkelä (1980), Gaál (1982), and Walser and Einarsson (1982) infer subduction towards the northeast below the Archean craton.

Another alternative, subduction towards the southwest as a result of the convergence of two continents, has been proposed by Bowes (1980) and Campbell (1980) supported by Koistinen (1981) and Neuvonen *et al.* (1982). Present evidence from the Ladoga-Bothnian Bay zone seems to favour subduction towards the northeast. Since no Archean crust is known southwest of the Kotalahti nickel belt, the continent-continent collision model of the Tibetan type lacks geochronological evidence. High-grade metamorphic rocks, with an associated gravity high, indicate uplifted crust northeast of the nickel belt, whereas the gravity trough southwest of the belt obviously marks a major fault genetically associated with the nickel-bearing intrusions. It is suggested that this fault dips steeply towards the northeast and that it is parallel to the ancient subduction zone underlying a thickened continental crust that was subsequently uplifted. Folds with S-SW vergence in the Haukivesi area seem to support this view (Gaál and Rauhamäki 1971).

The transcurrent faults controlling the nickel-copper deposits were probably subparallel to the continental margin of the Archean craton. They do not contradict the hypothesis of a subduction zone, as large transcurrent faults and shear belts play an important role at convergent plate margins (Wilcox *et al.* 1973).

Häkli (1971) recognized a U-shaped belt around the granitoid complex of Central Finland with mafic-ultramafic bodies favourable for the occurrence of nickel-copper deposits. Papunen *et al.* (1979) suggested that the nickel-bearing intrusions form a semicircular belt. The U-shaped belt has been found to consist of two linear, fault-controlled belts, the Kotalahti nickel belt (Gaál 1972) and the Kylmäkoski nickel belt, united by a third belt trending E-W parallel to the Svecofennian zone. Available data on nickel-copper deposits and nickel indications have since been compiled in two data banks at the Geological Survey of Finland (Tontti *et al.* 1979 and Saltikoff 1979) and we now have a fairly reliable picture of the nickel provinces of southern Finland. The nickel mineralization data were plotted on a gravimetric map by Kuosmanen *et al.* (1981), revealing correlations between the nickel-bearing area and Bouguer anomaly patterns around the U-shaped belt, which appears to be rather an angular feature composed of three linear belts. A discontinous zone of gravity high coinciding with zones of high-grade metamorphism is perceptible. Inside the U-shaped belt the Kotalahti and Kylmäkoski nickel belts are flanked by zones of gravity low. The Kotalahti and Kylmäkoski nickel belts have other features in common, e.g. the bimodal tholeiitic-trondhjemitic suites and schollenmigmatites as well as long, straight fault zones with a strike-slip component of movement. Although the Svecofennian nickel belt is less pronounced, one has the impression that the Kotalahti nickel belt swings around the granitoid complex of Central Finland, and that the Kylmäkoski belt forms its symmetric counterpart. It is reasonable to assume that the Svecofennian belt is bordered by a craton in the south. Archean rocks are known south of the Baltic Sea under the Russian platform cover.

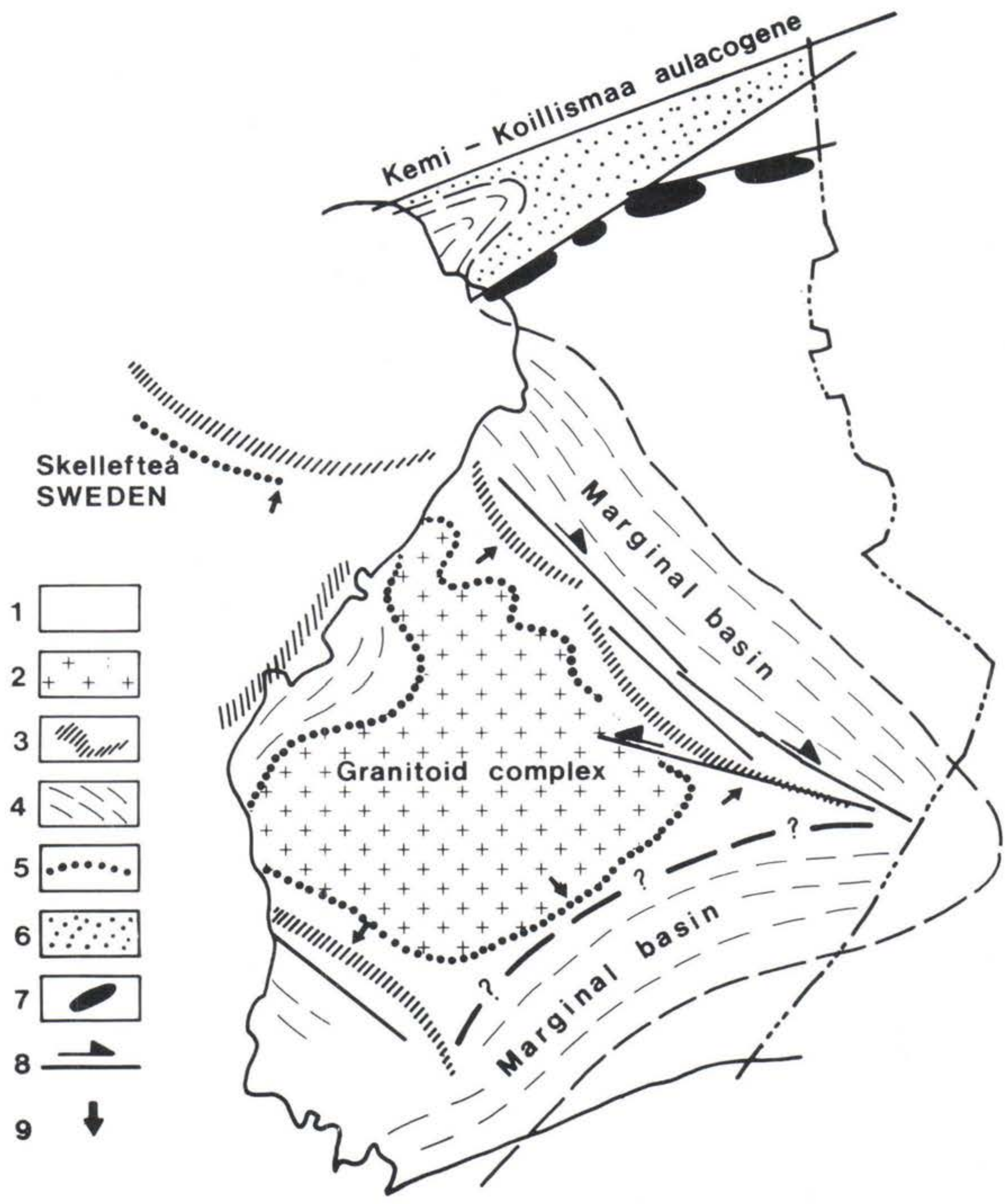

Fig. 4. Plate tectonic model of the Proterozoic nickel belts of the Svecokarelian geosynclinal complex. 1. Archean continental crust; 2. Proterozoic granitoids; 3. Tholeiitic island arcs and nickel belts; 4. Andesitic island arcs; 5. Geosynclinical rocks; 6. Epicontinental rocks; 7. Layered intrusions; 8. Fault with sense of movement; 9. Subduction.

Archean U-Pb ages of zircon were recorded in the young rapakivi granite of southern Finland (Vaasjoki 1978).

Figure 4 depicts the intergrated model, derived from the extension of the model profile. The nickel belts are presumed to be products of several subductions of oceanic crust below the Archean continent. They probably represent deeply eroded parts of ancient tholeiitic island arcs. The rocks of the marginal basin environment deposited between the nickel belts and the Archean craton. Behind the tholeiitic island arcs andesitic island arcs were formed above a subparallel major subduction zone which could have originated farther to the west, as envisaged by Hietanen (1976). This major subduction is also indicated by large batholiths of I-type granitoids and porphyry-type Cu-Mo deposits (Gaál and Isohanni 1979; Walser and Einarsson 1982, Nurmi *et al.* 1984).

GEOLOGY AND NICKEL-COPPER DEPOSITS OF THE KIANTA AREA, SUOMUSSALMI

J. KURKI and H. PAPUNEN

The Kianta area is situated on the western side of the lake Kianta, c. 45 km north of Ämmänsaari, the communal centre of Suomussalmi.

Investigations in the area were initiated by Outokumpu Oy after local people had submitted a Ni-Cu ore sample in 1960 that assayed 2.37 % Ni and 1.10 % Cu. The systematic investigations comprised boulder tracing, geological mapping, magnetic, electromagnetic and gravimetric surveys and finally diamond drilling in several phases, most lately in 1970. Two Ni-Cu occurrences were discovered, one at Hietaharju and one at Peura-aho (Fig. 5).

The ore reserves were estimated and serious consideration was given to mining the Ni-Cu deposits. The plans were rejected for several reasons, however, mainly because of the small size of the deposits.

GEOLOGY OF THE KIANTA-SAARIJÄRVI AREA

The Kianta area is part of the Suomussalmi Archean greenstone belt, which is the northern continuation of the Kuhmo belt, recently described by Blais *et al.* (1977, 1978), Jahn *et al.* (1974), Hanski (1980) and Taipale *et al.* (1980). The greenstone belt is surrounded by gneissose rocks with tonalitic or trondhjemitic bulk composition. In the Kianta area the greenstone is intersected and brecciated by an intermediate to silicic plutonic rock that varies in composition from diorite to granodiorite. Swarms of metadiabase dykes intersect all the other rocks in the area.

The greenstone belt comprises mainly volca-

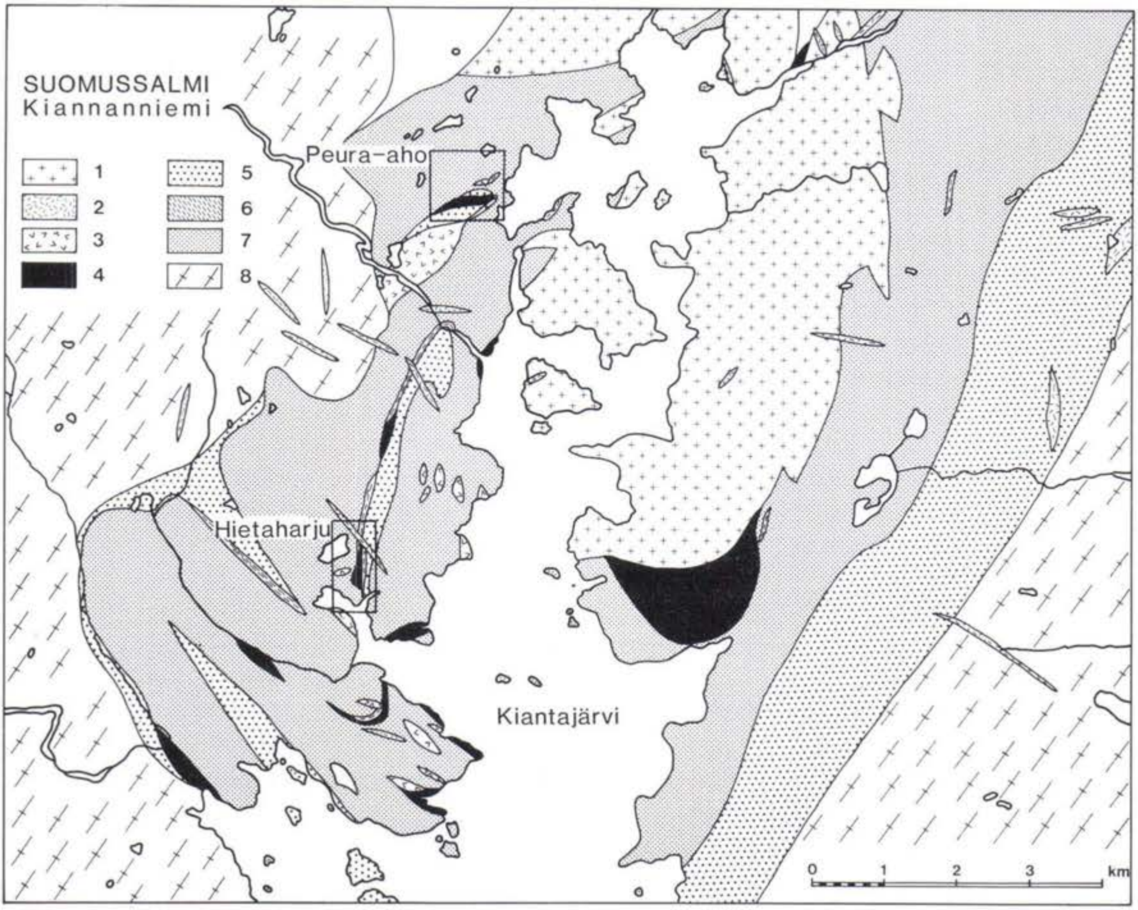

Fig. 5. Geological map of the Kiannanniemi area, Suomussalmi. 1. Quartz diorite; 2. Metadiabase; 3. Gabbro; 4. Ultramafite; 5. Felsic volcanics and metasediments; 6. Black schist; 7. Mafic metavolcanics; 8. Archean granitoids.

nogenic rocks from felsic to ultramafic in composition. Ultramafic intrusives, chlorite-amphibole rocks (metapyroxenites) and serpentinites (metadunites and metaperidotites) are also common. Sericite quartzites, phyllites and mica schists with black schist intercalations are metamorphic derivatives of originally euxinic metasediments. The mafic volcanites of the Kianta area probably belong to the Kellojärvi Group in the stratigraphic succession by Taipale *et al.* (1980).

Mafic metalavas are the most common rock types in the supracrustal greenstone belt lithosome. They are green, rather homogeneous and massive, and only locally schistose. Pillow structures are commonly deformed but well-preserved pillows and amygdaloidal lavas are also encountered.

More coarse-grained and homogeneous portions with hypidiomorphic textures are called metagabbros or gabbroic amphibolites. Uralite porphyrites occur as rather wide sills or as narrow intercalations in mafic lavas. Mafic metavolcanites also include distinctly foliated and banded metatuffs and tuffites. The greenstone belt comprises both Fe-rich tholeiitic and komatiitic suites of volcanics. The geochemistry of the Kianta area has not been studied in detail,

Table 4. Chemical analyses of the volcanogenic rocks in the Kianta-Saarijärvi area.

	1	2	3	4	5	6	7	8	9	10
SiO_2	39.93	42.33	49.97	44.09	50.06	55.95	55.33	48.82	73.15	75.97
TiO_2	0.70	0.57	0.95	0.30	0.49	1.26	1.86	0.94	0.47	0.30
Al_2O_3	4.59	4.90	7.88	6.89	13.92	13.57	13.57	12.93	15.51	15.12
FeO_{tot}	11.67	12.79	12.48	10.72	9.40	9.57	12.96	12.69	2.28	1.51
MnO	0.17	0.19	0.21	0.26	0.14	0.19	0.26	0.22	0.05	0.04
MgO	22.17	25.15	14.23	11.61	9.88	5.88	2.78	10.51	1.18	0.61
CaO	5.11	4.19	8.71	14.05	12.92	10.82	9.81	8.81	2.69	2.31
K_2O	0.02	0.00	0.14	0.03	0.08	0.15	0.16	0.12	2.48	0.95
Na_2O	0.38	0.78	0.28	0.00	1.75	1.24	1.27	1.63	0.45	1.63
P_2O_5	0.00	0.02	0.00	0.06	0.38	0.00	0.12	0.28	0.12	0.00
NiO	0.19	0.17	0.13	0.05	0.04	—	0.12	—	—	—
Cr_2O_3	0.33	0.54	0.27	0.20	0.14	0.00	0.01	0.09	0.00	0.00
LOI	11.74	8.34	4.48	9.19	n.d.	1.56	1.79	n.d.	2.55	2.20
	96.99	99.97	99.73	97.97	99.20	100.19	100.04	97.04	100.86	100.64

1. Talc-carbonate rock, Hietaharju, analyst K. Kojonen, 2. Serpentinite, Peura-aho, analyst K. Kojonen, 3. Amphibole-chlorite rock, Hietaharju, analyst K. Kojonen, 4. Amphibole-chlorite rock, Peura-aho, analyst K. Kojonen, 5. Coarse-grained amphibolite, Peura-aho, XRF analysis, Outokumpu Oy, 6. Mafic volcanite, Hietaharju, analyst K. Kojonen, 7. Mafic tuffite, Syrjäjoki, analyst K. Kojonen, 8. Uralite porphyry, Syrjäjoki, XRF analysis Outokumpu Oy, 9. Quartz-feldspar-schist, Hietaharju, analyst K. Kojonen, 10. Felsic porphyry, Peura-aho, analyst K. Kojonen.

but the data presented in Table 4 suggest mainly tholeiitic composition for the prevailing mafic metavolcanics.

Felsic metavolcanics, lavas and tuffs are less abundant than mafic rocks. The lavas, called felsic porphyry, are light-coloured porphyritic rocks with plagioclase (An 25—35) phenocrysts that range in size from 0.3 to 1.5 mm. The felsic tuffs have been metamorphosed into quartz-feldspar schists. The Kianta volcanites are bounded in the southwest and east by arkosic rocks that are presumed to represent weathering products of acid and intermediate volcanics (Taipale *et al.* 1980). The U-Pb age of this rock type is 2.96 Ga. (Geol. Survey Ann. Rep. 1964).

The sulphide Ni-Cu occurrences are associated with a rock sequence composed of felsic metavolcanics, mica schists and black schists overlain by a complex of mafic intrusive and ultramafic serpentinite bodies. The ultramafic rocks occur as lenses along the basal contact of the mafic intrusions against the underlying black schists. Locally they have been altered into talc-carbonate rocks.

Serpentinites and talc-carbonate rocks grade towards the contacts into a zone of chlorite-amphibole rock that corresponds to pyroxenite in chemical composition. Its intense foliation and cataclastic textures indicate that tectonic movements were the main generator of its present texture. Magnetite and chromite are common accessories in the serpentinite. The magnetite assays 0.3—0.4 % Ni.

According to Kojonen (1981), the lowermost parts of the ultramafic bodies are peridotitic in composition (MgO 26—27 %). Upwards the rock type changes first to pyroxenite (MgO 17—19 %) often followed by a coarse-grained metagabbro or gabbroic amphibolite (MgO 10—12 %). The overlying mafic metavolcanite is basaltic in composition (MgO 8 %). The mafic-ultramafic intrusive rock suite is characterized by high values of CaO/Al_2O_3 ratios, and resently Hanski (1984) proposed that the host intrusive suite belongs to »gabbro-wehrlite association» and is Proterozoic in age.

Stratigraphically the silicic porphyry — mica schist rock association seems to be interbedded with the mafic volcanics. The silicic belt trends to north, parallel with the general strike of the surrounding metalavas. The dip is subvertical. At the margins of the greenstone belt the dip is generally 45°—50° towards the centre of the belt. The schistosity is commonly subparallel to the bedding.

THE NICKEL-COPPER OCCURRENCES AND THEIR HOST ROCKS

Prospecting was guided by the association of sulphide-bearing ultramafic rocks with the graphite-rich black schist horizon. The black chist was easy to follow with geophysical survey. In some places the horizon includes layers of massive iron sulphides, and the sulphide Ni-Cu deposits occur in localities where serpentinite or talc-carbonate rock is in contact with the sulphide-bearing horizon. In a similar stratigraphic horizon some barren ultramafic bodies have also been intersected by diamond drilling. The host serpentinite bodies of the deposits are commonly surrounded by a chlorite-amphibole rock selvage that is pyroxenite in chemical composition. The serpentinites correspond to either dunites or more commonly to peridotites and Hanski (1984) considers them as ultramafic olivine-clinopyroxene cumulates of the layered Proterozoic dykes.

Both Ni-Cu deposits, Hietaharju and Peura-aho (Fig. 6 and 7) exist in roughly similar lithologic associations. The Ni-Cu sulphides occur as dissemination, veins and a brecciating network in serpentinite, talc-carbonate and chlorite-amphibole host rocks. Massive ores are common at the contact between amphibolite-chlorite rock and felsic volcanics, probably emplaced as a result of mobilization. Graphite-rich phyllites, black schists and locally also felsic volcanics host the iron sulphide occurrences.

Kojonen (1981) has divided the Ni-Cu ores into four main types:

1) Disseminated and impregnated ore type in serpentinite and talc-carbonate rock: The oxide minerals, chromite, ilmenite and magnetite, exist as dissemination and the sulphides, pyrrhotite, pentlandite and chalcopyrite, as thin veinlets and fine-grained impregnation.

2) Massive Ni-Co-Cu-Fe sulphide ore in talc-carbonate rock: the main ore minerals are pyrrhotite, chalcopyrite, pentlandite and magnetite; at deeper levels also gersdorffite, löllingite and sperrylite.

3) Massive pyrite-rich Cu-Ni ore at the contact between felsic volcanics and serpentinite: the main minerals are pyrite and pyrrhotite together with chalcopyrite and pentlandite. Magnetite is also common.

4) Pyrite-predominant copper and nickel-poor ore type associated with the black schists and locally with the felsic metavolcanites.

The ores of Hietaharju and Peura-aho are composed of several lenticular bodies that may differ considerably from each other in ore type and mineralogy. The most important ore types are those numbered from 1 to 3 above and which display the following characteristic averages: $Cu/(Cu+Ni) = 0.32$ and $Pt/(Pt+Pd) = 0.268$.

Hietaharju

The Ni-Cu ore of Hietaharju is situated in the western part of the village on Kiannanniemi. The ore zone is 200 m long and 7 m wide. It consists of four different lenticular bodies called A,

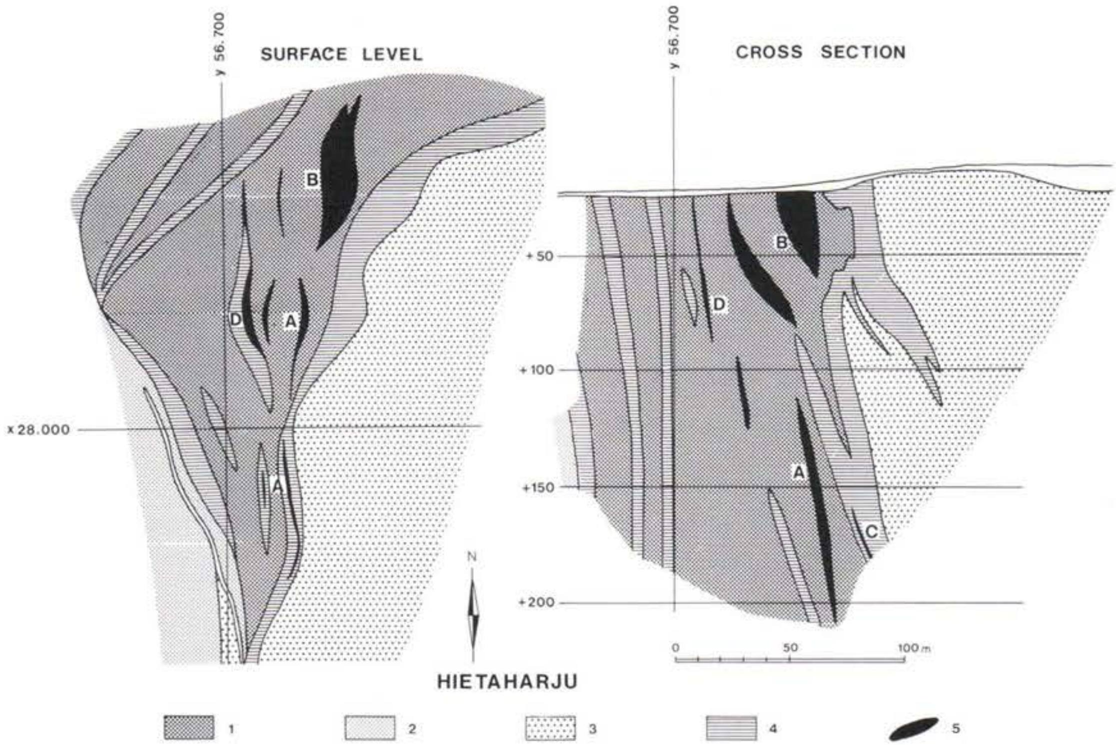

Fig. 6. Surface plan and cross section (x = 28.100) of the Hietaharju deposit. 1. Serpentinite; 2. Mafic metavolcanics; 3. Quartz-feldspar schist/quartz porphyry; 4. Chlorite-amphibolite rock; 5. Ore.

B, C and D (Fig. 6), which occur at the southern end of a talc-carbonate rock lens trending NNE (20°) near its hanging-wall contact with quartz-feldspar schist and felsic porphyry. The sulphides are commonly associated with zones rich in hornblende and chlorite. The dip of the talc-carbonate rock is 70° to east in the southern part of the body but subvertical in the north. Figure 6 depicts the surface plan and a cross-section of the Hietaharju deposit.

The ore lenses consist of disseminated, massive and brecciated ore types. The average contents of the metals are given in Table 5. The ore reserves have been estimated at about a quarter of a million tonnes assaying 0.86 % Ni, 0.43 % Cu, 0.05 % Co and 8.5 % S.

Table 5. The average metal and sulphur contents in the A—D ore bodies at Hietaharju. Data by Outokumpu Oy (Inkinen 1970). Metal values calculated for 100 % sulphides (38 % S) presented in parentheses.

	Cu	Ni	Co	S	Cu/Ni	Ni/Co	Cu/(Cu+Ni)	Pt/(Pt+Pd)
A	0.53 (2.37)	0.84 (3.76)	0.06 (0.27)	8.5	0.63	14.0	0.39	0.333
B	0.43 (0.92)	0.94 (4.20)	0.05 (0.22)	8.5	0.46	18.8	0.31	0.286
C	0.35 (1.39)	0.93 (3.68)	0.06 (0.24)	9.6	0.38	15.5	0.27	0.231
D	0.23 (1.78)	0.58 (4.50)	0.03 (0.23)	4.9	0.40	19.3	0.28	
A+B+C+D	0.43 (1.92)	0.86 (3.84)	0.05 (0.22)	8.5	0.50	17.2	0.33	0.283

Peura-aho

The ore deposit of Peura-aho is located c. 6 km N of Hietaharju. The local geology is characterized by an anticline structure with the axis plunging 65°—70° to east. In the horizontal plan the outermost arch of the fold is composed of mafic metavolcanics with intercalations of quartz-feldspar schist, black schist and chlorite schists. The bulk of the fold is made up of serpentinite, but the core consists of quartz porphyry. Chlorite-amphibole rocks occur at the contacts of serpentinite. Figure 7 depicts the surface plan and the +50 m plan of the Peura-aho mineralized areas.

The ore occurrence consists of five lenticular bodies, called A—E, which vary in ore and host rock types. The principal ore lenses are A and B. The disseminated ore body A, which is situated in the serpentinite host rock in the southern flank of the fold, is associated with talc-carbonate shear zones. The massive ore body B is complicated in shape and its host rocks vary from amphibole-chlorite rock to chlorite schists and quartz porphyry. The ore bodies C and D are rather weak sulphide disseminations along the inner contact zone of the serpentinite. Table 6 gives the average metal and sulphur contents of the ore bodies. The whole deposit of Peura-aho contains c. 260,000 tonnes of ore averaging 0.58 % Ni, 0.24 % Cu and 7.4 % S.

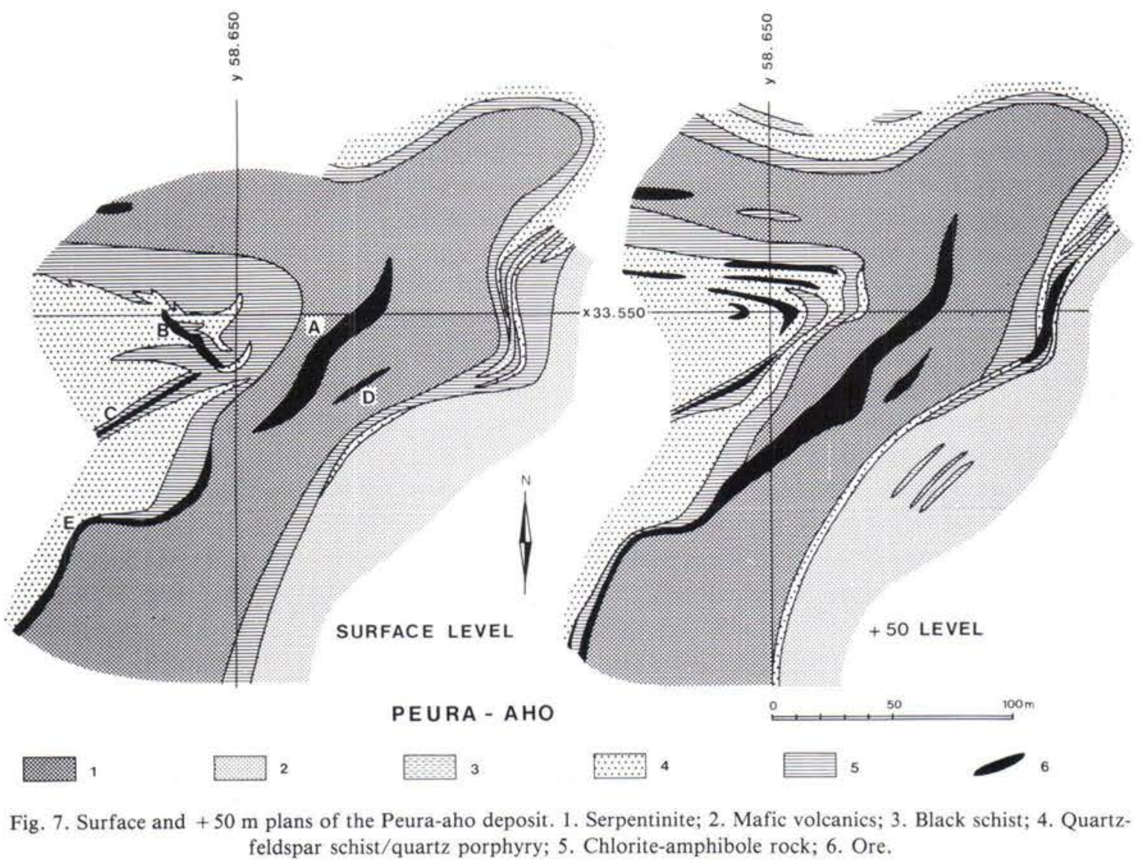

Fig. 7. Surface and +50 m plans of the Peura-aho deposit. 1. Serpentinite; 2. Mafic volcanics; 3. Black schist; 4. Quartz-feldspar schist/quartz porphyry; 5. Chlorite-amphibole rock; 6. Ore.

Table 6. The average metal and sulphur contents in the A—E ore bodies at Peura-aho (Pehkonen 1963; Inkinen 1970). Metal values calculated for 100 % sulphides (38 % S) presented in parentheses.

	Cu	Ni	Co	S	Cu/Ni	Ni/Co	Cu / Cu+Ni	Pt / Pt+Pd
A	0.20 (2.45)	0.52 (6.37)	0.03 (0.37)	3.1	0.41	17.3	0.29	0.333
B	0.31 (0.70)	0.76 (1.72)	0.03 (0.07)	16.76	0.41	25.3	0.29	0.176
C	0.51	0.81			0.62		0.39	
D	0.13 (3.53)	0.35 (9.50)	0.03 (0.81)	1.4	0.37	11.7	0.27	
E	0.14 (0.63)	0.44 (1.99)	0.05 (0.23)	8.4	0.33	8.8	0.25	
A+B+C+D+E	0.24 (1.23)	0.58 (2.98)	0.04 (0.21)	7.4	0.43	14.5	0.30	0.255

CONCLUSIONS

The horizons of felsic metavolcanics and graphite-sulphide-bearing metasediments seem to control the Ni-Cu mineralization. The host for the ore is commonly ultramafic rock, either serpentinite or its carbonated counterpart. Locally, however, the Ni-Cu sulphides extend into the sulphide-bearing metasediment. The disseminated sulphides in ultramafic host rocks invariably have higher tenors of Ni and Cu in the sulphide phase (calculated as 100 % sulphides) than the more massive and brecciated sulphides in metasediments or felsic volcanics. This is well documented, e.g. in the Peura-aho ore body »B», which is located in felsic schists and has a low tenor of nickel and copper in the sulphide phase. The high contents of Co and minerals such as gersdorffite and cobaltite have been encountered in the ore type with carbonated host rocks. The ultramafics overlying stratigraphically the ore horizon seems to be a fractionated sill with ultramafic cumulates at its base. The relatively high copper tenor in ore probably indicates that the bulk composition of the overlying rock was mafic. The structures suggest that the ores folded together with the metasediments and metavolcanics. Hanski's (1984) idea of the Proterozoic age of the fractionated mafic-ultramafic sills is based on the geochemical similarities with dated Proterozoic dykes in the Kuhmo area. However, the question of Proterzoic vs. Archean age of the ores and host rocks is open and cannot be solved without detailed field research and age determinations of the ultramafics.

PGE-BEARING COPPER-NICKEL OCCURRENCES IN THE MARGINAL SERIES OF THE EARLY PROTEROZOIC KOILLISMAA LAYERED INTRUSION, NORTHERN FINLAND

J. LAHTINEN

Mafic and ultramafic rocks that can be classified as layered intrusions occur in northern Finland (Fig. 8) at Koitelainen, Tornio, Kemi, Penikat, Suhanko and Koillismaa. Radiometric

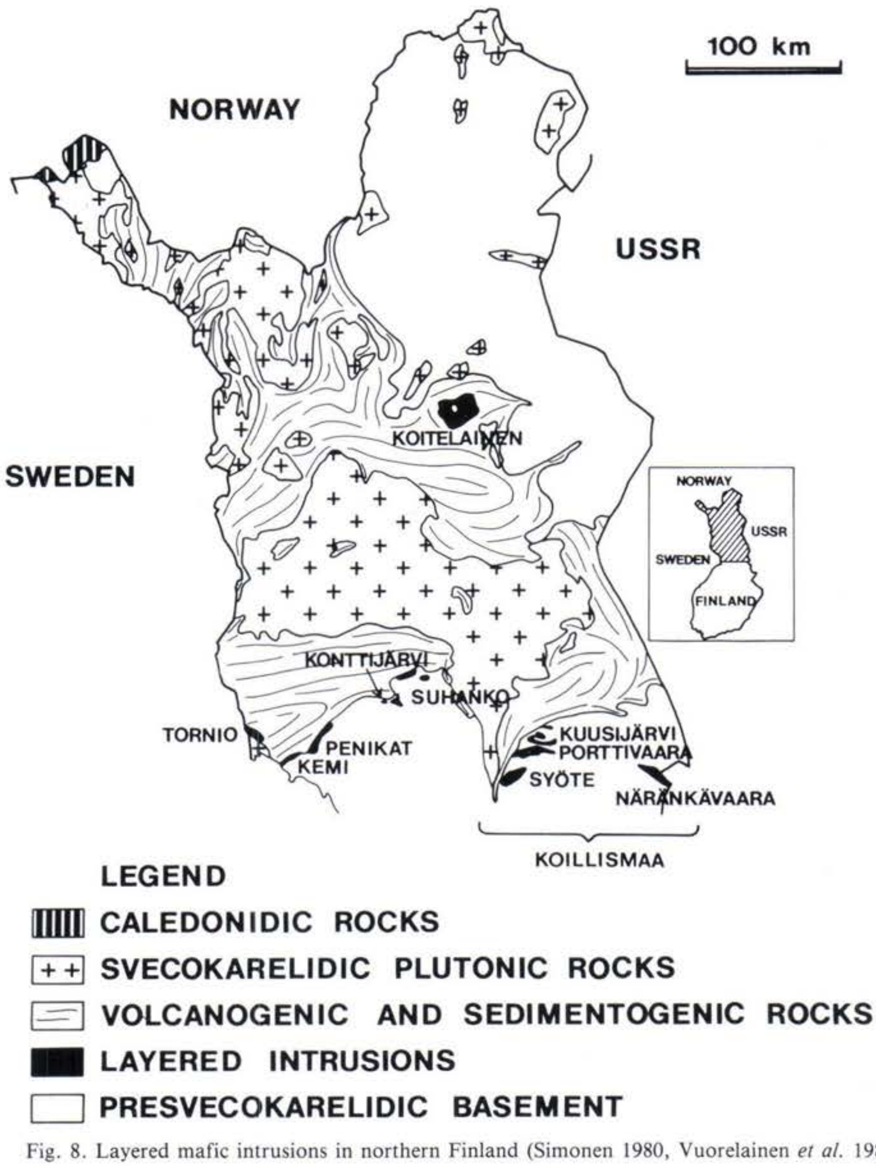

Fig. 8. Layered mafic intrusions in northern Finland (Simonen 1980, Vuorelainen *et al.* 1982).

datings undertaken by the Geological Survey of Finland (Kouvo 1977) show that the layered intrusions are associated with Early Proterozoic mafic magmatism that took place some 2 440 Ma ago (Fig. 9).

The magmatism was cratonic and it thus differs from the younger orogenic mafic magmatism (c. 1 885 Ma, Kouvo op. cit.) of the Kotalahti nickel zone and of southern Finland. The layered intrusions were originally emplaced in analogous environments between the Presvecokarelian granite gneiss complex (c. 2 800 Ma) and the overlying Lapponian volcanosedimentary sequence.

The economic significance of the layered intrusions is manifested by the two operating

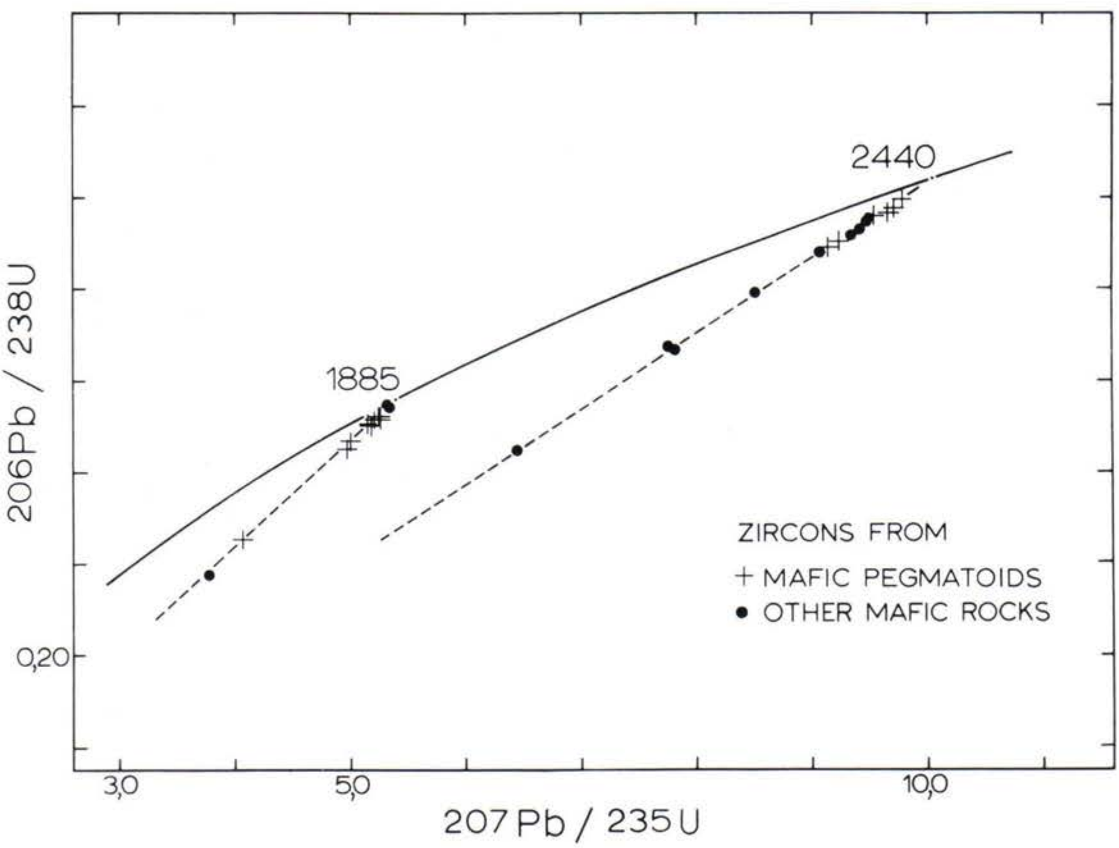

Fig. 9. Concordia diagram for U-Pb ratios of zircons from mafic layered intrusions of northern Finland (2 440 Ma group) and from mafic and ultramafic intrusions of southern Finland (Kouvo 1977).

mines: the Kemi chromium mine and the Mustavaara vanadium mine. Several non-economic sulphide and oxide occurrences are known in addition to these two, and many prospects are currently being studied.

Besides the main intrusion, there are also a number of smaller satellite intrusions in the Koitelainen area. A chromitite layer, with an average thickness of 1.3 m (Mutanen 1981), occurs in the anorthositic zone in the upper portions of the main intrusion. Several chromitite layers of varying thickness and sulphide accumulations with low nickel values in the sulphide phase have also been encountered in the lower parts on the layered intrusion (Mutanen, oral comm.).

The Tornio — Näränkävaara belt of layered intrusions extends right across Finland from the Tornio area in the west to Näränkävaara on the Finnish-Soviet border.

The intrusions in the western part of the Tornio — Näränkävaara belt are characterised by chromitite layers in the ultramafic zone at the base of the sequence. At Tornio (Söderholm and Inkinen 1982) and Penikat (Kujanpää 1964; Mälkki 1964) the chromitite layers are thin, but at Kemi the main chromium ore body is exceptionally thick, averaging 90 m (Kujanpää 1980).

Chromitites are absent from the middle of the belt of layered intrusions (Suhanko area); sulphides, however, occur in their marginal series. The disseminated mineralisation type that is as-

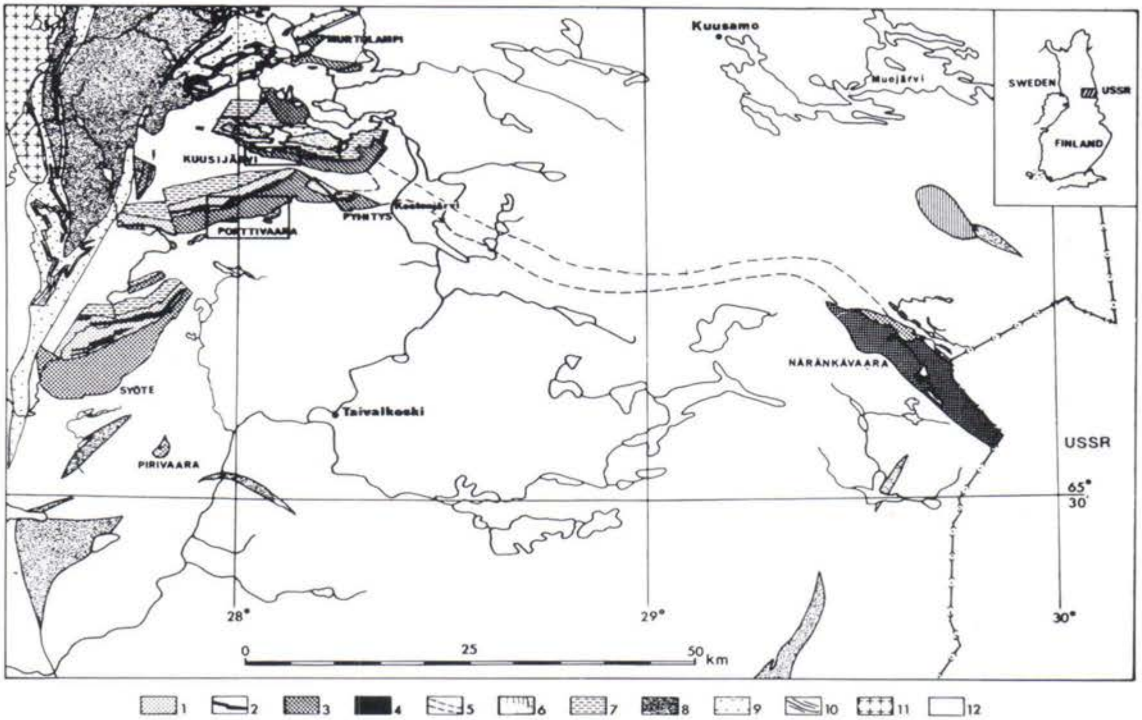

Fig. 10. Simplified geological map of Koillismaa (Alapieti *et al.* 1979 a). Rocks of layered intrusions: 1. Leucogabbro and anorthosite; 2. Magnetite gabbro; 3. Norite; 4. Ultramafite; 5. Connecting »dyke»; Surrounding rocks: 6. Alkaline rocks; 7. Biotite-albite rock; 8. Amphibolite; 9. Quartzite; 10. Mica schist; 11. Granite; 12. Granite gneiss.

sociated with the central and contaminated basal parts of the marginal series and which has high copper and fairly high nickel contents in the sulphide phase is represented by the PGE-bearing Cu-Ni occurrence at Konttijärvi (Vuorelainen *et al.* 1982). At Vaaralampi, in the southern margin of Suhanko intrusion a fairly large and almost massive pyrrhotite accumulation occurs at the basal contact of the intrusion, and, in places, in the granite gneiss complex (Reino and Hautala 1980). The nickel content of the sulphide phase of the pyrrhotite ores is low. The several $\delta^{34}S$ per mil values of the pyrrhotites from the Vaaralampi occurrence range between +2,0 and +2,4 suggesting a magmatic origin for sulphur. Sulphides derived from layered intrusions also occur in the granite gneiss in the Suhanko area as veins of the off-set type and as dissemination, which are often rich in copper and silver but usually depleted in nickel. As at Konttijärvi, these mineralisations have appreciable PGE and gold values.

The largest Cu—Ni occurrences in the layered intrusions in northern Finland are met with in the marginal series of the Porttivaara and Kuusijärvi blocks of the Koillismaa intrusion (Figs. 10, 13, 14 and 15). The sulphide occurrences in the marginal series and higher up in the sequence show moderate PGE and Au values. No ultramafic layers or chromitites have been met with in the layered series of the western blocks of the Koillismaa intrusion. The magnetite gabbro in the upper parts of the sequence contains vanadium, which is mined at Mustavaara in the Porttivaara block of the Koillismaa intrusion. The Näränkävaara block in the eastern portion of the intrusion is composed mainly of ultramafic cumulates, which here, too, occur in the layered sequence.

THE KOILLISMAA LAYERED INTRUSION

The following description of the geologic setup of the Koillismaa intrusion (Fig. 10) is based largely on findings of the Koillismaa Research Project at Oulu university (Piirainen *et al.* 1974; A. Juopperi 1977; Piirainen *et al.* 1978; Alapieti *et al.* 1979 a; Alapieti *et al.* 1979 b; Alapieti 1981) and on theses submitted by Mäkelä (1975), Isohanni (1976), H. Juopperi (1976) and Kerkkonen (1976).

The mafic and ultramafic intrusions at Syöte, Porttivaara, Kuusijärvi and Näränkävaara (Fig. 10) have been interpreted as blocks of the originally coherent Koillismaa layered intrusion (Fig. 11) which were pushed by movements into their present position and attitude (Piirainen *et al.* 1978). On the presentday surface the Syöte and Porttivaara blocks are surrounded mainly by the granite gneiss complex. Sedimentogenic and volcanogenic rocks overlie the Kuusijärvi basin-like block (Juopperi 1976). The longitudinal axis of the Syöte block trends SW-NE and the layering dips 30°—40° NW. The Porttivaara block trends largely in the same direction, except in its westernmost and easternmost parts, where the longitudinal axis of the block trends approximately W-E. The Kuusijärvi block, which is oriented roughly E-W, shows a basin structure: in the south the layering of the block dips northwards and in the north (at Lipeävaara) southwards. The layering of the small blocks of the intrusion north of Kuusijärvi also dips southwards. The Näränkävaara block, which is composed mainly of ultramafic cumulates, has been interpreted as the part of the Koillismaa intrusion that is located over the feeder channel (Alapieti *et al.* 1979 b). A strong gravity high joins the western blocks of the intrusion (Syöte, Porttivaara, Kuusijärvi) to Näränkävaara. The gravity high is thought to indicate the feeder channel of the mafic magma and the part of the intrusion that lies over the channel (Piirainen *et al.* 1978).

The original thickness of the intrusion varied (Fig. 11). The sequence was thickest at Syöte in the southern parts of the intrusion, where the primary thickness is assumed to have been about 3 km (Alapieti *et al.* 1979 a). The intrusion tapered northwards and at Porttivaara it was c. 2 km thick; at Kuusijärvi the thickness was still less. The bulk of the mafic magma was intruded in a single stage, although in some places there are signs suggesting that the emplacement took place in several pulses (Mäkelä 1975).

The best-known part of the Koillismaa intrusion is the Porttivaara block. Its main structural

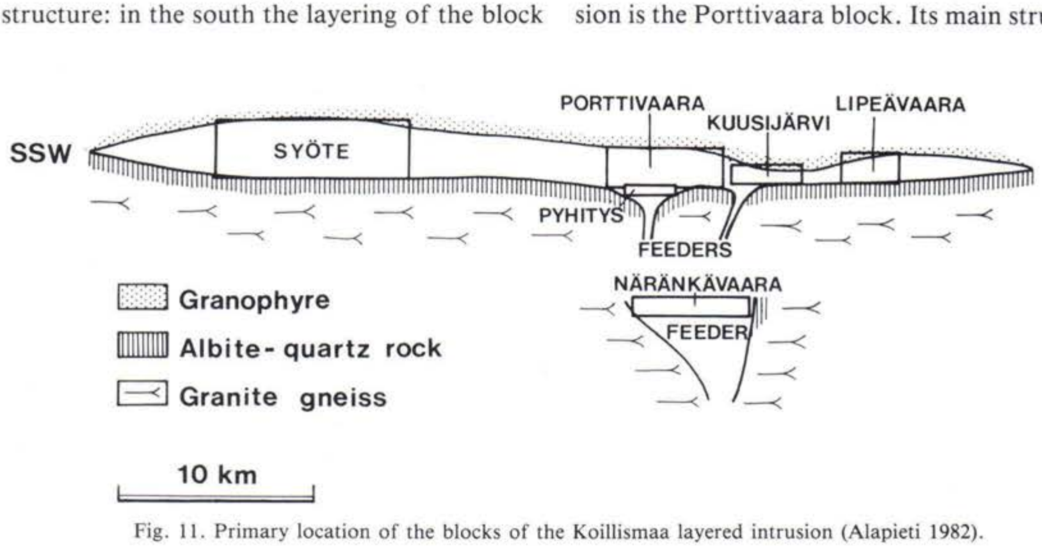

Fig. 11. Primary location of the blocks of the Koillismaa layered intrusion (Alapieti 1982).

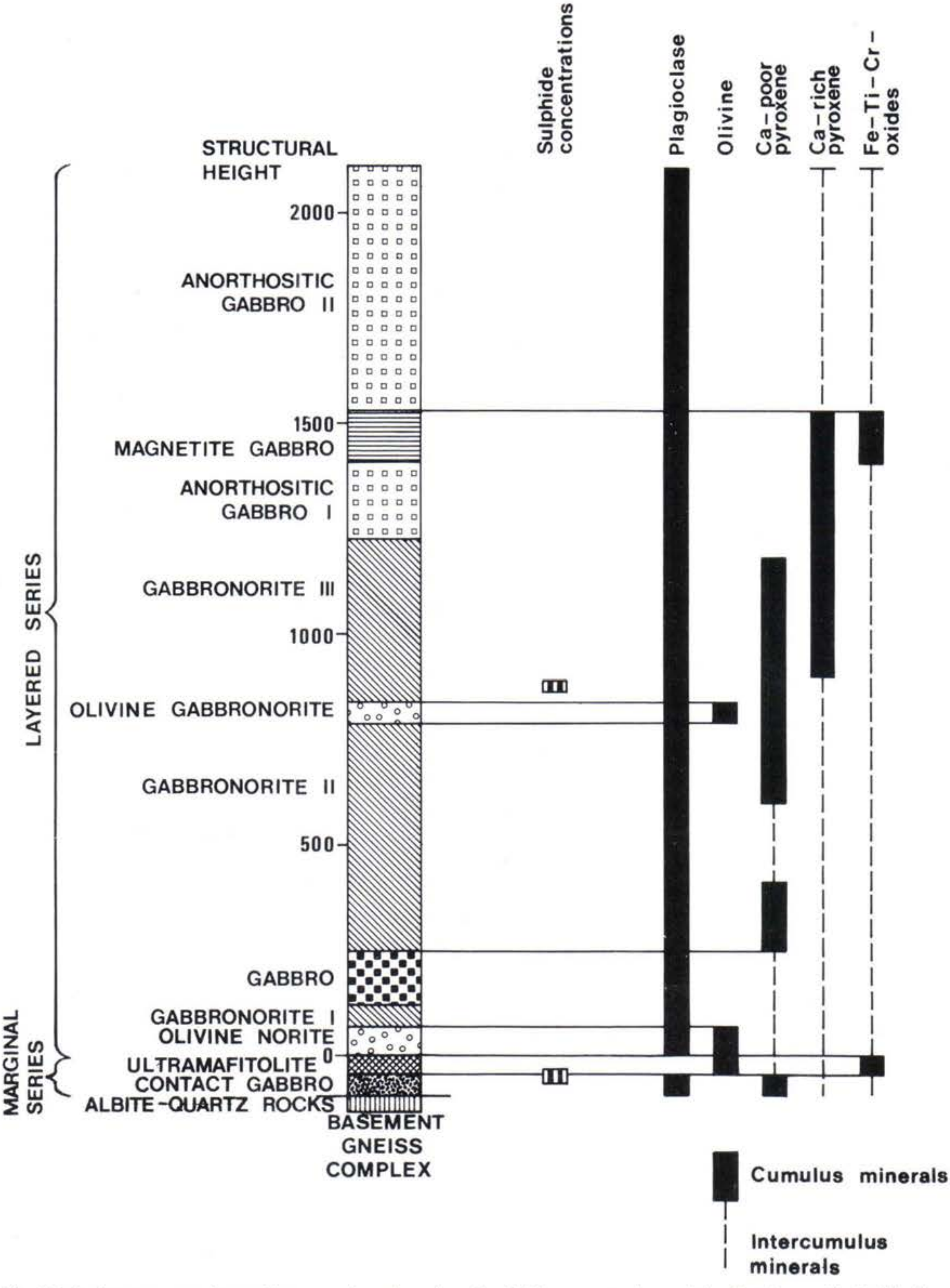

Fig. 12. Rock types, cumulus and intercumulus minerals and sulphide concentrations of the Porttivaara block (Piirainen *et al.* 1977, Alapieti 1981).

units, its rocks typified on the basis of Streckeisen's (1976) classification, and its major cumulus and intercumulus minerals are shown in Fig. 12.

The layered intrusions has two major parts. Against the granite gneiss basement there is a thin marginal series discordantly overlain (Mäkelä 1975) by a 2-km-thick layered sequence that crystallized following Fenner's series and which shows rhytmic and cryptic layering, and igneous lamination.

Norites with olivine as cumulus mineral occur at the base of the sequence. Gabbro norites with ortho- and clinopyroxenes predominate in the central parts, whereas anorthositic gabbros, are the major constituents in the upper parts. Between anorthositic gabbro I and anorthositic gabbro II there is a layer of magnetite gabbro with ilmenomagnetite, which is mined for vanadium at the Mustavaara mine (Juopperi 1977). Discontinuous and low-grade sulphide accumulations occur at the base of the gabbro norite III of the Syöte and Porttivaara blocks (Isohanni 1976). The biotite albite rocks overlying the layered intrusion are mainly granophyres (Alapieti 1981).

Albite-quartz rocks derived from gneisses partly melted and remobilised by the hot mafic magma of the Koillismaa intrusion occur between the granite gneiss complex and the marginal series.

The marginal series, which at Porttivaara is 50 to 200 m thick, includes in its lower parts gabbroic rocks (contact gabbro) and in its upper parts ultramafic rocks (ultramafitolite).

The contact gabbro overlying the albite-quartz rocks is fairly heterogeneous at its base, strongly contaminated and contains some albite quartz veins. In places the contact gabbro is brecciated by albite-quartz rocks. The upper part, where the bulk of the sulphides occur, is more homogeneous and usually coarse grained. Olivine normative gabbros predominate in this zone (Piirainen *et al.* 1977). The contact gabbro exhibits cumulus textures but also contains non-cumulate gabbroic rocks. The gabbro or gabbronorite with plagioclase (usually labradorite) as cumulus mineral predominates. Norites with orthopyroxene as primary cumulus mineral also exist. Clinopyroxene has been met with in only intercumulus. A narrow biotitised and silicified zone is present in drill hole section PSO-7 between the contact gabbro and the overlying ultramafitolite.

The uppermost part of the marginal series is composed of ultramafitolite with pyroxenites, olivine pyroxenites and peridotites as the primary rock types. The ultramafitolite includes gabbroic lenses and layers. The pyroxenites have orthopyroxene, and the olivine pyroxenites and peridotites have olivine as their primary cumulus minerals.

The primary silicates of the marginal series (olivine, orthopyroxene, clinopyroxene) are altered into the lower temperature minerals, serpentinite, talc, carbonate, uralite and chlorite; even so, the primary texture of the rocks is usually still recognisable.

Although no chill zone proper has been encountered against the granite gneiss basement, it has been assumed (Alapieti 1981) that certain fine-grained gabbroic rocks that occur as fragments in the more coarse-grained portions of the contact gabbro may represent the primary chilled margin from which they were removed by magma flows.

THE CU—NI SHOWINGS IN THE MARGINAL SERIES

The description of the sulphide showings in the marginal series at Kuusijärvi is based on data gathered by Outokumpu Oy, observations on the outcrops and data on two diamond drill

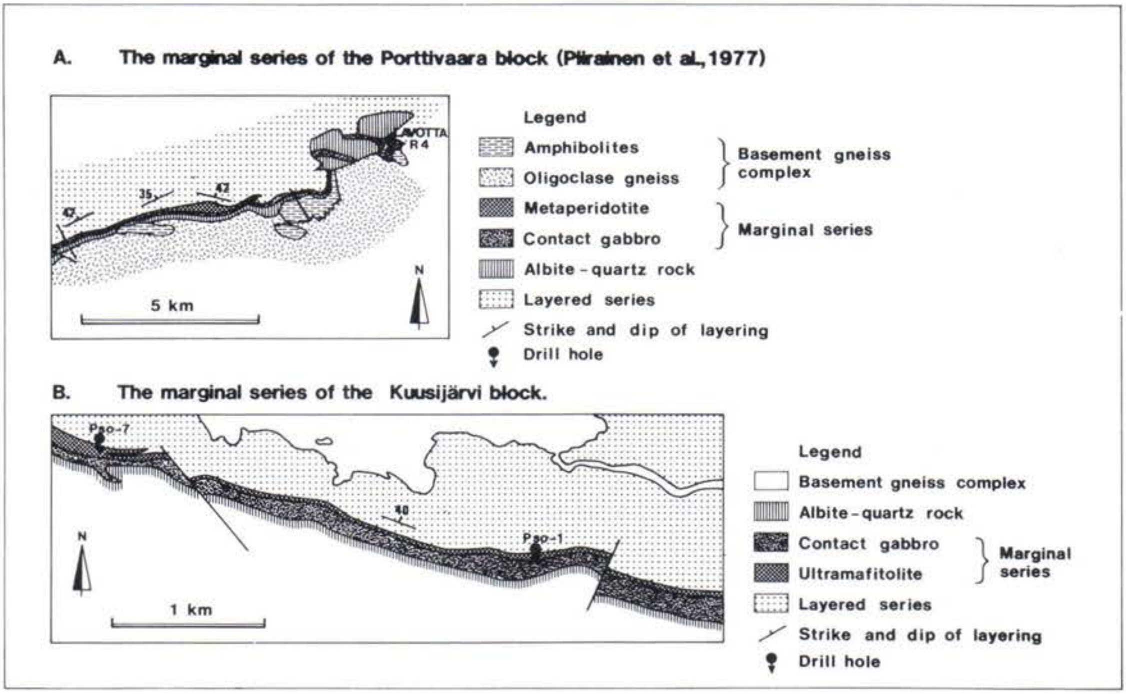

Fig. 13. Details of the geological map of the Koillismaa area (Fig. 10).

cores (PSO-1 and PSO-7). For the Porttivaara showing, the findings of the Koillismaa Research Project (Kerkkonen 1976; Piirainen *et al.* 1977) and data by Outokumpu Oy and Rautaruukki Oy were available.

The showing in the marginal series of the Porttivaara block has been traced for 11 km (Fig. 13). In the southern margin of the Kuusijärvi basin-like block the showing extends for about 9 km. The average thickness of both showings is about 20 m. At Kuusijärvi sulphide concentrations have also been encountered in the northern marginal series (Lipeävaara); for lack of relevant information, however, they are not dealt with in detail in this context.

The sulphides are located mainly in the coarse contact gabbro overlain by ultramafitolite, although in places they extend into the ultramafitolite as well (see Figs. 14 and 15). Dispersed sulphides may also be encountered in the basal parts of the contact gabbro (Fig. 15). The sulphides occur as dissemination of various grain sizes and as irregular blebs up to 10 cm in size. Micron-sized chalcopyrite-predominant sulphide dissemination is often encountered as inclusions in the uralite grains. In general the mineralisation does not exhibit well-defined contacts, the abundance of sulphides usually diminishing gradually both upwards and downwards (Fig. 14); even at its best the abundance of sulphides is only a few volume percentages. The sulphides fill the intersticies between the silicate grains and are often abundant when associated with specks of quartz and albite. Around sulphide-rich portions, plagioclase (originally labradorite) is typically altered into albite and epidote.

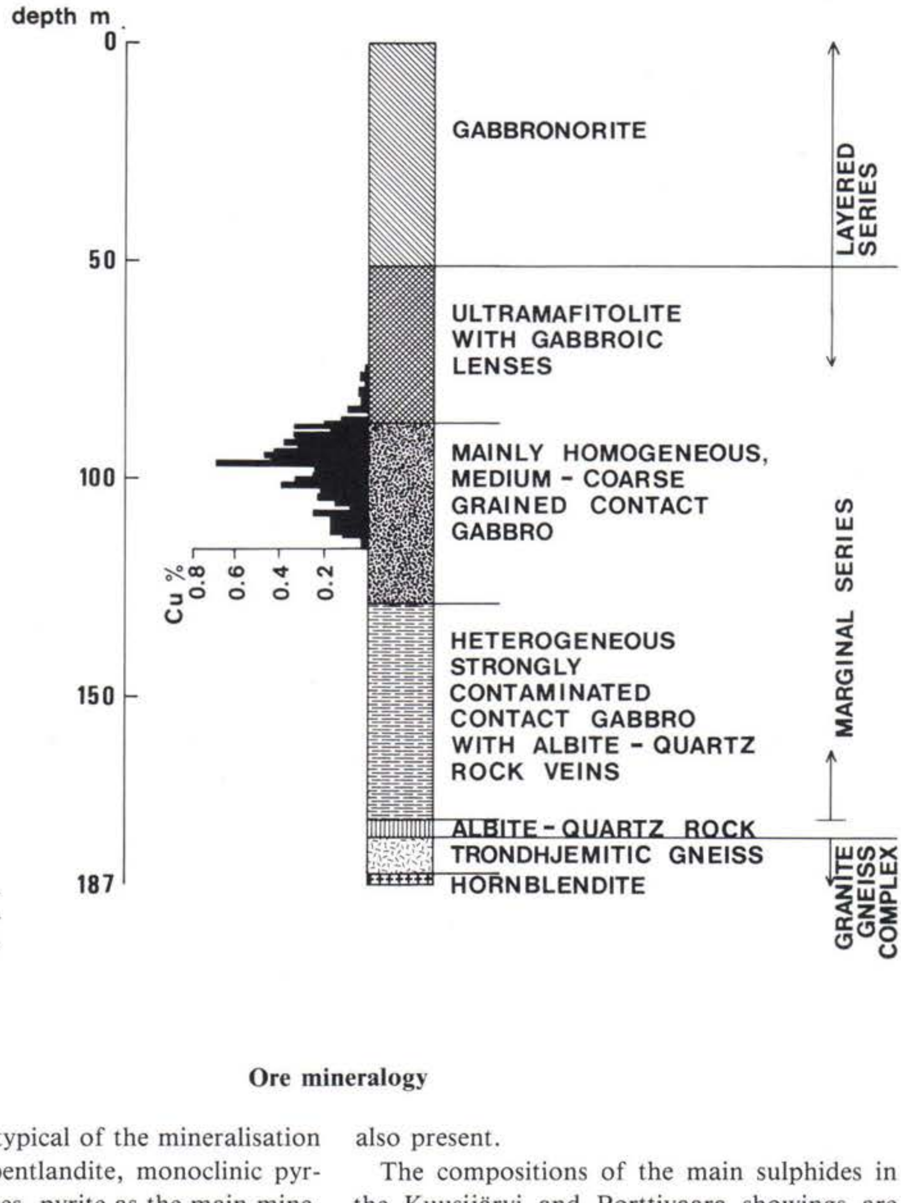

Fig. 14. Drill hole section Pso-7 of the marginal series, Kuusijärvi.

Ore mineralogy

The assemblage typical of the mineralisation has chalcopyrite, pentlandite, monoclinic pyrrhotite and, in places, pyrite as the main minerals. A sulphur-poorer assemblage of chalcopyrite-bornite-millerite-pentlandite is also encountered. The accessories are covelline, violarite, marcasite, mackinawite, sphalerite and argentian pentlandite. Palladium bismuthides and tellurides (froodite, michenerite and merenskyite), and hessite often occur as trace constituents as inclusions in and around the sulphides. Native copper, gold and electrum, and sperrylite are also present.

The compositions of the main sulphides in the Kuusijärvi and Porttivaara showings are given in Table 7. The pyrrhotite in both mineralisations is characterised by fairly high Ni values, above 0.45 % and low cobalt values ($\leq$ 0.05 %). Pyrite is an important carrier of cobalt, and the cobalt values fluctuate between 1.21 and 3.17 %. The nickel content of pentlandite varies from 35.2 to 39.58 % and that of cobalt from 0.44 to 2.19 %.

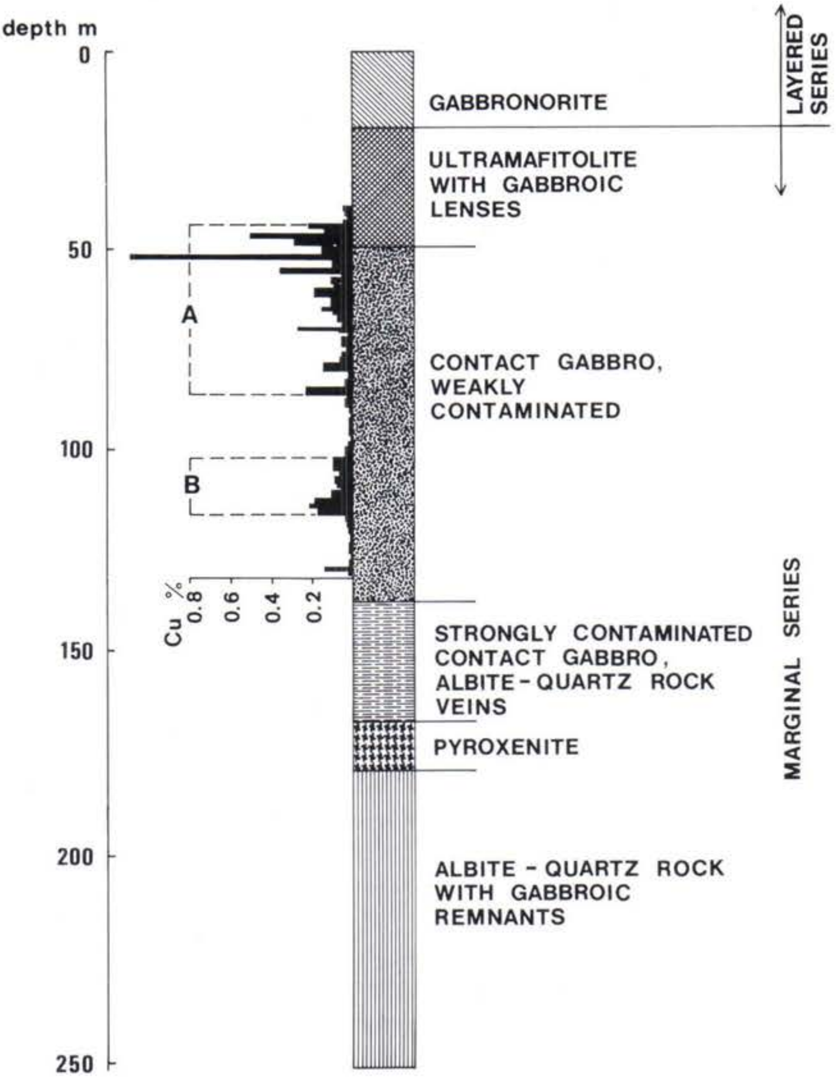

Fig. 15. Drill hole section Pso-1 of the marginal series, Kuusijärvi.

Metal contents and analytical methods

The sulphide occurrence in the marginal series at Kuusijärvi averages 0.15 % Cu and 0.09 % Ni. The corresponding figures for Porttivaara are 0.20 % Cu and 0.11 % Ni. Data on cobalt, silver, gold, palladium and platinum are available from only two drill holes at Kuusijärvi (PSO-1 and PSO-7) and from a single drill hole at Porttivaara (Lavotta R 4). The average ore intersections are given in Table 8. The richest portion of the occurrence assays 0.4 % Cu, 0.2 % Ni, 1 % S, 4 ppm Ag, 0.3 ppm Au, 0.6 ppm Pd and 0.2 ppm Pt (see Fig. 16). At Kuusijärvi the metal contents and proportions vary in a lateral direction. A direct comparison with the values for the Porttivaara showing, particularly the Ni values, is hampered by the difference in

Table 7. Microprobe analyses of sulphides in the marginal series of Porttivaara (A) and Kuusijärvi (B) blocks. Values in wt-%.

A. Porttivaara (Piirainen *et al.* 1977). Analyses were performed at the Institute of Electron Optics, University of Oulu.

	1	2	3	4	5	6	7	8	9	10	11
Zn	n.d.	0.01	n.d.	n.d.	n.d.	0.01	0.01	0.02	0.03	0.02	n.d.
Cu	n.d.	n.d.	32.8	33.2	70.0	0.11	0.17	0.01	n.d.	0.01	0.44
Ni	35.2	38.5	0.02	0.02	0.26	0.47	0.69	0.78	0.47	0.06	0.03
Co	0.61	0.95	0.03	0.04	0.07	0.04	0.05	0.05	0.04	1.21	2.14
Fe	31.0	28.7	30.6	30.6	—	61.7	59.1	59.1	59.5	47.0	44.5
S	33.4	32.2	34.1	34.1	27.8	40.0	38.7	38.9	40.0	52.6	51.5
Total	100.21	100.30	97.55	97.96	98.13	102.33	98.72	98.86	100.04	100.90	98.61

1 = Pentlandite, Specimen M278D, 2 = Pentlandite, Specimen M295, 3 = Chalcopyrite, Specimen M278H, 4 = Chalcopyrite, Specimen M295, 5 = Covellite, Specimen M278C, 6 = Pyrrhotite, Specimen M278D, 7 = Pyrrhotite, Specimen M278H, 8 = Pyrrhotite, Specimen M295, 9 = Pyrrhotite, Specimen M278C, 10 = Pyrite, Specimen M278D, 11 = Pyrite, Specimen M278C, n.d. = Not detected

B. Kuusijärvi. Analyses were performed at the Geological Laboratory of Outokumpu Oy.

	1	2	3	4	5	6	7	8	9	10
Ni	0.48	35.72	0.49	35.93	0.12	62.35	39.58	0.18	0.45	35.77
Co	0.03	0.77	0.01	0.50	3.17	0.54	0.44	1.99	0.02	1.29
Fe	59.46	30.34	59.07	30.16	43.73	1.75	26.37	44.49	59.37	30.01
S	39.16	32.28	38.56	32.48	52.93	33.43	32.32	52.00	39.03	32.63
Total	99.13	99.11	98.13	99.07	99.95	98.07	98.71	99.66	98.87	99.70

1 = Pyrrhotite PSO-7/93.00, 2 = Pentlandite PSO-7/93.00, 3 = Pyrrhotite PSO-7/95.20, 4 = Pentlandite PSO-7/95.20, 5 = Pyrite PSO-7/95.20, 6 = Millerite PSO-7/113.50, 7 = Pentlandite PSO-7/85.50, 8 = Pyrite PSO-7/85.50, 9 = Pyrrhotite PSO-7/89.20, 10 = Pentlandite PSO-7/89.20

the analytical methods applied.

The histograms in Figs. 16 and 17 illustrate the element variation in drill intersections PSO-7 and PSO-1 and show a strong positive correlation between the element values (Cu, Ni, S, Ag, Au, Pd, Pt). Particularly in section PSO-7 the metal values are highest in the middle but decline towards the margins of the occurrence.

The samples from Kuusijärvi drill intersections PSO-1 and PSO-7 were analysed for Cu, Co and Ag by AAS after HNO_3 leach. Nickel was assayed by AAS after a selective leach of sulphides (Bromine methanol leach; Penttinen *et al.* 1977). Sulphur was analysed on a Leco SR-32 sulphur determinator. For the palladium and platinum assays, a sample of 10 g was dissolved in aqua regia. Gold and palladium were extracted from 2-normal hydrochloric acid by means of a dibutyl sulphide dissolved in diisobutyl keton. Au and Pd were determined from the organic phase by AAS. Platinum was analysed docimastically. About 10 to 20 mg gold were added to a sample of 100 g. The precious metals were collected into a bead of lead, which was then evaporated. The nugget of precious metals thus obtained was dissolved in aqua regia and platinum was determined by AAS.

Drill intersection R 4 at Lavotta, Porttivaara, was analysed for copper, nickel and sulphur by XRF. For the platinum and palladium analyses, a pulverised sample (25 g) was heated (at 1 100°C) together with the flux, nickel and

Table 8. Weighed means of metal values (A), metal values recalculated to 100 % sulphides assuming 37 % S in the sulphide fraction (B) and metal ratios (C) of ore intersections of the marginal series of the Kuusijärvi and Porttivaara occurrences.

A. Metal contents

Element	Kuusijärvi PSO-7	Kuusijärvi PSO-1 A	Kuusijärvi PSO-1 B	Porttivaara Lavotta R 4
Cu ppm	2389	1273	1017	2832
Ni ppm	1201	723	443	2422
Co ppm	57	62	51	—
Ag ppm	2.75	3.58	2.93	1.09
Pd ppm	0.330	0.223	0.134	0.257
Pt ppm	0.145	0.049	0.056	0.185
Au ppm	0.096	0.044	0.023	—
S %	0.50	0.39	0.25	0.70

B. Metal values of sulphide fraction

Element	PSO-7	PSO-1 A	PSO-1 B	Lavotta R 4
Cu %	17.68	12.08	15.05	14.97
Ni %	8.89	6.86	6.56	
Co %	0.42	0.59	0.75	
Ag ppm	204	340	434	58
Pd ppm	24.42	21.16	*	13.58
Pt ppm	10.73	4.65	*	9.78
Au ppm	7.10	4.17	*	

C. Metal ratios

Ratio	PSO-7	PSO-1 A	PSO-1 B	Lavotta R 4
Cu/Ni	3.10	2.32	7.63	
Cu/(Cu+Ni)	0.69	0.64	0.76	
Ni/Co	19.75	10.20	7.60	
Pd/Pt	2.51	7.65	*	1.42
Pt/Pd	0.46	0.22	*	0.73
Pt/(Pt+Pd)	0.31	0.17	*	0.42

* not calculated because of low values of metals and sulphur

sulphur, whereupon the precious metals collected in the nickel sulphide layer at the base of the crucible. The Ni sulphide bead separated from the slag was pulverised and dissolved in hydrochloric acid. The undissolved precious metals were separated by filtering and then dissolved. Platinum and palladium were analysed by a flameless AAS. Silver was leached from the samples in aqua regia and then extracted from the HNO_3 solution into a tri-iso-octyltiophosphate-methyl-iso-butylketon mixture.

Composition of the sulphide phase

The metal contents of the sulphide phase in the showings at Kuusijärvi and Porttivaara (Table 8 B, Fig. 16) were calculated by assuming that the sulphur content of the sulphide phase was 37 %, which is probably close to the true value of the assemblage chalcopyrite-pentlandite-pyrrhotite (± pyrite) typical of the mineralisation.

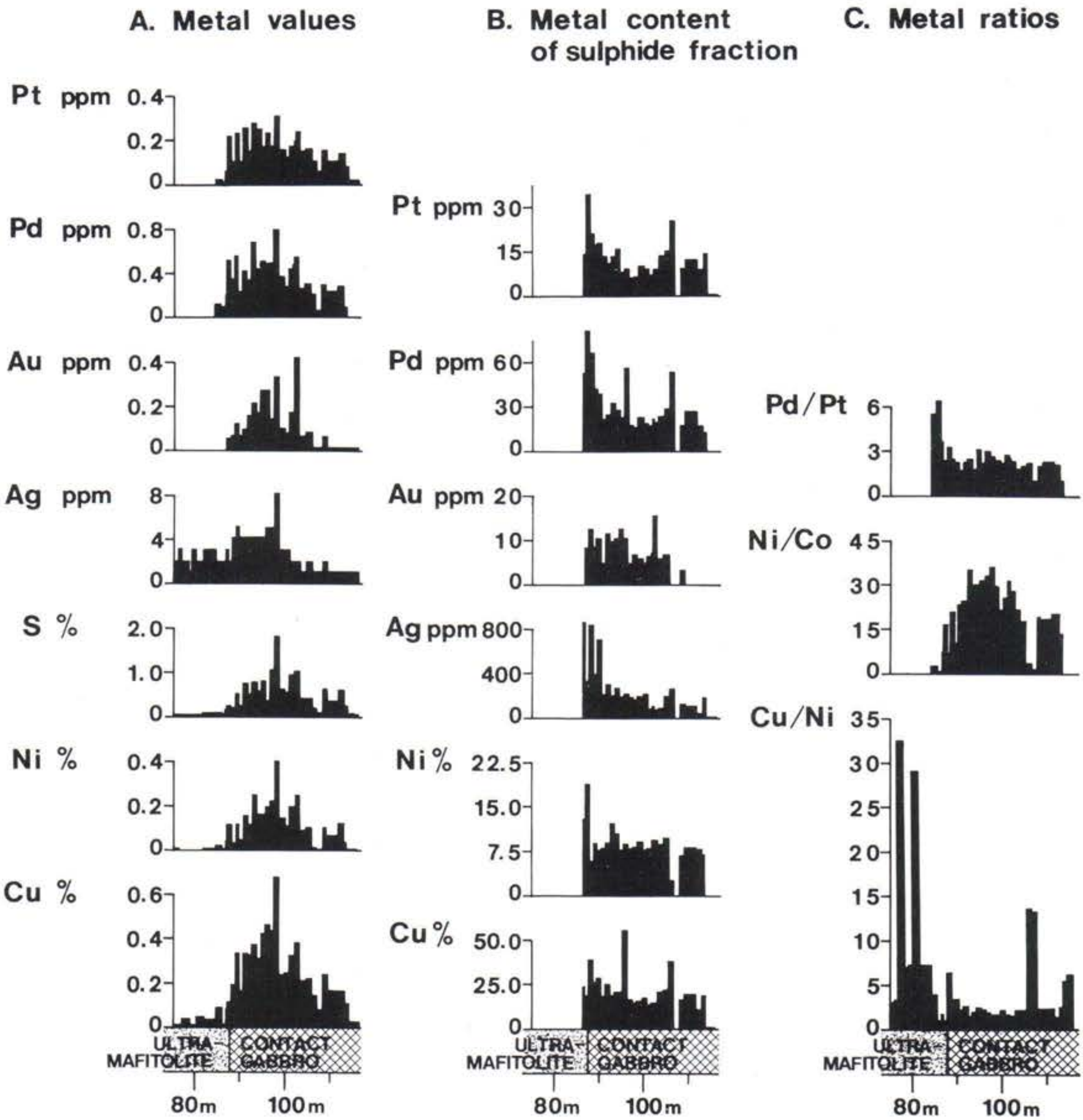

Fig. 16. Metal values (A), metal values of sulphide fraction (B) and some metal ratios (C) of section Pso-7, Kuusijärvi.

The sulphide phases of the showings are conspicuously high in copper and also in nickel, cobalt and precious metals. In ore intersection PSO-7 at Kuusijärvi the calculated sulphide phase averages 17.68 % Cu, 8.89 % Ni, 0.42 % Co, 204 ppm Ag, 7.10 ppm Au, 24.42 ppm Pd and 10.73 ppm Pt. The values of most of these metals are highest in the sulphide phase of the upper parts of the showing, where the proportion of sulphur is relatively low (Fig. 16).

Owing to the analytical method applied (XRF), it was not possible to calculate the

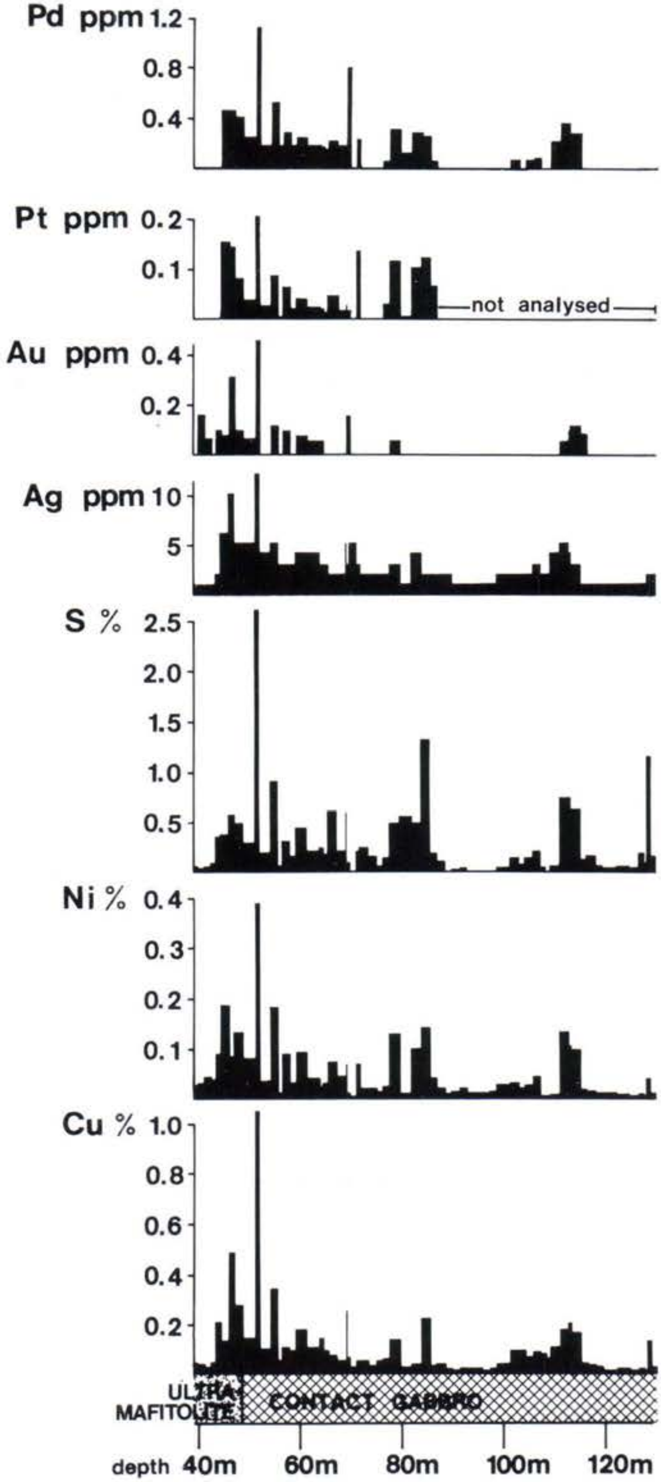

Fig. 17. Metal values of section Pso-1, Kuusijärvi.

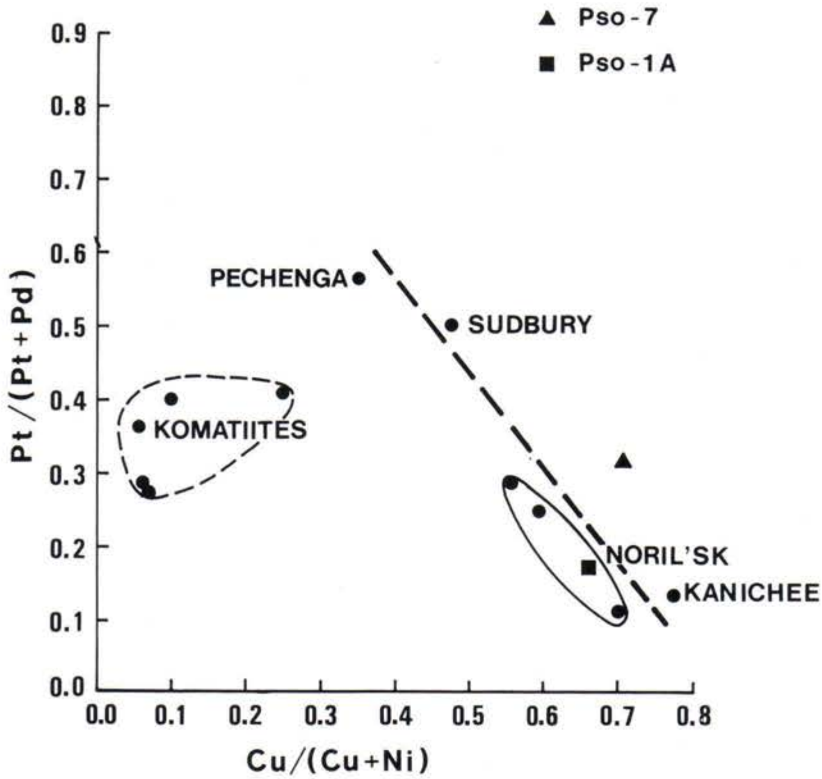

Fig. 18. Relationship between Pt/(Pt+Pd) and Cu/(Cu+Ni) in certain sulphide ores (Naldrett and Cabri 1976) and in the Kuusijärvi showing.

nickel content of the sulphide phase for intersection R 4 at Porttivaara (Table 8 B), because the analytical data include silicate nickel as well as sulphide nickel.

Metal ratios

Typical features of the sulphide showings in the marginal series are the preponderance of copper over nickel (Table 8 C) and the preponderance of palladium over platinum. At Kuusijärvi, the metal proportions vary markedly within the showing. Fig. 16 illustrates the variations of some metal ratios in drill intersection PSO-7. It is seen that the Pd/Pt ratio is highest in the upper portion of the showing, whereas the Ni/Co ratio is highest in the middle. The histogram displaying the Cu/Ni ratio shows clearly the strong copper predominance of the very weak and fine-grained sulphide dissemination outside the showing proper. Since the Ni analyses by XRF of intersection R 4 at Porttivaara include silicate nickel, it was not possible to calculate ratios with nickel as a component for Table 8 C.

In the Pt/(Pt+Pd) versus Cu/(Cu+Ni) diagram in Fig. 18 (Naldrett and Cabri 1976) the averages of the ore intersections at Kuusijärvi clearly plot in the tholeiitic field, PSO-1 A intersection, even in the field of the Noril'sk values.

SUMMARY AND DISCUSSION

The layered intrusion at Koillismaa is associated with the Early Proterozoic (2 440 Ma) cratonic mafic magmatism that extended over large areas of northern Finland. When the hot and dry magma penetrated between the granite gneiss basement and the overlying volcanites a sheet-like intrusion was formed. It had two parts, a thin marginal series and a thick layered portion that crystallised following Fenner's series (Piirainen *et al.* 1977). The sequence crystallised mainly as a closed system (Piirainen *et al.* op.cit.). The H_2O content and the oxygen fugacity were initially low in the magma, but at a later stage of crystallisation the oxygen fugacity increased and thus allowed the magnetite gabbro to form (Juopperi 1977).

The sulphide mineralisation in the marginal series was closely associated with events that took place at the base of the magma chamber during and immediately after the intrusion of the magma. At first a chilled margin was formed between the magma chamber and the granite gneiss basement (Piirainen *et al.* op.cit.). This, however, was brecciated and translated from its original place by later magma flows. The basement was melted by the thermal affect of the magma and the melt thus generated crystallised and altered afterwards to albite-quartz rocks (Alapieti 1982). This melt also contaminated the contact gabbro.

The Mg-Fe silicates (olivine, orthopyroxene) started to cumulate rather early on the contact gabbro, which was fairly viscose owing to salic contamination and partial crystallisation. Cumulating olivine and orthopyroxene gave rise to the ultramafitolite that acted as the hanging wall of the marginal series against the layered sequence. The contamination, the crystallisation of the Mg-Fe silicates, the drop in the temperature of the magma and the increase in the sulphur partial pressure in the gradually decreasing molten phase might all have reduced the so-

Table 9. Concentrations (averages) of metals in various deposits, metal contents of sulphide fraction. Modified after Naldrett *et al.*, 1979.

Type of deposit	Deposit	Ni	Cu	Co	Pt	Pd	Au
		wt-%			ppb		
Archean komatiites	Langmuir[1]	12.70	0.51	0.25	628	1182	94
	Mt. Edwards[1]	11.30	1.31	0.27	421	1063	67
	Kambalda[2]	12.10	0.84		<730	1314	402
Other ultramafic rocks (presumed komatiitic)	Pipe[1]	3.96	0.1	0.16	54	122	57
	Donaldson W.[1]	15.50	3.71	0.23	4131	15530	462
Sudbury	Levack W.[3]	5.00	3.70	0.13	1154	1253	150
	Little Stobie 1.[3]	3.60	4.40	0.19	1946	2108	733
	Little Stobie 2.[3]	4.00	3.67	0.17	2081	3132	859
Other gabbrorelated deposits	Noril'sk[4, 5]	7.60	10.90		13700	36000	1600
	Merensky[4]	10.90	4.65	0.18	258800	102000	21000
	Minnamax[6]	3.91	17.20	0.37	2640	8840	1170
Deposits related to layered intrusions in northern Finland	Konttijärvi[7]	12.19	34.80		151000	401000	
	Kuusijärvi (PSO-7)[8]	8.89	17.68	0.42	10730	24420	7100
	Porttivaara (R 4)[8]		15.55		10310	14250	
	Porttivaara (GBNO III)[9]	14.78	24.43	0.14			

References: 1. Naldrett *et al.* 1979, 2. Keays *et al.* 1976, 3. Hoffman *et al.* 1979, 4. Naldrett & Cabri 1976, 5. Smirnov 1977, 6. Naldrett & Duke 1980, 7. Vuorelainen *et al.* 1982, 8. This study, 9. Isohanni 1976, 7.—8. Showings in the marginal series, 7. Showing in metapyroxenite, 9. Showing in the layered séries, gabbro norite III lubility of sulphur in the silicate melt resulting in the segregation of the sulphide melt (Piirainen *et al.* op.cit.; MacLean 1969, Haughton *et al.* 1974; Shima and Naldrett 1975). When the liquid immiscibility of the sulphides took place, the interstices between the early cumulus minerals of the contact gabbro, and partly the ultramafitolite as well, probably still contained silicate melt. The crystallised portion was, however, so high that the sulphides were prevented by gravity from accumulating to form massive ores. The fairly high Cu/Ni ratio in the mineralisation also suggests that the sulphide melt segregated at a relatively late stage. The last to crystallise were the albite quartz veins and specks. The sulphide melt was equilibrated at a low temperature and crystallised as the final phase.

The $\delta^{34}S$ per mil values determined from the PSO-1 and PSO-7 ore intersections of the marginal series of the Kuusijärvi block range from +1.3 to 2.0 (Table 10), suggesting that the sulphur of the mineralisation is magmatic in origin.

The primary Mg-Fe silicates in the marginal series were altered after the crystallisation of the layered intrusion, possibly during the Svecokarelidic orogeny, c. 500 Ma later. It is highly probable that the sulphides recrystallised at the same time. The Svecokarelidic orogeny may also have been the factor that tore the originally coherent layered intrusion into several blocks.

Table 10. Sulphur isotope compositions from the marginal series of the Kuusijärvi intrusion.

Specimen: drill hole/depth		Fraction	$\delta^{34}S$ ‰
PSO-1	/ 46.42—47.20	Cpy	+2.0
	/ 47.20—48.98	Cpy	+1.2
	/ 59.62—61.54	Cpy	+1.8
	/ 59.62—61.54	Po	+1.5
	/111.63—113.20	Po	+1.4
	/113.20—113.67	Po	+1.3
PSO-7	/ 86.70—87.64	Po	+1.8
	/ 92.46—93.35	Cpy	+1.3
	/ 92.46—93.35	Po	+1.3
	/ 95.58—96.51	Cpy	+1.4
	/ 95.58—96.51	Po	+1.3
	/100.12—101.18	Cpy	+1.6
	/100.12—101.18	Po	+1.5
	/106.03—106.87	Cpy	+2.0

Error <0.2 ‰
Cpy = Chalcopyrite
Po = Pyrrhotite

The metal contents of the sulphide phases of the various Ni-Cu occurrences are compared in Table 9. The occurrences associated with komatiitic rocks show typically a strong preponderance of nickel over copper. Most of the occurrences in the tholeiitic intrusions listed in Table 9, and those in the tholeiitic intrusions in southern Finland, are nickel predominat (Vammala, Häkli *et al.* 1979; Laukunkangas, Grundström 1980). The sulphide disseminations in the marginal series of the layered intrusions in northern Finland are characterised by a fairly high nickel content, a very high copper content and a distinct copper predominance in the sulphide phase. The metal contents of the sulphide phases of the occurrences listed in Table 9, excluding the layered intrusions in northern Finland, are assumed to represent the values of the original sulphide melt (Naldrett *et al.* 1979). As to the sulphide showings in the marginal series of Koillismaa and the occurrence at Konttijärvi, which is also located in the marginal series, it is not quite clear whether the primary element values of the sulphide phase changed owing to the recrystallisation of the sulphides during the Svecokarelidic orogeny. Isohanni (1976) has noted that the sulphide phase of the showing in the gabbro norite III of the Porttivaara block of the Koillismaa intrusion has been secondarily enriched in some metals in relation to iron owing to the oxidation of iron after the crystallisation of sulphides and the subsequent depletion of sulphur. The sulphur is bound to the scapolite in the country rock.

The sulphide phases of the disseminated sulphides in the Koillismaa and Konttijärvi intrusions are rich in copper and nickel. The PGE values of the sulphide phase are also rather high and are characterised by a distinct preponderance of palladium over platinum. The sulphide phases of the massive pyrrhotite-predominant sulphide concentrations at the base of the Suhanko intrusion differ from the sulphide phases of Koillismaa and Konttijärvi in that the former are rich in iron and poor in nickel, copper and precious metals.

In spite of the differences between the Koillismaa and Noril'sk intrusions and between the associated sulphide occurrences, the sulphide phases of the Cu-Ni deposits are fairly similar in composition. Characteristic of both of them is the marked preponderance of copper over nickel and the similar PGE values and Pd/Pt ratios of the sulphide phases.

ACKNOWLEDGEMENTS

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I also wish to thank Outokumpu Oy and Rautaruukki Oy for the material they put at my disposal.

NICKEL OCCURRENCES OF THE OUTOKUMPU TYPE AT VUONOS AND KERETTI

J. PARKKINEN and J. REINO

The sulphide ores in the Outokumpu area are associated with formations composed of serpentinite lenses and enveloping quartz, skarn and carbonate rocks (Fig. 19). Known as the Outokumpu Association, the rocks constitute a ribbon-like meandering and intensely folded zone surrounded by Low-Proterozoic flysch metasediments. (Väyrynen 1939; Huhma 1970, 1971, 1975; Gaál *et al.* 1975; Peltola 1978; Koistinen 1981).

The serpentinites, which occassionally show relics of ultramafic rocks (Haapala 1936), are carbonated and chloritized to a variable degree, particularly at contacts and in shear zones. Serpentinite grades into dolomite at the margins of serpentinite lenses. The lenses are surrounded by skarn rocks and quartzite. The association is rimmed by black schists and is embedded in mica gneisses and mica schists.

The sulphides of the Outokumpu Association have been divided into three groups:

(1) The Cu ores are massive strata-bound deposits in quartzite between serpentinite and mica schist (Vähätalo 1953; Huhma 1976; Peltola 1978; Koistinen 1981, Figs. 20 and 23). They have been mined for copper, cobalt and zinc at Keretti, Vuonos and Luikonlahti.

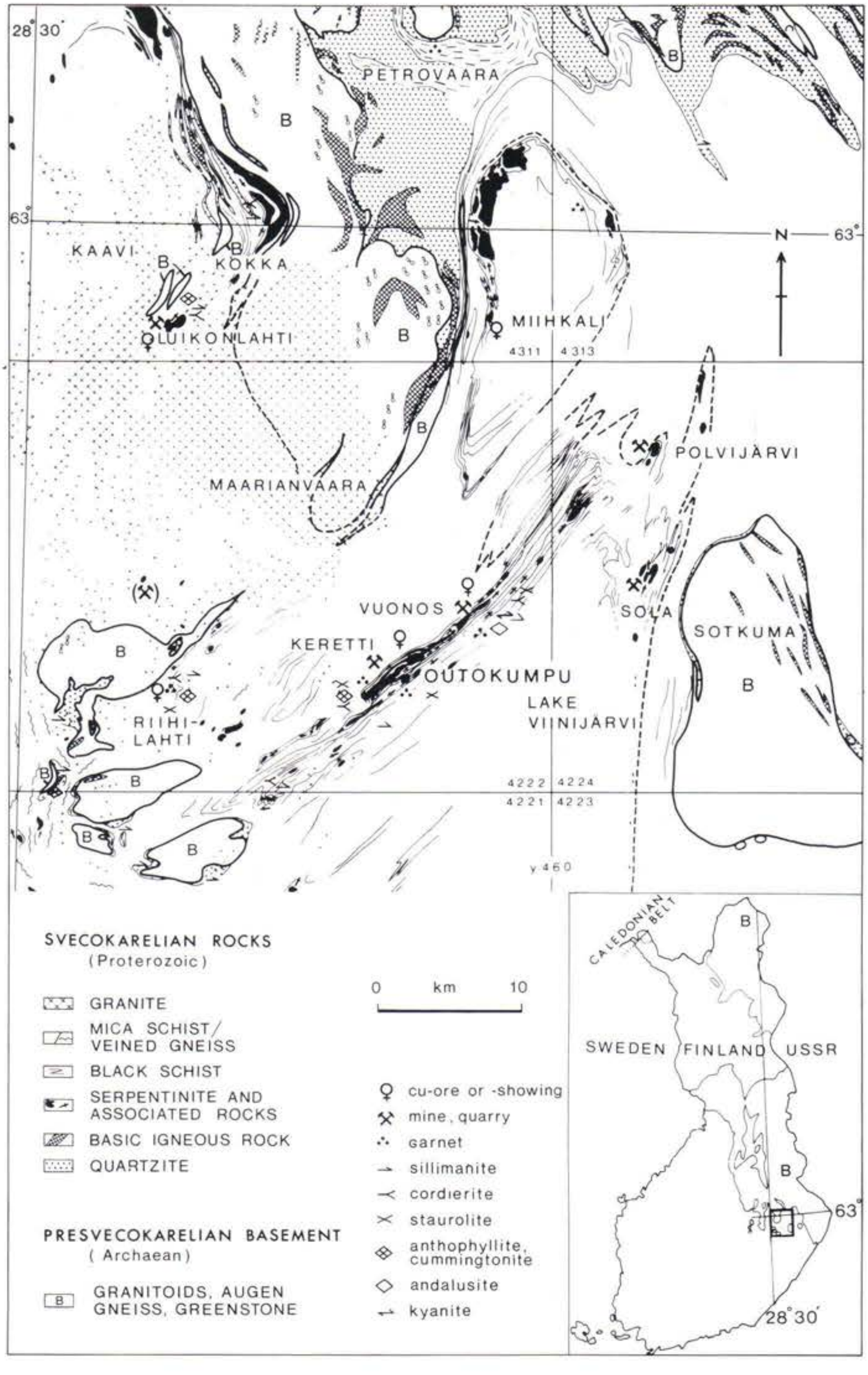

Fig. 19. The location and general geology of the Outokumpu area according to Huhma (1970, 1971) and Koistinen (1981).

Table 11. A. Minor element contents of the rocks in the Outokumpu association. Geometric means (Saastamoinen 1979). B. Average metal contents of the Vuonos Cu ore and Ni deposit. C. Average metal contents of the Keretti Cu ore and Ni deposit.

Rock type	Number of analyses	ppm			
		Cu	Ni	Co	Zn
A.					
Serpentinite	2,569	8	1,718	82	24
Chlorite schist	520	28	390	52	28
Dolomite	218	51	796	76	42
Tremolite skarn	937	62	736	59	35
Diopside skarn	1,080	88	1,053	83	46
Skarn quartzite	4,018	67	1,029	77	32
Quartzite	1,493	58	1,202	86	24
Mica schist	3,597	85	74	33	119
Black schist	1,811	260	359	39	879
B.					
Cu ore		24,500	1,300	1,500	16,000
Ni deposit		700	3 300	500	600
C.					
Cu ore		38,000	1,600	3,100	10,000
Ni deposit		3,600	4,400	1,300	1,000

(2) The Ni deposits are Ni-Cu-Co-Zn zones of the dissemination or stringer type. Associated with the Cu ores, they too occur in quartzite between serpentinite and mica schist (Vähätalo 1953; Peltola *et al.* 1971, Rauhamäki 1973; Koistinen 1981).

(3) A weak but rather nickel-rich sulphide dissemination, with some local enrichment, is typical of the rocks of the Outokumpu Association (Huhma & Huhma 1970, Table 11). The weak dissemination has no economic value as such, but nickel has been recovered as a by-product (Fig. 19) of the talc quarries in the serpentinite bodies of Sola and Polvijärvi.

The rocks of the Association are characterised by high chromium values (Table 13). The Ca-Mg minerals of the carbonate rocks and quartzites are invariably chrome-bearing: chrome diopside, chrome epidote, chrome tremolite, uvarovite, chrome tourmaline, fuchsite, etc. Disseminated chromite is common in all the rocks. The copper ores of Outokumpu contain sparse chromium (Table 13 and Peltola 1978, Table 12). The chromite of the Outokumpu type contains exceptionally abundant zinc and vanadium (Zn up to 9.6 %, V up to 3 %, Thayer *et al.* 1964; Weiser 1967). The chromites of the Ni deposits also exhibit anomalous Zn values (0.1 to 8 %) as do staurolite (0.40—0.87 %, Huhma 1967) and garnet (0.62 %, Treloar *et al.* 1981).

VUONOS

The Vuonos Cu ore deposit was discovered in 1965 by drilling based on structural geologic deductions and geochemical studies. At he same time, zones with anomalous Ni values ($\geqq$ 0.3 % Ni) were found above the Cu ore. In 1972—1977, 5 million tonnes of Ni ore were mined from the open pit and 500,000 tonnes from underground (Table 12). A total of 188,000 tonnes of nickel concentrate was produced.

The Vuonos Ni deposit in located in the quartzite-skarn zone between serpentinite and mica schist. About 2.5 km long, it extends as a steeply dipping body from the ground down to above the upper edge of the Cu orebody and in places even down to the lower edge (Fig. 20). In detail the Ni deposit is discontinuous, thinning in places to almost nil or disintergrating into separate lenses. Here and there, the deposit is composed of two parallel zones a few metres apart.

The hosts of the Ni deposit are quartzite, skarns and chlorite schist. Common constiti-

Table 12. Exploitation data on the Vuonos Cu ore and Ni occurrence. Mill feed of Cu ore in 1972—1981 and that of Ni ore in 1972—1977.

	Cu ore 4.1 mt	Ni ore 5.5 mt
Cu %	2.18	0.04
Zn %	1.38	0.04
Co %	0.13	0.03
Ni %	0.12	0.2
S %	14.76	2.5
Ag ppm	10	0.3
Se ppm	12	3

Table 13. A. Geometric means of Cr_2O_3 values for the Keretti ore and the country rocks. Numbers 1—9 refer to the location of samples in Fig. 23. The number of drill core samples (n) and their mean length are also given.

No	rock type	n	length m	Cr_2O_3 %
1	serpentinite	2	2.3	0.18
3	skarn ± dolomite	2	2.5	0.20
4	skarn ± quartzite	6	2.9	0.50
5	quartzite + skarn	1	4.6	0.38
6	nickel deposit[1]	5	—	0.81
7	quartzite	10	1.9	0.19
8	rocks anom. in nickel[2]	1	0.8	0.96
9	copper ore	52	4.3	0.08

[1] Data from Treloar *et al.* (1981)
[2] Ni 0.98 %

B. Cr_2O_3 data on the country rocks of the Keretti Cu orebody according to Peltola (1967).

Rock type	n	Cr_2O_3 %
serpentinites	53	0.40
contact skarns between quartzite and serpentinite	10	0.53
contact skarns between ore and serpentinite	12	0.50
skarn interlayers in quartzites	2	0.29
various quartzites	11	0.24
skarn-bearing interlayer in Cu ore	5	0.10

tuents of the quartzite-skarn association are quartz, diopside, tremolite, fuchsite and carbonate, although some diagnostic minerals are also present in the Ni deposit. The portion of the formation that extends from the surface down to a depth of c. 70 m is characterised by cordierite, biotite-phlogopite, chlorite, muscovite, almandine, orthoamphibole, cummingtonite and plagioclase (Fig. 21). These rocks, known as mica rocks, occur as a breccia-like network in quartzite and skarn. The minerals of the chlorite schist that occurs conformably below the serpentinite at the base of the Ni deposit are chlorite, hornblende, biotite-phlogopite and carbonate.

The Ni deposit exhibits diffuse boundaries with the environment. Two structural types are discernible: One is made up of sulphides that occur as fine-grained banded dissemination in quartzite, and as rather coarse and heterogeneous dissemination and local clusters in skarns and chlorite schist. The other, i.e. the breccia ore, is mainly encountered in mica rocks but also locally in quartzite and skarn. The richest portions of the Ni deposit are breccia ore. There are also some small lenses of massive sulphides.

A typical sulphide assemblage contains pyrrhotite + pentlandite + chalcopyrite + sphalerite. Pyrite is most abundant at the base of the Ni deposit close to the mica schist. When pyrite is the predominant mineral, the Ni values of the deposit are lower than usual.

The mica rocks occasionally contain abundant Zn chromite, an accessory that is common in the immediate vicinity of the ore deposits of the Outokumpu Association. Silicates, biotite, and chlorite in particular, often replace the sulphides. The accessories are mackinawite, cubanite, violarite, siegenite, gersdorffite, niccolite, maucherite, molybdenite, magnetite, ilmenite, eskolaite, uraninite (Inkinen 1967) and graphite.

The predominant Ni mineral, pentlandite, occurs as flame-like exsolution bodies in, or as small grains associated with, pyrrhotite and in places as discrete grains. In the breccia ores the grain size may be several hundreds of microns. The nickel content of the pentlandite in the Ni deposit varies from 30 % to 36 % (mean 31.5 %) and the Co content from 3 % to 14 % (mean 3.8 %). The pyrrhotite of the Ni deposit

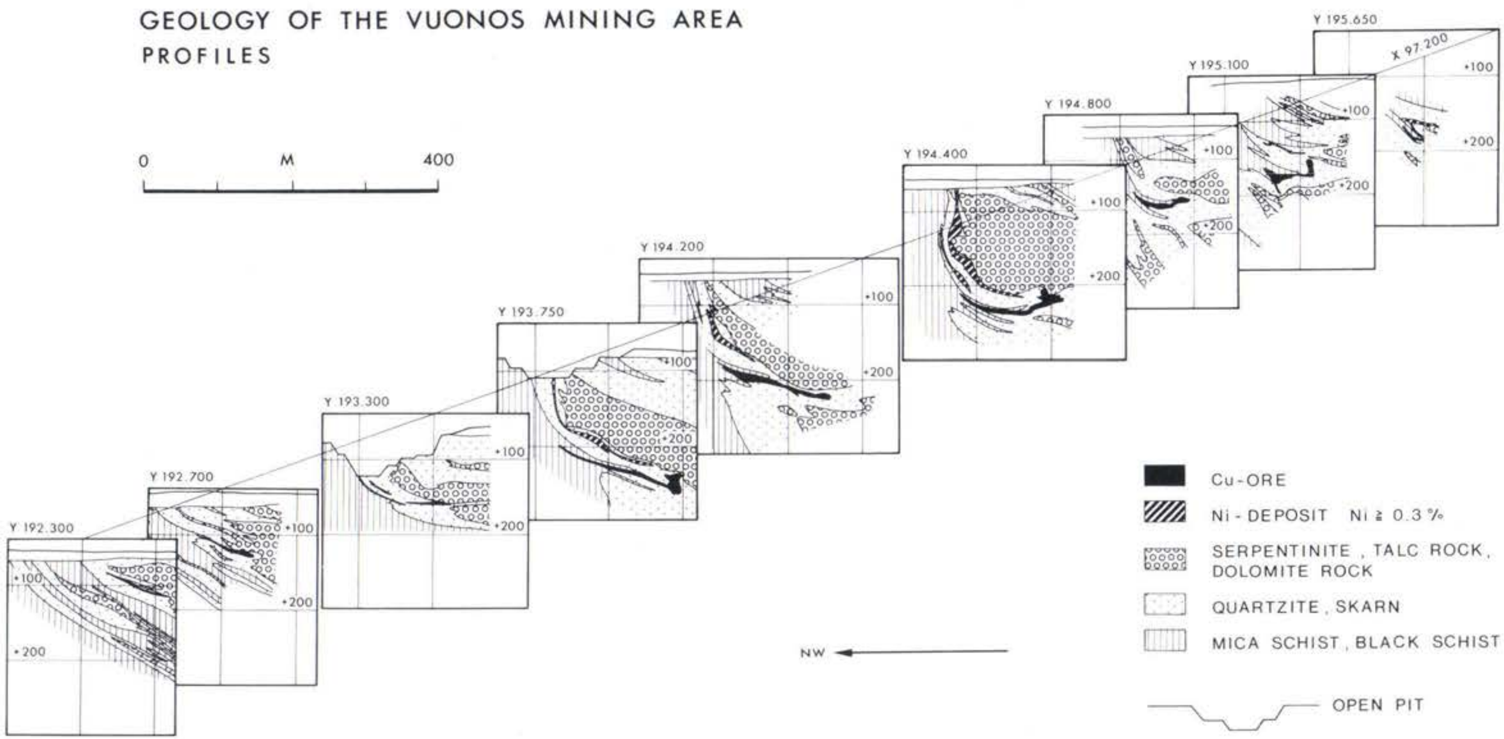

Fig. 20. A set of profiles showing the geological positions of the Vuonos Cu orebody and the Ni occurrence.

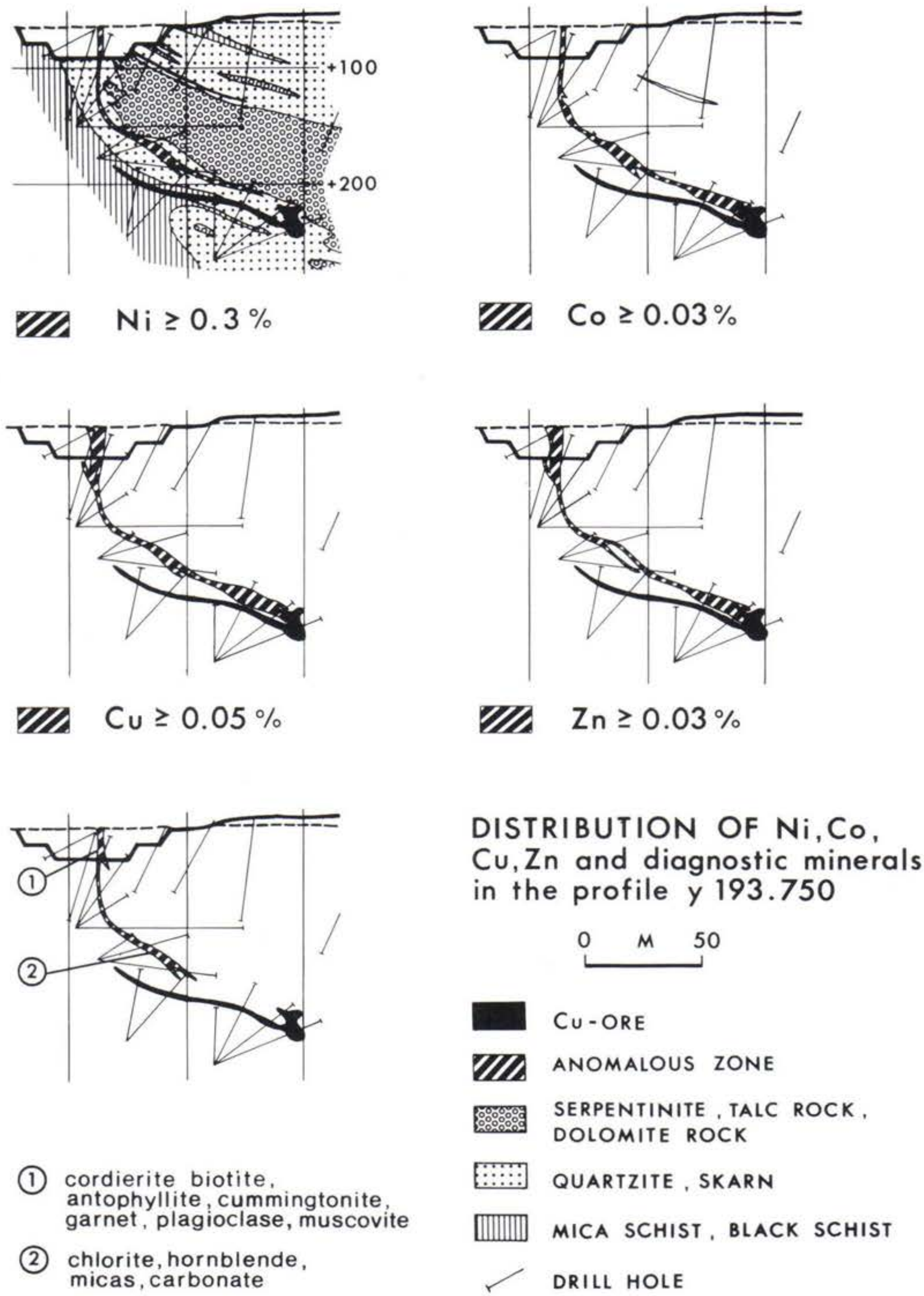

Fig. 21. Profile 193.750 of the Vuonos Ni occurrence.

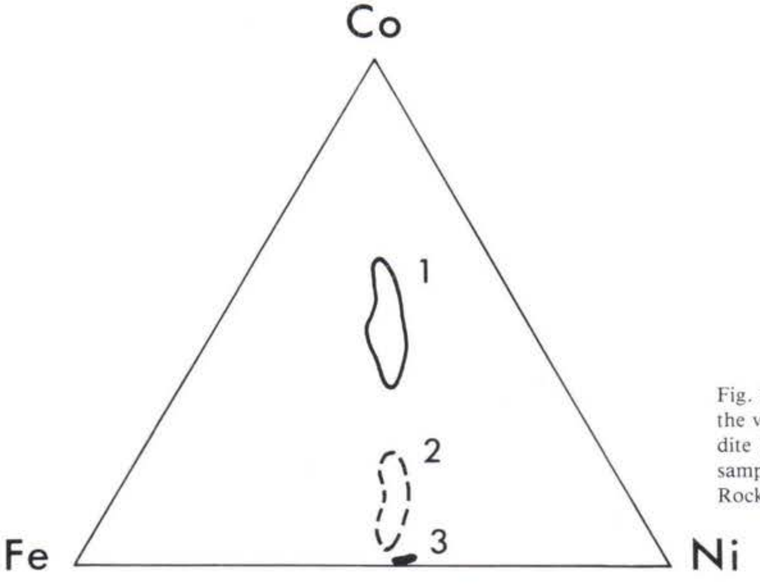

Fig. 22. Co-Ni-Fe ternary diagram showing the variation in the composition of pentlandite in the Vuonos deposit. 1. Cu ore, 68 samples; 2. Ni occurrence, 22 samples; 3. Rocks of the Outokumpu Association, 6 samples.

assays 0.19—0.65 % Ni (mean 0.35 %) and 0.00—0.37 % Co (mean 0.03 %, Huhma & Huhma 1970). The nickel content of the sulphide phase is about 3 %.

The pentlandite of the Cu ore averages 17 % Ni and 33 % Co. The pyrrhotite of the Cu ore contains 0.18 % Ni and 0.10 % Co. The Ni-Co-Fe ratios of the pentlandites of the Cu ore, Ni deposit and rocks of the Outokumpu Association are plotted in Fig. 22. In addition to nickel, other elements that are strongly concentrated in the rocks of the Outokumpu Association in the zone called the Ni deposit in the present context are Co, Zn and Cu (Fig. 21). The portion of the quartzite-skarn zone hosting the Ni deposit and Cu ores shows elevated metal values along its whole length. In the other structurally analogous portions of the formation, i.e. below the Cu ore and above the large central serpentinite body, the metal contents only occasionally and locally reach the boundaries in Figure 21.

KERETTI

The Keretti Cu ore deposit was discovered in 1910 while tracing the parent rock of a float that was unearthed some 50 km southeast of Outokumpu. The sulphide accumulations of the nickel deposit had been noted at an early stage of the investigations but they were considered to be intimately associated with the Cu ore. Vähätalo (1953) was the first to mention the Ni deposit as a separate unit. The richest portion of the occurrence was located by drilling in 1961 and 1962. Supplementary drilling was undertaken in 1980 and 1981.

Like the corresponding Cu ores, the Ni deposits at Keretti and Vuonos are analogous in geological setting, size, shape and mineral composition (Koistinen 1981). The Keretti Ni deposit is

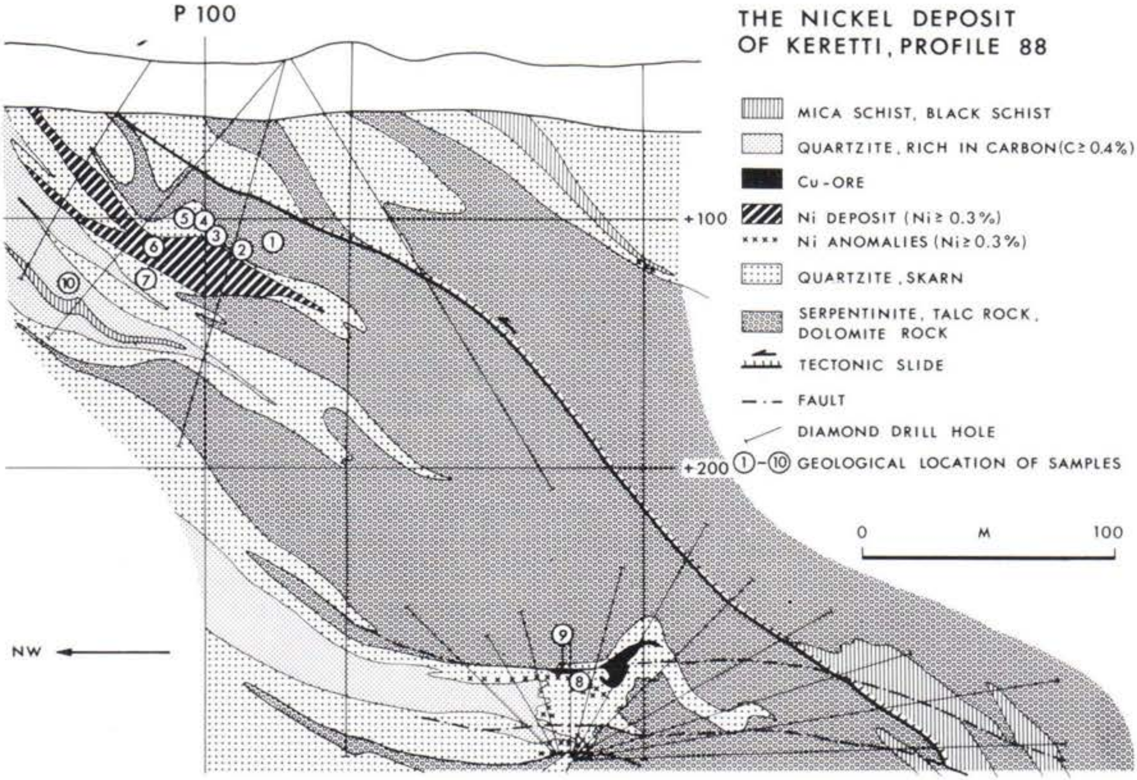

Fig. 23. The Keretti Cu orebody and Ni occurrence in profile 88. Samples 1—10 refer to Tables 13 and 14.

richest and most coherent over a distance of some 600 m above the SW end of the Cu orebody but the diagnostic features of the Ni deposit can be traced for the whole length of the Cu orebody. At its best, the Ni deposit forks into two branches resembling a prostrate V in shape. The lower edge of the deposit is much farther from the upper edge of the Cu orebody than is the lower edge of the Ni deposit at Vuonos. The upper edge of the Ni deposit crops out (Fig. 23).

The Ni deposit is hosted by a banded, occasionally slaty quartzite. The banding is attributed to the variation in grain size; the early quartz veins conformable with the bedding (Koistinen 1981); the skarn bands; and the variation in the abundance of Ca-Mg minerals, dust-like sulphides, microcrystalline carbon and chromite (Peltola 1960; Gaál *et al.* 1975). In the stratigraphic base of the ore-potential quartzite horizon, the abundance of Ca-Mg minerals and skarn bands increases towards serpentinite (Koistinen 1981). Correspondingly, the abundance of graphitic carbon increases towards mica schist. Like the Vuonos Cu orebody, the Keretti Cu orebody occurs in the upper part of a quartzite horizon rich in carbon, whereas the major part of the Ni deposit is located in the base characterised by abundant Ca-Mg minerals (Koistinen 1981). The Ni deposit has diffuse boundaries, and the country rocks adjacent to the mineralised portions, but least of all the serpentinites, are richer in Ni and Co than elsewhere (Table 11 and Table 14). As at Vuonos, the mineral composition of the Ni deposit at Keretti and in its environment differs from the common skarn quartzite (Gaál *et al.* 1975; Kois-

Table 14. Chemical data and geometric means of the Keretti ores and rock types. Numbers 1—10 refer to the location of samples in Fig. 23. The number of drill core samples (n) and their mean length (1 m) are also given.

Samples		Geometric means of analyses, ppm						%				
No	rock type	n	length m	Cu	Ni	Co	Zn	MgO	CaO	C	Fe(S)	S
1	serpentinite	34	9.6	27	1,904	105	19	34.5	0.75	0.43	3.39	0.58
2	dolomite ± serpentinite	29	7.1	29	1,573	98	23	23.9	7.64	1.46	2.71	0.41
3	skarn ± dolomite	19	3.9	76	1,008	81	18	25.1	13.0	1.41	2.02	0.96
4	skarn + quartzite	24	3.7	251	1,718	153	150	8.46	9.55	0.63	2.63	1.50
5	quartzite + skarn	16	4.8	67	1,616	106	14	2.56	2.47	0.22	1.77	1.12
6A	nickel dep.[1]	80 (5)	2.6	1,893	3,798	943	275	2.81	1.69	0.14	5.72	3.55
6B	nickel dep.[2]	5	—	1,679	4,612	1,266	2,334	15.9	0.32	—	—	1.98
7	quartzite	10	6.8	86	1,792	139	21	0.63	0.66	0.19	1.73	1.13
8	rocks anom. in nickel	8	2.1	421	5,609	732	967	3.48	3.17	0.20	8.39	5.98
9	copper ore: »Baby ore»[1]	66 (6)	2.4	19,368	1,899	1,668	11,152	4.79	1.76	0.32	15.2	15.2
10	quartzite, rich in carbon	22	4.6	34	1,509	96	25	1.64	1.75	0.78	2.25	1.50

[1] The number of MgO, CaO and C analyses in brackets (n). The other analytical data are geometric means weighed with the length of drill core sample. »Baby orebody» is a branch of the Keretti Cu orebody.

[2] Data from Treloar *et al.* (1981).

tinen 1981; Treloar *et al.* 1981). In addition to or replacing the green Cr-bearing skarn minerals, the rocks contain anthophyllite gedrite, pinitised cordierite, almandine-pyrope (Treloar *et al.* 1981), chlorite and local cummingtonite, staurolite, andalusite, hornblende, spinel and plagioclase. The main minerals of the sulphide assemblage are chalcopyrite, pyrrhotite, sphalerite, pentlandite and, in places, pyrite. Typical accessories are mackinawite, cubanite, siegenite, cobaltite, valleriite, arsenopyrite, stannite, rutile, chromite, ilmenite and gahnite. As at Vuonos, the cordierite-anthophyllite rocks occur in the upper part of the formation as narrow conformable bands and a breccialike network filling fractures in quartzite. These rocks are absent at the extreme lower end of the Ni deposit, around the tip of the prostrate V (Fig. 23), a place that is occupied by a garnetiferous chlorite rock.

The rocks associated with the Ni deposit are abnormallity rich in Mg, Fe and Al, and poor in Ca (Peltola 1967: »stockwork», Treloar *et al.* 1981; Table 14, sample 6 B). A corresponding simultaneous enrichment of Ni and Mg in the Vuonos Ni deposit has been reported by Peltola *et al.* (1971). The present material, however, does not corroborate the above behaviour of Mg and Ca (Table 14, sample 6 A).

The sulphides occur as dissemination and, in the richer portions, as breccia stringers and blebs. Chalcopyrite and pyrite are more abundant than in Vuonos. Pentlandite contains 24—32 % Ni (mean 28 %) and 2—16 % Co (mean 7.5 %) (Huhma 1967).

The pentlandite of the Cu ore averages 17 % Ni and 33 % Co as it does in Vuonos (Kouvo *et al.* 1959; Huhma 1967; Mikkola and Väisänen 1972; Hänninen 1981). The increase in the pyrite abundance close to the mica schist and the predominance of pyrrhotite adjacent to the serpentite, i.e. at the probable stratigraphic base of the formation, seems to be a marked structural feature shared by the Vuonos and Keretti Ni deposits. Note that the same structural feature is also visible in the Cu orebodies (Peltola 1967, 1978; Koistinen 1981). Associated with this is the fact that the nickel values are high wherever the pyrrhotite values are highest. Peltola attributes this structural feature to metamorphism but Koistinen maintains that it is due to premetamorphic layering.

Unlike Vuonos, the Keretti Ni deposit has a second, narrow (0.5—4 m) and discontinuous, although possibly initially continuous, Ni-bearing zone in quartzite below the Cu orebody (Fig. 23, Peltola 1967). It is characterised by Ni values from 0.3 % to 1.1 % and variable Cu, Co and Zn content (0.003—0.8 %, 0.01—0.36 % and 0.003—4.3 %, respectively; Table 14, sample 8). Gangue minerals such as anthophyllite and cordierite, which are not common constituents of quartzite, are absent. This Ni-anomalous zone is located exactly in the continuation of the lower edge of the Cu orebody, and it follows the contact of the serpentinite body nearest the ore. The zone may be a local enrichment of the areal weak dissemination, but it may equally well be part of the Ni deposit.

DISCUSSION

Geochronology, petrology, mineralogy, geochemistry and deformation analyses have demonstrated that the Outokumpu Association and its Cu ores and Ni deposits are genetically related to each other (Vähätalo 1953; Mäkelä 1977; Bowes 1978; Koistinen 1981).

The lead age of the Outokumpu ore, i.e. 2100 Ma, which is close to the mantle growth curve, indicates that the lead is of mantle origin (Stacey *et al.* 1977, according to Koistinen 1981). Koistinen feels that the ultramafic-mafic matter of the Outokumpu Association might also have derived from the mantle. The formation of the Outokumpu ores, which was temporally related to the precipitation of quartzites as chemical sediments (Huhma 1970, Huhma 1976), took place less than 2100 Ma ago.

The regional metamorphic processes and the accompanying deformation reworked the rocks of the Association by thickening the Cu orebodies and Ni deposits. These processes also affected the gabbro, which occurs in the Association as tectonic inclusions; its U-Pb zircon age, 1970 Ma, refers to the youngest known premetamorphic chrystallisation stage D_1 (Koistinen 1981). Hence the Outokumpu Association was formed sometime between 2100 and 1970 Ma ago. The maximum temperature of the regional metamorphism affecting the Association was reached during deformation stage D_3, about 1900 Ma ago (Koistinen 1981). It has been estimated that the P-T conditions of the metamorphism were 3.5 ± 0.5 kb and 600 ± 50°C, with a paleogeotherm of 50°C/km (Treloar *et al.* 1981).

Borchert (1954) was the first to suggest a marine volcanic exhalative model for the genesis of the ores of the Outokumpu type. The model was tested and developed by Mäkelä (1974), Huhma (1976) and Peltola (1978). The exhalation was assumed to have taken place during the eugeosynclinal stage of the Karelian orogeny. The ore invaded as a gel the then unconsolidated quartz rock during the early flysch period.

It is far from simple to juxtapose the mechanisms of the genesis of the Cu ores and the Ni deposit. The solving of this problem is the crux of the exhalation model developed by Bowes (1978, 1981), Koistinen (1981) and Treloar *et al.* (1981). According to this model the evaluation of the Association began with the crystallisation of the ophiolitic volcanic suite and was followed by fluid leach. Penetrating the mafic units of the ophiolite suite, the fluids leached the metals that were then precipitated and concentrated in the upper part of a specific SiO_2-rich layer.

When the fluids migrated through the already consolidated quartz and carbonate layer they altered the chemistry of the layer, thus giving rise to the cordierite amphibole rocks, chlorite rocks and sulphide assemblages in the isochemical metamorphism that followed the leach. The premetamorphic processes expelled Ca from the rocks and added Mg, Fe, Al, Ni, Cu, Co and Zn. Changes like these are typical of the feeding channels of volcanogenic ores (Sangster and Scott 1976).

We are still short of data to back the above model. An ophiolitic volcanic suite would require the existence of basaltic rocks, layered gabbros and vein complexes in the Outokumpu area. So far only small occurrences of gabbros and basaltic pillow lavas have been encountered (Park and Bowes 1981). Consequently, observations on the leached basaltic rocks are also lacking.

On the other hand, the cordierite amphibole rocks that are considered as diagnostic are met with not only in connection with the Cu ores and Ni occurrences but also elsewhere in the Outokumpu Association. They are not uncommon in the contact zones between the serpentinites and mica gneisses (Huhma 1970, 1971, 1975).

Compared with the rocks of the Outokumpu Association and the Cu ores, the rocks representing the feeding channels of the fluids have low contents of metals. Further, the geological location of the Ni deposits and the Ni anomalous zone, which in the present context is compared with the former with some reservation, and the structural analogies between the Cu ores and the Ni occurrences suggest that the special features of the formations are due simply to the order of formation: first an extensive but thin and discontinuous Ni occurrence was formed, and this was followed immediately by the deposition or intrusion of the Cu ore. The source of the fluids and the location of the feeding channels will remain to be established.

The material from the mantle may have reached the sea bed of that time along deep-seated fractures that extended to the mantle (Mäkelä 1977). According to Ruchkin (1981), the fractures may have been parts of a zone equivalent to the Benioff zone. To solve this problem to material transfer, Koistinen (1981) suggests that the Outokumpu Association, before undergoing various metamorphic deformations, moved with its country rocks as a nappe to its present geologic environment as a result of a collision between continental plates.

So far we have not been able to test the translation hypotheses of the matter. The other genetic mechanisms mentioned above will however be clarified in the near future thanks to the intensity with which geologic research is being conducted in the Outokumpu area.

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THE ORAVAINEN NICKEL OCCURRENCE IN WESTERN FINLAND

M. ISOHANNI

The Oravainen nickel occurrence is located in western Finland on the coast of the Gulf of Bothnia about 50 km north of Vaasa. Covered by an 18-m-thick layer of till and mud, the occurrence is in the sea bottom at a depth of 8 m and about 1 km from the shore.

The first indication of the mineralisation was given in the summer of 1972 when a sample from a glacial float assaying 2.24 % Ni was sent to Rautaruukki Oy. Drilling was carried out on the basis of the results of a boulder search, geological mapping, geochemical sampling and a geophysical survey, and in February 1973 the occurrence was localised about 10 km from the site at which the boulder was discovered.

Drilling performed in 1973 and 1974 established a subvertical pipe-like ultramafic intrusion about 2 000 m^2 in surface area. Down to a depth of 250 m it has been estimated to contain 1.3 million tonnes of ore averaging 0.95 % Ni and 0.16 % Cu. An ultramafic intrusion of almost the same size but only very weakly mineralized was discovered near the mineralised pipe. In the following, the mineralised ultramafite is called the Ni ultramafite or the Ni intrusion and the weakly mineralised intrusion the B intrusion or the B ultramafite. In 1976—1980 Outokumpu Oy continued exploration in the environment of Oravainen. All the geophysical anomalies tested have turned out to be caused by graphite- and pyrrhotite-bearing mica gneisses and calk-silicate-bearing quartzites.

GENERAL GEOLOGY OF THE ORAVAINEN AREA

The ultramafic Oravainen intrusions are located in the Vaasa granite area, which, according to Saksela (1935), is a migmatitic, synorogenic gneiss granite of heterogenous composition and structure. Supracrustal biotite-plagioclase gneiss inclusions of various composition abound in the area. Saksela (op.cit.) describes them as predominantly sedimentogenic but also to a lesser extent as volcanic in origin.

In the Oravainen area (Fig. 24) the Vaasa granite is mainly kinzigitic gneiss granite. It is foliated and in some places banded although elsewhere it is almost homogeneous and macroscopically a plutonite-looking gneiss. The main minerals are plagioclase (An_{25-35}), quartz and biotite, and occasionally garnet, cordierite and potassium feldspar. Accessories are sillimanite and rutile. The mineral assemblage suggests that the kinzigitic gneiss granite crystallised under P-T conditions of the granulite facies.

On the basis of the difference in the grade of granitisation, the kinzigitic gneiss granite has been subdivided into three concentric zones. The innermost zone, almost 20 km in diameter, contains abundant potassium felspar megacrysts that may exceed 3 cm in diameter. Potassium feldspar also occurs as poikilitic grains in the groundmass. This zone, which is almost wholly devoid of garnet, sillimanite and cordierite, is richest in pegmatitic granites and equigranular aplitic granites. The middle transitional zone shows less potassium feldspar, and the megacrysts are smaller in size. In the outermost zone potassium feldspar porphyroblasts are

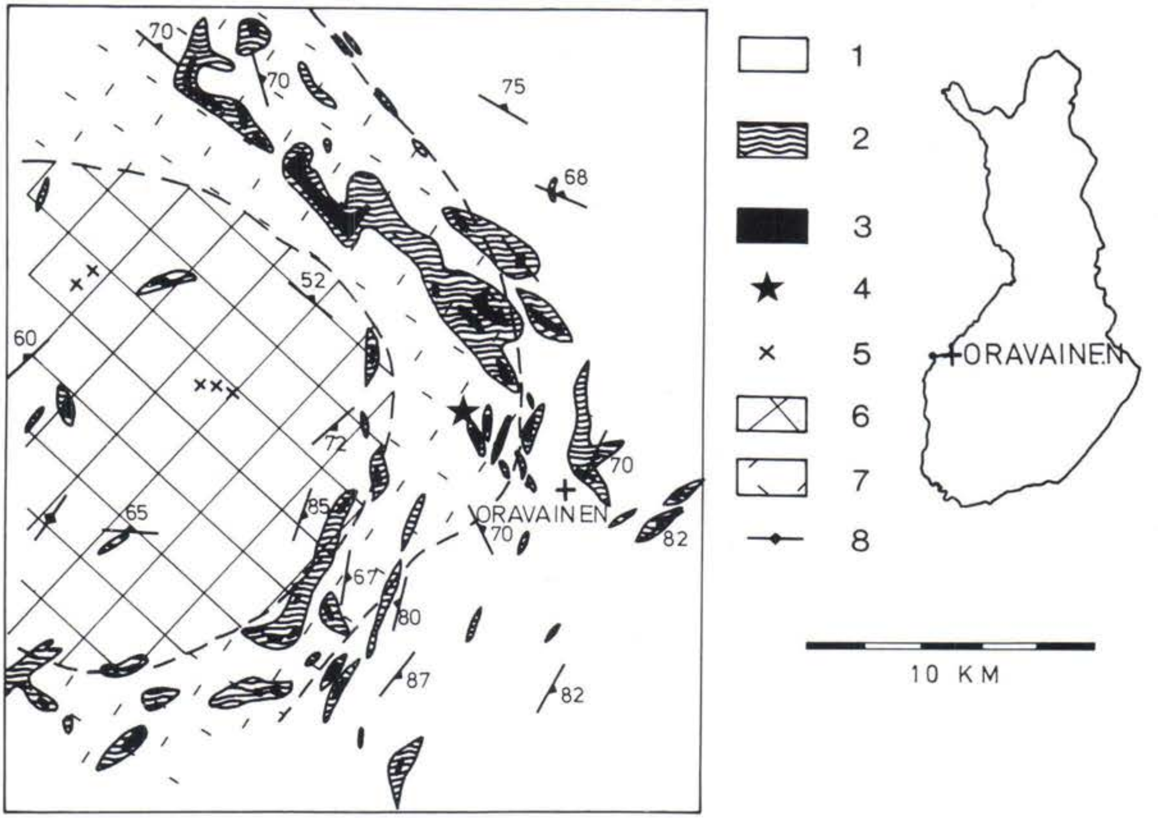


Fig. 24. Geological map of the Oravainen area. 1. Kinzingitic gneiss granite; 2. Migmatitic mica gneiss and graphite mica gneiss; 3. Calc-silicate-bearing quartzite; 4. Ultramafite; 5. Pegmatitic granite; 6. Area of strong granitisation; 7. Area of moderate granitisation; 8. Schistosity.

rare and the proportion of potassium feldspar is low in every respect. Garnet, cordierite and sillimanite are only slightly altered.

The kinzigitic gneiss granite contains abundant schist portions varying in size. The smallest of these, which are about one decimetre in diameter, are often almost completely granitised into ghost-like inclusions. Aeromagnetic data suggest that the largest schist portion is over 10 km long. Migmatitic mica gneiss predominates among the schist fragments. The best preserved fragments exhibit phyllitic and greywacky features, and even the primary layering shows up rather well.

As graphite and pyrrhotite increase the mica gneisses grade into graphite gneisses. The transition zone between the migmatitic mica gneiss and the kinzigitic gneiss granite is often rich in garnet.

The migmatitic mica gneisses also grade into calc-silicate-bearing quartzites. Skarns and limestones are only encountered in the area as floats. Typical mineral assemblages of the calc-silicate-bearing quartzites are quartz, anorthitic plagioclase, amphibole, diopside, calcite or graphite, sulphides and often magnetite. The magnetite content of the chalc-silicate-bearing quartzites which often occupy the central part of the schist zones, is such that they are displayed on magnetic maps as maxima.

The kinzigitic gneiss granite also contains hypersthene quartz diorite and quartz hypersthene gabbro, which, as indicated by the outcrops, mainly occur as inclusions or small fragments. The largest continuous portions are encountered adjacent to the ultramafites and in drill holes about 10 km to the NW. Ultramafites are met with only in the Oravainen nickel occurrence and in the B intrusion adjacent to it. The floats suggest that there are ultramafites, hornblendite in composition, in the sea area to the north or northwest of the Oravainen ultramafic intrusions. Some of the floats show a weak nickel mineralisation.

The difference in the grade of granitisation in the kinzigitic gneiss granite is also manifest in the tectonic structure of the area. The schist areas follow the ring structure and form a concentric ring around the most intensely granitised zone. Fig. 24 shows the eastern portion of the schist ring. The schistosity dips steeply and almost invariably outwards from the centre of the ring structure. Intense granitisation seems to have produced the dome-like structure that dominates the Oravainen area.

SHAPE AND NEIGHBOURHOOD OF THE ULTRAMAFIC BODIES

The Ni ultramafite covers an elliptical area of about 2,000 m^2. The E-W trending major axis is about 90 m long and the minor axis 30 m long. At the 100 level (Fig. 25) the major axis of the intrusion has rotated counter-clockwise in an almost NE-SW direction. Drilling suggests that the pipe-like Ni intrusion extends to a depth of at least 250 m. Between the ground surface and the +250 level the major axis of the pipe plunges about 70° eastwards. The Ni ultramafite was intersected by nine drill holes.

The B ultramafite is located about 50 m SW of the Ni ultramafite. Magnetic gradient measurement shows it to be a rounded ellipse 60 × 40 m^2 in size on a sea-bottom level. This ultramafic intrusion, which was intersected by a single drill hole, exhibits only a weak sulphide dissemination.

The most common country rocks of the ultramafites are kinzigitic gneiss granite or pyroxene quartz diorite (Fig. 25). Both are intensely deformed at the contact. Southwards the Ni ultramafite is bordered by a sheared pegmatite vein. The pegmatite is interpreted as being of the same age as the numerous pegmatite veins that crosscut the ultramafites.

The contact between the ultramafites and the country rocks is often occupied by a fine-grained banded or non-foliated mafic hornfels that appears to be variably hybridic. The hornfels is generally less foliated than the country rocks and in places it occurs as vein-like portions in the kinzigitic gneiss granite close to the contact.

THE ROCK TYPES OF THE ULTRAMAFIC BODIES

At the +100 level the Ni ultramafic exhibits a concentric pattern. In the middle there are two small dunitic portions enveloped by a peridotite that contain over 50 % sulphides (Fig. 26). At the NE end of the intrusion there is a narrow crescent of pyroxenite. The adjacent B ultrama-

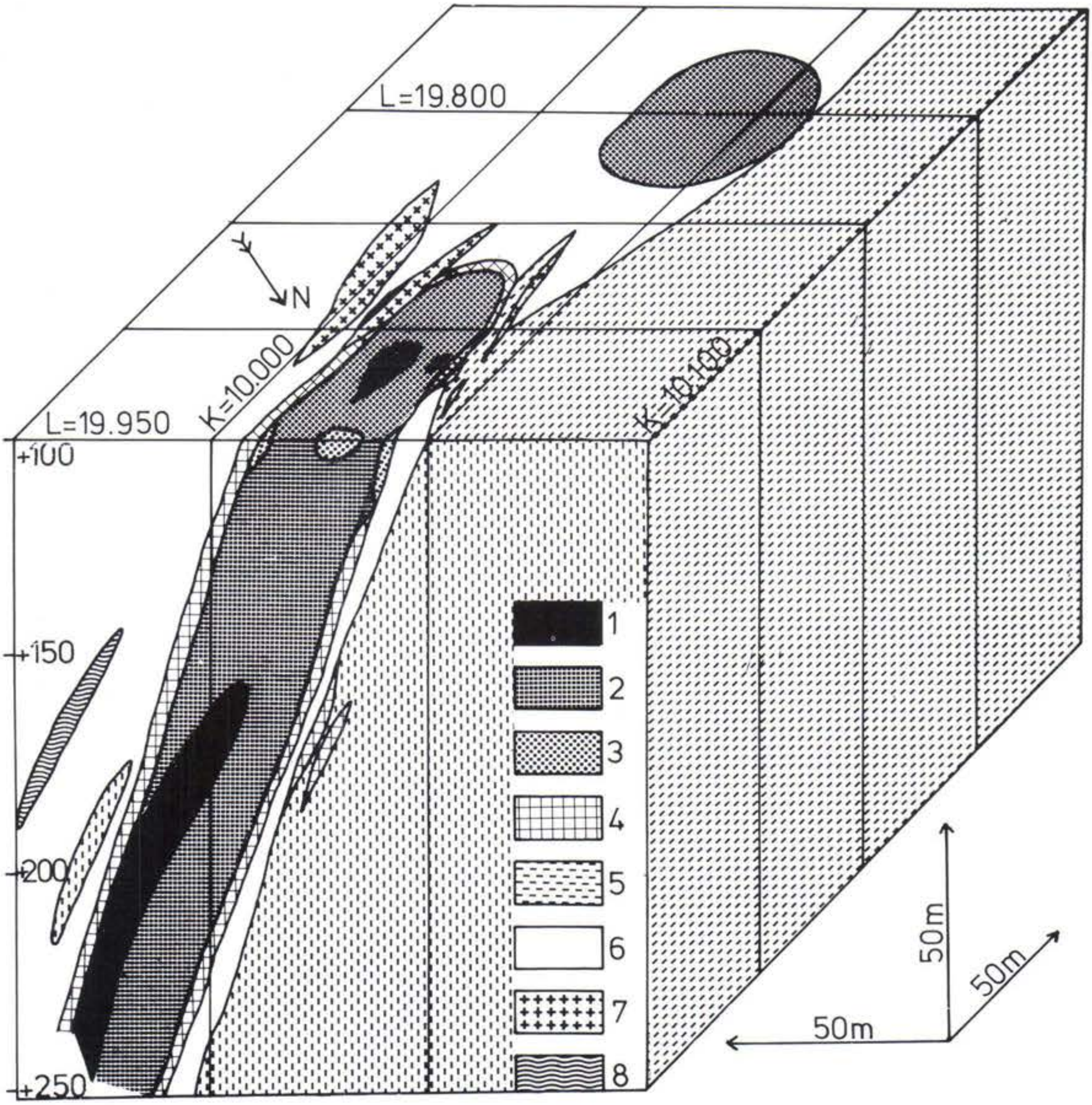
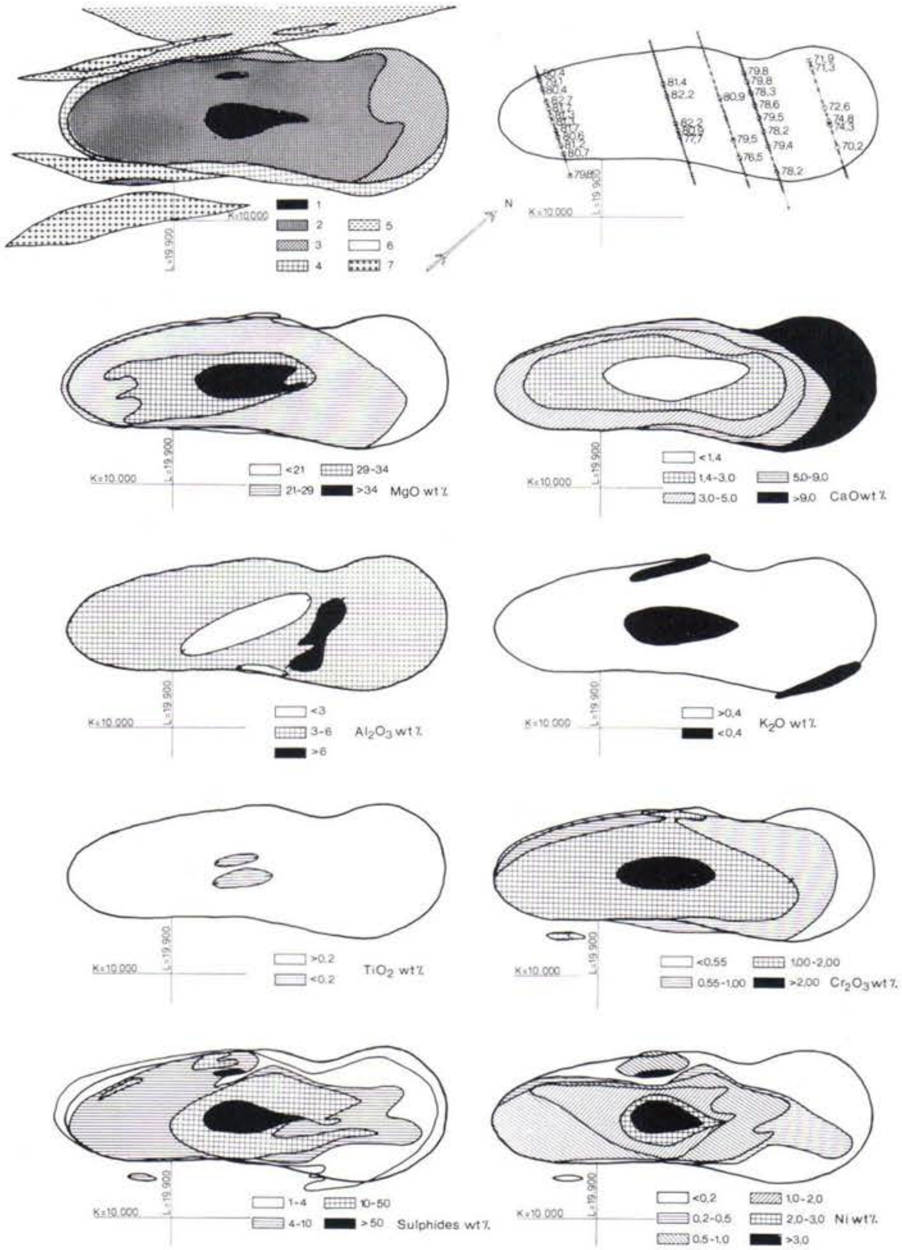


Fig. 25. Schematic block diagram of the Oravainen ultramafites. Rock types: 1. Massive ore + metadunite; 2. Peridotite and metaperidotite; 3. Pyroxenite and metapyroxenite; 4. Hornfels; 5. Pyroxene quartz diorite; 6. Kinzingitic gneiss granite; 7. Pegmatitic granite; 8. Migmatitic mica gneiss + graphite gneiss.

fite is less distinctly differentiated and its is composed entirely of peridotites. The dunitic core of the Ni intrusion is wholly altered into metadunite. The peridotitic and pyroxenitic differentiates are also largely altered, although fairly fresh portions are also encountered.

The peridotites and pyroxenites are not classified on the map in terms of their degree of alteration. Neither does the map show the pegmatitic veins, which vary in width from a few decimeters to a few meters.



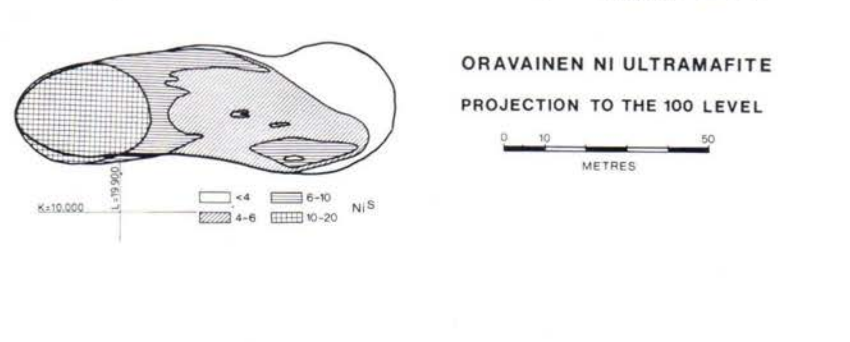


Fig. 26. The geology, sample points, forsterite content of the olivines, and distribution of MgO, CaO, Al_2O_3, K_2O, Cr_2O_3, TiO_2 and sulphides, and that of Ni and Ni in 100 % sulphides at + 100 level of the Oravainen Ni ultramafite. Rock types as in Fig. 25.

Petrography

The metadunites have rare enstatite and augite as relics of the primary silicates. Olivine in contrast is completely serpentinised. Serpentine, amphiboles, phlogopite and chlorite are encountered as alteration products. The sulphides occur as matrix ore containing embedded pseudomorphs after olivine with a diameter of 0.1 to 2 mm, occasionally even 3 mm. In certain variants some of the sulphides occur as blebs. The pseudomorphs after enstatite and augite are larger than those after olivine and they show poikilitic texture in relation to the latter. The dunitic differentiates were probably formed when the sulphides displaced the residual silicate melt of the partly crystallised ultrabasic magma.

The primary mineral assemblage of the silicate phase in peridotites consists of olivine, enstatite and augite. Presumably some of the amphiboles and a part of the phlogopite are also primary minerals. Serpentine, amphiboles, phlogopite, chlorite, talc and carbonate are encountered as alteration products. In the well-preserved peridotites olivine is usually euhedral and from 0.1 to 2 mm in size. Enstatite often occurs as subhedral poikilitic grains 2 to 10 mm in size. Augite is rather anhedral. Phlogopite usually occurs as large anhedral and poikilitic grains. In some sulphide-rich variants, the euhedral olivine and poikilitic enstatite, with a diameter of about 3 to 10 mm, occur as silicate nodules in the sulphide matrix.

In mineralogy and texture, the peridotites of the B ultramafite are analogous to the peridotites of the Ni ultramafite. The only difference is that in the former the sulphides occur as a very weak dissemination and as small blebs 1 to 2 mm in diameter.

The pyroxenites and metapyroxenites occur mainly at the NE end of the Ni ultramafite and in a narrow zone in the NW margin. The transition seam between hornfels and peridotite often contains narrow pyroxenite portions. Enstatite generally occurs as rather euhedral prismatic grains up to 6 mm in size. Augite is more anhedral, and primary phlogopite occurs as large ragged and often poikilitic grains. The sulphides are usually encountered as fine-grained dissemination or as blebs. In places, the sulphides, together with biotite and quartz, form nodules 1 to 3 mm in diameter.

The hornfels that occurs in the contact is usually banded, granoblastic and heterogeneous. In places, accumulations and bands of cummingtonite, obviously a pseudomorph after enstatite, are met with. Vein-like portions richer in plagioclase may also occur. Some of the structures can be interpreted as hybridic and some as hornfelsic. The constituents of a typical mineral assemblage are hornblende, cummingtonite, andesitic-bytownitic plagioclase, biotite, quartz, saussurite, carbonate and opaques. Relics of augite and estatite are often encountered. The opaques usually include ilmenite as well as sulphides.

The crosscutting pegmatites tend to be very coarse and contain only a few dark minerals in the cores. A typical mineral assemblage is oligoclase or andesine, quartz, potassium feldspar, biotite, chlorite, sericite and epidote. Close to the contacts, the pegmatites contain abundant chlorite and biotite. The abundance of sulphides, which usually occur as veins, varies. The sulphide phase is often exceptionally rich in copper.

Geochemistry of the rock types

The chemical composition of the rock types in the Ni ultramafite was determined by taking samples on a fairly regular grid from holes that intersected the 100 and 250 levels. Samples

Table 15. Average chemical compositions and C.I.P.W. norms of the Oravainen rocks.

	1	2	3	4	5	6	7	8	9
Number of samples	6	5	18	9	12	102	10	23	2
SiO_2	65.21	54.42	57.38	54.85	52.79	46.26	47.05	39.08	64.36
TiO_2	0.42	0.82	0.32	0.28	0.29	0.24	0.23	0.19	0.26
Al_2O_3	16.72	17.22	8.75	4.57	5.25	4.99	3.27	2.28	18.71
Cr_2O_3	0.056	0.060	0.401	0.524	0.658	1.086	0.937	2.299	0.022
FeO* (-Fe sulf.)	3.83	7.97	9.17	9.97	9.50	14.87	13.25	16.75	2.14
MnO	0.067	0.145	0.181	0.197	0.199	0.221	0.202	0.200	0.033
MgO	3.91	7.98	15.26	19.46	20.65	27.41	29.75	37.52	3.02
CaO	2.84	7.31	5.90	9.05	8.97	3.66	4.31	0.95	1.43
SrO	0.024	0.033	0.010	0.003	0.004	0.005	0.007	0.003	0.028
BaO	0.088	0.074	0.034	0.012	0.014	0.013	0.012	0.006	0.114
Na_2O	2.88	1.71	1.01	0.52	0.98	0.48	0.42	0.42	3.47
K_2O	3.81	2.06	1.45	0.485	0.63	0.70	0.51	0.270	6.17
P_2O_5	0.132	0.188	0.091	0.069	0.074	0.050	0.053	0.037	0.221
ZrO_2	0.025	0.014	0.009	0.004	0.004	0.003	0.004	0.002	0.024
Quartz	20.99	6.54	9.35	4.25					12.71
Orthoclase	22.96	12.62	8.75	2.93	3.80	4.21	3.10	1.63	37.03
Albite	24.37	14.47	8.55	4.40	8.29	4.06	3.55	3.55	29.36
Anorthite	13.23	33.01	14.97	8.67	8.03	9.36	5.49	0.23	5.65
Corundum	2.93							1.21	4.15
Diopside WO		0.85	5.72	14.94	15.03	3.54	6.49		
Diopside EN		0.58	4.16	10.93	11.24	2.56	4.83		
Diopside FS		0.20	1.04	2.60	2.29	0.65	1.03		
Hypersthene EN	9.74	19.29	33.85	37.53	33.92	26.74	27.16	8.63	7.52
Hypersthene FS	2.29	6.74	8.47	8.92	6.92	6.83	5.33	1.83	1.18
Olivine FO					4.39	27.30	29.51	59.43	
Olivine FA					0.99	7.69	6.91	13.91	
Ilmenite	0.80	1.56	0.61	0.53	0.55	0.46	0.44	0.36	0.05
Magnetite	2.25	3.57	3.70	3.40	3.42	4.87	4.23	4.89	1.50
Chromite	0.08	0.09	0.59	0.77	0.97	1.60	1.38	3.39	0.03
Apatite	0.31	0.45	0.22	0.16	0.18	0.12	0.13	0.09	0.52
Cu	0.010	0.012	0.012	0.018	0.126	0.166	0.017	0.346	0.009
Zn	0.009	0.012	0.068	0.006	0.009	0.009	0.010	0.010	0.005
Ni	0.007	0.012	0.031	0.058	0.503	0.759	0.112	3.113	0.009
Co	0.001	0.001	0.002	0.004	0.022	0.032	0.007	0.125	0.001
S	0.25	0.10	0.28	0.52	3.55	5.12	0.29	21.58	0.20
$\frac{Ni}{Ni+Cu}$	0.41	0.50	0.72	0.76	0.80	0.82	0.87	0.90	0.50
Ni^S	1.4	4.6	4.2	4.2	5.4	5.6	14.7	5.5	1.7

1) Kinzigitic gneiss granite, 2) Hyperstene quartz diorite, 3) Hornfels, 4) Hornfels/metapyroxenite, 5) Pyroxenite + metapyroxenite (Ni ultramafite), 6) Peridotite + metaperidotite (Ni ultramafite), 7) Peridotite + metaperidotite (B ultramafite), 8) Metadunite (Ni ultramafite), 9) Pegmatite. FeO* = FeO + Fe_2O_3 in silicates and oxides. Ratio FeO/Fe_2O_3 in C.I.P.W. norms from Le Maitre (1976). Ni^S = nickel recalculated in 100 % sulphides.

clearly contaminated by pegmatites were rejected. Likewise those samples were omitted that showed abnormally high values of K_2O and Na_2O. Owing to the high sulphide abundance in the Ni ultramafite all the XRF data were reduced for the sulphide phase. The Ni, Cu, Co and Zn of the sulphide phase were assayed by AAS after bromine methanol leach. The sulphur was determined on an automated Leco sulphur analyser. Häkli *et al.* (1979) have described the laboratory procedures in detail. The iron of the sulphide phase was calculated

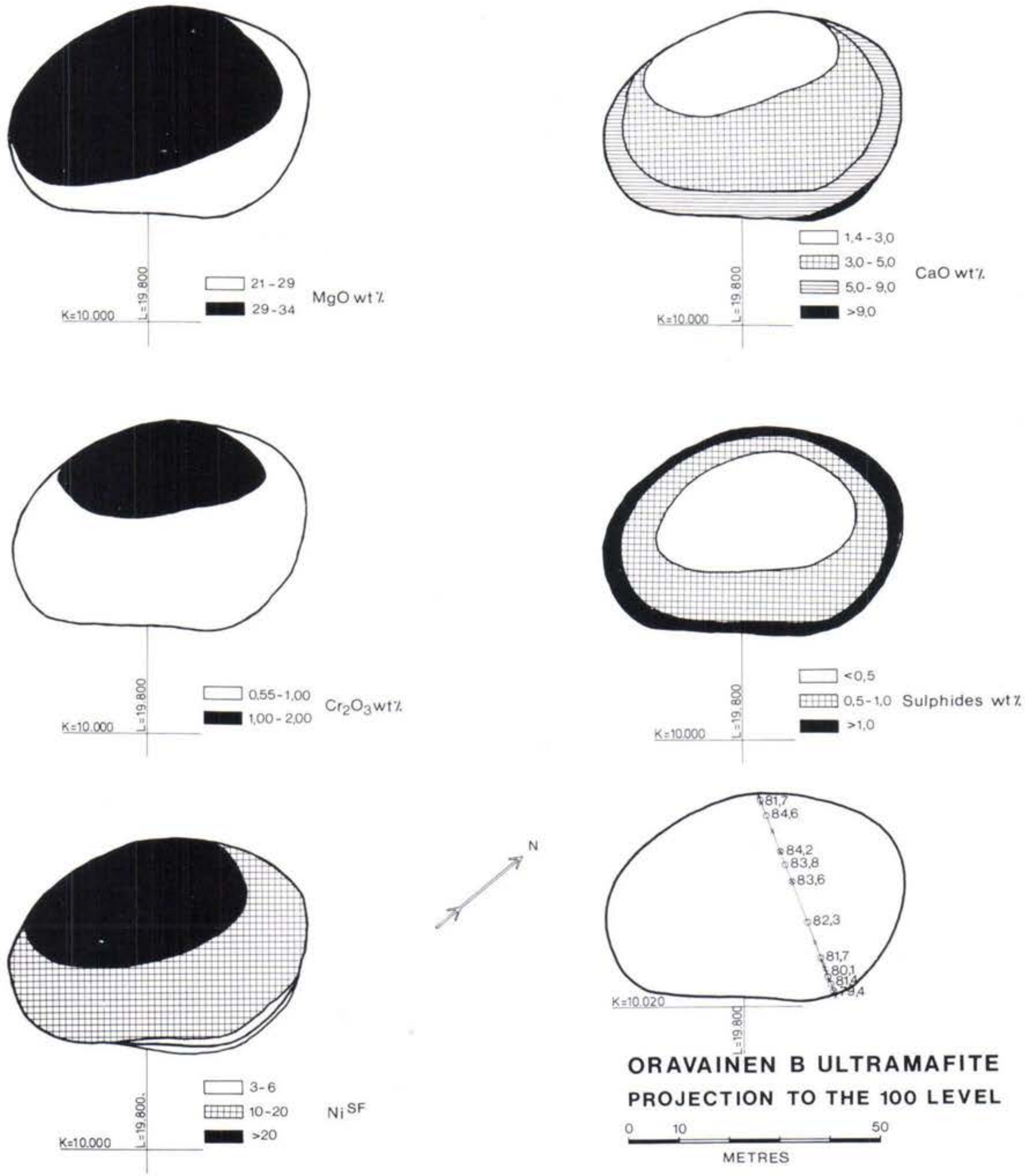


Fig. 27. Sample points, forsterite content of the olivines, and distribution of MgO, CaO, Cr_2O_3 and sulphides, and that of Ni in 100 % sulphides at + 100 level of the Oravainen B ultramafite.

by assuming the sulphur content of the sulphide phase to be 38 %. The chemical content of the silicate- and oxide phases was determined by subtracting the content of elements in sulphide phase from the total. To ease the handling of the data the volatile-free sum was normalised to

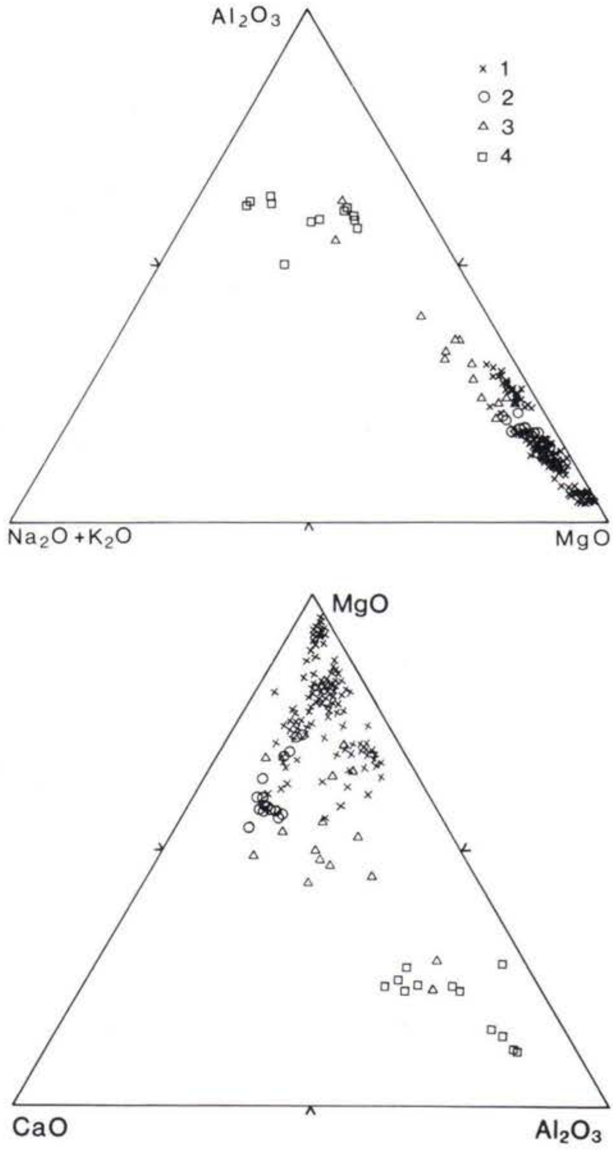
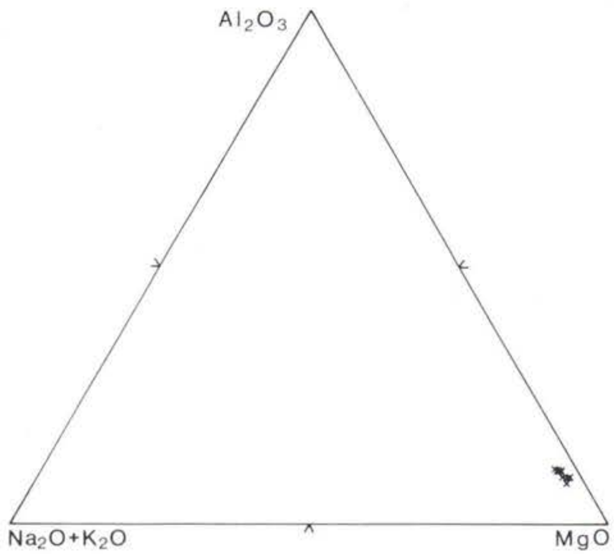


Fig. 28. $(Na_2O + K_2O)$ — MgO — Al_2O_3 diagram and CaO — MgO — Al_2O_3 diagram of the Oravainen Ni ultramafite. 1. Metadunite and peridotite; 2. Pyroxsenite; 3. Hornfels; 4. Kinzingitic gneiss granite and pyroxene quartz diorite.

100 %. The results are given in Table 15.

Metadunite, an almost extreme SiO_2-MgO-FeO rock in composition, is marked by its high Cr_2O_3 content. If the compositions of the metadunite and metaperidotites are compared with each other, it is noted that the differences are greatest in the Al_2O_3, MgO and CaO values.

The chemical composition of the silicate phases of the peridotites in the Ni ultramafite and of the adjacent B ultramafite are very similar. The pyroxenitic rocks are markedly richer in CaO and Na_2O and poorer in FeO and MgO than are the peridotitic rocks. The difference is due to the lower olivine/pyroxene ratio and to the higher augite/enstatite ratio in the pyroxenites and to the variation in the composition of the minerals. Both ultramafites are characterised by an abnormally high value of alkalies compared



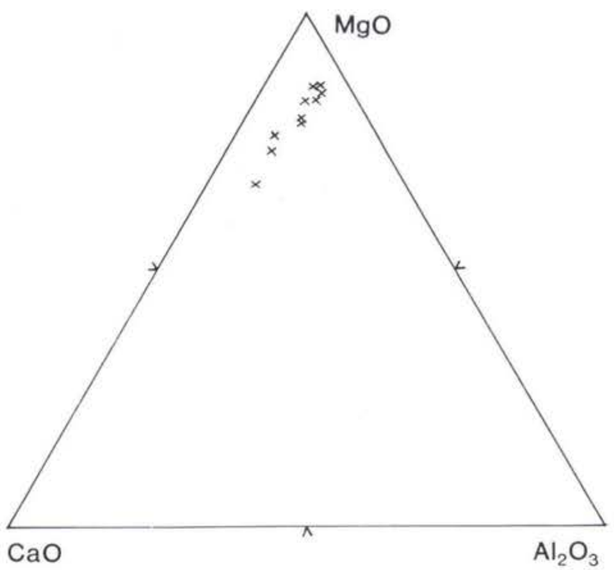


Fig. 29. (Na_2 + K_2O) — MgO — Al_2O_3 diagram and CaO — MgO — Al_2O_3 diagram of the Oravainen B ultramafite.

with other ultramafites in Finland (Häkli *et al.* 1979, Papunen 1980, Isohanni *et al.* 1980). If this is due to contamination, the mode of occurrence of phlogopite suggests that the contamination took place during a magmatic stage.

Both the Ni and the B ultramafites show distinct differentiation. This is best illustrated by the isopleth maps of two of the main components, MgO and CaO (Figs. 26 and 27). The metadunitic core of the Ni intrusion is richest in magnesium and poorest in calcium and the values grade towards the margins concentrically. The distribution of these elements further demonstrates that the SW end is markedly more basic than NE end. In the B ultramafite the NW margin is slightly more basic than the SE margin. The distribution map of Cr_2O_3 exhibits the same patterns for both ultramafites as do the distributions of MgO and CaO. In terms of potassium and titanium, both ultramafites are only very slighly differentiated. On the distribution maps of these elements in the Ni intrusion metadunite is located at the minimum. The potassium also shows two narrow minima close to the contacts. In the distribution of aluminium the metadunite is shown as a distinct minimum. Another marked feature on the distribution map of Al_2O_3 is the well-developed maximum within the intrusion near its NE part.

The step-wise variation in the Al_2O_3 values in also clearly visible in the (Na_2O + K_2O) — MgO—Al_2O_3 and CaO—MgO—Al_2O_3 diagrams, in which the dunitic rocks of the Ni intrusion form a separate group and the peridotitic differentiates plot in two separate fields (Fig. 28). In the Ni ultramafite the differentiation is manifest as a distinct increase in Al_2O_3 and CaO. The alkali values show only a slight differentiation. In the (Na_2O + K_2O) — MgO—Al_2O_3 diagram the pyroxenites plot between the two peridotite groups. In the CaO—MgO—Al_2O_3 diagram they are clearly CaO-richer differentiates of the Al_2O_3-poorer peridotites.

The (Na_2O + K_2O) — MgO—Al_2O_3 diagram shows that the B ultramafite is only slightly differentiated, whereas the CaO—MgO—Al_2O_3 diagram indicated a distinct differentiation in terms of CaO (Fig. 29). As a whole the peridotites of the B intrusion are slightly richer in MgO and CaO and poorer in Al_2O_3 and alkalies than are the peridotites of the Ni intrusion. The (Na_2O + K_2O) — MgO—Al_2O_3 and CaO—MgO—Al_2O_3 diagrams demonstrate that the hornfelses are enriched more in CaO and Al_2O_3 than in alkalies. This corroborates the hybridic nature of the contacts.

Chemical composition of the silicate minerals

The variation in the composition of the silicates was studied by analysing the olivines, enstatites, augites and amphiboles for Fe and Ni on an electron microprobe. In addition, two spinels were assayed for their composition.

The Fo content of the olivine varies between 84.6 and 70.2 %. The highest forsterite values are encountered in the B ultramafite, in which the values range from 84.6 to 79.4 Fo % (Fig. 27) with 1 990 to 770 ppm Ni (averages 82.3 and 1 350, respectively). Table 16 lists the average Ni and Fe contents of olivines, enstatites, augites and amphiboles from the drill intersections mentioned above. The olivines from the NW margin are slightly richer in Fo and Ni.

In the Ni intrusion the Fo content of the olivine varies between 82.7 % and 70.2 % and that of Ni between 2 380 and 380 ppm. The Fo content of the olivine from the drill intersection at the SW end fluctuates between 82.7 and 79.1 % and the Ni content between 2 380 and 1 330 ppm (average 80.9 and 1 850, respective-

Table 16. The average nickel and iron contents in olivines, enstatites, augites and amphiboles in some Oravainen drill holes.

	OL			EN			AUG			AF		
Drill hole	n	Ni ppm	Fe %	n	Ni ppm	Fe %	n	Ni ppm	Fe %	n	Ni ppm	Fe %
OR-21	10	1350	13.0	7	250	8.2	4	120	2.3	8	370	3.4
OR-22	12	1850	14.0	7	400	9.2	3	240	2.6	8	640	3.3
OR-6	5	770	14.0	5	170	9.1	4	100	2.8	11	230	3.9
OR-28	6	510	19.4	2	100	11.9	3	50	3.4	3	140	4.7

OR-21 = B ultramafite, OR-22 = SW end of the Ni ultramafite, OR-6 = Central part of the Ni ultramafite, OR-28 = NE end of the ultramafite. n = number of samples.

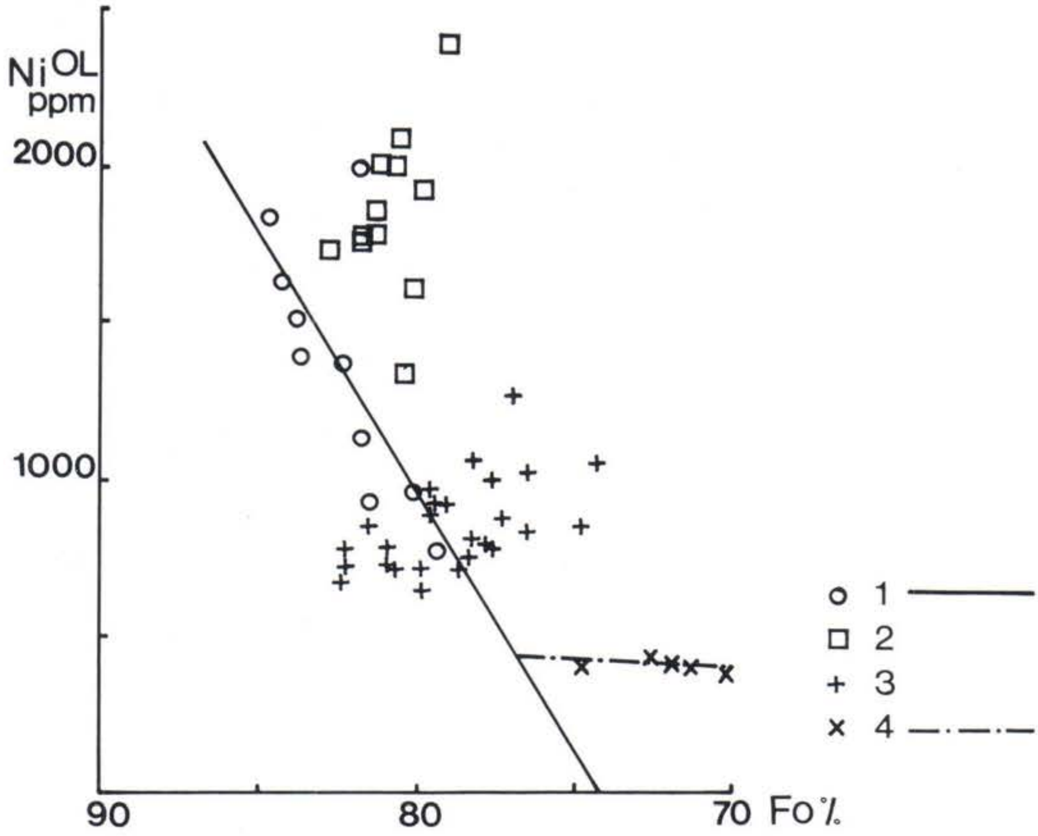


Fig. 30. Nickel versus Fo in olivine in the Oravainen ultramafites; 1. B ultramafite; 2. SW part of the Ni ultramafite; 3. Peridotites in the central part of the Ni ultramafite; 4. Pyroxenite in the NE part of the Ni ultramafite.

ly). In the Ni ultramafite the highest Fo contents are encountered in the SW end of the body. In the drill intersection in the central part of the body the variation is between 82.2 and 77.7 Fo % and 850 and 720 ppm Ni (average 80.9 and 770, respectively). No fresh olivine was detected in the metadunite. The Fo content of the olivines in the NE end intersection ranges from 74.8 to 70.2 % and the nickel content from 1 050 to 380 ppm (averages 72.5 and 510, respectively).

Fig. 30 illustrates the variation in the nickel content of olivine as a function of its Fo content. In the B ultramafite the Ni content of the olivine has a clear positive correlation with the Fo content. If the values are compared with those given by Duke and Naldrett (1978), all the nickel values except one correspond to those that are 100 to 350 ppm less than the nickel values of the oliviness when the magma is sulphide-undersaturated. The slope of the line is almost parallel to the sulphide-undersaturated curve (Duke and Naldrett op. cit. Fig. 4). The saturation point of the sulphides was obviously reached at a rather late stage of fractional crystallisation, a concept that is corroborated by the low average sulphur content, 0,25 %, of the corresponding samples (Shima and Naldrett 1975).

In the figure, the olivines of the Ni intrusion are classified into three groups. The largest group consists of the olivines of the peridotitic samples from the core of the ultramafic, for which the nickel content of the sulphide phase averages 5.8 %. The nickel-rich olivines from the SW end constitute a distinct group in which the average nickel content in the 100 % sulphides is 12.6 %. The third group consists of the olivines in the pyroxenites in the NE end, where the average nickel content of the 100 % sulphides is 3.6 %.

If the composition of the olivines of the Ni ultramafite is examined in the light of the studies by Duke and Naldrett (1978), the group of peridotites that is rich in sulphides but poorer in nickel of the sulphide phase and olivine plots mainly in the field of the magma saturated with sulphides. The poor negative correlation may be partly due to subsolidus postcrystallisation events. The nickel-rich group from the SW end shows a weak negative correlation, too. The nickel values of the olivines are consistently higher than those corresponding to the saturation point of sulphur, even though the sulphur content varies from 0.87 to 4.81 % (average 2.04 %). Subsolidus reactions after crystallisation may have redistributed nickel between the sulphide and silicate phases.

Table 16 gives the average Ni and Fe values for the olivines, enstatites, augites and amphiboles from three drill intersections in the Ni ultramafite and from one drill intersection in the B ultramafite. In terms of Fe values, the results are fairly compatible with the corresponding values for olivine. Häkli (1971) has studied the distribution of nickel between various minerals in many mafic and ultramafic intrusion. If the Ni^{Ol}/Ni^{En}, Ni^{Ol}/Ni^{Aug} and Ni^{Ol}/Ni^{Af} partition coefficients for the Oravainen ultramafite are compared with those reported by Häkli (op. cit.) for peridotites, the coefficients of the Oravainen ultramafites are on an average considerably higher for augite, clearly higher for enstatite and slightly higher for amphiboles.

Crystallisation temperature of the silicates

Häkli (1968) has applied the nickel partition coefficient of the mineral pair olivine-augite to estimate the model crystallisation temperature of the Parikkala mafic intrusion according to Macaopuhi model temperatures determined by Häkli and Wright (1967). In the Ni ultramafite at Oravainen, the nickel values of olivine, enstatite and augite have changed owing to the sulphide phase to such an extent that even the average ratios have changed. The highest temperatures are obtained for the pyroxenite, the differentiate that was presumably the last to crystallise. Except in one sample, the application of the above methods to the coexistent mineral pair olivine-enstatite of the B ultramafite gives 1 220°—1 300°C (average 1 250°C) as the model crystallisation temperature (Table 17). The temperatures calculated from the olivine-augite pair are correspondingly 1 240°—1 300° C (average 1 270°C). The chemical composition suggests that the corresponding crystallisation temperatures of the Ni ultramafite are somewhat lower.

Table 17. Partition coefficients $K = Ol^{Ni}/Aug^{Ni}$, $K = Ol^{Ni}/En^{Ni}$ and the model crystallisation temperatures in Oravainen B ultramafite (OR-21).

$K = Ol^{Ni}/Aug^{Ni}$	C°	$K = Ol^{Ni}/En^{Ni}$	C°
9.24	1270	5.25	1220
10.51	1300	5.72	1260
		4.54	1160
8.86	1260	5.23	1220
		6.11	1300
8.28	1240	5.27	1230
		5.38	1240
A = 8647		A = 4969	
B = 7.838		B = 4.977	

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

Parametres A and B from Häkli (1968)

ORE OCCURRENCES

Distribution of sulphides

Of the two adjacent ultramafites in the Oravainen area, one is only slightly sulphide bearing whereas the other is almost entirely heavily mineralized. In the B ultramafite the sulphides appear to be slightly concentrated in the margins (Fig. 27). In the Ni ultramafite the reverse is true, the sulphides being distinctly accumulated almost concentrically in the core of the ultramafite at the 100 level (Fig. 26). Moreover, in the NW margin, there is a small maximum parallel to the contact. On account of the differences in the composition of the sulphide phase, the concentricity is even more pronounced on the nickel distribution map (Fig. 26). At the 250 level, the sulphide-richest portion, in which the sulphide abundance exceeds 50 %, is located in the NW margin close to the hanging-wall contact (Fig. 25).

Ore types

There is a clear correlation between sulphide abundance and ore type. In the B ultramafite the sulphides occur as a very fine-grained dissemination. Small bleds of 1 to 2 mm are also encountered locally. In the Ni ultramafite the fine-grained dissemination is the predominant texture as long as the abundance of sulphides does not exceed a few percent. Sometimes small blebs may be associated with it. The grain size of the dissemination and the blebs increases as the sulphide abundance increases. At the SW end, where the nickel value of the sulphide phase is high and the abundance of sulphides is less than 10 wt %, the fine to medium-grained interstitial dissemination is the sole textural type. At the NE end, blebs are also encountered. At the same end there are portions that, in addition to the interstitial dissemination, contain sulphide-mica portions, a few millimetres in diameter, in which pyrrhotite occurs as narrow skeletal grains.

In the core of the Ni ultramafite the interstitial dissemination grades into disseminated blebs as the abundances of sulphides increases. The size of the blebs increases as the sulphide abundance increases and they grade along the margins into interstitial (Fig. 31) and further into network (Fig. 32) dissemination. In the variants richest in sulphides the network textures often show larger bleb-like portions. The meshes in the network are mainly euhedral olivine pseudomorphs 0.1 to 3 mm in size, or sometimes rounded enstatite grains, 3 to 10 mm in size, or their pseudomorphs enclosing olivine poikilitically. Especially the texture of the disseminated blebs, but to some extent also the network textures, exhibit distinct foliation in places. Microcracks filled with sulphides are common. Narrow massive sulphide veins are encountered close to the pegmatite veins. Massive sulphide portions with breccia structures occur at the 250 level at the contact of the ultramafite.

Ore minerals

The main minerals of the sulphides assemblage are pyrrhotite, pentlandite and chalcopyrite. Cubanite, mackinawite and valleriite are also often encountered, particularly in the central parts of the Ni ultramafite. In the disseminated ores, in which abundant magnetite is associated

Fig. 31. Oriented dissemination (buck shot ore) with interstitial margins. Oravainen, Ni ultramafite. Photo E. Halme.

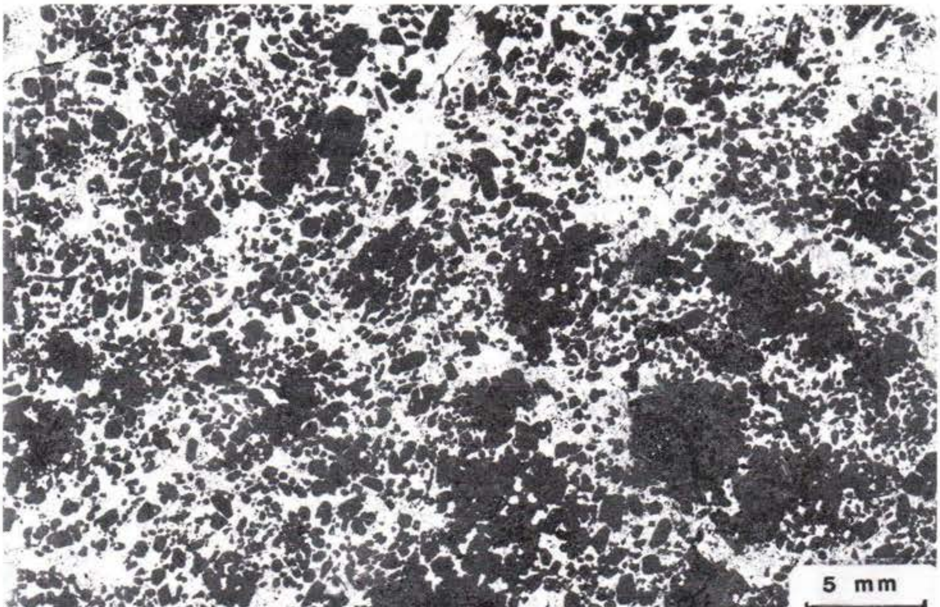


Fig. 32. »Net texture». Oravainen Ni ultramafite. Photo E. Halme.

with the sulphides, pyrite is a minor constituent. Other accessories are gersdorffite, niccolite, maucherite, sphalerite, graphite and PGMs. Violarite has been encountered only in weathered floats. The other oxide minerals besides magnetite are chromite and, near the contacts, ilmenite.

Magnetite occurs partly as an alteration product of olivine and partly associated with the sulphides. In places, the sulphides contain abundant magnetite. Magnetite occasionally exhibits intergrowth textures with pyrite. The mode of occurrence of magnetite suggests that it partly replaces the sulphides.

Chromite is encountered as two generations: the one, which is opaque in thin sections, is fairly euhedral and was obviously the first to crystallise; the other is brown and distinctly transparent. Five electron microprobe determinations made on the first type show that the Cr_2O_3 values vary between 38.0 and 48.0 % (average 42.9 %), five determination on the second type gave values between 26.0 and 31.2 % (average 28.5 %). Sometimes chromite may form micrographic intergrowths with pyrrhotite.

Pyrrhotite is predominantly monoclinic or hexagonal. At the NE end of the Ni ultramafite there are also sulphide assemblages in which troilite occurs as narrow lamellae in the hexagonal pyrrhotite. The pyrrhotite grains are generally large. Along the rims and basal pinacoidal cleavage the monoclinic pyrrhotite often replaces the hexagonal variant. The bulk of the pentlandite occurs as large grains of up to 3—4 mm. It often shows intensely developed cleavages that are usually filled with magnetite and minor chalcopyrite. Pentlandite occasionally occurs as smaller grains close to the cleavages in pyrrhotite, as exsolution bodies in pyrrhotite and as roundish exsolutions in chalcopyrite. Pentlandite exsolutions are encountered close to the microfractures of the pyrrhotite grains, particularly at the contacts of the ultramafite. Chalcopyrite mainly occurs as fairly large grains together with the other sulphides. In addition, it often forms a narrow seam around the sulphide portions together with magnetite and cubanite. Cubanite is also encountered as lamellae in association with chalcopyrite. Mackinawite mainly occurs as a replacement product of pentlandite, and valleriite as fine-grained stringers in the silicates parallel to the edges of the sulphide grains.

Arsenides are mainly encountered as fine-grained dissemination or as a filling in microcracks. In places euhedral concentric grains are met with in which the core is niccolite surrounded by a gersdorffite rim. As at Hitura (Häkli *et al.* 1976), irarsite or hollingworthite have been encountered as tiny cores in gersdorffite grains (Y. Vuorelainen, oral communication).

Chemical composition of the sulphides

Microscopic examination shows that pyrrhotite varies from monoclinic pyrrhotite to troilite in compostion. Electron microprobe analyses on the pyrrhotite corroborate the microscopic observations (Table 18). The pyrrhotites in the E margin of the B ultramafite are obviously entirely monoclinic in composition, the calculated composition of pyrrhotite, $(Fe, Ni)_{0.872}S$, being very close to that of the monoclinic pyrrhotite, ($Fe_{0.875}S$ or Fe_7S_8). Several determinations were done on each sample. The data from one sample indicate that the pyrrhotite in the W margin of the B ultramafite is close to hexagonal in composition.

The sum of the cations of the pyrrhotite in the SW end of the Ni ultramafite ranges from 0.882 to 0.902. The latter is close to the composition of the hexagonal pyrrhotite (Fe_9S_{10}). In a

Table 18. Electron microprobe analyses of pyrrhotites and pentlandites.

	1		2		3		4		5		6		7
	PO	PN	PO	PN	PO	PN	PO	PN	PO	PN	PO	PN	PN
Fe	59.30	32.14	59.94	31.54	60.18	33.29	60.82	31.37	59.60	30.66	59.55	29.95	31.89
Co	0.01	1.58	0.01	0.86	0.02	0.78	0.01	1.02	0.02	1.49	0.04	4.03	3.69
Ni	0.36	32.48	0.50	34.02	0.25	32.69	0.34	34.15	0.32	33.68	0.32	32.61	30.88
S	39.30	33.38	38.76	33.10	39.33	33.29	38.93	33.23	39.50	32.99	39.44	33.14	33.03
Total	98.97	99.58	99.21	99.52	99.78	100.05	100.10	99.76	99.44	98.82	99.35	99.78	99.49
Σ Cat	0.872	8.879	0.895	8.980	0.882	8.986	0.902	8.959	0.871	8.986	0.872	8.985	9.005
Σ An	1.000	8.000	1.000	8.000	1.000	8.000	1.000	8.000	1.000	8.000	1.000	8.000	8.000
At % Ni		25.2		26.4		25.3		26.5		26.6		25.3	24.0
At % Ni+Co		26.4		27.1		25.9		27.3		27.8		28.5	26.9

1) E border of the Oravainen B-ultramafite, 2 samples, 2) W border of the Oravainen B-ultramafite, 1 sample, 3) S border of the Oravainen Ni ultramafite, 2 samples, 4) SW contact of the Oravainen Ni ultramafite, 1 sample, 5) Central area of the Oravainen Ni ultramafite, 4 samples, 6) N border of the Oravainen Ni ultramafite, 1 sample, 7) NE border of the Oravainen Ni ultramafite, 1 sample. PO = pyrrhotite; PN = pentlandite.

sample in which the sum of the cations of pyrrhotite is 0.882, the monoclinic pyrrhotite replaces the hexagonal variety and in places there is some pyrite. The hexagonal pyrrhotite is obviously metastable in this assemblage (Misra and Fleet 1973). The pyrrhotite in the core of the mineralized ultramafite is predominantly monoclinic (the sum of the cations equals 0.871).

The sulphide assemblages in the NE end of the Ni intrusive contain pyrrhotite, which varies from an almost pure monoclinic type to a combination of hexagonal pyrrhotite and troilite.

The composition of pentlandite varies from 24.0 to 26.6 at % Ni (25.9 to 28.5 at % Ni + Co) (Table 18). The variations in the compositions of the pentlandites generally correspond to those reported for various mineral assemblages by Misra and Fleet (1973). An exceptionally low Ni value was recorded for one of the two samples from the S end of the Ni ultramafite, the assemblage of the sample being hexagonal pyrrhotite, monoclinic pyrrhotite, pyrite and pentlandite. The composition of pentlandite is 25.1 at % Ni (25.8 at % Ni + Co) and the calculated Ni content in the sulphide phase 14.4 % wt %. The mineral assemblage is probably metastabile and derived from low-temperature oxidation.

Table 19 gives chemical compositions of the arsenides in the Ni ultramafite.

Table 19. Electron microprobe analyses of arsenides.

	Niccolite		Gersdorffite		Maucherite	
	1	2	1	2	1	2
Fe	.58	.13	6.38	5.11	1.69	.36
Co	.28	.30	17.82	18.66	0.69	.56
Ni	41.61	42.53	11.04	10.63	47.68	48.02
Cu	n.a.	n.a.	1.23	1.27	n.a.	n.a.
As	53.01	54.67	42.32	43.04	46.19	47.91
S	1.04	.28	20.98	20.48	0.24	.27
Sb	.40	.47	0.13	0.02	0.13	.38
Total	96.92	98.38	99.90	99.21	96.62	97.50

Chemical compositions of the sulphide occurrence

The contents and ratios of the chalcophile elements vary considerably between intrusions and between the various parts of the Ni intrusions. The highest nickel values in the 100 % sulphides are encountered in the B ultramafite. Table 20 gives the averages calculated for samples with over 0.05 wt % S. The sulphur content averages 0.29 %, Ni 0.112 %, and the Ni content in sulphide phase 14.67 %. The Ni/Cu ratio, 6.6, is higher, but the Ni/Co ratio, 16.5, lower than in the Ni ultramafite. This can be attributed to the low sulphide abundance (Häkli 1979, Isohanni *et al.* 1980).

The highest calculated Ni values of the sulphide phase in the Ni ultramafite (average 12.90 % Ni) and the highest Ni/Cu and Ni/Co values (averaging 6.5 and 36.9, respectively) are encountered at the SW edge of the ultramafite. The forementioned parameters all decrease towards the NE part of the ultramafite. In the intersection in the central part of the body the Ni value of the sulphide phase has been reduced to 5.46 %, the Ni/Cu ratio is almost the same (5.8) and the Ni/Co ratio has decreased to 23.0. In the intersection at the NE end of the ultramafite the nickel content of the sulphide phase averages a mere 4.0 %, the Ni/Cu ratio is 3.5 and that of Ni/Co 17.8. For comparison, Table 20 lists the arithmetic mean of the sulphide phases of all the ultramafic rock types in the Ni ultramafite. The average nickel value of the sulphide phase is 5.55 %, the Ni/Cu ratio is 5.8 and that of Ni/Co 24.4. These are fairly close to the corresponding values obtained from the intersection in the central portion of the ultramafite.

The Cu-Co-Ni diagram in Fig. 33 shows that the Co values remain fairly constant for most of the peridotites and dunites in the Ni ultramafite. The Ni/Cu ratio varies considerably. In places, particularly adjacent to the pegmatitic portions, chalcopyrite is remobilised. The Ni/Cu ratio is markedly lower in the pyroxenites than in the peridotites and the ratio is reduced still further in the hornfelses. The Ni/Cu ratios of some of the hornfelses exhibit lower values than do those of kinzigites and pyroxene quartz diorites. The variation in the Ni/Cu ratio is largely due to the readiness of copper to remobilise. The Ni-Cu-Co-ratios vary little in the B ultramafite (Fig. 34). The average Ni/Cu ratio of the Oravainen ultramafites is clearly above the average for nickel occurrences in Finland (Papunen *et al.* 1979).

As a random check, 31 samples from the mineralized ultramafite at Oravainen were analysed for platinum and palladium. In 23 of these, the Pt values were under the detection limit of 0.02 ppm. In seven samples, the Pd values were under the detection limit of 0.02 ppm for the analytical method applied. The hig-

Table 20. The average content and ratios of the chalcophilic elements in the Oravainen ultramafites (wt %).

	n	Ni	Cu	Co	S	Ni^S	$\frac{Ni}{Cu}$	$\frac{Ni}{Ni+Cu}$	$\frac{Ni}{Co}$
OR-21	10	0.112	0.017	0.0068	0.29	14.67	6.6	0.87	16.5
OR-22	15	0.708	0.109	0.0192	2.16	12.90	6.5	0.87	36.9
OR-6	33	2.133	0.367	0.0927	14.92	5.46	5.8	0.85	23.0
OR-28	9	0.187	0.053	0.0105	1.77	4.00	3.5	0.78	17.8
OR-6, -22, -23, -25, -26, -28	135	1.149	0.196	0.047	7.86	5.55	5.8	0.85	24.4

OR-21 = B ultramafite, OR-22 = SW end of the Ni ultramafite, OR-6 = Central area of the Ni ultramafite, OR-28 = NE end of the Ni ultramafite, OR-6, 22, 23, 25, 26, 28 = Ni ultramafite on average.

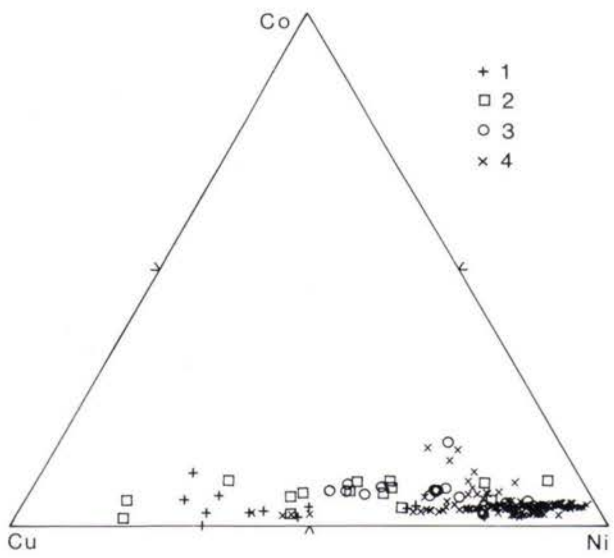


Fig. 33. Cu-Co-Ni diagram of the Oravainen Ni ultramafite. 1. Kinzingitic gneiss granite; 2. Hornfels; 3. Pyroxenite; 4. Peridotite and metadunite.

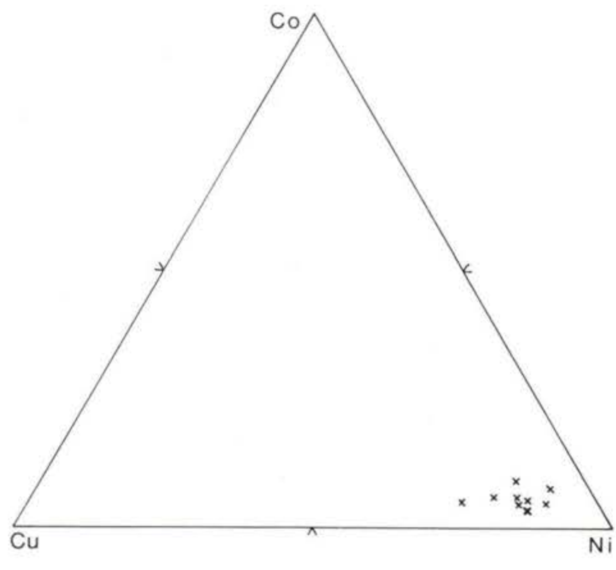


Fig. 34. Cu-Co-Ni-diagram of the peridotites in the Oravainen B ultramafite.

hest concentrations were obtained from a copper-rich portion, one sample having 1.06 ppm Pd and 1.65 ppm Pt. In eight samples, the values of both elements exceeded the detection limits; the arithmetic means for these samples were 0.21 ppm Pd and 0.28 ppm Pt.

RELATION BETWEEN THE NICKEL CONTENT IN OLIVINE AND IN SULPHIDE PHASE

The olivines of the Oravainen ultramafites can be subdivided into four groups on the basis of the nickel versus forsterite content. The same grouping is clearly shown in the Ni^{Ol}/Ni^{S} ratio

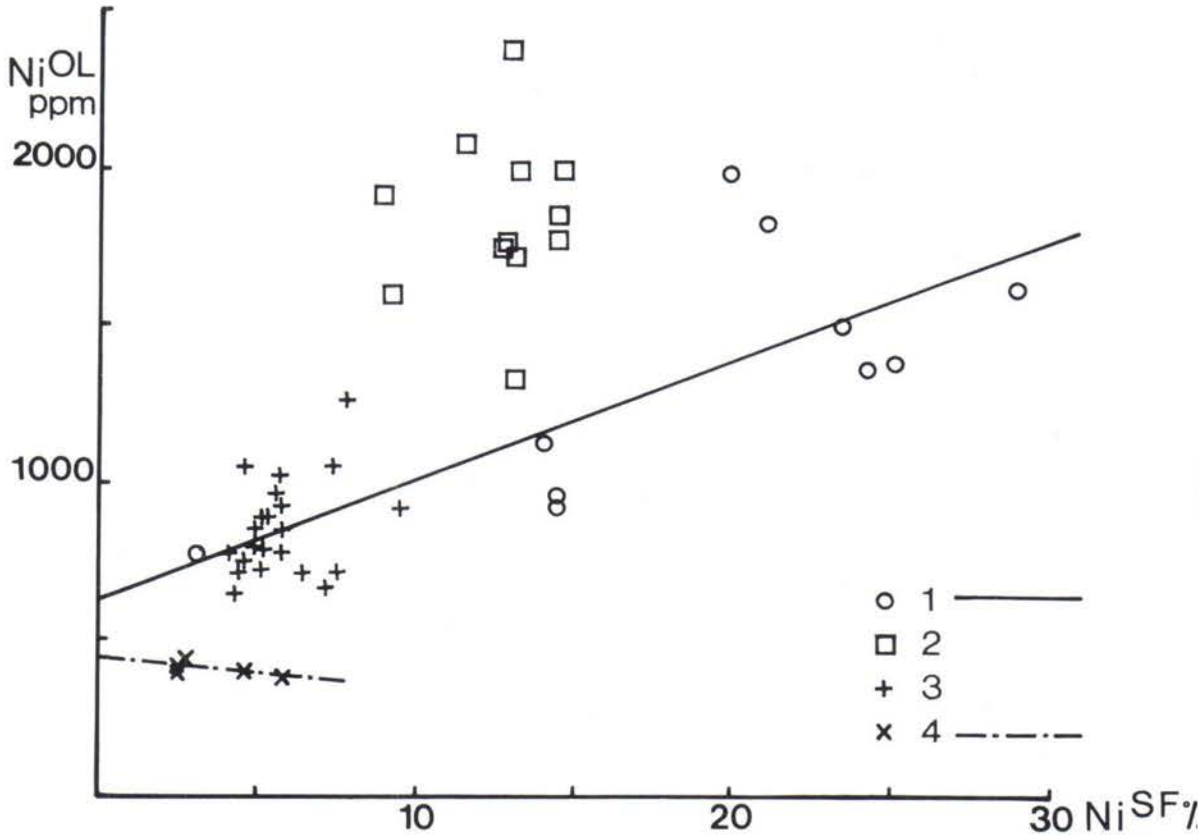


Fig. 35. Nickel in the olivine versus nickel in 100 % sulphides. 1. B ultramafite; 2. Peridotites in the SW part of the Ni ultramafite; 3. Peridotites in the central part of the Ni ultramafite; 4. Pyroxenites in the NE part of the Ni ultramafite.

(Fig. 35). The sulphide-rich samples from the central part of the Ni intrusion, with an average of 5.8 % Ni in sulphide phase, plot within a rather small field. The Ni^{Ol}/Ni^{S} relation shows a fairly weak positive correlation within this group. The high Ni^{Ol} and Ni^{S} values in the intersection at the SW end show a very weak positive correlation. In the five samples from pyroxenites at the NE end of the Ni intrusion the Ni content of olivines is very constant, and the Ni content in 100 % sulphides varies between 2.5 and 5.8 %.

For the B ultramafite, the Ni^{Ol}/Ni^{S} relation is clearly positive and the correlation (0.71) is good. If the variation is approximated with a line, its equation is $Ni^{Ol} = 0.063 + 3.8 \times 10^{-3}Ni^{S}$.

In their studies on the fractionation of olivine and sulphide melt form the komatiiatic magma, Duke and Naldrett (1978) have shown that there is a clear positive correlation between the nickel and forsterite content of olivine, and between the MgO content in the melt and the nickel content in the sulphide phase. The nickel values in olivine and in the sulphide phase depend largely on the crystallisation stage at which the saturation point of the sulphides is reached. Fleet *et al.* (1977) have studied the partition of nickel between olivine and immiscible sulphide melt, and Fleet *et al.* (1981) between olivine, silicate melt and sulphide melt. Their results were partly contradictory: »If the Ni content of natural olivine were controlled by equilibration with an immiscible sulfide liquid, the overall variation of Ni with MgO would be directly opposite to that observed (Fleet *et al.*, 1977, Fig. 5), with low Ni in Mg-rich olivine and high Ni in Fe-rich olivine». The forementioned trends may be seen in olivines with high sulphide contents in the Oravainen Ni intrusion (Figs. 30 and 35).

SULPHUR ISOTOPES

Sulphur isotope determinations were done on ten samples from a drill intersection in the Ni ultramafite at Oravainen. The $\delta^{34}S$ values vary between +2.4 and +3.4 ‰ (average +2.8). For comparison, two determinations were done on the graphite mica gneisses in the neighbourhood, which showed $\delta^{34}S$ values of —8.1 and —7.8 ‰. Hence it is likely that the sulphur in the Oravainen mineralisation is largely magmatic in origin (Papunen and Mäkelä 1980).

SUMMARY AND CONCLUSIONS

The Oravainen ultramafites are located at the NW rim of the zone of Ni-potential ultramafites, 1.9 to 1.85 Ga in age, that forms a ring pattern around the central Finland plutonite region. To date they are economically the most important group in Finland.

The nickel occurrence of Oravainen and the adjacent B ultramafite were probably emplaced before the metamorphic events that took place under P-T conditions of the granulite facies, in any case, before retrogressive metamorphism and granitisation. The Ni ultramafite, which is a pipe-like body in structure and differentiation and in the mode of occurrence of the sulphides has been interpreted as a feeding channel for magma. The B ultramafite also seems to be pipe-like in structure.

It is not easy to estimate the composition of the original magma, but it was probably ultramafic. The abnormally high alkali values can be attributed to contamination, which the textures suggest took place at the stage when the content of liquid was still quite high. The hornblendites in the environment may be products of the same magmatism. Parts of the olivine and chromite were obviously already crystallised when the emplacement occurred. The gravitative concentration of some olivine in the SW-W margins of the two ultramafites contributed to fractioning and gave rise to eccentricity in the otherwise rather concentric pipes. In spite of the small horizontal section, the path of the crystallisation of the silicates in relation to the liquid immiscibility of the sulphides was different in each ultramafite and in different parts of the Ni ultramafite. Being more basic and containing slightly less alkalies, the B ultramafite crystallised at a higher temperature. The small sulphide blebs, 1 to 2 mm in diameter, and the weak interstitial dissemination indicate that immiscibility of the sulphide melt took place at a very late stage of crystallisation. Consequently, the sulphides did not have time to concentrate.

Depending on the stage of silicate crystallisation at which the immiscibility point of the sulphides was reached, sulphide melts with varying composition were formed in the Ni ultramafite. The Ni-rich dissemination at the SW end of the

Ni ultramafite was formed as a result of early sulphide melt immiscibility, and the sulphides were concentrated partly gravitatively in the footwall of the subvertical ultramafite. The proportion of silicate residual melt was relatively small at the moment of sulphide immiscibility.

The silicates in the central part and at the NE end of the Ni ultramafite crystallised later. The sulphides had time to concentrate into larger blebs and to form network textures. Almost massive ores and dunitic differentiates were formed in the central part of the ultramafite at a fairly early stage of the crystallisation of the silicate melt when the sulphides displaced the silicate residual melt either gravitatively or by »filter pressing».

At the SW end, the sulphide immiscibility took place at the end of the silicate crystallisation, and the composition of the sulphide melt remained fairly close to that of the initial model by Duke and Naldrett (1978). In the middle and at the NE end of the mineralised pipe, the sulphide immiscibility took place at an earlier stage of silicate crystallisation, and the Ni content of the sulphide phase in equilibrium with the silicates is markedly lower (op. cit. the subsequent model).

The silicate sulphide nodules in pyroxenite were formed at a very late stage from a melt rich in volatiles.

Serpentinisation and the alteration of the sulphide phase took place after the magmatic stage. As a result of the alteration, the sulphides were partly replaced by magnetite, and the Ni contents of the sulphides phase and silicates were probably also changed to some extent.

The Ni ultramafite and the B ultramafite at Oravainen are very similiar in silicate composition and both are Ni potential. On the basis of the total composition of the silicate and sulphide phases, attempts were made to estimate the mutual relation between the crystallisation and the stage of sulphide melt immiscibility, to assess the ability of the sulphides to concentrate, and to establish the composition of the sulphide phase. The Oravainen ultramafites show that ultramafites considered as Ni potential must be submitted to detailed investigations, because the Ni potentiality varies largely, even in different parts of a small intrusion.

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GEOLOGY AND NICKEL-COPPER ORES OF THE NIVALA AREA

M. ISOHANNI, V. OHENOJA and H. PAPUNEN

The Nivala area (Fig. 36) is part of the Bothnian Svecokarelian schist zone (Mäkinen 1916, Salli 1964 and 1966). Numerous Ni-Cu ore boulders discovered in glacial drift since the early 1930s have revealed the area potential for nickel deposits. The Nivala area has therefore been the target of a wide variety of explorational activities by the Geological Survey and Outokumpu Oy. The first period of exploration started in 1936 and the Makola nickel deposit was discovered by the Geological Survey in 1937. About 415,000 tonnes of ore were mined at Makola in 1941—1948 and again in 1951—1954.

In 1937, during the exploration and development stage of the Makola mine, boulder tracing and subsequent geophysical survey disclosed a sizeable ultramafic body with some low-grade Ni-Cu sulphide occurrences at South Hitura.

In 1961 the Geological Survey of Finland reactivated exploration in the area. This led to the discovery of the North Hitura ultramafic complex and its allied Ni-Cu occurrences. Geophysical survey and geological studies revealed an ultramafic body and several orebodies under an overburden of 15 to 45 m. In 1964 the property was optioned to Outokumpu Oy. Development work commenced in 1969 after underground exploration, comprehensive mineralogical and process research and feasibility studies. Production started in 1970, the projected capacity being 200,000 tpy. In 1975 the capacity was raised to 300,000 tpy and then gradually expanded to 450,000 tpy. Owing to low metal prices the Hitura mine was temporarily closed in 1982—1984.

GENERAL GEOLOGY OF THE NIVALA AREA

Outcrops are sparse in the immediate environment of Hitura, and geological maps are based largely on geophysical surveys and field observations in peripheral areas. The main rock types in the Nivala area are intensely metamorphosed geosynclinal metasediments, intervening metavolcanics and extensive felsic intrusives (Fig. 36). The character of the volcanism and sedimentation, the cutting relations, the grade of metamorphism, and the migmatization in the Nivala area permit the supracrustal rocks to be divided into two groups and the plutonic rocks into three groups (Table 21). The boundary between gneiss granite and certain syntectonic plutonic rocks has been drawn on the basis of the degree of mobilization and is only tentative.

Table 21. Stratigraphic scheme of the Nivala area.

	Supracrustal rocks	Plutonic rocks
	Intermediate and acid metavolcanics	Late orogenic gabbros-diorites-monzodiorites-granodiorites-granites (~ 1800 Ma)
II	Greywacke with intercalations of intermediate and acid tuffites and phyllites; basic intermediate and acid metavolcanics	Synorogenic gabbros-granites (1860—1900 Ma)
I	Migmatitic mica gneiss with intercalations of graphite and sulphide-bearing gneisses and amphibolites	Ultramafic and mafic intrusions (≥ 1900 Ma)
	Gneissose granite (mobilized)	

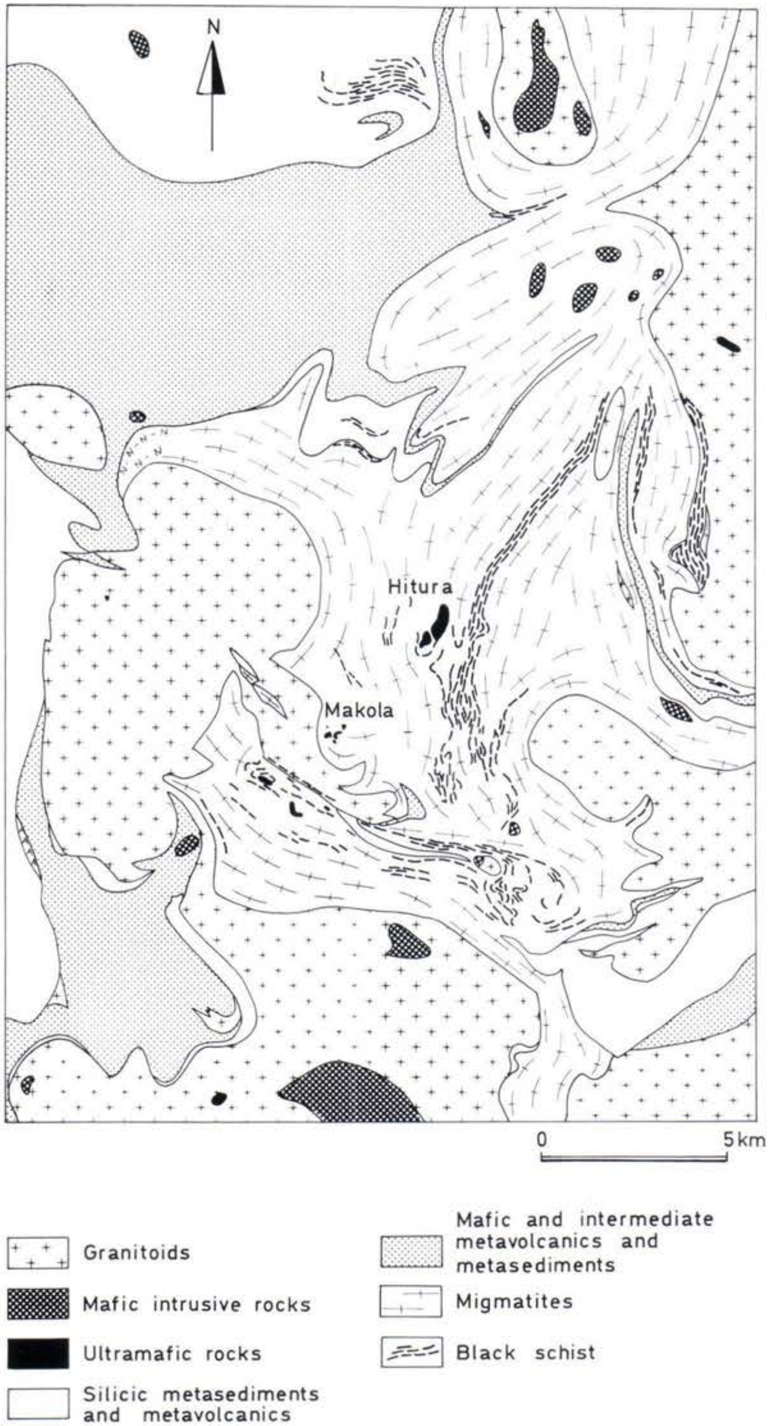


Fig. 36. General geology of the Nivala area.

Gneissose granite

In the eastern part of the area presented in Figure 36 there is a heterogeneous gneissose granite that trends from north to south. The composition varies from granite to granodiorite and quartz diorite. The homogeneous parts are only slightly foliated and banded, but the heterogeneous portions often show ghost-like remnants of sedimentary structures, which indicate that the rock is an extensively granitized metasediment.

Remnants of the felsic tuffites and arkosites have been encountered in some localities. Mafic metavolcanics and carbonate-bearing metasediments occur as boudins. The migmatitic gneiss granite is nebulitic or schollen migmatitic in structure. In places a network of younger coarse-grained potassium granite brecciates and migmatizes the gneiss granite. This gneiss granite area has been interpreted as the almost wholly mobilized basement for volcanism and sedimentation.

Supracrustal rocks

The lower group consists of migmatitic mica gneisses and interlayers of graphite and sulphide-bearing gneisses and amphibolites. The migmatitic mica gneiss is the country rock of the ultramafic intrusions at Hitura and Makola and many other places. The portions that are least migmatized are medium-grained banded metagreywacke. The heterogeneity is due to various primary interlayers that include meta-arkoses, felsic tuffites, skarns and amphibolites of various grain size. The abundance of garnet is locally very high. The bulk of the mica gneiss has undergone intense venitic migmatization and is now veined gneiss in structure.

In the immediate environment of the Hitura mine and elsewhere the structure is schollen migmatitic. The migmatitic mica gneisses exhibit variable graphite and pyrrhotite abundances. The portions with abundant graphite and sulphides have been marked on the map as graphite and sulphide-bearing gneisses. Aerogeophysical surveys and ground measurements show them as distinct electric and magnetic anomalies.

According to geophysical survey, the amphibolites constitute long and narrow ribbon-like zones that often occur either at the contact between plutonic rocks and migmatitic mica gneiss or as interlayers in the migmatitic and mica gneiss-like metasediment. The amphibolites are banded or striped in structure. The well-preserved portions suggest that the amphibolites derive from pyroclasts, lavas and dyke rocks.

The upper group consists of two volcanic suites between which there is a sequence of sedimentary rocks composed mainly of greywackes. The rocks of the lower metavolcanite suite are usually andesitic or dacitic in composition although basaltic and rhyolitic metavolcanics have also been encountered. The primary structures are locally well preserved, suggesting that the rocks were originally pyroclasts: tuffites, tuffs, agglomerates and volcanic conglomerates. Lava structures and dyke rocks are also met with. The volcanics seem to represent a suite that erupted and deposited in shallow water or on land. The volcanics are overlain by a sequence of metagreywackes and intermediate tuffites with narrow conglomerate and phyllite interlayers. Also present are intermediate plagioclase porphyry dykes that mainly intersect the wall rocks but in places occur as sills.

The intermediate and felsic volcanics some 20 km west of the Nivala area constitute the youngest supracrustal series in the area, which includes agglomerates, lavas and tuffs. The plagioclase porphyry dykes encountered at Hitura probably belong genetically to this series.

Plutonic rocks

The oldest suite of intrusive rocks in the area consists of the ultramafic and mafic intrusives that host the Hitura and Makola nickel ores as well as several smaller nickel occurrences. The intrusive rocks of this group occur in gneiss granite and in the migmatitic mica gneisses but not in the sequence of supracrustal rocks that is stratigraphically above the mica gneisses.

Younger than this group is the syntectonic intrusive series, which is composed of gabbros, diorites, quartz diorites, granodiorites, tonalites and granites. Located about 20 km NW of Hitura, the Ylivieska layered gabbro, which is one of the members of this group, is 1880 ± 20 Ma old (Kouvo 1976). The predominant rock type in this group is heterogeneous granodiorite or tonalite in which more mafic plutonic rocks or schist remnants occur as fragments.

The youngest plutonic suite is late-kinematic and consists of diorites, monzodiorites, quartz monzodiorites, granodiorites and granites. The rocks often occur as batholiths whose rock types were emplaces in several stages. Some of the granite veins in the metavolcanites probably also belong to this group.

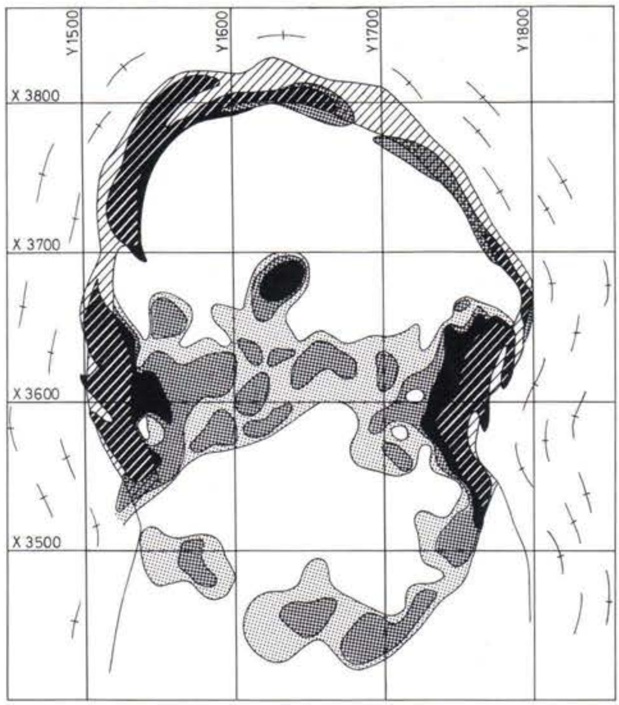
Structural geology

The tectonic pattern of the Hitura environment is characterized by isoclinally folded migmatitic mica gneisses in the synform areas and plutonites in the antiform areas. The schistosity and bedding of the mica gneisses often conform with the contacts of the plutonic areas. The volcanites and greywackes seem to be less deformed than the migmatitic mica gneiss. According to Gaál (1972), the Nivala area is part of a long belt characterized by a swarm of subparallel and NW-SE trending wrench faults. The NE-SW trending fault zone, which can be recognized at Ainaslampi, Makola, Hitura and Saarineva, appears on the aeromagnetic map as a distinct break in the anomaly zones and as partial plastic bending parallel to the fault. This NE-SW trending fault zone coincides with the northwestern margin of the roughly 400-km-long and 40-km-wide parallel negative gravimetric anomaly.

THE HITURA MINE

The Hitura mine of Outokumpu Oy is located in the municipality of Nivala, some 90 km east of the town of Kokkola.

The Hitura ultramafic complex consists of two separate closely spaced serpentinite bodies in migmatized mica gneiss, North Hitura and South Hitura. The dimensions of the complex are some 0.3 × 1.2 km. The extension in depth



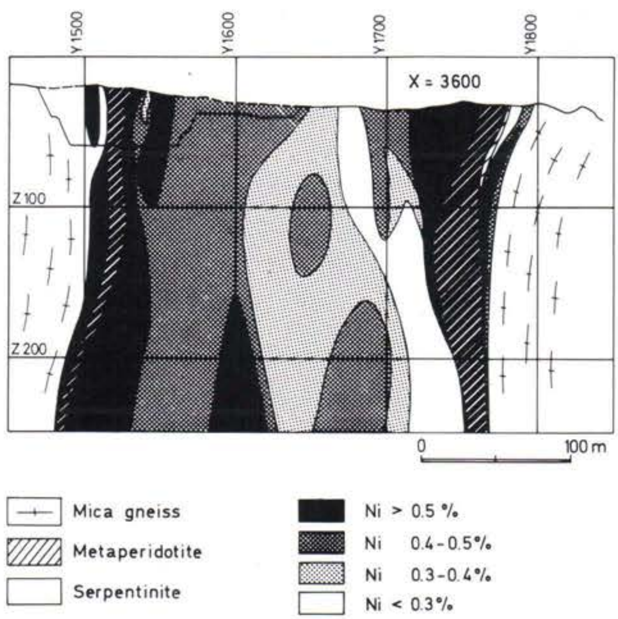


Fig. 37. Distribution of the rock types and tenor of Ni at the +60 m level and in cross section X = 3600 of the Hitura mine.

has not been established. The deepest diamond drill section is at the 550 m level. The core of the complex consists mainly of serpentinite and the contact zone chiefly of amphibole-rich mafic to ultramafic varieties (Papunen 1970). Separated from each other by a narrow mica gneiss tongue the intrusions of North Hitura and South Hitura are so similar that separate descriptions are not warranted.

Several small low-grade Ni-Cu ore bodies and a large but very low-grade Ni-Cu occurrence are located in the ultramafic complex (Fig. 37). Both ore types have been exploited by open-cast mining. The small contact ore bodies reaching down to the 400—500 m level will be mined underground. The total ore reserves with 0.3 % Ni cutoff are about 35 million tonnes and with 0.5 % Ni cutoff about 10 million tonnes.

The ultramafic complex

The core of the ultramafic complex (Figs. 37 and 38) is composed mainly of a dark grey or black, porous, fine-grained, light-weight variety of serpentinite ($d = 2.4—2.6\ g/cm^3$). The main minerals are serpentine (80—90 %), chlorite, calcite and magnetite (7—9 %). The amount of sulphides varies. Additional minerals are talc, amphiboles, graphite and micas. Accessories are chromite and arsenides.

The present texture of the serpentinite is the result of hydration of primary Mg-Fe silicates, subsequent replacement of the primary sulphide minerals and the appearance of the secondary sulphide assemblage. Alteration has been most effective in the middle of the complex where the mesh-textured serpentinite contains a network of fine-grained secondary magnetite. Common features of the serpentinite core are replacement of pyrrhotite by magnetite and chlorite in the primary sulphide blebs and the deposition of second-generation sulphides and magnetite as minute grains scattered within and between serpentinite minerals.

Primary cumulus texture can be recognized locally at the marginal variety of the metaperidotite because hydration has not been so effective in the ultramafics adjoining the contact zone as in the core of the body. Tremolite-actinolite forms a network between pseudomorphs of orthopyroxene and rare monoclinic pyroxene. The pseudomorphs often consist of flakes of chlorite and biotite. The sulphide dissemination is more coarse-grained than in the serpentinite core. Occasional massive sulphide »sacks» range in size from a few centimetres to several decimetres. The average tenor of Ni at the contact zone is from 0.45 to 0.6 % but locally the ore grade is higher (Figs. 37 and 38). This marginal ore type is mined and processed.

The immediate contact zone between the ultramafic complex and the gneiss wall rock is composed of a heterogeneous sequence of fine to medium-grained varieties of ultramafic chlorite-amphibole rock (Fig. 38). The thickness of the contact rock varies from nil to several tens of metres. Transition from the contact rock is gradual. Banding is to be seen at sites of only modest disturbance. Towards the contact the amount of serpentine decreases and that of amphibole and sheet silicates increases. The rock is generally speckled in appearance with pale green amphibole — sheet silicate grains in dark grey serpentinite, that ratio reversing towards the contact. At the contact a pale green, soft talcose rock occurs.

The main minerals of the contact rock are amphibole, serpentine and sheet silicates. Additional minerals include graphite, magnetite and

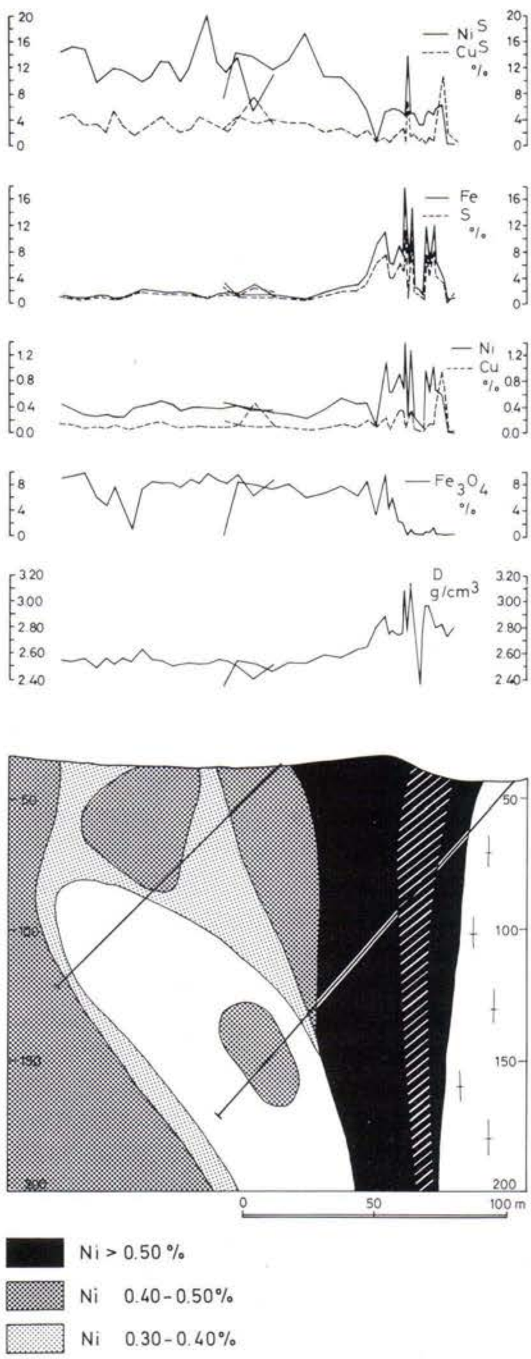


Fig. 38. Cross section X = 3625; distribution of Ni and Cu calculated to 100 % sulphides (Ni^S, Cu^S), Ni, Cu, Fe, S, magnetite content (Fe_3O_4) and density (D) of the diamond drill cores projected on the horizontal level (Hautala and Sotka 1976).

ilmenite. Accessory relict pyroxene, chromite, arsenides and zircon may be present. Ni-Fe-Cu sulphides are either main minerals or accessory components. The amphibole minerals are tremolite-actinolite, anthophyllite and cummingtonite.

The sheet silicates, chlorite, talc, phlogopite and biotite, occur between the amphibole grains. Common features are abundant ilmenite and scarce magnetite. The average density is 2.8—2.9, depending on the abundance of sulphides.

It is assumed that, while emerging, the contact rocks experienced both the effects of thermal gradient and contamination by the silicic wall-rock gneiss. Hydration of the primary Mg-Fe silicates and subsequent replacement of primary sulphides by secondary sulphide minerals were important factors in the rock-forming process, although less so than in the serpentinites in the ultramafic core of the complex.

The contact itself is always tectonic, sharply undulating and filled with fine-grained, talcose joint mortar. Dislocated mafic blocks, erratic wall-rock inclusions and massive sulphide lumps interspersed with soft, earthy talcose muck frequently occur. Angular gneiss inclusions occasionally exist along the contacts, and close to it the wall-rock gneiss is broken in appearance with mylonitic zones. Pale green steatite and white carbonate fill the fractures. In some places, however, highly competent and homogeneous coarse-grained amphibole rocks rim the complex for a considerable distance.

The Hitura ultramafic body is characterized by an irregular pattern of prominent faulting that pervades the whole body. In the middle of the body large blocks with graphite slickensides are separated by chlorite-talc shear zones, whereas at the contact zones smaller dislocated fragments prevail.

Pegmatite veins

The ultramafic complex is randomly intersected by pale grey pegmatite veins that are often brecciated and range in width from a few centimetres to 2 m. They are most abundant close to the contact. Like the ultramafic complex itself, the veins have experienced the hydrothermal alteration that pervades the whole body. A zonal reaction rim composed of an almost monomineralic succession of talc, actinolite, anthophyllite and chlorite, starting from unaltered peridotite, occurs in the serpentinite along the pegmatite vein. Potassium, aluminium, iron and silica occur in greater abundance in the zones than in the pure serpentinite (see Papunen 1970).

The pegmatite veins are composed of oligoclase, biotite and muscovite with accessory zircon. Unevenly distributed, remobilized sulphide blotches and thin impregnation are common. Copper is commonly more abundant than nickel.

The U-Pb age of the zircon fractions separated from the pegmatite vein was determined by Dr. O. Kouvo at the Geochronological laboratory of the Geological Survey of Finland. The age, 1877 $\pm$ 2 Ma, represented the minimum age of the ultramafic complex.

Geochemistry of the Hitura ultramafic complex

Samples from diamond drill cores were analysed by the XRF method for main and trace elements. Because the rocks of the body are strongly altered serpentinites and serpentine-chlorite-talc-amphibole rocks which are hard to classify petrographically, the samples analysed were classified by increasing content of aluminium as follows: group 1: Al_2O_3 < 1 %, 2: Al_2O_3 = 1—5 %, 3: Al_2O_3 = 5—10 %, and 4: over 10 % Al_2O_3. The average chemical compositions of the various rock types are given in Table 22 and the variation of main elements in the samples analysed in Figure 39.

All the rocks in groups 1 to 3 are serpentinites but the rocks in group 3 contain appreciable amounts of chlorite and amphiboles in addition to serpentine. The rocks in group 4 are amphibole-chlorite-rocks from the contact zone of the ultramafic body. The rocks in group 1 contain serpentine, minor talc and carbonates, which make the sum of analysed oxides very low. The rock corresponds to altered pure dunite in chemical composition, whereas the rocks in groups 2 and 3 are peridotitic.

High values of Al_2O_3 compared with CaO are typical of the metaperidotites and amphibole rocks. This high ratio is well indicated in the CaO-Al_2O_3-MgO diagram in Figure 39 and in the CIPW norm by the high percentage of normative corundum. The variation in the Al_2O_3 to CaO ratio is larger in the amphibole rocks, indicating the heterogeneous origin and composite character of this contact rock type. Despite the high tenor of aluminium, the other components of the typical salic contamination, alkalies and silica remain at a relatively low level.

As the hydrous and altered minerals are abundant in metaperidotites it seems reasonable that also the chemical composition of the rock has been changed in hydrothermal alteration. It is well documented that high water to rock ratio in hydrothermal processes can cause depletion of calcium whereas aluminium can preserve almost unchanged and hence the relative abundances of aluminium will increase.

The values of titanium and of phorphorous are very low in the rocks of Hitura. Chromium

Table 22. Average chemical compositions, Niggli values and C.I.P.W. norms of the rocks of Hitura.

	Dunite	Meta-peridotite	Meta-peridotite	Amphibole-rock
n	15	15	15	14
SiO_2	33.60	38.10	38.81	49.53
TiO_2	0.04	0.09	0.19	0.39
Al_2O_3	0.48	3.66	7.42	14.48
Cr_2O_3	0.43	0.64	0.60	0.07
FeO	14.54	15.60	15.02	7.82
MnO	0.19	0.20	0.22	0.12
MgO	32.86	36.66	27.53	13.19
CaO	0.23	1.26	1.85	1.52
SrO	0.001	0.002	0.007	0.049
BaO	0.005	0.004	0.014	0.087
Na_2O	0.12	0.16	0.33	2.36
K_2O	0.11	0.13	0.47	3.00
P_2O_5	0.005	0.023	0.026	0.064
ZrO_2	0.001	0.002	0.004	0.020
Cu	0.054	0.113	0.074	0.078
Ni	0.269	0.336	0.224	0.185
S	0.462	0.693	0.659	0.406
Σ	83.40	97.69	93.45	93.36
si	54.3	53.3	63.9	107.0
al	0.46	3.02	7.21	21.07
fm	98.8	94.7	88.5	64.53
c	0.40	1.90	3.27	4.03
alk	0.31	0.34	1.03	10.38
qz	—46.9	—48.1	—40.2	—34.55
mg	0.80	0.81	0.76	0.75
k	0.38	0.35	0.48	0.45
o	0.009	0.009	0.012	0.027
ti	0.05	0.10	0.23	0.72
p	0.006	0.01	0.02	0.06
C	—	1.02	3.32	5.46
Or	0.83	0.83	3.01	20.51
Ab	1.27	1.44	3.05	23.10
An	0.50	6.37	9.73	8.27
Pl	1.77	7.81	12.77	31.37
An	28	82	76	26
Di	0.66	—	—	—
Hy	9.98	3.83	20.43	12.84
Ol	83.44	83.22	56.70	25.37
Mt	2.70	2.39	2.64	3.16
Im	0.09	0.19	0.38	0.85
Ap	0.02	0.05	0.07	0.17
Sal	2.59	9.66	19.11	57.34
Fem	96.89	89.69	80.22	42.40

is rather high, even in the dunitic rock type, indicating that chromite is the main carrier of that element. The drop in Cr values in the amphibole rocks is probably due to the lack of original cumulus phases in that part of the intrusion.

The zoning of the Hitura ultramafic body may be the result of either assimilation of the wall-rock material at the margins or magmatic

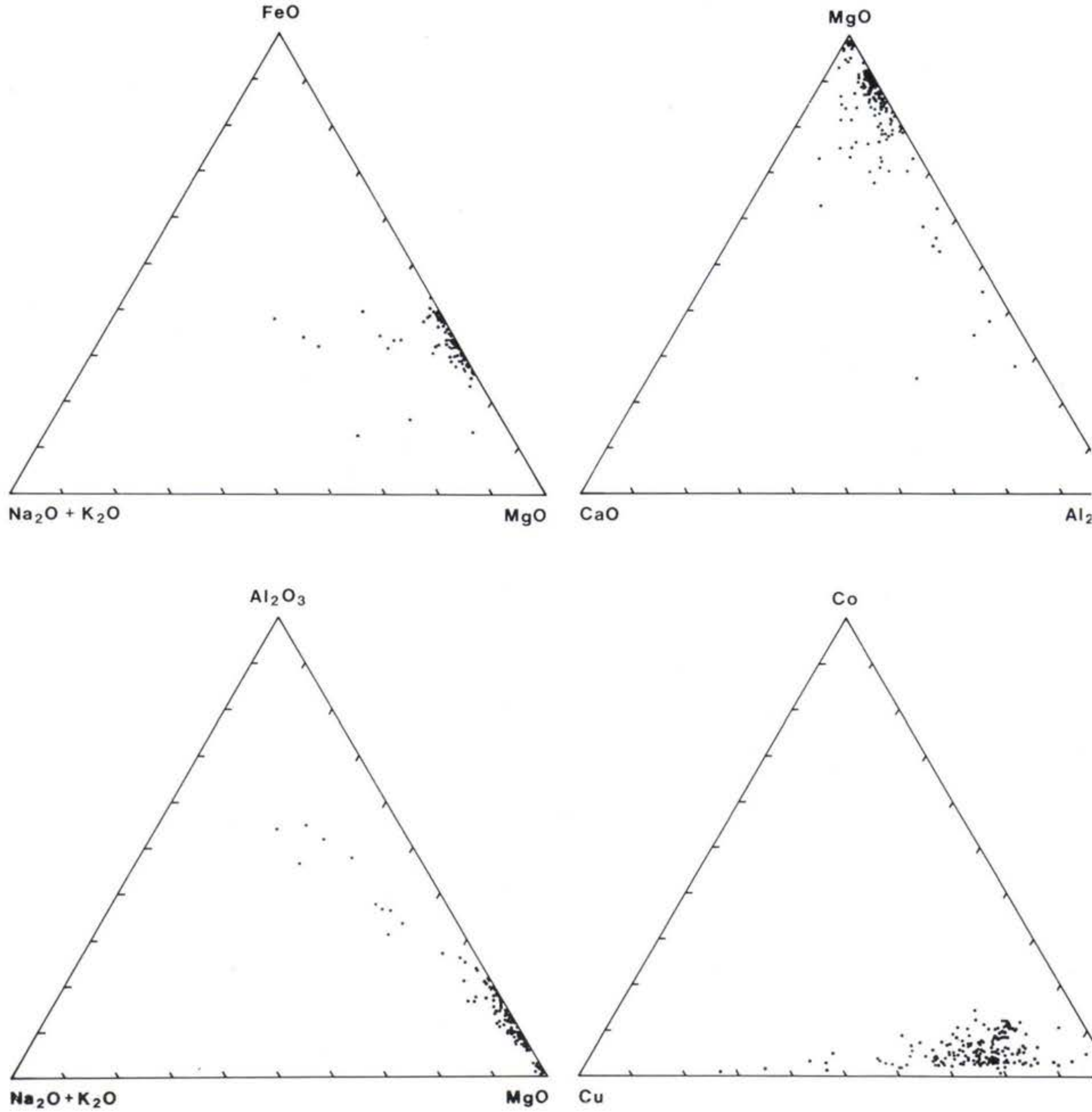


Fig. 39. Ternary diagrams depicting the variation in chemical composition of the ultramafics and ore of Hitura.

fractionation of primary cumulus material in the centre, or a combination of the two. Because the primary minerals are almost completely hydrothermally altered, the chemical composition of the ultramafic body has undergone similar processes, and the original fractionation is hard to decipher.

Chemical composition of mafic silicates

Fresh olivine exists only in some metaperidotite varieties close to the contact zone. The composition of olivine is more or less constant, evidently buffered by the co-existence of sulphides. The values of nickel fluctuate between 681 and 1316 ppm with 1010 ppm as an average. The percentage of iron varies from 11.6 % to 15.0 % Fe with 13.7 as the average. Colourless monoclinic amphibole has an average of 3.36 % Fe and 309 ppm Ni. One grain of orthopyroxene yielded 184 ppm Ni and 9.9 % Fe and an analysed monoclinic pyroxene gave 170 ppm Ni and 2.4 % Fe. The number of silicates analysed was too small to enable the distribution coefficients of nickel between different silicates to be calculated.

Sulphur isotopes

According to Papunen and Mäkelä (1980), the sulphur isotope composition of the disseminated sulphides in the serpentinite core is rather constant with $\delta^{34}S$ averaging + 2.5 ‰. The sulphide-rich contact zone displays more heterogeneous values but the average, + 2.2 ‰, is close to that of serpentinite. The sulphides of the wall-rock gneisses differ slightly in $\delta^{34}S$ values (average + 4.3 ‰) from the ultramafic body, indicating that the wall-rock sulphides have a different origin. Dispersion halos of Ni and Cu extending some ten metres from the rich contact ore are to be found in the wall-rock gneiss. The same zone of mixed sulphides are also shown by the sulphur isotopes, indicating that the magmatic sulphides invaded the wall rock.

ORE TYPES

The Hitura Ni-Cu deposit consists of three different ore types: 1) scattered fine-grained disseminated sulphides in serpentinite; 2) medium to coarse-grained, moderate dissemination and massive accumulations in the marginal serpentinite and adjoining amphibole rock; 3) fairly high-grade interstitial dissemination and massive ore in the amphibole rocks of the contact zone. In addition, veins and disseminated iron sulphides with accessory Ni and Cu occur in the wall-rock gneiss.

Disseminated ore in serpentinite

The fine-grained opaque mineral dissemination in the serpentinite core of the complex consists of magnetite, valleriite, pentlandite, mackinawite, chromite and graphite. The average sulphide mineral content is 1.2 wt-% with 0.15—0.25 % Ni and 0.30—1.00 % S. The tenor of Ni in the sulphide phase calculated for 100 % sulphides is generally more than 14 %. Magnetite averages 7—10 % (Figs. 37 and 38).

The mineral assemblage is assumed to be a relic after primary pyrrhotite-pentlandite-chalcopyrite-cubanite drop-textured dissemination. Replacement textures are far more common than primary ones. Small pentlandite grains are often capsulated by secondary magnetite, or then the pentlandite forms graphic lamellar chlorite-magnetite-pentlandite intergrowths that locally exhibit book texture or hymn-book texture. Nebulous Fe or Cu-valleriite dust occurs together with mackinawite within the serpentine mesh.

Ore in the marginal serpentinite

The predominantly disseminated Ni ore, the main target of mining operations, is close to the northern contact of the North Hitura ultramafic body between the western and eastern contact ore bodies. It is fairly heterogeneous and is generally considered to be of marginal grade. The ore-grade serpentinite includes 2—5 % sulphides averaging 0.4—0.55 % Ni. The Ni content of the sulphide phase varies from 8 to 12 %. Magnetite ranges from 4 to 8 % (Fig. 38).

The primary sulphide mineral assemblage consists of pentlandite, pyrrhotite, chalcopyrite and cubanite. The secondary mineral assemblage is composed of magnetite, mackinawite, valleriite, cubanite and graphite. Accessory pyrite, ilmenite, chromite and some arsenides, mainly nickeline, gersdorffite and cobaltite, may occur. Although alteration has been fairly intese, the primary interstitial texture of the sulphides can still be recognized. The degree of hydration and replacement textures tend to increase towards the interior of the body.

Ore of the contact zone

The most important ore type with regard to production is located along the contact zone of the ultramafic body. Several varieties occur, depending on the rock type. Pyrrhotite, pentlandite and chalcopyrite generally exist as medium to coarse-grained disseminated ore with occasional massive intersections. The Ni content varies from 0.4 to 1.5 %, the average being 0.6—0.7 %. The abundance of pyrrhotite fluctuates considerably, and the tenor of sulphur varies accordingly from 2 to 10 %. The Ni content of the sulphide phase varies from 4 to 8 %. The density of the rock is between 2.8 and 2.9 g/cm^3, being well over 3 in the high-grade ore (Fig. 38).

There are two generations of sulphide minerals. The first generation of opaque minerals comprises pyrrhotite, pentlandite I, chalcopyrite, cubanite I and accessory sphalerite, chromite and ilmenite. They display either well-preserved interstitial or drop textures with occasional massive intersections. The second generation assemblage of magnetite, vallerite, mackinawite, pentlandite II and cubanite II is the result of hydration, replacement and recrystallization processes. The alteration is most conspicuous in the ore with a serpentinite base, whereas the contact ore in the amphibole-rich host rock is well preserved with distinctive primary textures. Table 23 present the chemical composition of

Table 23. Microprobe analyses of the sulphide minerals. Hitura mine.

Host rock type	Coordinates	Pyrrhotite							Pentlandite						
	x/y/z	Fe	S	Co	Ni	Cu	Σ	S/(Ni + Co + Fe + S)	Fe	S	Ni	Co	Cu	Σ	(Ni + Co)/Fe
serpentinite	3609/1729/92	61.55	38.27	0.07	0.12	0.01	100.02	0.3826							
»	3550/1733/294	63.14	36.80	0.05	0.01	0.01	100.01	0.3680 t	36.52	32.88	29.83	1.08	0.03	100.34	0.846
»	3598/1532/169	59.47	39.40	0.06	0.10	0.02	99.05	0.3978 m	34.66	32.56	32.13	0.88	0.04	100.27	0.952
»	3497/1729/108	60.58	38.48	0.06	0.15	0.00	99.27	0.3876 h	34.54	32.83	31.45	1.07	0.05	99.94	0.942
»	3661/1629/86	62.03	38.98	0.07	0.11	0.02	101.21	0.3851 h	35.57	32.76	30.48	1.02	0.07	99.90	0.885
metaperidot.	3437/1664/205	61.32	38.62	0.01	0.05	0.01	100.01	0.3862							
»	3544/1723/205	61.63	39.23	0.06	0.20	0.01	101.13	0.3879 h	35.05	32.97	31.09	1.16	0.08	100.35	0.920
»	3544/1718/205	61.36	38.80	0.04	0.17	0.01	100.38	0.3865 h	34.37	33.27	31.85	1.04	—	100.53	0.957
»	3300/1653/205	60.97	38.44	0.07	0.13	0.03	99.64	0.3858 h	34.43	32.85	29.09	2.81	0.05	99.23	0.926
»	3591/1763/129	63.25	37.74	0.06	0.10	0.04	101.19	0.3730 t	36.00	32.84	30.28	0.93	0.03	100.08	0.867
»	3544/1722/205	61.35	38.51	0.05	0.17	0.02	100.10	0.3847 h	35.66	32.94	30.25	1.08	0.03	99.96	0.878
amphibole rock	3593/1759/124	61.29	38.95	0.05	0.23	0.02	100.54	0.3874 h	34.68	32.46	32.29	1.08	0.04	100.55	0.962
»	3541/1752/311	62.16	36.85	0.07	0.02	0.02	99.12	0.3718 t	36.45	32.90	29.25	0.73	0.04	99.37	0.822
»	3553/1729/187	61.26	38.49	0.04	0.23	0.02	100.04	0.3847 h	35.05	32.85	30.86	0.98	0.04	99.78	0.908
chlorite shear zone	3535/1736/205	61.19	38.89	0.06	0.12	0.01	100.27	0.3878 h	33.87	32.94	31.68	0.78	—	99.27	0.958
biotite gneiss	3617/1496/140	60.57	38.70	0.04	0.38	—	99.69	0.3882 h	34.58	32.83	31.61	0.55	0.04	99.61	0.930
granite	3500/1722/102	59.67	39.93	0.06	0.16	0.05	99.87	0.3998 m	33.80	32.51	32.78	0.85	0.04	99.98	0.995
troilite	average (3)	62.85	37.13	0.06	0.04	0.02			36.32	32.87	29.79	0.91	0.03		
hexagonal po.	average (10)	61.22	38.75	0.054	0.19	0.014			34.78	32.87	31.06	1.16	0.04		
mkl po	average (2)	59.57	39.66	0.06	0.13	0.03			34.23	32.63	32.45	0.86	0.04		
mackinawite	Hi-260/38.25	55.86	35.75	0.55	7.99		100.15								

h = hexagonal pyrrhotite, m = monoclinic pyrrhotite, t = troilite.

Table 24. Average chemical compositions of the ore types in the Hitura mine (Hautala and Sotka 1976).

Ore type (disseminated ores)	N	D(g/cm³)	mt	Ni	Cu	Co	Fe	S	Ni^S	Cu^S	Co^S	Fe^S	S^S
wall rock mica gneiss	28	2.84	0.34	0.06	0.03	0.005	4.74	2.96	0.63	0.56	0.05	57.94	40.84
marginal ore in amphibole-rock	13	2.92	0.62	0.49	0.09	0.02	7.02	4.59	6.27	1.79	0.24	55.39	36.46
marginal ore in serpentinite	27	2.71	4.89	0.65	0.17	0.03	5.01	3.38	7.97	2.22	0.34	53.79	35.37
margin of the serpentinite core	16	2.55	6.89	0.55	0.20	0.02	2.78	1.82	10.50	3.63	0.46	51.67	33.86
serpentinite core	186	2.51	6.83	0.29	0.10	0.02	1.25	0.93	12.23	3.83	0.82	47.09	35.99

N = number of samples, D = density, mt = abundance of magnetite in weight percent, Ni^S, Cu^S, Co^S, Fe^S, S^S = elemental abundances calculated in 100 % sulphides.

sulphide minerals.

Depending on the type of the host rock, the sulphide dissemination may be either fine, medium or coarse-grained. The texture is most commonly interstitial to silicates, but coarse buck shot dissemination and large massive blotches may also occur. The average chemical composition of the ore types is presented in Table 24.

Remobilization of sulphides seems to be related to faulting, and in the serpentinite it has produced a submicroscopic network of sulphide veins. Veins occur more frequently in the contact zone, where they vary in width up to several centimetres; massive accumulations of sulphides up to several cubic metres may also occur close to the contact shear zones. The sulphide mineral assemblage consists mainly of pyrrhotite and pentlandite. At the contacts chalcopyrite is more abundant in impregnation, veins and massive blotches. A thin chalcopyrite impregnation is commonly seen in the wall-rock gneiss within a few tens of centimetres of the contact. The narrow sulphide veins in the wall-rock gneiss mean that the abundances of Ni and Cu are locally increased for a distance of over ten metres. Noteable offsets have not been found.

Platinum-group elements

The distribution and abundances of the PGE have been described by Häkli *et al.* (1976). Percussion drill assay samples from a large area of the open pit indicate that the serpentinite contains fairly evenly distributed PGE averaging 0.010 ppm Pt, 0.015 ppm Pd and 0.005 ppm Rh. The distribution of the PGE in the amphibole rock of the contact zone is heterogeneous, ranging from 0.025 to 0.075 ppm Pt, 0.015—0.050 ppm Pd and 0.010 ppm Rh. Process samples collected from c. 20,000 tonnes of mill feed when the best PGE accumulation was mined yielded 0.034 ppm Pt, 0.041 ppm Pd and 0.015 ppm Rh, half of which was recovered into the concentrate.

Sperrylite is the only independent Pt mineral. Of the Pd minerals michenerite, Pd-bearing irarsite and a Pd-bearing nickel bismuth telluride have been recognized. Homoaxial intergrowths of iridarsenite, irarsite, hollingworthite and nickelian cobaltite are the iridium and rhodium minerals detected (Häkli *et al.* 1976).

Serpentinization seems to have caused relocation of trace amounts of PGE, the main carrier of the metals into their present location being the chloride solutions which are frequently observed in the mine waters (Häkli *et al.* 1976).

THE MAKOLA NI-CU ORE

The exhausted Makola mine is located among a cluster of small ultramafic intrusions about four km southwest of Hitura (Huhta 1954). The host rock of the Makola ore is a funnel-shaped subvertical body, some 120 × 20—40 m^2 in surface area and 200 m deep, that contains metadunites, metaperidotites and metapyroxenites (Fig. 40). It shows fairly conformable contacts

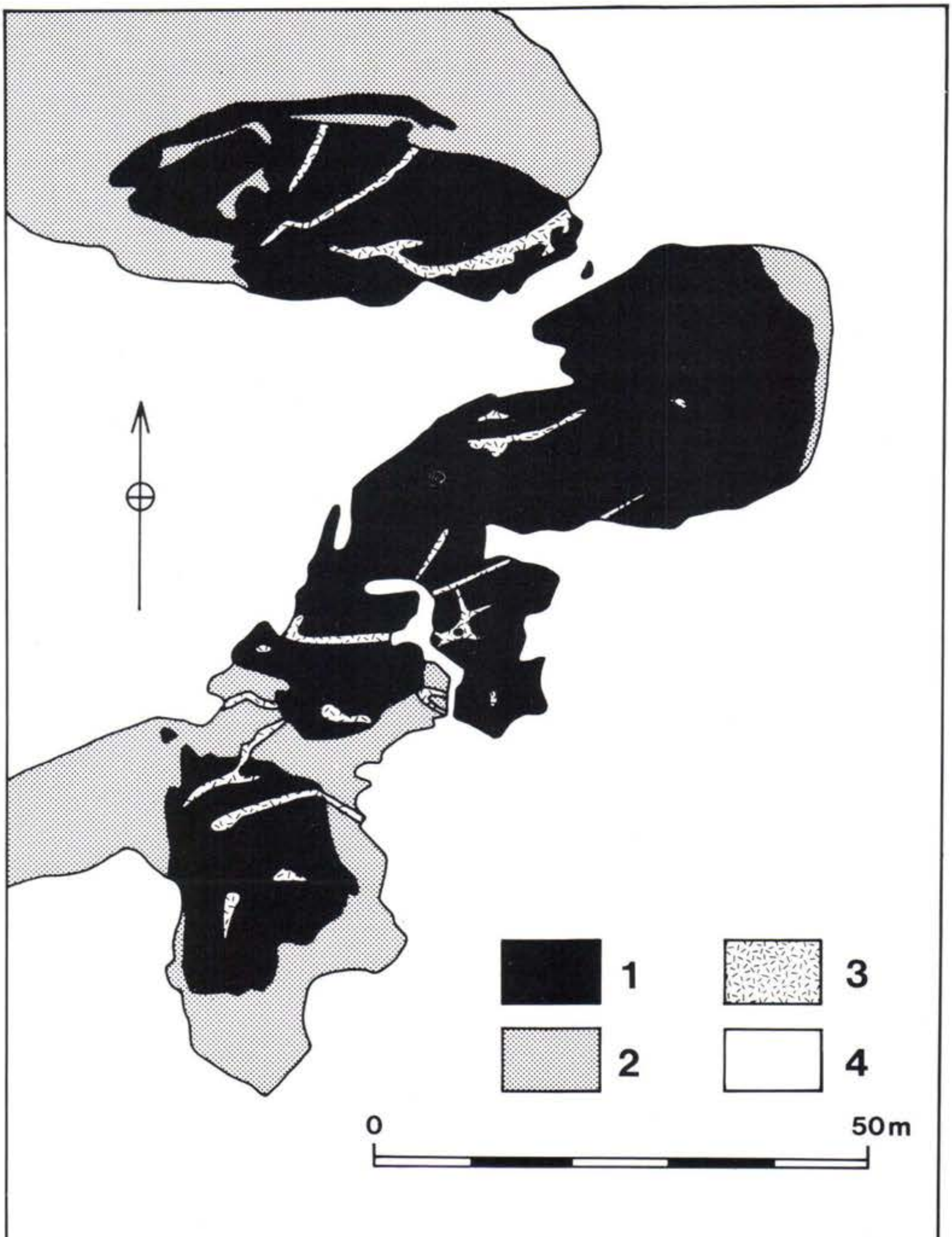


Fig. 40. Surface plan of the Makola intrusion (Huhta 1954). 1. Ore; 2. Ultramafics; 3. Felsic dykes; 4. Migmatitic mica gneiss.

Table 25. Chemical composition, Niggli values and C.I.P.W. norms of the rocks of Makola.

	Meta-dunite	Meta-peridotite	Meta-pyroxenite
n	10	16	5
SiO_2	45.08	49.17	50.77
TiO_2	0.12	0.21	0.28
Al_2O_3	1.73	3.72	5.33
FeO	17.62	13.90	15.31
MnO	0.16	0.17	0.18
MgO	34.73	30.18	24.48
CaO	0.29	2.29	2.82
Na_2O	0.21	0.20	0.21
K_2O	0.06	0.16	0.63
	100.00	100.00	100.00
si	66.2	79.9	90.5
al	1.50	3.56	5.60
fm	97.7	91.9	87.9
c	0.46	3.98	5.39
alk	0.36	0.48	1.08
qz	−35.2	−22.0	−13.8
mg	0.78	0.79	0.74
k	0.15	0.35	0.66
o	0.01	0.01	0.01
ti	0.13	0.26	0.37
p	—	—	—
C	0.78	—	—
Or	0.33	0.97	3.71
Ab	1.81	1.67	1.79
An	1.46	8.78	11.74
Pl	3.27	10.45	13.52
An	45	84	87
Di	—	2.06	1.80
Hy	37.98	54.66	63.68
Ol	55.06	28.98	14.18
Mt	2.35	2.48	2.58
Im	0.22	0.40	0.53
Ap	—	—	—
Sal	4.39	11.42	17.23
Fem	95.62	88.59	82.77

n = number of analyses. Chemical composition recalculated volatile-free.

with the enveloping mica gneiss, and folding seems to have affected all the rocks simultaneously.

The Makola ultramafic body is almost wholly mineralized. In Figure 40 the boundary of the ore is drawn at 0.5 to 0.6 % Ni. Particularly in metadunite, the sulphides occur as homogeneous and abundant interstitial dissemination. In metaperidotite and especially in the metapyroxenite portions the sulphides are more randomly distributed and the sulphide-silicate textures vary intensively. In the contact zone the ore occurs as massive breccia matrix and veins that often extend to the mica gneiss. The sulphide phase in the veins is commonly very rich in copper.

Table 26. Chemical composition of the Makola ore recalculated to 100 % sulphides (wt %).

	Cu	Zn	Ni	Co	Fe	n
metapyroxenite	5.08	0.78	5.15	0.29	27.04	6
metaperidotite	3.48	0.15	4.52	0.29	24.62	17
metadunite	2.89	0.05	3.73	0.28	44.67	9

Alteration processes have almost wholly obliterated the primary structures, and abundant chlorite-talc-amphibole rocks abound, particularly in association with the metapyroxenites. These rocks are also encountered in the contact zones of the plagioclase-rich dykes that crosscut the intrusion. Metadunite fragments of variable size are often met with in the metaperidotite and metapyroxenite. The other ultramafic bodies adjacent to the Makola deposit are only slightly mineralized.

Only the main components of the rocks at Makola have been analysed (Table 25), but these show that the body is much like that at Hitura. The ratio Al_2O_3/CaO is very high at Makola, and, as a consequence, corundum is a normative mineral in the most magnesian rock types. Because the body is much smaller than that at Hitura, the heterogenity and contact effects are more comprehensive. The content of titanium is somewhat higher at Makola and chromium is about the same as at Hitura.

The composition of sulphides, calculated to 100 % sulphide phase, is given in Table 26 and figure 41 depicts the variation in chemical composition of the ultramafic host rocks and ores of Makola.

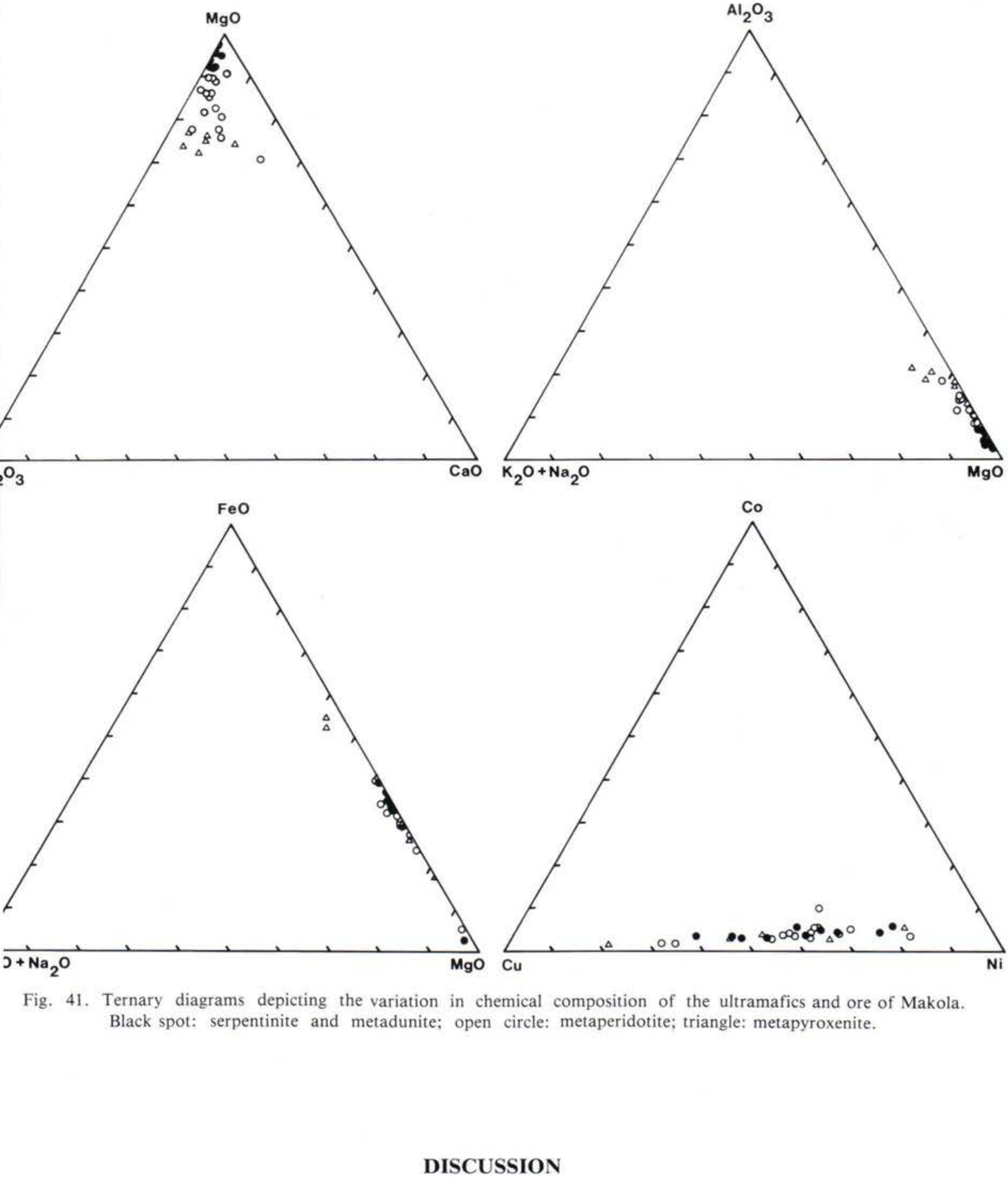


Fig. 41. Ternary diagrams depicting the variation in chemical composition of the ultramafics and ore of Makola. Black spot: serpentinite and metadunite; open circle: metaperidotite; triangle: metapyroxenite.

DISCUSSION

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

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

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

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

GEOLOGY OF THE KOTALAHTI NICKEL-COPPER ORE

H. PAPUNEN and J. KOSKINEN

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

Development work started in April 1956 with the sinking of an exploration shaft at Vehka and the driving of the associated drifts. The mine went into operation of 1st October 1959 when the exploitation of the ores above the +250 level started.

Underground exploration demonstrated that the ore deposit continues downwards below the +250 level. The mine was deepened in 1971 and the +600 level became the haulage level for the ore. Drilling data indicate that the Jussi orebody and the Huuhtijärvi occurrence continue below the +600 level.

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

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

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

GENERAL GEOLOGY OF THE AREA

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

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

A heterogeneous belt of amphibolites and

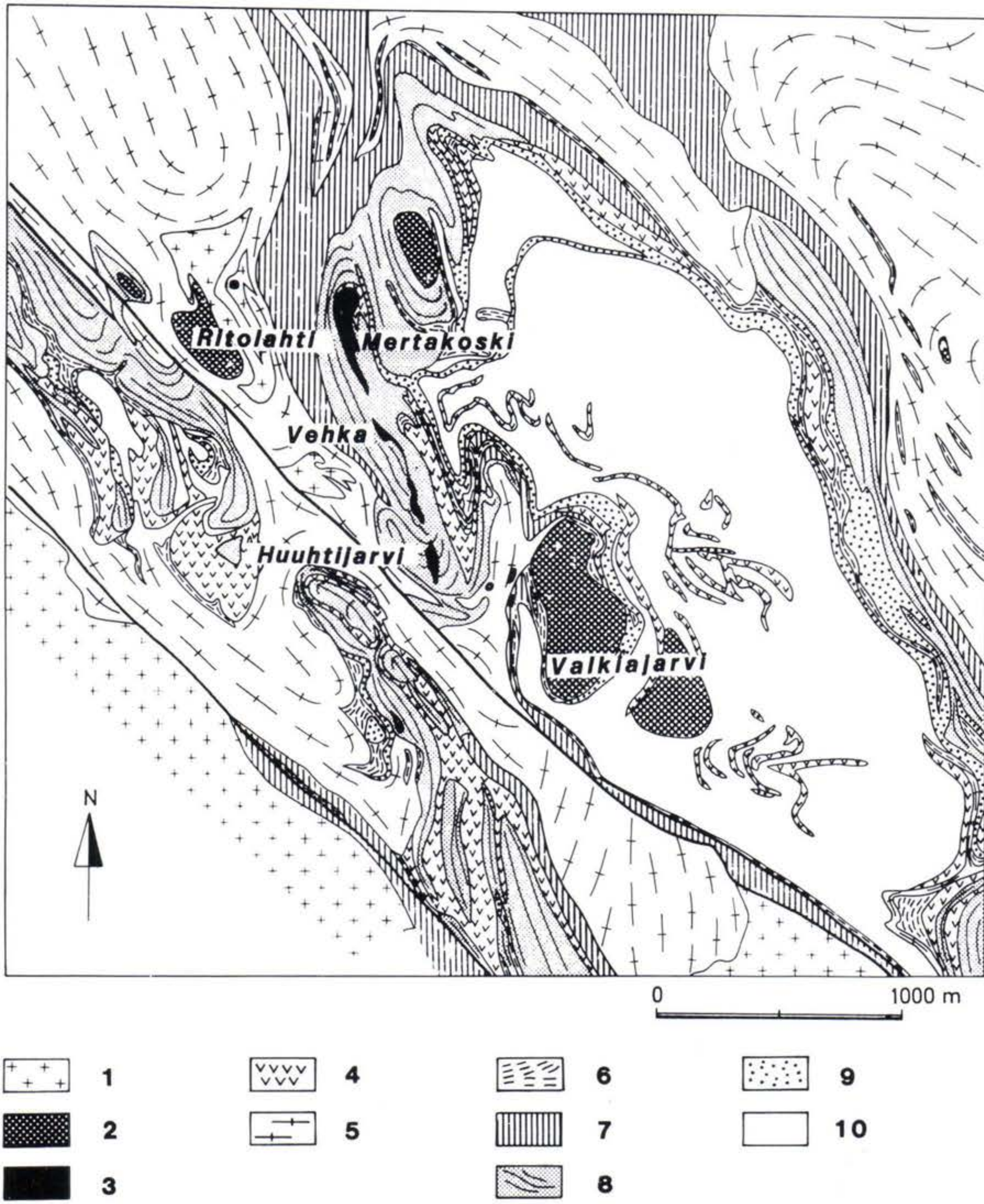


Fig. 42. Geological map of the Kotalahti area (Gaál 1980). 1. Svecokarelian granitoids; 2. Gabbro; 3. Ultramafics; 4. Amphibolite; 5. Veined mica gneiss; 6. Graphite schists; 7. Hornblende gneiss; 8. Leucocratic gneiss; 9. Quartzite and calc-silicate rock; 10. Granite gneiss.

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

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

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

DATING

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

THE GEOLOGY OF THE KOTALAHTI INTRUSION

Host rocks

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

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

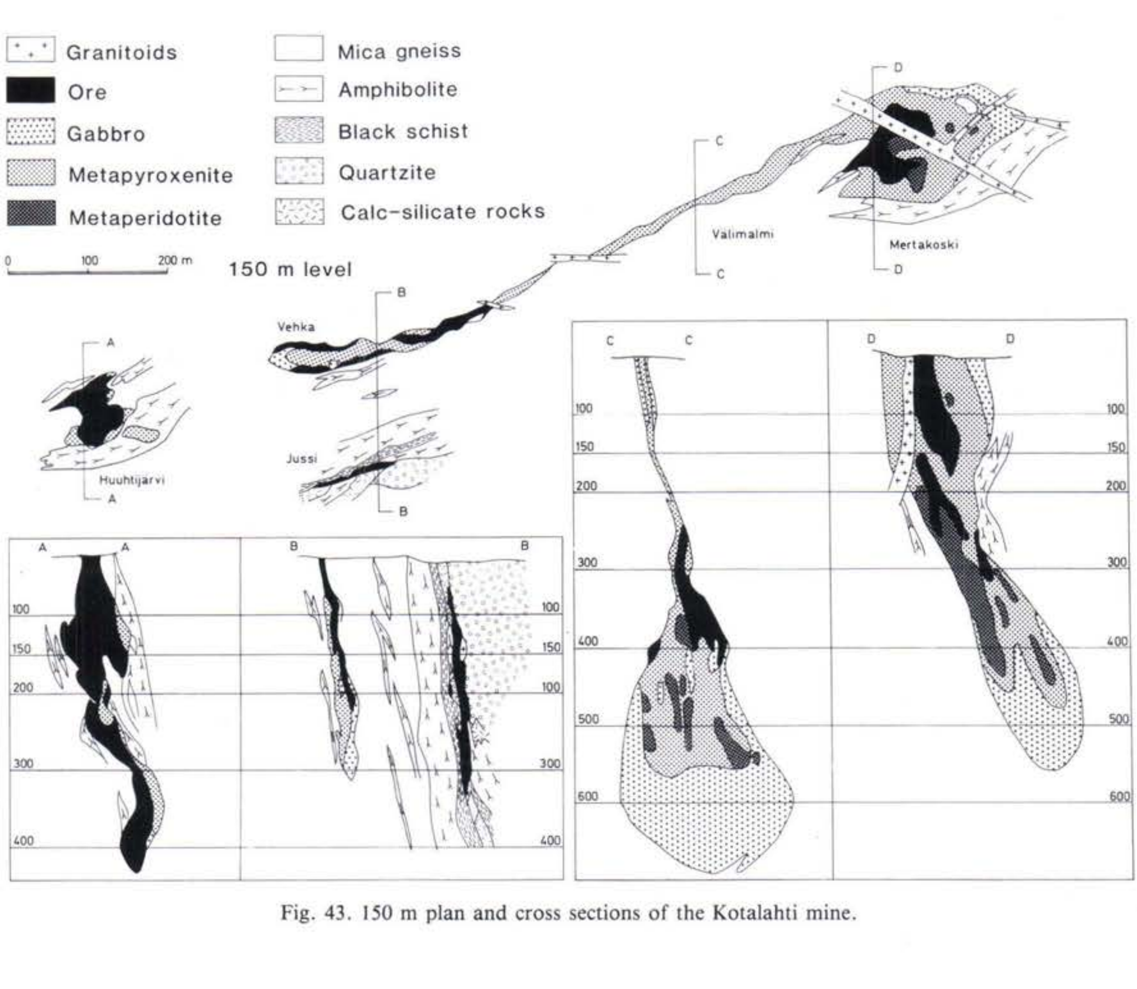


Fig. 43. 150 m plan and cross sections of the Kotalahti mine.

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

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

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

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

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

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

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

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

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

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

n = number of analyses.

Geochemistry of the intrusion

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

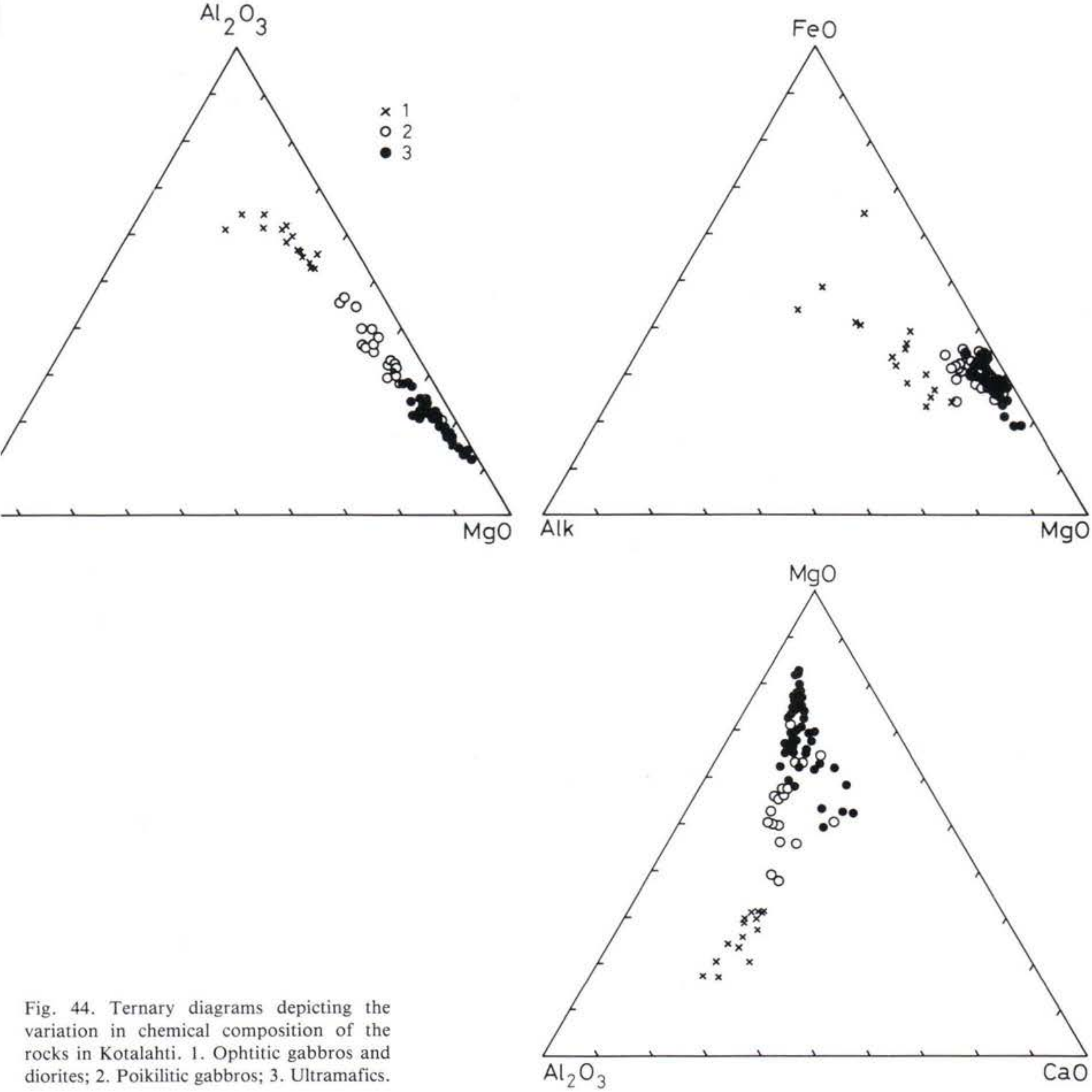


Fig. 44. Ternary diagrams depicting the variation in chemical composition of the rocks in Kotalahti. 1. Ophtitic gabbros and diorites; 2. Poikilitic gabbros; 3. Ultramafics.

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

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

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

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

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

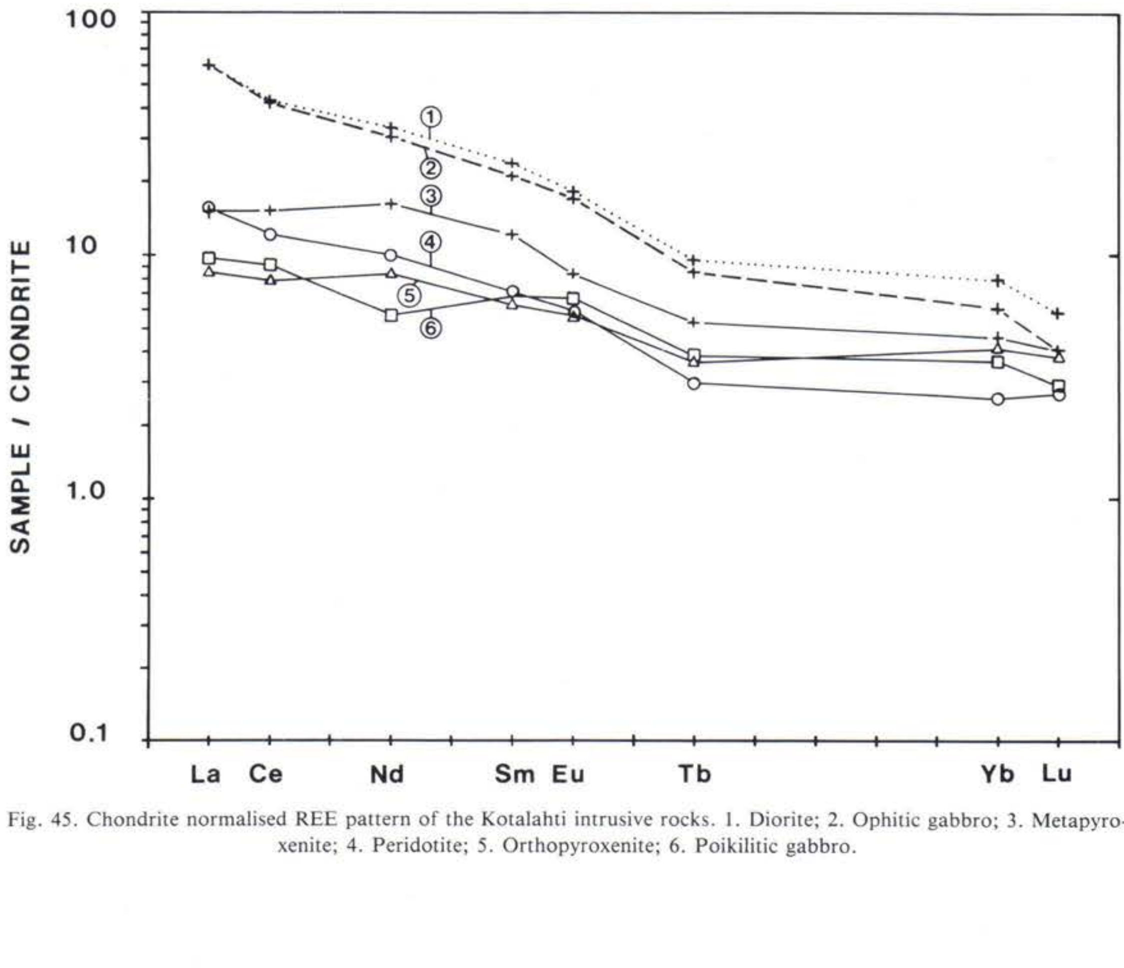


Fig. 45. Chondrite normalised REE pattern of the Kotalahti intrusive rocks. 1. Diorite; 2. Ophitic gabbro; 3. Metapyroxenite; 4. Peridotite; 5. Orthopyroxenite; 6. Poikilitic gabbro.

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

Nickel in silicate minerals

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

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

Sulphur isotopes

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

The ore types

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

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

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

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

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

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

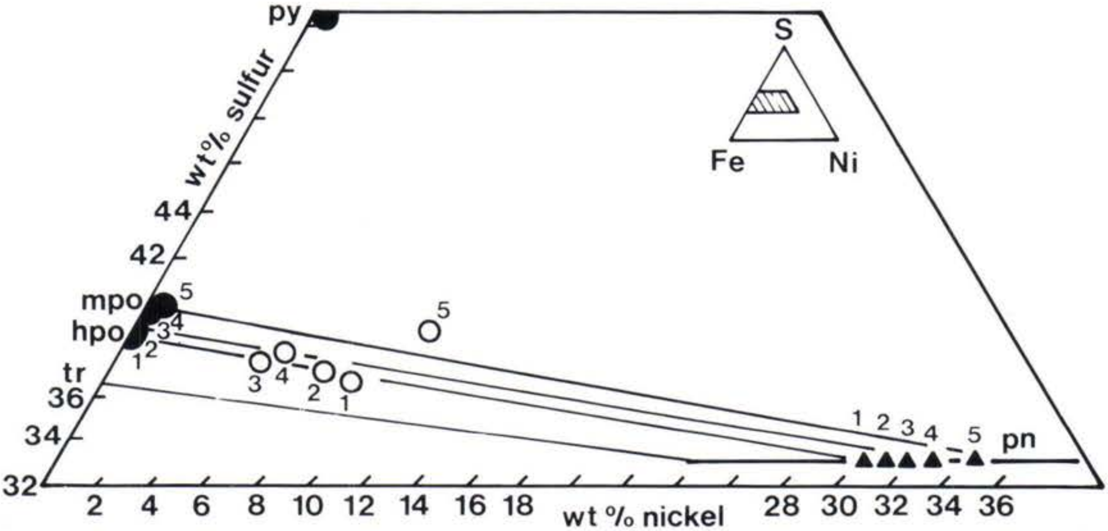


Fig. 46. Part of a Fe-Ni-S diagram depicting bulk composition of the sulphides (○) with corresponding composition of pyrrhotite (●) and pentlandite (▲). Ore types: 1. Disseminated ore in peridotite; 2. Disseminated ore in pyroxenite; 3. Disseminated ore in gabbro; 4. Breccia ore; 5. Massive offset ore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

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

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

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

CONCLUSIONS

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

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

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

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

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

THE LAUKUNKANGAS NICKEL-COPPER DEPOSIT

L. GRUNDSTRÖM

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

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

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

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

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

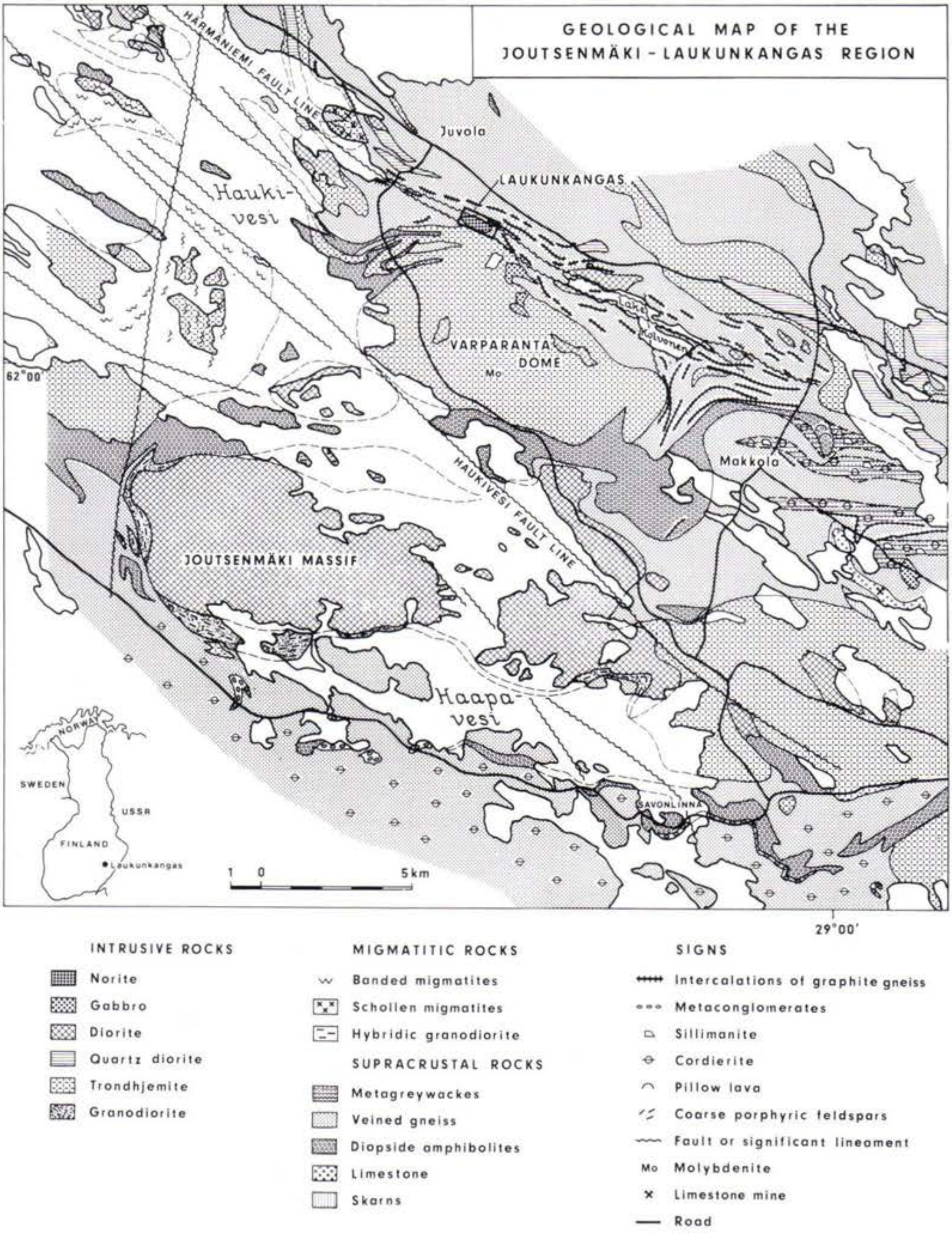


Fig. 47. Simplified geological map of the Joutsenmäki—Laukunkangas region. Partly after Gaál and Rauhamäki (1971).

300 samples were analysed for Ni and Fe. In addition, some 400 samples were submitted to total rock analyses. The scrutiny of the data demonstrated that the intrusion has an internal layering that allows the direction of the differentiation to be established. It was possible to

show that the southeastern end of the Laukunkangas intrusion has a potential for better quality ore than that already detected. This concept was confirmed by the results of supplementary ground geophysical surveys. Drilling revealed high-quality nickel ore mainly associated with the peridotites in the potential area (Grundström 1982 a). This portion of the intrusion was studied by means of the nickel programme technology in section × = 34.775. The results were compared with those reported previously (Grundström, 1980). The geology in profile L = 62.775 was also dealt with to supplement the previous data and to allow a broader comparison.

GEOLOGY OF THE ENVIRONMENT

The Laukunkangas Ni-Cu deposit is located in a Svecocarelian synorogenic plutonite in southeastern Finland (Fig. 47) in the area that Kahma (1973) called the »main sulphide ore belt». In this belt, Gaál (1972) has distinguished the separate »Kotalahti nickel-copper ore zone» in which Laukunkangas is located. Hackman (1931) has published a geological map of the area with explanation (Hackman, 1933). Häkli (1968, 1970, 1971), Papunen (1970), 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 that the »Kotalahti Ni-belt» is only a part of that area.

Figure 47 is a simplified geological map of the Joutsenmäki-Laukunkangas region. The supracrustal rocks and the plutonites that crosscut them from the major lithologic units. The supracrustal rocks can be subdivided into a volcanogenic section, in which diopside amphibolites predominate, and sedimentogenic schists, composed mainly of metagreywackes and calcarous metasediments. The rocks in the schist area are migmatised to varying degrees. The plutonites occur as major silicic or intermediate intrusions or as minor mafic-ultramafic bodies; the largest is the Joutsenmäki intrusion (Parkkinen 1971, 1975). Laukunkangas is one of the minor bodies.

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

TECTONICS

The concept of the ore potentiality of the »Lake Ladoga — Bay of Bothina zone» was originally proposed by Paarma and Marmo (1961). It was later corroborated by Mikkola and Niini (1968), Mikkola (1971) and Gaál (1972). Gaál *et al.* (1971) suggested further that the intrusions that act as host rocks for the nickel ores are associated with transcurrent faults, domes and brachyantiforms. Back in 1963, Wahl had suggested that the emplacement of the pyroxene-bearing rocks in the Ladoga — Bothnian Bay-zone was controlled by two fracture lines trending NW-SE. Later on, fault tectonic analyses of the zone were undertaken by Härme (1961) and Salli (1970), and lineament interpretations by Talvitie (1971, 1975) and Talvitie and Ekdahl (1975). A more detailed study of tectonics and their relation to nickel ores was made by Gaál *et al.* (1971, 1978 a, 1978 b), Gaál (1980), Kahma (1973, 1978), and Parkkinen (1971, 1975). The larger structural system has been described by Petrov (1970), Tuominen and Kuosmanen (1977) and Kuosmanen *et al.* (1981).

The general trend of the Laukunkangas mica gneiss zone is N70W. The dip varies from 60° to 90°, either to NE or SW, and the gneisses are isoclinally folded. Detailed observations show that the intrusions conform 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° and the plunge 80°.

DESCRIPTION OF THE INTRUSION

Geological and geophysical data show that the intrusion is elliptic in shape on the surface plan (Fig. 48). The wall-rock tongues that in places penetrate deep into the intrusion give a certain heterogeneity to the internal structure (Fig. 51). In a vertical direction, the intrusion resembles a chimney as it plunges steeply at 75—85° NW. The internal vertical movements and shears encountered in the middle of and along the southern margin of the intrusion brecciate the rocks to a marked degree. The maxium length of the intrusion is about 950 m and the maximum width some 300 m. The downward extension reaches 800 m at least.

Figure 48 illustrates the geology of the intrusion. The Varparanta trondhjemite dome (Saltikoff, 1965) and the Laukunkangas intrusion are separated from each other by a gneiss zone, about 100 m wide, with abundant graphite gneiss and black schist interlayers. The frequency of the graphite gneisses is highest north of the intrusion, where they have undergone intense folding in places.

The most recent drilling has revealed in the eastern end of the intrusion high-quality Ni-Cu ore associated with ultramafite The surface projection of the ore is marked on the map by a heavy dashed line. The diabase dyke shown on the map is the youngest rock, and it crosscuts all the other rocks and structures and possibly extends to the wall rock.

The Laukunkangas intrusion is composed of a differentiation series from peridotites tò quartz diorites. The distribution and chemistry of the rock types have been described earlier (Grundström 1980). Detailed studies on profiles K = 34.650 and K = 34.700 in the course of the nickel programme demonstrated that the Laukunkangas intrusion is characterised by the following features:

1. A distinct differentiation series from peridotites to quartz diorites. The rocks belong to the olivine tholeiitic series (Yoder and Tilley 1962).
2. An internal cryptic layering that dips steeply towards NW and manifests itself as separate lithologic plates differing in composition, expecially in their MgO, Sr, Ba and Zr.
3. The nickel incorporated in silicates also

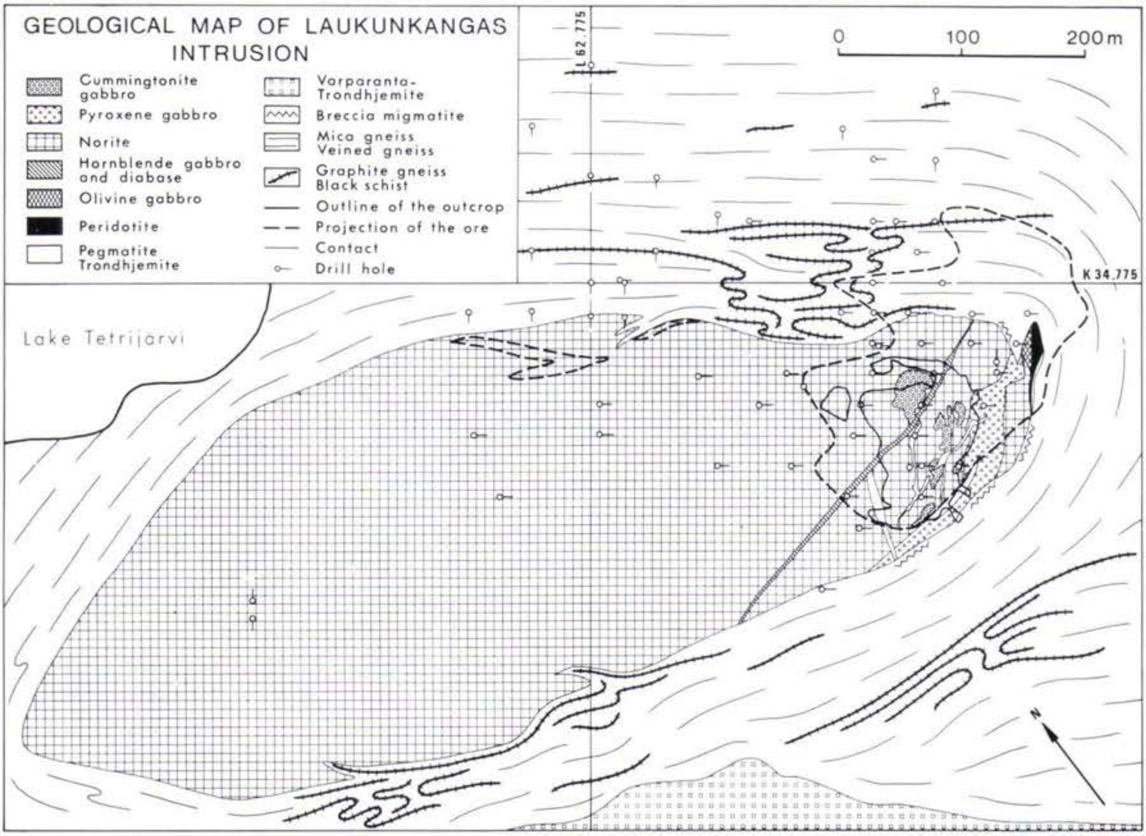


Fig. 48. Geological map of the Laukunkangas intrusion.

clearly demonstrate the existence of the cryptic layering.

4. The internal layering is further shown by the distribution of the nickel content of the sulphide phase.
5. The layers were emplaced successively, brecciating the rocks of the former intrusion stages. During the emplacements, graphite-bearing fragments torn from the wall rock, and which now survive in the intrusion as wall-rock tongues, underwent nickeliferous sulphide mineralisation that clearly differs from that in the wall-rock graphite rocks.
6. The intrusion is crosscut by numerous silicic pegmatite veins and mafic diabase dykes.

Description of the rock types

The Laukunkangas intrusion is composed of a series of differentiated rocks that grade from one to the other as the mineral proportions change (Grundström 1980).

The following describes the main rock types:

The most ultramafic member of the series is harzburgitic metaperidotite, in which olivine is largely serpentinised. The main minerals include phlogopite and chlorite as well as hornblende and the ore minerals. Bytownitic plagioclase occurs as rare lath-shaped and generally fresh grains. The serpentinisation being almost complete, only small amounts of olivine have survived. Perknites, which are alteration products of pyroxenites, contain orthopyroxene, hornblende and biotite as the main minerals.

The bulk of the intrusion is composed of the mafic members of the differentiation series: olivine gabbros, olivine norites, norites, pyroxene gabbros, hornblende gabbros, metagabbros and cummingtonite gabbros.

The olivine gabbros and olivine norites are coarse grained, hypidiomorphic and fairly equigranular rocks. The main minerals are olivine, orthopyroxene, hornblende, plagioclase (labradorite) and sulphides. Orthopyroxene is cloudy and pleochroic hypersthene. Brown »basaltic» hornblende is often associated with it as interlocked grains. Plagioclase is clear (fresh) and lath-shaped. Olivine is almost completely serpentinised in metanorites, which also contain coarse phlogopite. Their plagioclase is intensely sericitised.

Norites predominate in the intrusion. They are hypidiomorphic (hypidiomorphic-granular) in texture and their grain size varies from that of the coarse pegmatite norites to that of the fine-grained foliated norites. Plagioclase is clear and lath-shaped. Biotite exhibits strong pleochroism. The main minerals often include opaques. The pure norites have very few accessory minerals.

Pyroxene gabbros form large coherent zones with well-defined borders. They differ from the norites mainly in the abundance of clinopyroxene. The norites contain hardly any clinopyroxene, whereas augite is one of the main minerals in the pyroxene gabbros where it occurs as subhedral grains or is intergrown with coarse enstatite and amphiboles. Hornblende is of the greenish, »normal» type. Plagioclase is andesine, euhedral and fresh. Biotite is a common constituent, and the opaques are met with less frequently than in the above rocks. The accessories are quartz, apatite, tremolite and cummingtonite. Hornblende gabbros are not very common. Metagabbros and cummingtonite gabbros occur as fairly large portions. Under the microscope they are paler than the other gabbros and in exposures they are weathered less intensely than, say, the norites, owing to the lower sulphide abundances. The abundance of secondary minerals is a typical feature of the metagabbros and cummingtonite gabbros. Diorites and pyroxene quartz diorites, which are uncommon, occur mainly in the heterogeneous and brecciated contact zones of the intrusion. Quartz diorites and trondhjemites occur close to the contact zone and in the wall rock where they form conformable veins. Silicic pegmatitic and mafic diabase dyke rocks abound. The mafic dykes are pyroxene diabases and »gabbroic amphibolites», granoblastic in texture.

The wall-rock mica gneiss is migmatitic and brecciated along the contact zone. The numerous graphite gneiss, black schist and graphite fragments within the intrusion are very heterogeneous, strongly folded and brecciated. They are often fairly rich in nickel and thus differ clearly from the corresponding rocks in the environment (Grundström 1980).

Associated with the shear or breccia zones and the contacts with the pegmatite veins are mylonites. Blastomylonites are most frequent in the central parts of the intrusion. The thickest blastomylonite, 3.0 m wide, has noritic fragments as inclusions.

Composition of the minerals

Listed in Table 30 are the previously reported analytical data (Grundström 1980), corrected for the Fe values. Table 31 gives the mean Ni and Fe values of olivine, enstatite, augite and

Table 30. The average nickel and iron contents and standard deviations in olivine, enstatite, augite and amphibole, and the densities of some rock types (Grundström 1980, corrected).

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/cm^3)
Peridotite	13	1 081.1	19.02	227.1	11.11	173.3	3.61	339.1	5.68	3.24
Perknite	7	—	—	287.0	13.91	166.0	4.65	397.8	8.12	3.12
Olivine gabbro	6	1 107.0	19.00	253.5	11.11	157.7	5.51	350.8	5.76	3.05
Norite	127	—	—	136.2	17.21	135.0	—	220.2	8.07	3.08
Pyroxene gabbro	64	—	—	109.9	17.51	96.7	6.25	169.3	9.07	3.00
Hornblende gabbro	56	—	—	108.8	17.28	33.0	9.31	224.3	10.75	2.97
Diorite	8	—	—	49.1	20.11	23.0	7.60	72.9	9.10	2.94
Quartz diorite	8	—	—	44.7	19.70	—	—	44.7	10.49	2.90
Diabase	6	—	—	43.0	19.37	23.0	19.98	62.5	10.05	2.93
Granite	2	—	—	—	—	—	—	28.5	15.57	2.86
Pyroxene gneiss	2	—	—	42.0	15.99	—	—	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/cm^3)
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

Table 31. The average nickel and iron contents and standard deviations in olivine, enstatite, augite and amphibole of the rocks in profile K = 34.775.

Rock type	n	Ol^{Ni} ppm	Ol^{Fe} %	En^{Ni} ppm	En^{Fe} %	Aug^{Ni} ppm	Aug^{Fe} %	Af^{Ni} ppm	Af^{Fe} %
Peridotite	11	1 004	19.55	220	11.47	148	4.45	353	6.09
Metaperidotite	3	947	18.70	265	11.85	116	4.20	418	4.32
Olivine gabbro	14	1 137	19.45	224	11.15	134	4.22	338	5.95
Norite	15	—	—	144	17.31	117	6.68	236	9.02
Hornblende gabbro	6	—	—	52	28.10	—	—	131	10.60
Quartz diorite	1	—	—	49	21.50	—	—	91	18.00

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} %
Peridotite	11	167.3	1.21	30.6	0.75	24.8	0.57	36.3	0.43
Metaperidotite	3	—	—	41.7	1.49	—	—	130.9	4.32
Olivine gabbro	14	161.5	2.34	33.2	1.61	21.5	0.83	50.7	0.46
Norite	15	—	—	79.1	2.53	84.7	1.08	122.7	2.96
Hornblende gabbro	6	—	—	—	—	—	—	107.9	3.28
Quartz diorite	1	—	—	—	—	—	—	—	—

amphiboles, together with their standard deviations, for the rock types in profile K = 34.775. Figure 49 shows the data from Tables 30 and 31 as a Ni versus Fe diagram. The augite curve demonstrates that in profile K = 34.775 the distribution of nickel between peridotites, olivine gabbros and norites (148—138—117 ppm) is straight forward; the trend is similar to that shown by the previous data, as is that in the Fe values.

The En^{Fe}/En^{Ni} curves have parallel trends. The metaperidotite in profile K = 34.775 (265 ppm Ni, 11.85 % Fe) behaves as the perknite did in the previously reported results (287 ppm Ni, 13.91 % Fe). The similarity between the curves suggests that nickel was incorporated in the silicates mainly before the crystallisation of the noritic rocks. The slight difference in behaviour between perknites and metaperidotites may be attributed to contamination or alteration reactions. On the other hand, the silicates in the sulphide-bearing peridotites and olivine gabbros became depleted in nickel owing to the subsolidus reaction $Ni^{silic} \rightarrow Ni^{sulph}$. The above diagrams show distinctly the effect of the differentiation on the Ni and Fe values of the silicates.

As an example of the mineralised portion, Figure 50 a shows the geology of profile K = 34.775, in which the proportions of peridotites and olivine gabbros are considerably higher than those in profile K = 34.700 (Grundström 1980). The norites, gabbros and diorites mainly occur in the hanging wall. In drill holes 45 and 43, the upper portion of the formation lacks peridotite. Massive ore is encountered in the footwall contact in drill holes 67, 36 and 35 and in the upper portion of drill holes 36 and 35. Drill hole 43 intersected strongly folded black schist and graphite gneiss interlayers, associated with which there is an offset ore in the wall rock of the intrusion (Fig. 50 c).

The histograms in Figure 50 b show the distribution of Ni and Fe in olivine and MgO in the drill holes. Table 32 presents average chemi-

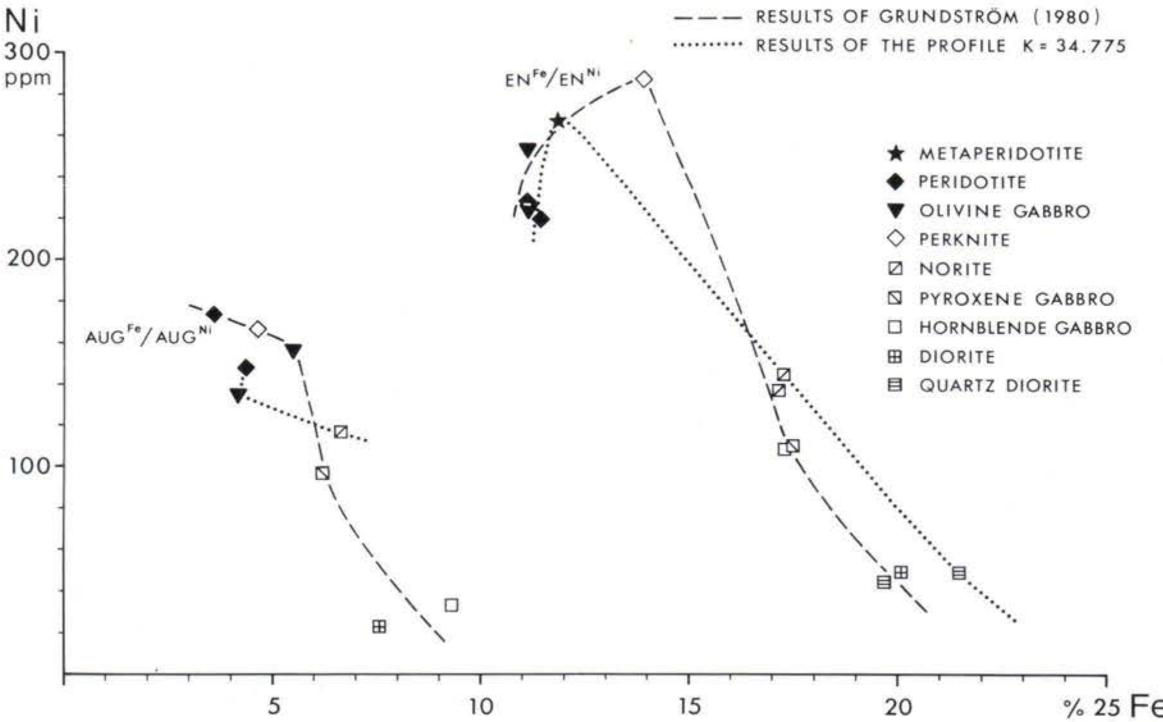


Fig. 49. Nickel in augite and enstatite versus iron in the same minerals in the rocks of the Laukunkangas differentation series.

cal compositions of the rock types. The MgO values in the peridotites are uniform, varying from 20.1 to 27.9 %. The nickel contents of the olivines in peridotites range between 895 and 1 611 ppm and the Fe contents between 17.9 and 20.8 %. The rapid variation in the Ni values of the olivines within such a narrow range of Fe values indicates that, during crystallisation, the rock contained sulphides (Naldrett *et al.* 1978). The high Ni values of olivine correlate fairly well with the total nickel content. Figure 50 c also gives the Ni and Fe values of the orthopyroxenes. The Ni values of the orthopyroxenes vary more than the Ni values of the olivines. In drill hole 67, the orthopyroxene of the gabbros is lower in Ni than are the orthopyroxenes of the peridotites in the same drill hole: the Fe values behave in the reverse fashion.

Section L = 62.775 (Fig. 51) shows the nickel data on and the general geology of drill hole 49.

Here the intrusion contains gabbros but neither olivine gabbros nor peridotites. Drill holes 73, 53, 49 and 54 reveal a mica gneiss tongue with associated graphite gneiss and black schist that penetrates the massif and transforms its internal structure, particularly in the northern contact. This tongue also hosts the offset ore illustrated in Figure 50 a. Drill hole 54 intersected nickel sulphides, the so-called deep orebody, in norites close to the south contact and partly in the wall rock. The MgO values of drill hole 49 are very uniform, varying between 9.83 and 15.2 % (22 analyses). The Fe value of the orthopyroxene varies between 11.6 and 17.9 %, and the Ni value between 49 and 221 ppm. No distict correlation can be seen between the total nickel con-

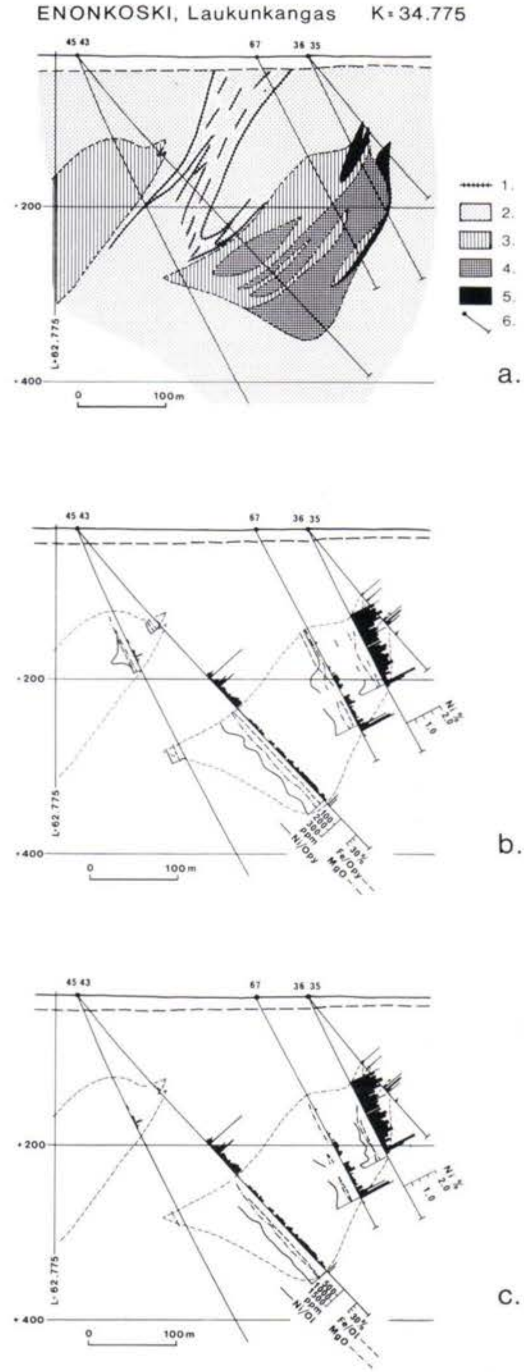


Fig. 50. Longitudinal section of the ultramafic and mafic bodies. 1. Black schist and graphite gneiss; 2. Mica gneiss; veined gneiss; 3. Norite, gabbro, diorite; 4. Peridotite, olivine gabbros; 5. Massive ore; 6. Diamond drill hole.

Table 32. Average chemical compositions. Niggli values and CIPW norms of the Laukunkangas intrusive rocks.

	Peri-dotite	Olivine-norite	Norite	Gabbro
n	10	12	23	6
SiO_2	44.51	43.77	51.53	51.80
TiO_2	0.57	0.64	0.76	1.16
Al_2O_3	8.69	10.47	14.86	13.25
Cr_2O_3	0.37	0.33	0.24	0.16
FeO	16.42	15.76	10.02	11.48
MnO	0.21	0.20	0.19	0.19
MgO	23.51	22.11	12.02	10.95
CaO	4.07	4.91	7.08	7.24
SrO	0.015	0.019	0.040	0.041
BaO	0.029	0.034	0.056	0.061
Na_2O	1.08	1.13	2.09	1.77
K_2O	0.33	0.40	0.80	1.71
P_2O_5	0.179	0.208	0.328	0.710
ZrO_2	0.006	0.007	0.012	0.019
Σ	100.01	100.00	100.02	100.54
si	74.7	74.3	114.1	117.1
al	8.61	10.5	19.3	17.6
fm	81.9	78.3	58.1	58.4
c	7.32	8.9	16.8	17.5
alk	2.11	2.29	5.62	6.34
qz	−33.6	−34.9	−8.32	−8.26
mg	0.71	0.71	0.68	0.63
k	0.16	0.19	0.20	0.38
o	0.02	0.02	0.03	0.04
ti	0.73	0.81	1.27	1.98
p	0.12	0.15	0.31	0.68
Qz	—	—	—	1.24
Or	1.95	2.36	4.73	10.05
Ab	9.14	9.59	17.69	14.89
An	17.92	22.31	28.78	22.99
Pl	27.05	31.88	46.46	37.88
An	66	70	62	61
Di	0.88	0.54	3.37	6.58
Hy	21.06	15.05	39.17	36.25
Ol	44.10	44.97	0.44	—
Mt	3.02	3.10	3.28	3.86
Im	1.10	1.22	1.44	2.20
Ap	0.43	0.50	0.78	1.68
Sal	29.01	34.24	51.19	49.17
Fem	70.59	65.39	48.48	50.57

n = number of analyses

tent and the silicate data. The profile differs clearly from profile K = 34.775.

In Figure 52 a the analytical data are plotted by rock group in the ternary diagram CaO-

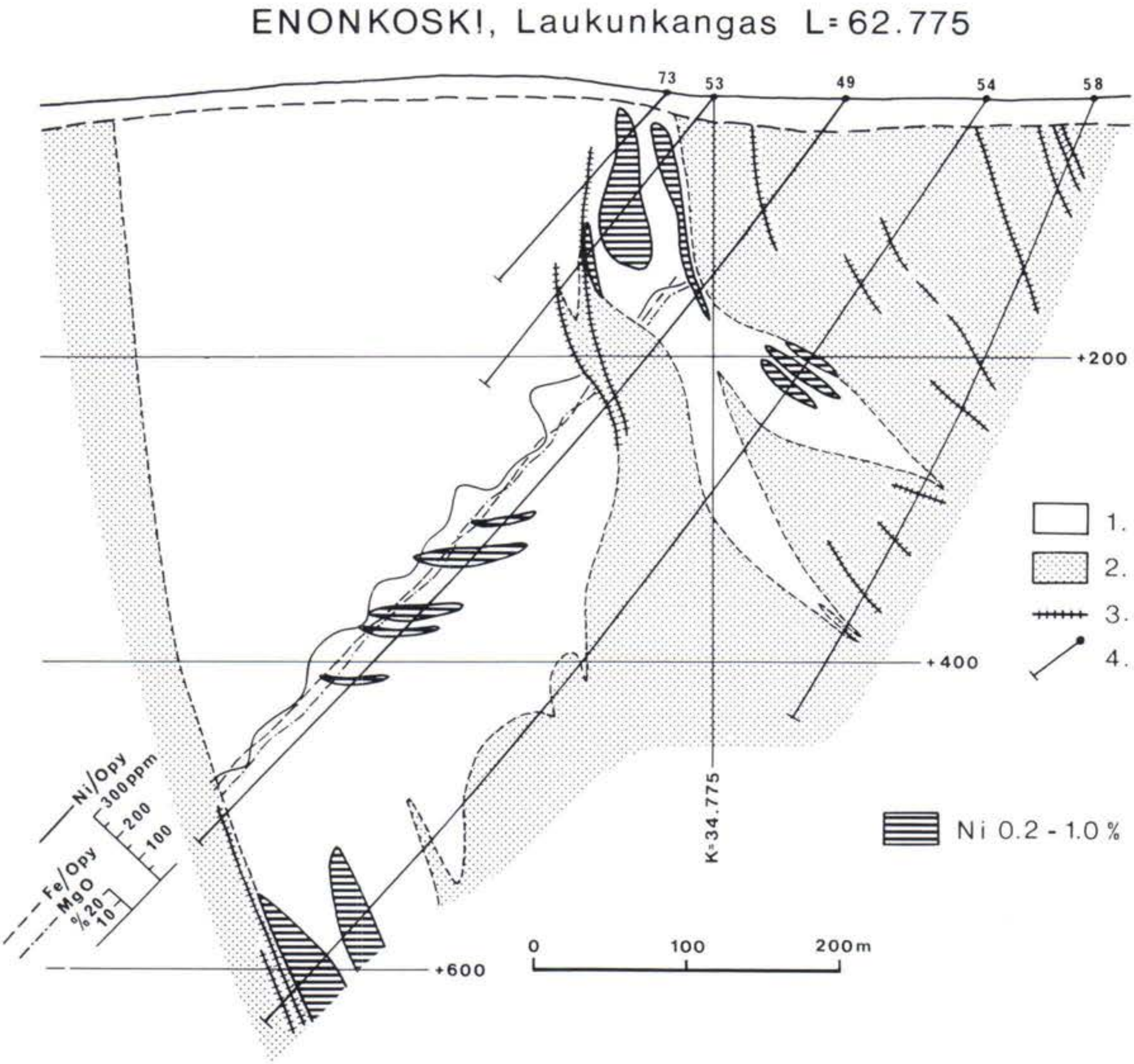


Fig. 51. Cross section of the mafic body. 1. Norite and other mafic rocks; 2. Mica gneiss, veined gneiss and kinzigite; 3. Black schist, graphite gneiss; 4. Diamond drill hole.

Al_2O_3-MgO. A gapless differentiation exists from ultramafic rocks to gabbros. When the diagram is compared with a similar one (Fig. 52 b) for komatiitic rocks in West Australia (Marston *et al.* 1981), it is seen that the rocks of Laukunkangas tholeiitic suite clearly plot in a different part of the diagram. The difference betweem komatiites is also manifest in the mineralogy.

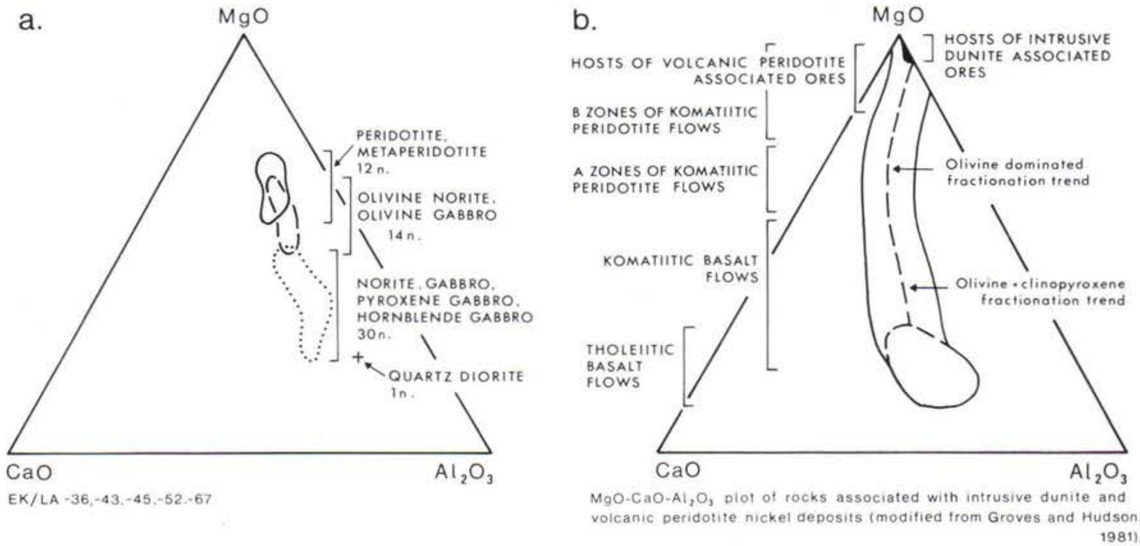


Fig. 52. MgO-CaO-Al_2O_3 diagrams. a) Laukunkangas, plot of rocks listed in Table 3; b) Nickel sulphide deposits in Western Australia (Marston *et al.* 1981).

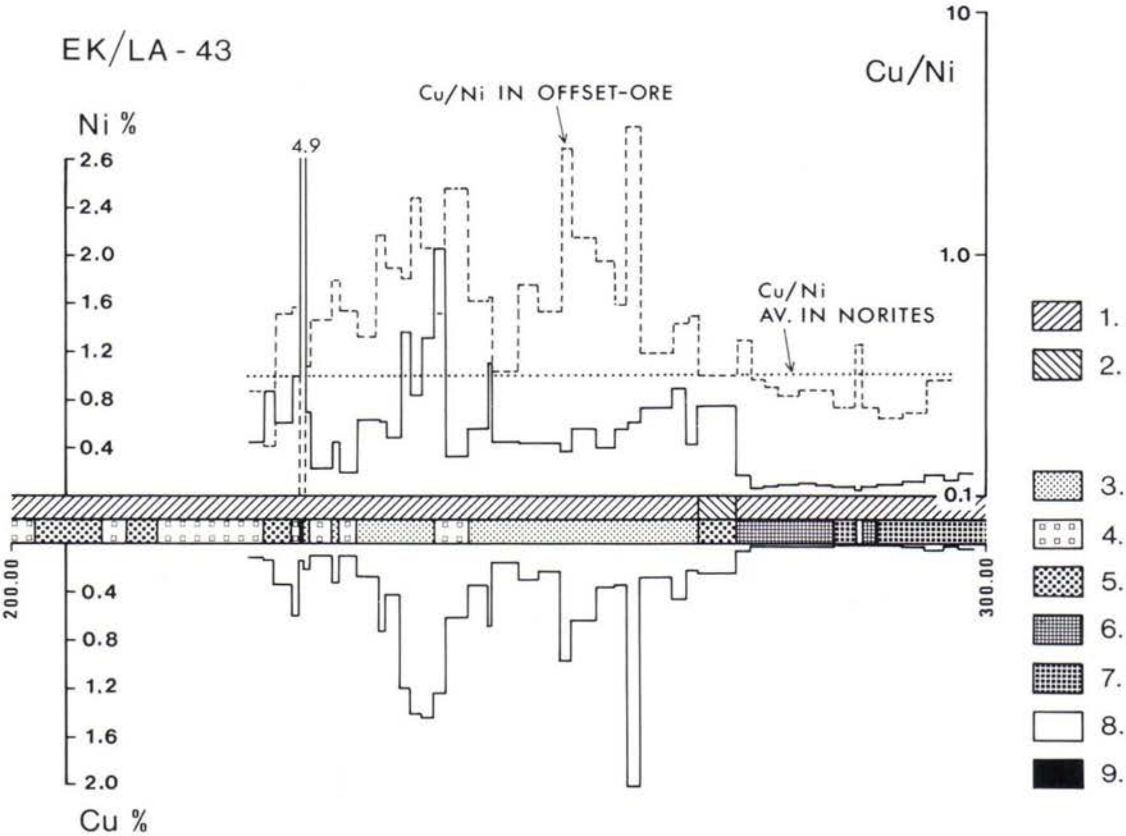


Fig. 53. Offset ore in drill hole Ek/La-43. 1. Pyrrhotite-chalcopyrite-pentlandite assemblage; 2. Pyrite-pentlandite-chalcopyrite assemblage; 3. Veined gneiss; 4. Trondhjemite gneiss; 5. Black schist; 6. Norite; 7. Peridotite; 8. Pegmatite; 9. Ore.

Orebodies

The sulphides have accumulated in the ultramafic rocks at the eastern end of the Laukunkangas intrusion. Scattered, lower grade occurrences are encountered elsewhere in the intrusion and along its contacts. In the ore reserve assessment (Grundström 1982 b), the deposit is subdivided into 4 independent orebodies:

1. The main orebody, which consists of the exposed norite portion and the peridotite-predominant high-grade ore northeast and north of if (Fig. 48) together with the associated massive ores. This orebody extends about 350 m below the surface.
2. The slope orebody, which is a lower-grade occurrence of sulphides at the northern contact mainly in norite. This orebody, which lies between the wall-rock tongue penetrating the intrusion (Fig. 51) and the wall-rock gneiss proper, is known to extend some 150 m downwards.
3. The deep orebody, which contains the sulphide occurrences at the southern contact and the scattered, weak lens-shaped dissemination in the middle of the intrusion. They have been traced down to a depth of 800 m.
4. The offset orebody, which is in mica gneiss, trondhjemite and black schist north of the intrusion and which has been intersected by drill holes Ek/La-43 and -81 (Fig. 53). This orebody probably joins the massive ores in the hanging wall of the high-grade ore. However, an account of its host rocks it is consedered as a potentially individual orebody.

Ore types

The ores can be subdivided into disseminated ores in norites and gabbros, disseminated ores in ultramafic rocks, breccia ores, massive ores, and sulphide-bearing graphite schists and gneisses.

The sulphide assemblage at Laukunkangas is simple. The main minerals are pyrrhotite, pentlandite and chalcopyrite. The accessories are generally magnetite, ilmenite, violarite, rutile, graphite and anatase; rare sphalerite and molybdenite are encountered here and there. Veins of nickel arsenides occur in the contact zone and in the ore associated with ultramafic rocks.

The disseminated ores in norites and gabbros have fine-to coarse-grained sulphides whose grain size varies from less than 0.1 mm to several cm. The anhedral pyrrhotite grains often contain inclusions of euhedral or subhedral pentlandite grains. Moreover, pyrrhotite almost invariably includes anhedral chalcopyrite inclusions. Pentlandite exsolution bodies and »flames» are common in the pyrrhotite. The sulphide grains are generally fresh and replacement textures are rare. Whenever sulphides abound, the texture is intergranular.

The sulphides occur in peridotites either as an interstitial dissemination or as a continuous intergranular network. Violarisation of pentlandite is somewhat more common than in norites, and magnetite has often been developed along the borders and fracture cleavages of the sulphide grains. This can be attributed to the serpentinisation of olivine as a result of which magnetite was formed. Ilmenite is a rare constituent and occurs as separate grains.

Sulphide breccias and veins of massive sulphides are common close to the contacts of the intrusion. The veins of massive sulphides abound in the hanging wall and footwall of the high-grade ore but also occur as a separate offset ore in the eastern border of the intrusion. They are usually composed entirely of massive sulphides, although they occasionally contain wall-rock inclusions and fragments.

The main minerals are pyrrhotite, pentlandite and chalcopyrite. Chalcopyrite and pentlandite occur as coarse-grained crystals or as intergranular stringers between the pyrrhotite grains. Pentlandite exsolution bodies are common in pyrrhotite. The accessories are sphalerite, gersdorffite, ilmenite, magnetite, rutile and graphite.

The sulphides in the graphite gneisses in the intrusion and the wall rock (Fig. 53) are in places pyrite predominant and thus differ markedly from the above ores. The sulphides occur as bands or massive veins in intensely folded graphite schists and gneisses. Fine-grained chalcopyrite, pentlandite and millerite are encountered as inclusions in pyrite. In places sphalerite is a fairly common constituent.

Shown in Figure 53 is the offset ore intersected by drill hole Ek/La-43. The nickel mineralisation begins in trondhjemite gneiss and extends through mica gneisses to black schists, in which the Ni values vary from 0.2 % to 4.9 %. In the norite intrusion proper, the Ni values decrease rapidly. The highest copper values of the offset ore are about 2 %. The Cu/Ni ratio of the offset ore is shown by a dashed line. The dotted line refers to the mean Cu/Ni ratio in norites. These two ratios differ markedly because the offset ore is notably richer in Cu than are the ores associated with norites. The sulphide assemblage in the black schist at the base of the drill hole is pyrite, pentlandite and chalcopyrite, whereas elsewhere the assemblage pyrrhotite-pentlandite-chalcopyrite predominates. The offset ore seems to be one of the early-formed massive sulphide veins. As it penetrated deep into the wall rock it became enriched in copper.

Table 33. Average chemical composition of pentlandites. Electron microprobe determinations.

Sample	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Number of analyses	3	4	3	3	3	3	5	4	4	1	5	4	5
Fe	29.68	27.84	29.06	29.87	29.67	29.33	30.10	29.94	29.95	34.96	30.05	30.15	30.33
Ni	34.33	38.54	34.05	35.54	34.21	34.71	36.10	34.96	35.39	33.22	35.62	35.18	36.04
Co	2.37	0.04	3.19	0.86	3.17	2.38	0.90	1.51	1.12	0.78	1.24	1.38	0.02
S	33.80	33.26	33.12	33.42	33.42	33.33	32.74	32.60	32.81	33.39	32.65	32.60	32.80
Total	100.18 %	99.68 %	99.42 %	99.69 %	100.47 %	99.75 %	99.84 %	99.00 %	99.28 %	102.35 %	99.56 %	99.31 %	99.19 %

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 mylonitied ore (Ni = 0.40 %)
6. Ek/La-16, 39.00 disseminated ore in norite (Ni = 0.83 %)

Off-set ore:

7. Ek/La-43, 226.50 disseminated ore in black schist (Ni = 0.88 %)
8. Ek/La-43, 229.70 granular pentlandite, massive ore (Ni = 5.36 %)
9. Ek/La-43, 229.70 intergranular pentlandite, massive ore (Ni = 5.36 %)
10. Ek/La-43, 229.70 pentlandite flames in pyrrhotite, massive ore (Ni = 5.36 %)
11. Ek/La-43, 233.50 disseminated ore in mica gneiss (Ni = 0.44 %)
12. Ek/La-43, 244.10 disseminated ore in garnet-bearing trondhjemite (Ni = 2.44 %)
13. Ek/La-43, 271.40 disseminated ore in black schist (Ni = 0.77 %)

Chemical compositions of the ore minerals

Analytical data on the pentlandites, pyrrhotites and pyrites are given in Tables 33—35.

Pentlandite is encountered in two sulphide assemblages. Samples 2, 7 and 13 in Table 33 are of black schist; of them, sample 2 contains pyrite and millerite together with pentlandite. Millerite is lacking in samples 7 and 13. The highest Ni content of pentlandite, 38.54 %, is in sample 2, in which pentlandite occurs in association with pyrite and millerite. In samples 7 and 13 the Ni values of pentlandite are also high, 36.10 and 36.04 %, respectively. Harris and Nickel (1972) have demonstrated that the nickel content of pentlandite is related to the coexisting sulphide assemblage. In the massive ore, the nickel value of pentlandite is 35.54 %; in the offset ore, the corresponding values range from 33.22 % (massive ore) to 35.39 %. Pentlandite has the lowest Co value, 0.02 %, in sample 13. About the same value, 0.04 %, was obtained from sample 2. The values of the pentlandites in the offset ore, i.e. 0.78—1.38 % Co, are markedly higher. The Co values of pentlandites are highest in the mylonitised ore and in the disseminated ores in norite. The sulphur values are fairly constant, varying between 32.60 and 33.80 %.

At Kotalahti, the Ni value of the pentlandite

Table 34. Average chemical compositions of pyrrhotites. Electron microprobe determinations.

Sample	1.	2.	3.	4.	5.	6.	7.	8.	9.
Number of analyses	4	4	3	3	3	5	4	5	4
Fe	59.60	59.69	59.62	59.48	59.49	60.01	59.37	59.64	59.75
Ni	0.50	0.29	0.37	0.40	0.36	0.46	0.42	0.29	0.35
Co	0.04	0.01	0.02	0.02	0.03	0.01	0.02	0.06	0.05
S	39.53	39.33	39.72	39.80	39.99	39.05	39.26	39.18	38.99
Total	99.67 %	99.32 %	99.73 %	99.70 %	99.87 %	99.54 %	99.06 %	99.16 %	99.13 %

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 mylonitised ore (Ni = 0.40 %)
5. Ek/La-16, 39.00 disseminated ore in norite (Ni = 0.83 %)

Offset ore:

6. Ek/La-43, 226.50 disseminated ore in black schist (Ni = 0.88 %)
7. Ek/La-43, 229.70 massive ore (Ni = 5.36 %)
8. Ek/La-43, 233.50 disseminated ore in mica gneiss (Ni = 0.44 %)
9. Ek/La-43, 244.10 disseminated ore in garnet-bearing trondhjemite (Ni = 2.44 %)

Table 35. Co and Ni contents in pyrites. Electron microprobe determinations.

n	Co %	Ni %	av. Co %	av. Ni %
1. (14)	0.00—0.93	0.00—0.21	0.025	0.10
2. (6)	0.00—0.08	0.00—0.26	0.04	0.10
3. (5)	1.10—1.76	0.00—0.11	1.32	0.05
4. (3)	0.02—0.24	0.01—0.08	0.09	0.03

1. Ek/La-30, 170.00 black schist (Ni = 0.21 %)
2. Ek/La-12, 84.00 black schist
3. Ek/La-43, 271.40 Co-rich pyrite, disseminated ore in black schist (Ni = 0.77 %)
4. Ek/La-43, 271.40 Co-poor pyrite, disseminated ore in black schist (Ni = 0.77 %)

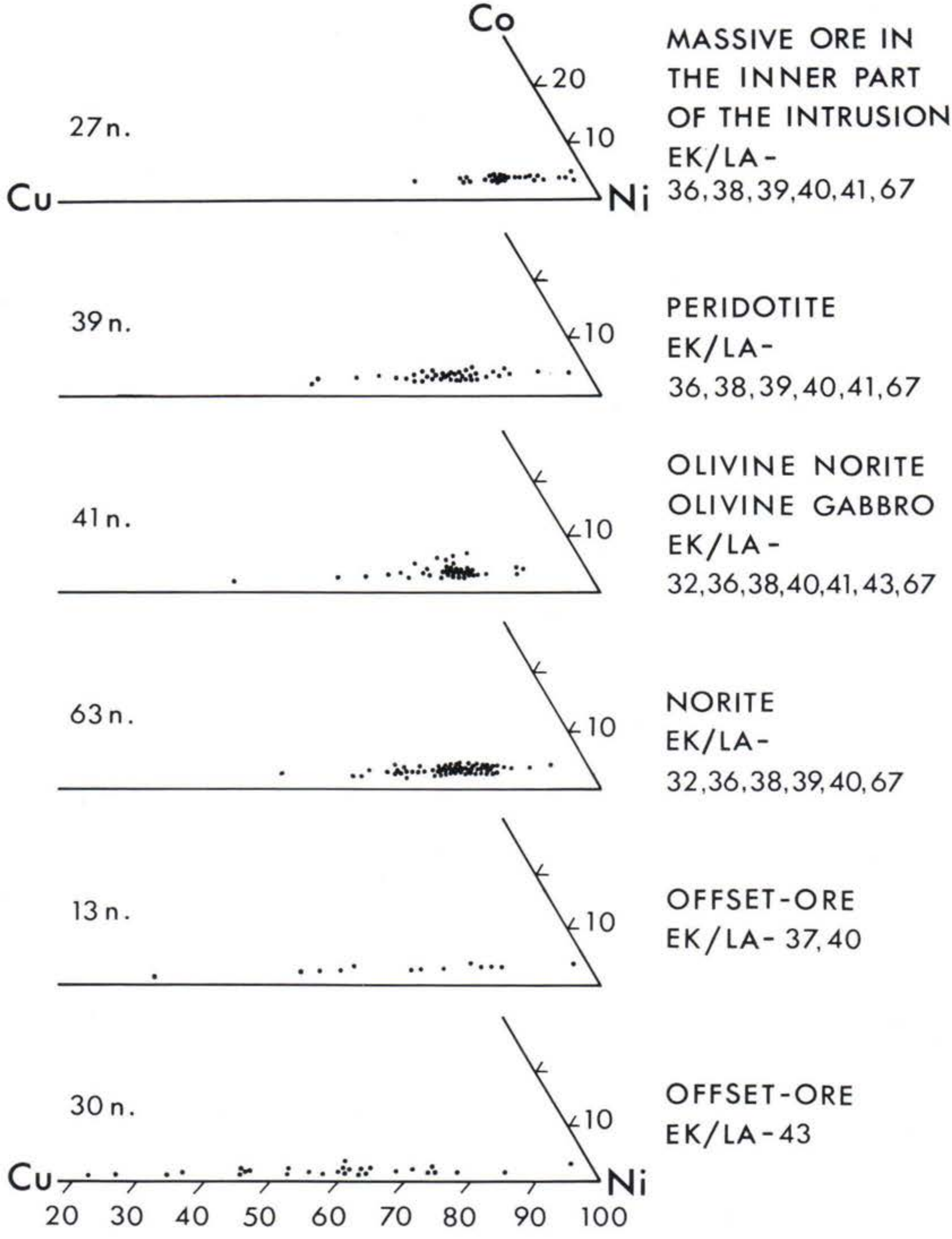


Fig. 54. Chemical compositions of different ore types in the Cu-Ni-Co-diagram. n. = number of samples in the diagram.

is highest in the Jussi orebody (Papunen, 1970), where the Co value is lower than the corresponding values of the pentlandites in the other Kotalahti orebodies. Samples 2 and 13 in Table 33 compare well with the samples from the Jussi orebody.

The Ni values of pyrrhotites (Table 34) are rather uniform, Ni = 0.29—0.50 %. The Co values are low, 0.01—0.06 %, and the S values do not differ much between the ore types. Pyrrhotite occurs as monoclinic and hexagonal variants. The cores of the crystals are generally hexagonal pyrrhotite, and the borders and fracture cleavages are mainly rimmed by monoclinic pyrrhotite. The samples analysed were obviously admixtures of these two variants.

As a rule, the Ni values of pyrites (Table 35) are low, 0.00—0.26 %. Samples 3 and 4 contain both Co-rich (Co = 0.10—1.76 %) and Co-poor (Co = 0.02—0.24 %) pyrites that derive from the mylonitised offset ore.

Chemical compositions of the ore types

Figure 54 shows the Cu-Ni-Co contents of the massive ores in the intrusion; of the ores in peridotites, olivine norites, olivine gabbros and norites; of the offset ore associated with the high-grade ore; and of the offset ore in wall rock.

The number of samples is given in the figure (e.g. 27 n), as are the drill holes dealt with in the present study. The massive ores, which are the richest in Ni, clearly constitute a group of their own. This can be explained by assuming that the sulphides of the massive ores segregated early from the melt when, owing to the low degree of fractionation, the Ni/Cu ratio of the melt was still high. Parallel to the progress of the crystallisation from peridotites through gabbros to norites the sulphides became slightly enriched in Cu in relation to Ni. The olivine gabbros and olivine norites are relatively richer in Co than are the peridotites. The Co values are lowest in the offset ore proper, the same ore from which derive the samples richest in Cu.

Characteristic ratios of the ore

The ratios given in Table 36 were calculated from the data in the ore reserve assessment by classifying the ores in 5 grades (Grundström 1982 b). On the basis of the results obtained, the ranges and mean values listed in the table were calculated for each orebody. Note that the individual Ni values calculated from individual analyses give Ni values as high as 6—8 % for 100 % sulphides. The value 4.5 % shown in the table thus refers to the mean of the main ore. The Ni content of the sulphide phase was calculated from the formula

$$Ni_s = 37.5 \times \frac{\text{Ni content}}{\text{S content}}$$

Table 36. Characteristic parameters of ore bodies.

	Ni/Co	Ni/Cu	Cu/Co	Ni content in 100 % sulphides
1. Main orebody	15.0—23.0 av. 21.1	3.4—3.8 av. 3.5	4.4—6.2 av. 6.1	5.0—3.7 av. 4.5
2. Slope orebody	15.0—17.4 » 17.4	1.8—3.8 » 2.8	4.3—9.3 » 6.1	2.9—3.3 » 3.0
3. Deep orebody	17.1—18.8 » 18.2	3.1—3.7 » 3.4	5.0—6.0 » 5.3	3.4—4.0 » 3.5
4. Off-set orebody	25.5—37.8 » 34.2	1.0—2.3 » 1.8	14.3—24.7 » 19.2	1.6—6.4 » 1.9

THE TELKKÄLÄ NICKEL DEPOSIT

T. A. HÄKLI

REGIONAL GEOLOGY

The Telkkälä ultramafic intrusion, some 16 km northwest of Lappeenranta in SE Finland, hosts a small nickel deposit embedded in Svecokarelian mica gneisses. The Telkkälä area is part of the Saimaa basin, which is composed of Svecokarelian supracrustal and plutonic rocks and Postsvecokarelian rapakivi granites (Fig. 55).

The bulk of the supracrustal rocks are argillaceous sediments (Vorma 1965), although calcareous and arenaceous interlayers may also be encountered. The supracrustal rocks are in-

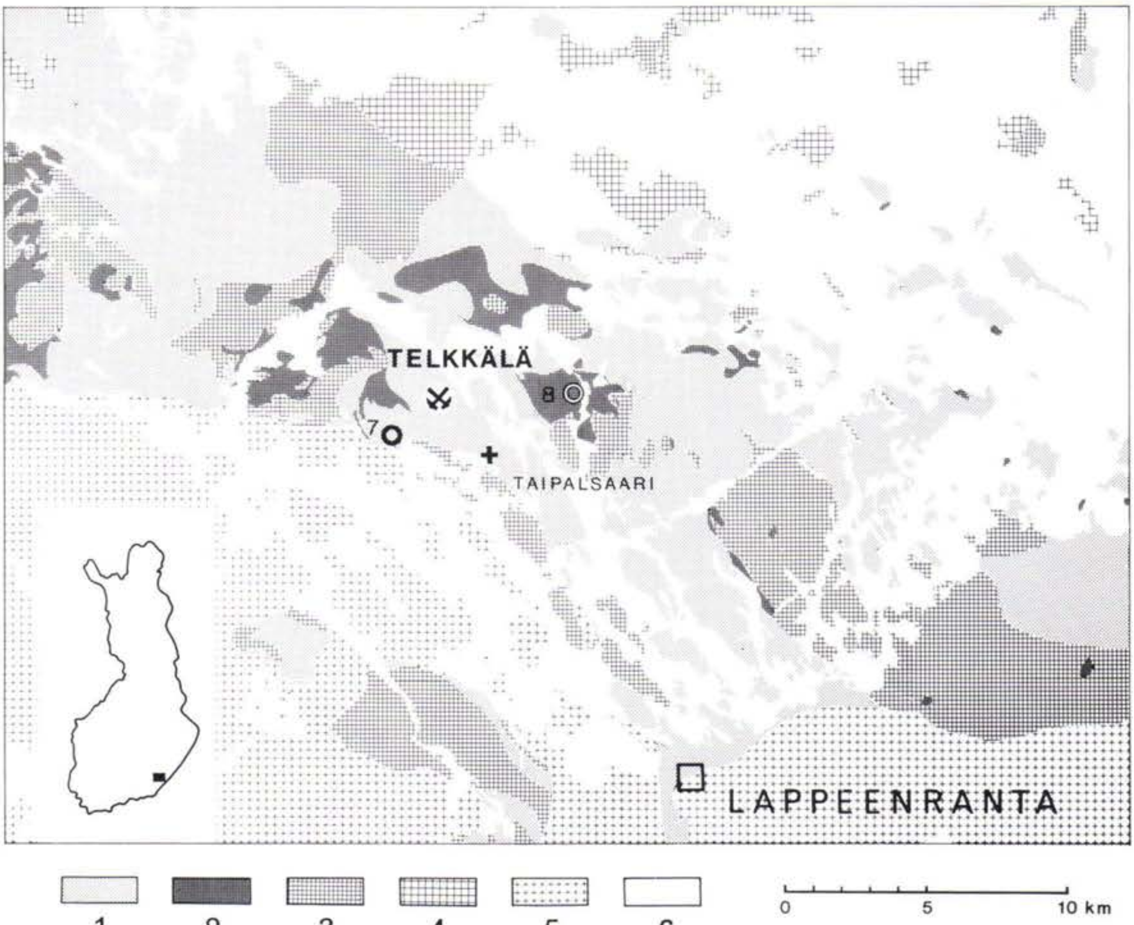


Fig. 55. Simplified geological map of the Telkkälä area after Häkli *et al.* (1975). 1. Mica gneiss; 2. Gabbro or diorite; 3. Granodiorite to quartz diorite; 4. Granite; 5. Rapakivi granite; 6. Lakes; 7. Haikkaanlahti Ni-showing; 8. Ahokkala Ni-showing.

truded by plutonic rocks ranging from granites to hornblendites and other ultramafics in composition.

The hornblende variety predominates among the gabbros but norites are also met with, particularly west, north and east of Telkkälä. South and southwest of Telkkälä large areas of bedrock are occupied by Postsvecokarelian anorogenic rapakivi granites.

Nickel showings, albeit small, occur in various parts of the Saimaa area. Two of them are close to the Telkkälä nickel deposit (Fig. 55): One at Ahokkala in a noritic body some 5 km east of Telkkälä and the other in a small mafic body at Haikkaanlahti, 2 km southwest of Telkkälä. There is a minor nickel deposit (Kitula) at Puumala (Marmo 1955), about 35 km north-northeast of Telkkälä. The latter was mined by Outokumpu Oy in 1970 at the same time as the Telkkälä deposit.

PETROLOGY OF THE INTRUSION

The Telkkälä nickel deposit is associated with a mafic intrusive measuring 50 × 150 metres in size (Fig. 56). The major axis of the intrusive parallels the NW-SE strike of schistosity of the surrounding mica gneiss (Häkli *et al.* 1975).

The intrusive is differentiated, ranging from peridotite to cummingtonite gabbro in composition. The distribution of the lithologic units exhibits a concentric pattern, a peridotitic core being enveloped by a narrow rim of perknite. The outer portions are cummingtonite gabbro.

The geophysics and tectonic features suggest that the intrusion plunges gently towards SE. The mica gneiss in the contact with the mafic body has frequently altered into garnet and cordierite gneisses, presumably owing to the thermal action of the intruding mafic magma.

The peridotites show a large variation in mineral composition from olivine-rich variants to subperknites. The olivine grains are often fresh and coarse although in some places they are altered into serpentine. The olivines average 15.5 % iron and 600 ppm nickel.

The orthopyroxene, which assays 9 % Fe and 155 ppm Ni, occurs as idiomorphic grains with partly uralitizated borders but it is also encountered as fine-grained crystals that seem to be of a younger generation than the idiomorphic ones. The amphibole, which crystallized later than the olivine and pyroxene, occurs in the intercumulus. The amphibole of the peridotites averages 4.4 % iron and 225 ppm Ni. The amphibole of the perknites is somewhat darker and richer in iron than is that of the peridotites, assaying 7.3 % Fe and 320 ppm Ni. The orthopyroxene of the amphibole is also richer in iron and nickel, averaging 13.4 % Fe and 190 ppm Ni. The orthopyroxene is often altered into cummingtonite. Monoclinic pyroxene is an accessory. The perknites grade into gabbros with the appearance of plagioclase.

The gabbros are hypidiomorphic in texture, with orthopyroxene, hornblende and cummingtonite as main minerals. Biotite may or may not be one of the major constituents. The composition of the plagioclase varies from An_{50} to An_{60}, although in rocks with some quartz it is andesine. The orthopyroxene averages 13.3 % Fe and 155 ppm Ni. The corresponding figures for the amphibole are 6.9 % Fe and 245 ppm Ni. Biotite, chlorite, apatite, quartz, titanite, sericite, carbonates and zircon are the accessories. The abundance of sulphides varies, but it usually exceeds 5 %. The cummingtonite gabbro at the NW end of the intrusion is, however, almost devoid of sulphides.

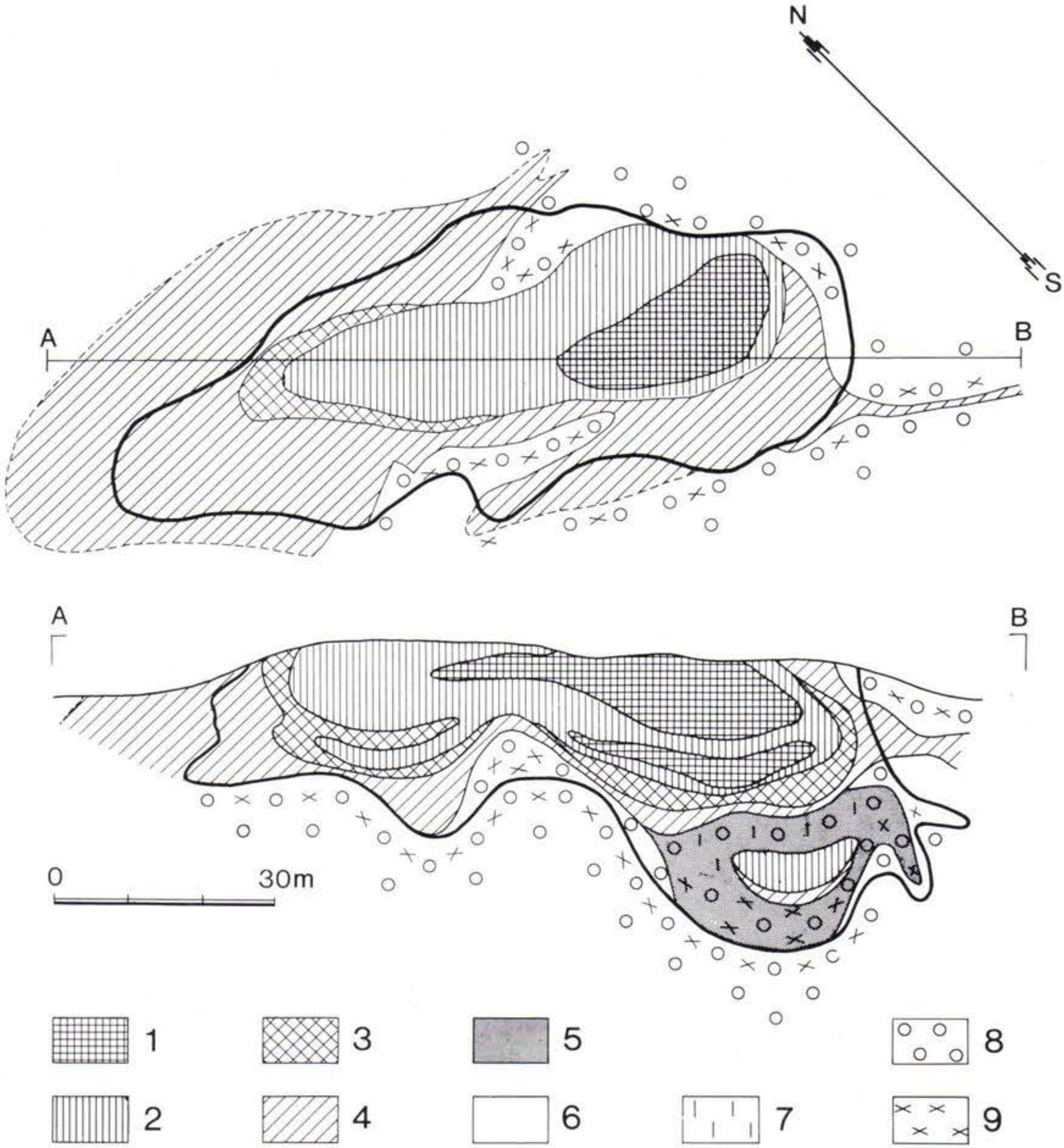


Fig. 56. Geological plan and cross section of the Telkkälä deposit after Häkli *et al.* (1975). 1. Peridotite; 2. Perknite; 3. Norite; 4. Cummingtonite gabbro; 5. Massive sulphides; 6. Mica gneiss; 7. Ultramafic fragments in ore; 8. Garnet; 9. Amphibole. The heavy line denotes the cut-off boundary.

The gabbros range in composition from the plagioclase-poor perknitic types through pale norites to cummingtonite gabbros. Orthopyroxene is altered to some extent into cummingtonite, whose abundance increases towards the contact of the intrusion with the mica gneiss. Adjacent to the mineralized portions, plagioclase, orthopyroxene and cummingtonite are altered into chlorite.

At the contact of the mafic intrusion with the mica gneiss, the cummingtonite gabbro grades into sulphide-poor cummingtonite gneiss as quartz and biotite increase. The transitional rock was presumably formed when the mafic magma interacted with the country rock.

The massive ore either favours the contact with the mica gneiss or is associated with the pegmatite veins. The high-grade ore often exhibits sulphide network texture, in which garnet, hornblende, quartz, oligoclase, biotite and sometimes chloritized pyroxene and siderite are embedded in a sulphide matrix. Narrow pegmatite veins with oligoclase, microcline and quartz as main minerals and biotite, chlorite, apatite and opaques as accessories crosscut the mafic intrusion.

GEOCHEMISTRY

The compositional variation in the Telkkälä intrusion is shown in the ternary diagrams in Figs. 57 and 58. The most ultramafic members of the body are high-magnesia rocks that plot close to the MgO apex. The rock suite forms a gapless series from the MgO apex towards the Al_2O_3 apex. The bulk of the samples are low in alkalies. Few samples, however, have elevated alkali values, presumably owing to contamination by the adjacent pegmatite veins or mica gneiss country rock. The intrusive exhibits CaO values that are low in relation to the MgO and Al_2O_3 values. In this respect, the Telkkälä intrusion differs from the Kylmäkoski mafic body (Papunen 1980) and the Vammala, Stormi ultramafic intrusion (Häkli *et al.* 1979). These three intrusions are not, however, directly comparable, because at Telkkälä the rocks are heavily minaralized, whereas at Vammala and Kylmäkoski large portions of the intrusion show only slight, if any, mineralization.

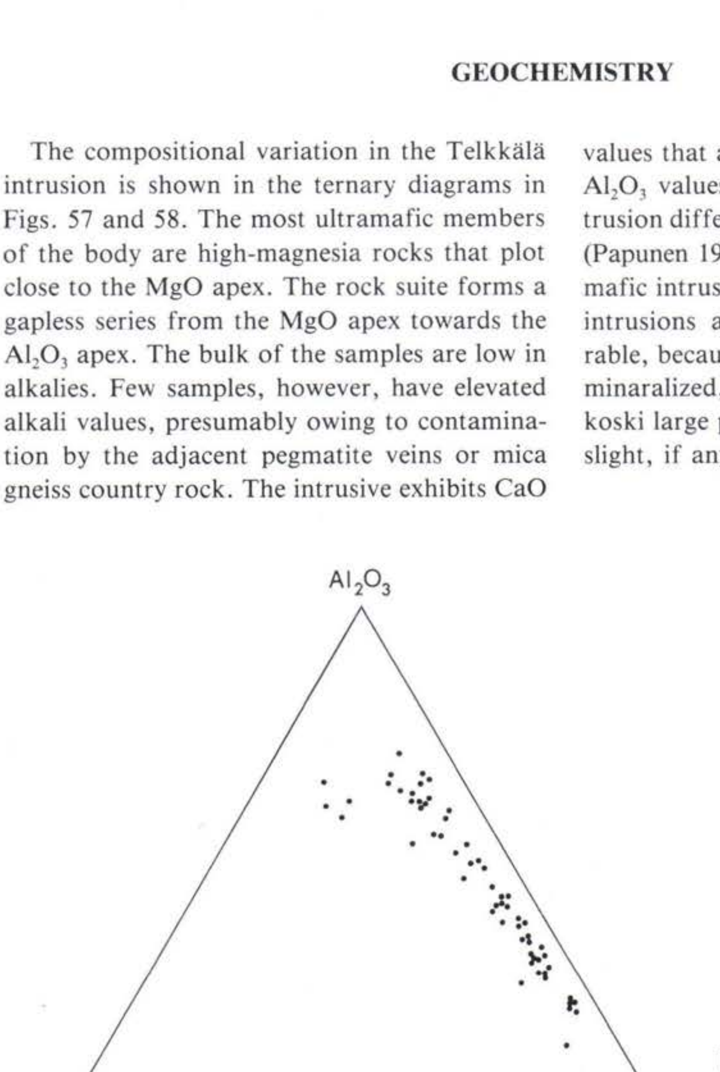


Fig. 57. $(Na_2O + K_2O)$ — Al_2O_3 — MgO diagram showing the compositions of the Telkkälä rocks.

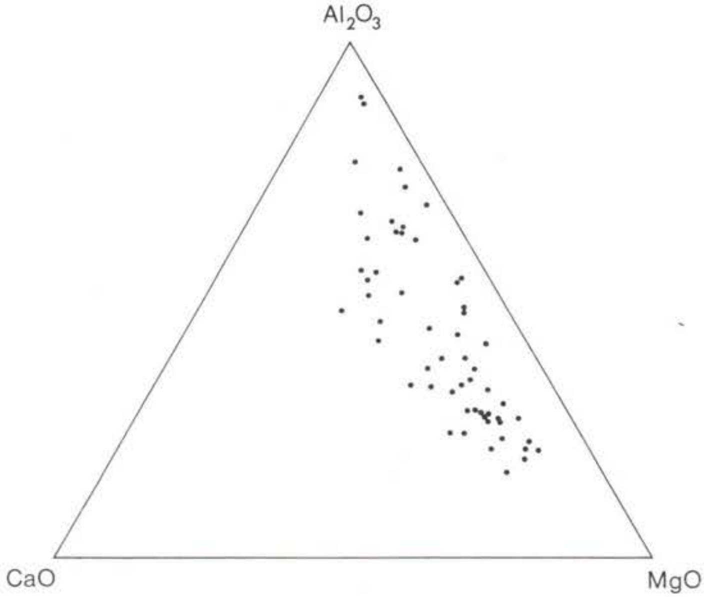


Fig. 58. CaO — Al_2O_3 — MgO diagram showing the compositions of the Telkkälä rocks.

ORE TYPES

The sulphides occur as three ore types: massive ores, matrix ores and disseminated ores. The massive ores are mainly restricted to the peridotites and perknites, whereas the matrix and disseminated ores favour cummingtonite gabbros.

Pyrrhotite, pentlandite and chalcopyrite are the major primary sulphides. Sphalerite is occasionally encountered in abundances unusual for a nickel deposit. Ilmenite, like ilmenomagnetite, chromite and rutile, which are met with in peridotite, are primary oxides.

Monoclinic pyrrhotite, which is more abundant than the hexagonal variety, is usually rather rich in nickel (average 0.35 %). Pentlandite occurs as discrete grains together with and as exsolution bodies in pyrrhotite. Chalcopyrite often rims the pentlandite and pyrrhotite grains but it also occurs as stringers in gangue and massive ore.

Supergene processes have produced secondary minerals that replace the primary sulphides. The alteration is mainly restricted to the SE part of the deposit, where pyrite, marcasite, bravoite, violarite, hematite, goethite and magnetite are encountered.

The alteration that entails the depletion of iron from the sulphides began in the pyrrhotite with the formation of marcasite-pyrite lamellae parallel to the basal parting. The nickel abundance of pyrite and marcasite thus formed is only slightly higher than that of pyrrhotite. When in larger cavities, however, these minerals are richer in nickel; nickel values up to 3.5 % have been recorded in marcasite, and as much as 4.6 % in bravoitic pyrite.

Pentlandite is often altered into violarite, and the process, which begins from the grain boundaries and cleavages, seems to precede the alteration of pyrrhotite. In places violarite is further replaced by chalcopyrite and marcasite; in fact the nickel-rich marcasites probably owe

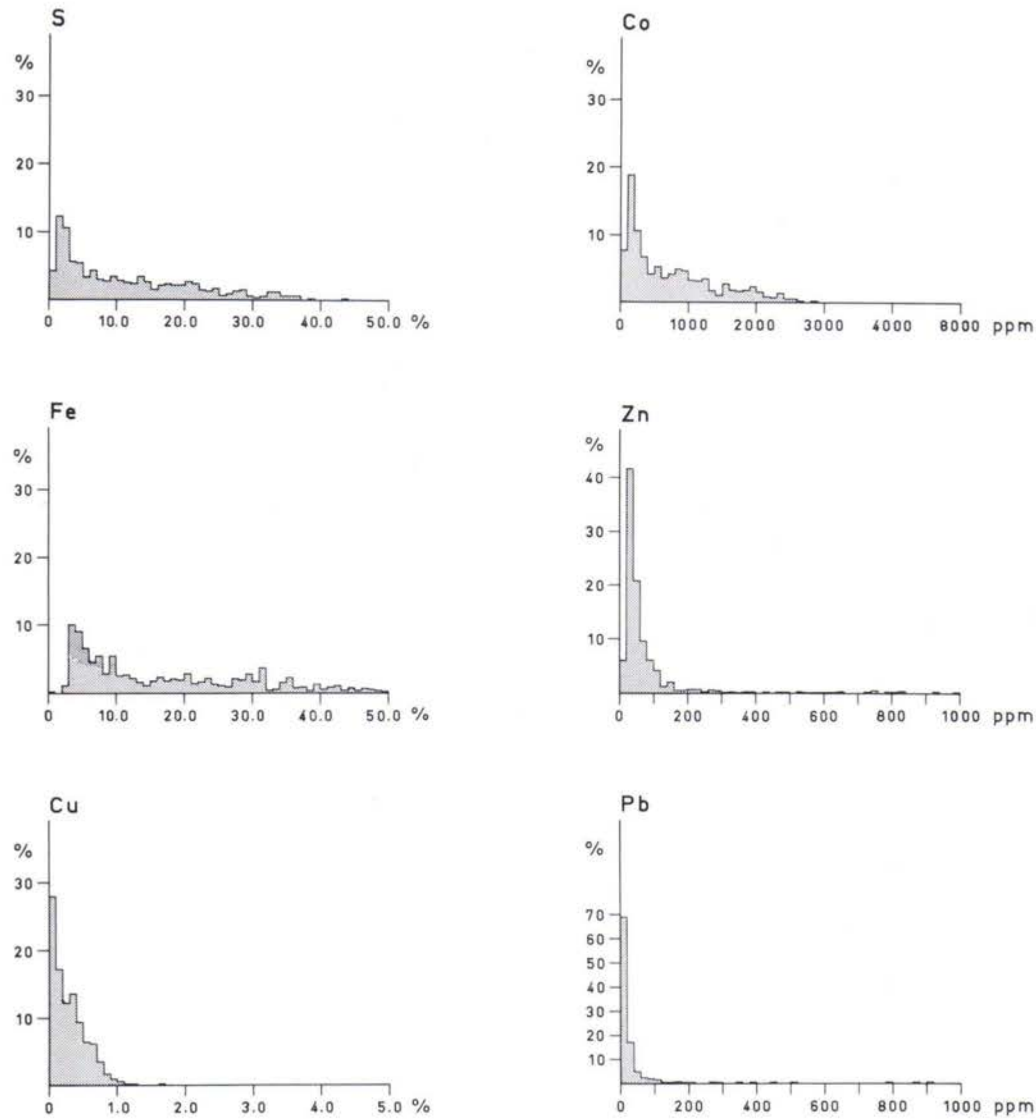


Fig. 59. Frequency distributions of S, Fe, Cu, Ni, Co, Zn and Pb in the Telkkälä deposit after Häkli *et al.* (1975).

their nickel to disintegrated violarite.

With the exception of gossan, which partly covered the deposit, the amount of oxides produced by the alteration processes is surprisingly small.

ORE GEOCHEMISTRY

In 1969—1970 about 200,000 tonnes of ore, averaging 1.06 % Ni and 0.29 % Cu, were mined from the open pit. The frequency distributions of the elements incorporated in sulphides are positively skewed (Fig. 59). The large variation in S, Fe, Ni and Co is caused by the mode of occurrence of the sulphides, which varies from low grade dissemination to massive ores.

The factor analyses performed on the geochemical data (Häkli *et al.* 1975) demonstrates that four mutually independent agents were active during the formation of the sulphide deposit. They gave rise to the disseminated and matrix ores in cummingtonite gabbro, deposited the massive sulphides at the base of the intrusion, produced stringers and dissemination of the second generation chalcopyrite in country rocks, and finally generated the Zn-Pb mineralization.

CONCLUSIONS

A genetic model has been proposed by Häkli *et al.* (1975) for the formation of the Telkkälä nickel deposit, dated by the lead-lead method at 1820 Ma. In this model, the concentric structure of the mafic intrusion is attributed to the discharge through a vent of mafic silicate melt carrying appreciable amounts of sulphides in dispersed immiscible melt. On account of gravitative settling, the sulphide liquid concentrated in depressions at the base on the intrusion where it remained mobile after the consolidation of the magma. At a lower temperature the increased water pressure brecciated the rocks. The open spaces were then invaded by the sulphide liquid, and breccia and massive ores were produced. A copper-rich sulphide liquid, which segregated from the bulk of the sulphide liquid after it had been crystallized as a monosulphide phase, produced chalcopyrite stringers of the second generation. The monosulphide solid solution then recrystallized at lower temperatures as pyrite, chalcopyrite, pentlandite and monoclinic pyrrhotite.

Somewhat later, the vent introduced more sulphur and cobalt and probably also some iron, zinc and lead, thus reducing the Ni/S and Ni/Co ratios, generating disulphides and producing a low-grade Zn-Pb mineralization at the base of the intrusion.

ACKNOWLEDGEMENT

I thank the Outokumpu Company for permission to publish this paper.

THE KYLMÄKOSKI NICKEL-COPPER DEPOSIT

H. PAPUNEN

The first hints of the Kylmäkoski ore were received in 1962, when two schoolboys found a big glacial boulder of Ni-Cu ore in the village of Taipale. The following year a small ultramafic sulphide-bearing body was detected with the aid of geophysical survey and diamond drilling only a few hundred metres NW of the first ore boulder. The body was completely covered with glacial overburden.

In 1963 the ore reserves were estimated on the basis of drilling data to be 515,000 tonnes assaying 0.48 % Cu and 0.55 % Ni. The decision on exploit the ore was made in 1970 after ownership of the deposit has passed to Outokumpu Oy. In March 1971 mining operations started in an open pit. From October 1973 they continued underground until September 1974 when the whole deposit was exhausted. During that period, 689,616 tonnes of ore and 839,586 tonnes of barren rock were hoisted. The total recovery of nickel was 1,829 tonnes and of copper 579 tonnes.

The geology of the Kylmäkoski deposit has been described by Papunen (1976, 1980) and the broad geological environment by Matisto (1976).

GENERAL GEOLOGY OF THE KYLMÄKOSKI AREA

The Vammala deposit (Häkli *et al.* 1979) is the largest of the Ni-Cu occurrences in the Pori-Kylmäkoski belt, which includes the occurrences of Kylmäkoski, Sääksjärvi, Harjunpää, Hyvelä and Korkeakoski (Kahma 1973; Häkli *et al.* 1979).

The ultramafic body that hosts the Kylmäkoski sulphide ore is located in a migmatized gneiss belt that runs in a WNW-ESE direction about 40 km south of the well-preserved metasediments and metavolcanics of the Tampere schist area (cf. Eskola 1963). The body is embedded in mica gneisses and migmatites (Fig. 60). The paleosome of migmatite is mainly biotite gneiss but bands with garnet, cordierite, hornblende or graphite are also common. Amphibolites with interbedded uralite and plagioclase porphyrites represent volcanogenic rock types south of the Kylmäkoski gneiss belt. Owing to the high degree of deformation and migmatization, the origin of the mica gneisses cannot usually be established. Locally, however, some well-preserved parts display textures similar to metaturbidites, suggesting sedimentary origin. The grade of regional metamorphism is upper amphibolite facies.

The migmatites are intersected by synkinematic intrusive rock series: hornblendites, gabbros, diorites and quartz diorites, which constitute a differentiation series. South of the Kylmäkoski migmatite belt, there is a large area of heterogeneous, partly porphyritic quartz diorite that includes irregular bodies of diorite, gabbro and hornblendite. In the north the Kylmäkoski migmatite belt is bordered by equigranular quartz diorite; even there, however, bodies of porphyritic granodiorite occur with porphyroblasts of potassium feldspar ranging up to 3 cm in diameter.

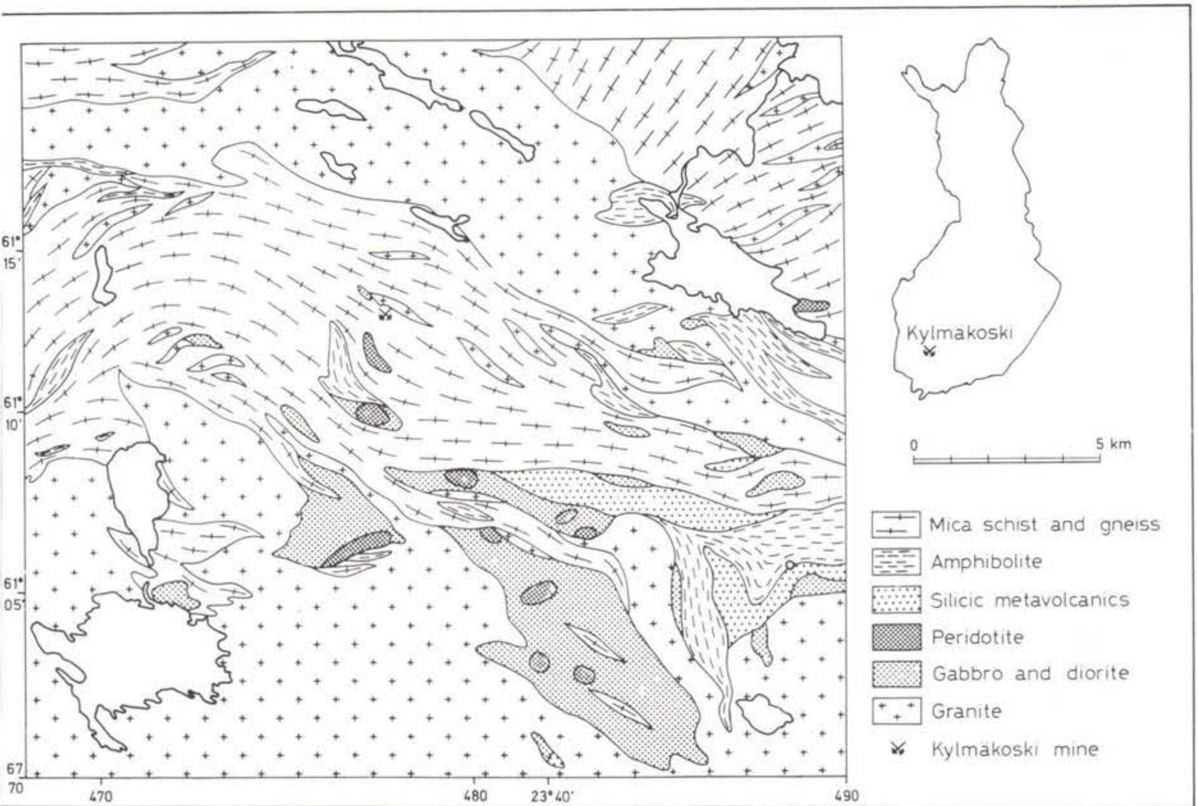


Fig. 60. Geological map of the Kylmäkoski area (Matisto 1976).

SHAPE AND ENVIRONMENT OF THE ULTRAMAFIC BODY

The body is about 260 m long and a maximum of 100 m wide and 80 m deep (Fig. 61). The wide northern part of the body has migmatitic gneiss as wall rock on its western side. The same gneiss appears as lenses in the northern and northeastern contacts, but in the east, farther north and in the basal contact of the northern part, the body is surrounded by quartz diorite that also intersects the body as several dykes. The narrow southern part pinches out in depth in migmatitic gneiss wall rock. Against the quartz diorite the ultramafic body exhibits crooked, locally also rectlinear contacts; against the migmatized mica gneiss, however, the contact curves smoothly and in many places forms, surprisingly, small-scale folds that vary in axial direction like folds in a migmatite environment (Fig. 62).

The body extends no deeper than 80 metres from the surface. A continuation of the body beyond the intruding quartz diorite in the northwest has not been established. During exploration a body of hornblendite was detected about 500 m northwest of the ore body, but it was barren of sulphides and the tenor of nickel was very low.

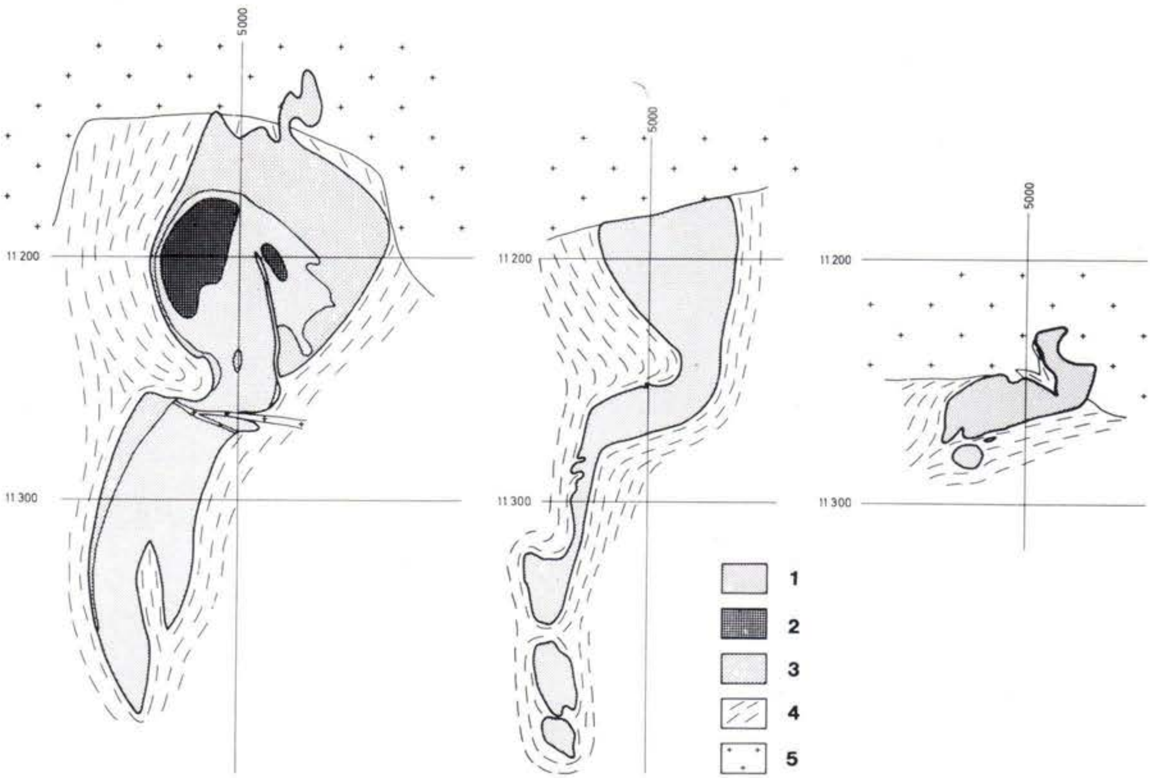


Fig. 61. Surface plan (left), 40 m plan and 65 m plan (right) of the Kylmäkoski mine. 1. Peridotite; 2. Orbicular peridotite; 3. Metapyroxenite and hornblendite; 4. Mica gneiss; 5. Quartz diorite.

The rock types

The rock types of the ultramafic body can be classified into peridotites, pyroxenites and perknites, hornblendites, cummingtonite rocks, gabbros and diorites (Fig. 61). Peridotites abound in the central, thicker parts, whereas perknites and hornblendites prevail in the tapering, peripheral parts and ends of the body. Cummingtonite rocks occur only in the northern part, close to the eastern contact zone. Diorites and gabbros differ from the other rock types in chemical composition and are evidently hybridic contact varieties.

Two types of peridotites occur: normal equigranular peridotite and a peculiar nodular, locally orbicular type with large olivine nodules. The nodular peridotite exists as irregular portions in normal peridotite in the northern end of the ultramafic body.

The normal type of peridotite consists of partially serpentinized olivine, orthopyroxenes, clinopyroxenes and brownish hornblende. Alteration processes have produced serpentine from olivine, cummingtonite from orthopyroxene and tremolite and actinolite from clinopyroxene. With increasing abundances of amphiboles the rock type grades into cummingtonite rock or hornblendite with a cortlandite variety as a transitional rock type.

The nodular peridotite is a rare rock type that is distinguished from the normal equigranular

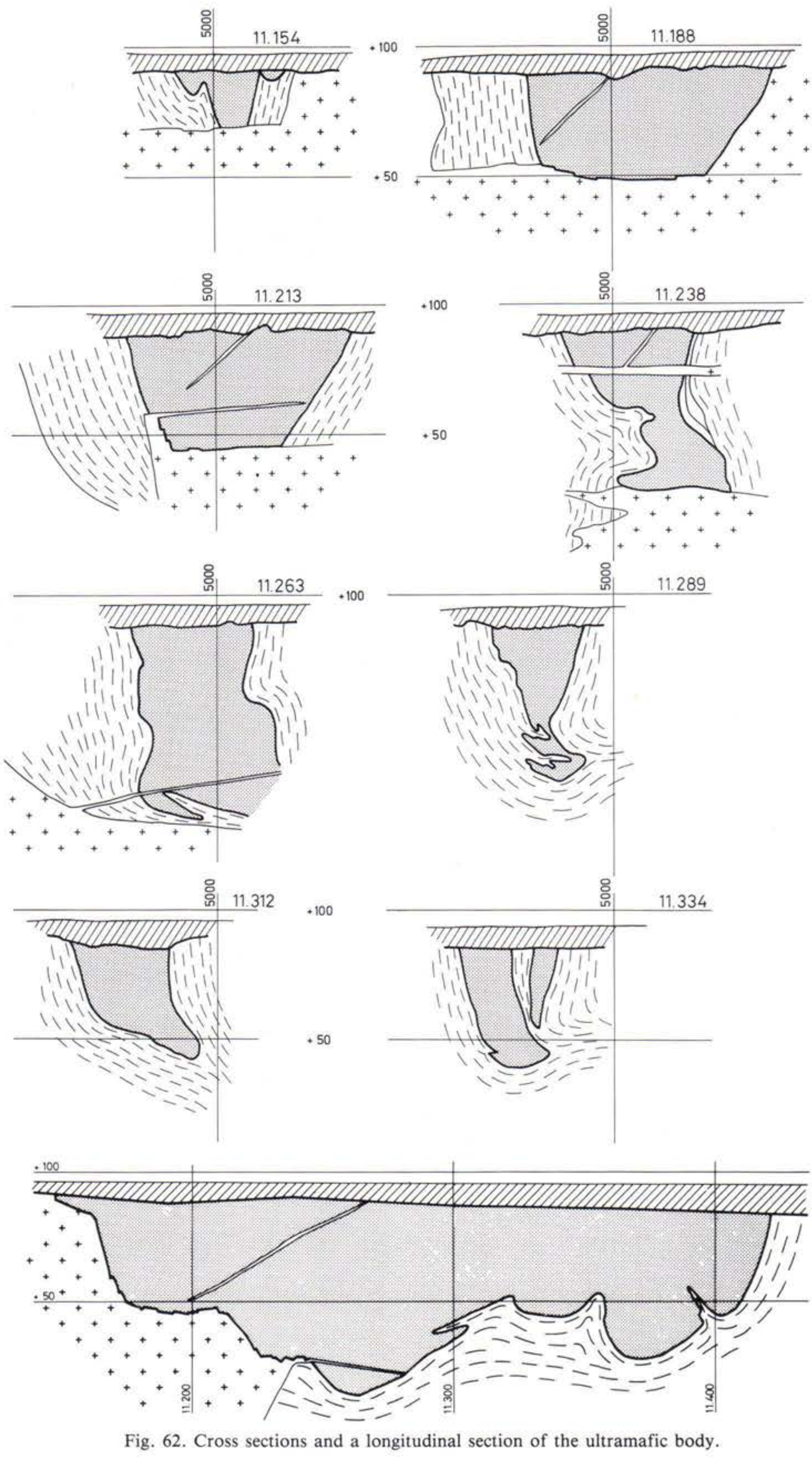


Fig. 62. Cross sections and a longitudinal section of the ultramafic body.

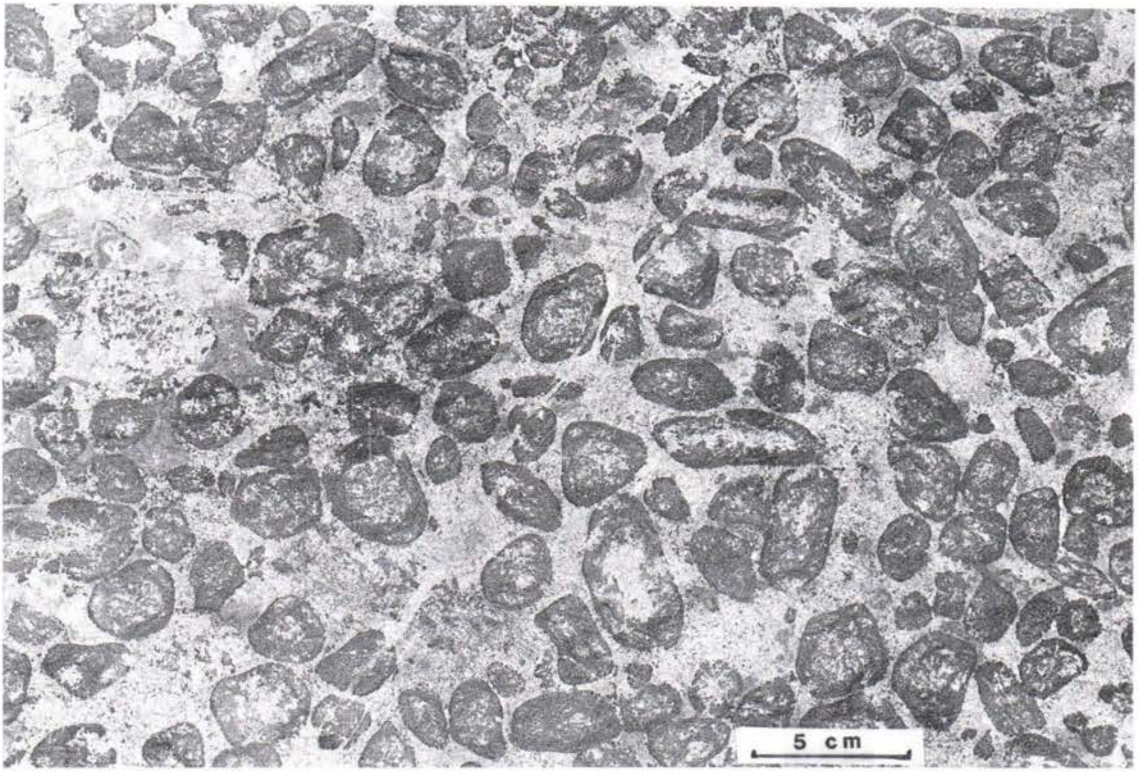


Fig. 63. Orbicular variety of peridotite; polished surface of the rock.

peridotite by its olivine nodules ranging from 1 to c. 5 cm in diameter (Fig. 63). The nodules commonly exhibit external crystal forms of olivine, and in thin section they appear as large, almost equidimensional single crystals of olivine. They differ in shape from the large metamorphic blades of olivine described by Evans and Trommsdorff (1974) and also from the harrisitic or crescumulate olivine noted in some layered igneous rocks (Wagner and Brown 1968). A few nodules, however, are roundish synneutic aggregates of small olivine grains. Being oriented, they give rise to a »wavy extinction» in the whole nodule under crossed polarizers. The olivine is partly, or almost totally, serpentinized. The »groundmass» in the interstices of the euhedral olivine nodules is composed of medium-grained pyroxenes and amphiboles, locally also of scattered olivine grains and sulphide accumulations. Only the outer shell of the nodules is usually olivine; the interior consists of coarse, locally poikilitic pyroxene and individual small olivine crystals. Thus, the material resembles the groundmass outside the nodules.

In some places the olivine shells seem to be refused, although concentric radial zoning of olivine, pyroxenes and amphiboles is also encountered. The term »orbicular» is proposed for this type. The olivine forms a roundish »eggshell» around radial or poikilitic crystals of pyroxene or amphibole.

A feature common to the zoned »orbicular» type and the euhedral shells of olivine nodules is that the abundance of sulphide inside the nodules is lower than that in the external groundmass. This is probably due to the sulphide melt immiscibility that preceded the rapid crys-

Table 37. Average chemical compositions of the rock types (N = number of analyses).

	Nodular peridotite	Peridotite	Pyroxenite	Horn-blendite	Gabbro
SiO_2	39.91	46.08	49.20	49.00	45.08
TiO_2	0.36	0.30	0.44	0.50	1.05
Al_2O_3	2.99	4.34	5.63	6.12	17.02
FeO (total)	14.34	13.45	13.03	11.92	14.91
FeO (silic.)	12.91	12.04	11.05	9.56	14.12
MnO	0.19	0.19	0.19	0.18	0.21
MgO	28.33	23.50	19.49	15.30	9.44
CaO	4.07	7.84	8.84	12.10	8.18
Na_2O	0.09	0.31	0.64	0.61	1.07
K_2O	0.06	0.08	0.08	0.22	1.33
P	0.06	0.11	0.11	0.19	0.14
S	1.06	1.05	1.48	1.77	0.59
As	0.002	0.010	0.004	0.00	0.00
Cu	0.15	0.21	0.19	0.14	0.06
Ni (total)	0.25	0.26	0.24	0.26	0.09
Cr	0.09	0.28	0.28	0.43	0.06
N	9	16	8	25	4

tallization of the olivine nodules. The sulphide melt has settled above the olivine nodules and, as a result, sulphide layering exists locally in the nodular peridotite. The forsterite component is highest in the olivine shell, the values being slightly lower for the groundmass olivine, which indicates early crystallization of the olivine nodules.

The euhedral shape and large size of the nodules is a result of rapid growth of crystals in the melt. In shape and size the olivine orbicules resemble the chromite orbicules described from chromite pods of ophiolites (Leblanc *et al.* 1981).

Olivine-poor pyroxenites proper are rather uncommon, whereas metapyroxenites abound in the northern part of the body. It contains hornblende, augite and/or hypersthene as main components and forms a transition zone from peridotite to hornblendite in the northernmost part and in the tapering southern end of the body. The hornblende is either greenish or brown in thin section. The brown hornblende seems to be a primary mineral, whereas the green variety envelopes the augite crystals and seems to be, at least partially, of secondary origin. Minor plagioclase exists locally, and the rock type grades into hornblende melagabbro or gabbro.

The rock type characterized by abundant cummingtonite is met with in the northeastern part of the body. It often contains remnants of orthopyroxene, augite and hornblende in addition to pale, intensely twinned laths of cummingtonite. The microscopic textures indicate that the rock type is an alteration product of pyroxenite.

Gabbros and diorites are quite rare. As mentioned above, the hornblendite grades into gabbro with increasing plagioclase abundances, but these variants are local and restricted in size. Diorite has been met with on the surface level close to the eastern contact of the body. Gabbros and especially the graphite-bearing diorite were formed as a result of assimilation of the wall-rock material by ultramafic magma. This is supported by evidence from sulphur isotope determination (Papunen and Mäkelä 1980).

A set of coarse-grained and very dark pegmatite veins intersects the peridotite, especially on the +45 level in the mine. At the contacts of the pegmatite the peridotite exhibits an almost monomineralic succession of alteration zones composed of talc, actinolite, anthophyllite and chlorite in this order, starting from the unaltered peridotite. The alteration zones are from one to 10 cm wide except at the contacts of the intersecting quartz-diorite dykes, where they may be up to 20 cm wide. The alteration zones exist only when the peridotite is the host rock of the dykes. The contacts of pegmatite against pyroxenite or hornblendite are sharp and without alteration features. Similar zoning exists in the peridotites of Hitura and Kotalahti (Papunen 1970) and in Vammala.

Chemical composition of silicate minerals

The abundance of nickel in olivine (Table 38) is about the same as that in the lower, sulphide-rich ultramafic layer of the Stormi intrusion; at Kylmäkoski, however, the Fo abundance of olivine is somewhat lower (Häkli *et al.* 1979). There is no correlation between Ni and Fo abundances in olivine and in this respect, too, the variation in composition is similar to that in the Stormi ultramafics. In a small sulphide-bearing intrusive like that at Kylmäkoski the subsolidus reactions between olivine and sulphides equilibrated the composition of sulphide and silicate phases at a certain level.

Table 38. Microprobe analyses of nickel in silicate minerals (ppm).

	Peridotite			Pyroxenite and hornblendite		
	Average	Range	N	Average	Range	N
Olivine	1092	583—1404	13	1041	825—1407	6
Orthopyroxene	221	140—269	6	245	192—274	3
Augite	170	75—326	11	158	118—207	8
Hornblende	375	188—663	13	352	139—558	27

N = number of analyses

Geochemistry of the rock types

The chemical compositions of the rock types are similar to those for the Stormi ultramafic complex (Häkli *et al.* 1979), except that the dunitic member is lacking from Kylmäkoski. The nodular peridotite is the most magnesian member of the Kylmäkoski rock suite. In the ultramafic rocks of the suite the ratio Ca to Al is generally more than unity. The variation in the Mg to Fe ratio from nodular peridotite to hornblendite is small, but the compositional difference is manifest in the abundances of calcium, aluminium and alkalies.

Häkli *et al.* (1979) explained the similar variation within the Stormi ultramafic complex as a result of migration of these elements from the wall rock into the ultramafic magma. The same explanation can well be applied to the Kylmäkoski rock series. The location of hornblendites at the contacts and in the tapering ends of the body supports this concept. The heterogeneous graphite-rich gabbros and diorites assimilated a graphite-rich portion of the wall rock.

THE ORE TYPES

The sulphide minerals exist mainly as dissemination, which is locally abundant enough to form a continuous net between the silicates. In the olivine and pyroxene-rich peridotites the dissemination is interstitial but in the hornblendite the sulphides often exist as round spheres indicating that they crystallized earlier than the host hornblende. In the nodular peridotite the sulphides occasionally occur as small massive layers that grade upwards into a interstitial dissemination between nodules of overlying peridotite. In the coarse-grained dissemination in the nodular peridotite, chalcopyrite is often seen close to the top edges of the sulphide grains that rest on the olivine nodules. The texture demonstrates that the heavy sulphide drops settled as massive layers in melt that contained large nodules of previously crystallized olivine. The texture lends excellent support to the »billiard-ball model» of Naldrett (1973). Along the basal contacts of the body the sulphides occur as fine-grained breccias that locally extend for a few metres into the wall rock gneiss. In cummingtonite rocks the sulphides exist as anhedral grains penetrated by amphibole needles as a result of metamorphic recrystallization of amphibole.

The sulphides also form rectlinear massive veins up to 20 cm wide that can be followed for over ten metres. The veins are enveloped by chlorite-rich slickensides that continue without sulphides when the sulphide vein dies out. Massive Ni arsenides occur locally as a continuation of the massive Ni-Cu sulphides in the veins. As a rule, however, the nickel arsenide veins are encountered in the tapering ends of quartz-diorite dykes or in the contact shear zones of intrusive quartz diorite.

The ore minerals

The main ore minerals in the disseminated and breccia ores are pyrrhotite, pentlandite and chalcopyrite, but, especially in the breccias rich in Cu, lamellae of cubanite are almost as abundant as chalcopyrite. The same is true of the dissemination in the cummingtonite rock. Pyrrhotite is mainly of hexagonal phase, but in the breccia ores a minor amount of monoclinic phase appears as lamellae in the hexagonal host.

The minor opaque minerals include mackinawite, which occurs as small oriented flakes in pentlandite, especially in the serpentinized parts of the body or as small flake veinlets along former cracks of serpentinized olivine grains and as independent dissemination in serpentinite. Graphite is locally very common in the eastern part of the body. It exists in brecciated ores as large flakes or as a fine-grained mass, and it may form round spheres in pyrrhotite. Some flakes of molybdenite are met with in the graphite-rich part of the body. Argentian pentlandite is a common minor constituent of the chalcopyrite-rich ores in breccias and sulphide veins. In the disseminated ores rare euhedral grains of gersdorffite-cobaltite are encountered together with sulphides; in the nickel arsenide veins, however, zoned grains of gersdorffite-cobaltite are locally the main opaque minerals. Nickeline and maucherite are often the predominant minerals in the arsenide veins. This mineral assemblage also includes chalcopyrite with abundant argentian pentlandite, common pentlandite and minor wehrlite and galena as well as minerals of PGE, of which michenerite has been identified.

Chemical composition of the sulphides

A set of samples of every rock and ore type was collected from diamond drill cores. The average compositions of different ore types based on 281 analyses are given in Table 39. The correlation coefficients and R-mode factor analysis were presented by Papunen (1980). The average compositions presented in Table 39 indicate that the tenors of nickel and cobalt increase parallel to the increasing magnesium content of the host rock. Zinc is concentrated together with copper in brecciated ore of the contact zone.

The analyses of platinum-group elements indicate low tenors of PGE in disseminated and breccia ores and enrichment of PGE in the nickel arsenide ore type in which Pd is more abundant than Pt. In disseminated sulphides the reverse is often true. The tenors of Pd were up to 1.0 ppm and those of Pt 0.4 ppm in the nickel arsenide vein.

Table 39. Average chemical compositions of the ore types calculated in 100 % sulphides.

	Ni %	Cu %	Co %	Zn (ppm)	Pb (ppm)
Disseminated sulphides in nodular peridotite	7.07	3.74	0.39	941	503
Disseminated sulphides in peridotite	6.69	3.52	0.33	840	428
Disseminated sulphides in pyroxenite	5.20	3.74	0.31	503	319
Disseminated sulphides in hornblendite	4.98	2.91	0.25	623	349
Chalcopyrite-rich breccia ore	4.59	22.7	0.18	1916	465
Massive sulphide vein	5.06	0.59	0.26	139	19

Sulphur isotopes

Papunen and Mäkelä (1980) determined the sulphur isotope composition for 30 ore samples of Kylmäkoski. The $\delta^{34}S$ values range from —1.6 to +1.3 per mil, with —0.2 per mil as the mean value of 28 samples. The isotopic composition of sulphides varies somewhat more than in the Kotalahti and Hitura deposits. Anomalously light sulphur was noted in two samples rich in graphite, the $\delta^{34}S$ values being —4.2 and —11.1 per mil. These graphite-rich gabbros and diorites are the result of wall-rock contamination of the basic melt and received the anomalously light sulphur from the wall-rock metasediments.

DATING

Papunen (1980) reported the age determinations based on lead isotope data. The isochron defined corresponds to an age of 1856 (+179, —203) Ma, which is consistent with the lead-lead age of the Telkkälä deposit (Häkli *et al.* 1975) and slightly younger than the ages reported from Kotalahti (Gaál 1980) and Vammala (Häkli *et al.* 1979). The difference may be due to the method used.

DISCUSSION

The shape, setting and metamorphic alteration of the Kylmäkoski ultramafic body suggest that the body was already in its present environment when the wall-rock gneisses were migmatized and folded. The palingenic neosome of the migmatite intersects and brecciates the ultramafics as pegmatite veins. The zoned alteration selvages along the contacts of the pegmatite veins developed in peridotite, as a result of diffusion of alkalies, silica and aluminium, from pegmatites that darkened and are now composed mainly of plagioclase.

The Kylmäkoski body is a subconformable wedge in migmatite and is intersected by quartz diorite. Similarities in the structure and composition of the Kylmäkoski ultramafics and the Stormi ultramafic complex suggest that they have a similar history of emplacement.

The peculiar texture of the nodular and orbicular peridotite is explained by rapid crystallization (Papunen 1980). The skeletal crystallization of the nodular peridotite is consistent with the hypothesis of rapid injection of magma into a rather cool environment.

The immiscibility of sulphides started before the olivine nodules crystallized and the sulphide melt settled. The olivine nodules crystallized from silicate melt that was already depleted in sulphides. Hence the interiors of the nodules do not contain much sulphides. The nodules settled together with the sulphide melt, and sulphides occasionally form massive but minute layers in the ultramafic body.

The small ultramafic body underwent deformation, alteration and regional metamorphism.

THE VAMMALA NICKEL DEPOSIT

T. A. HÄKLI and K. VORMISTO

INTRODUCTION

The Vammala nickel deposit is located in southwest Finland, some 5 km east of the town Vammala, within the Ahlainen—Kylmäkoski nickel belt.

The first indications of the nickel ore were obtained in 1960 when a farmer sent sulphide-bearing peridotite samples from Stormi, a village near Vammala, to Outokumpu Oy. The exploration undertaken by Outokumpu Oy resulted in the discovery of several ultramafic bodies, two of which contained enough nickel sulphides to warrant exploitation.

In 1975—1977 experimental mining was carried out at Kovero-oja and some 460,000 tonnes of marginal ore at 0.4 % Ni and 0.3 % Cu were extracted from open-pit and underground workings.

In 1978 Outokumpu Oy started full-scale production at an annual rate of 300,000 to 350,000 tonnes ore with a mill feed (1981) at 1.0 % Ni and 0.6 % Cu.

REGIONAL GEOLOGY

The Vammala area (Fig. 64) is located south of Tampere schist belt (Sederholm 1897). According to Matisto (1978), it represents a deeply eroded anticlinorium composed of miogeosynclinal sediments of the slow evolution stage of the Svecokarelidic orogeny. The ore geology of the Vammala area places it in the Ahlainen—Kylmäkoski nickel-potential belt.

The sedimentary rocks are metamorphosed veined mica gneisses with quartz, plagioclase and biotite as major minerals. Garnet occurs as porphyroblasts, particularly adjacent to the plutonic rocks.

Tuffaceous amphibolite, uralite and plagioclase porphyrites are encountered as interlayers in mica schists. These rocks also contain calcium-rich concretions and diopside gneiss portions. In places the mica gneisses grade into kinzigites that contain garnet, cordierite and, occassionally, sillimanite and graphite.

The graphite gneisses are usually associated with the kinzigites: They are fine-grained rocks with quartz, plagioclase, biotite and cummingtonite as main minerals. The abundance of graphite attains 20 per cent in the gneisses in the north of the area.

Granodiorite and quartz diorites are the predominant plutonic rocks. The cataclastic garnetiferous quartz diorite east of Stormi exhibits an arch-like structure that opens towards the west. Granites are rare and mainly occur as pegmatitic and aplitic veins.

Ultramafics occur in the mica gneiss as isolated and often rather small bodies. Gabbros and diorites are rare, and they exist either as discrete intrusions or grade into quartz diorite.

The ultramafics contain abundant amphibole and occur as massive or, locally, porphyritic hornblendite or cortlandite. The ultramafic bodies usually also contain peridotitic or dunitic

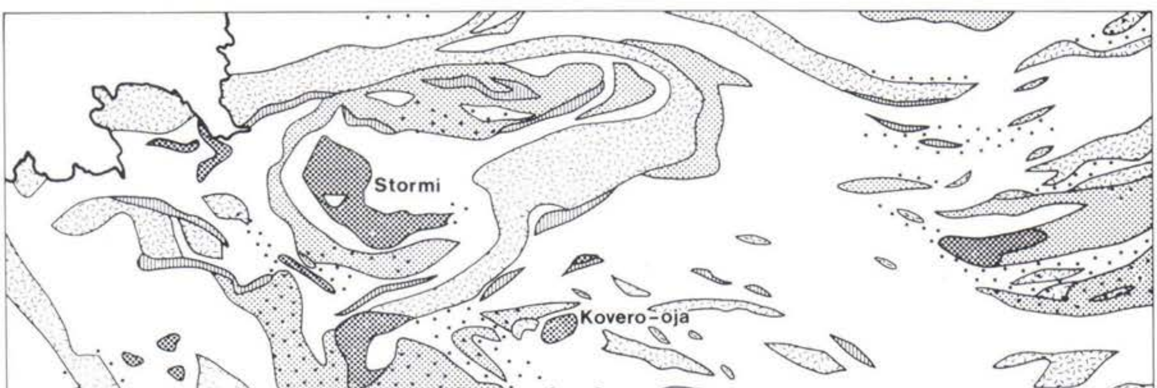


Fig. 64. Geology of the Vammala area. 1. Mica gneiss; 2. Kinzigite; 3. Graphite gneiss; 4. Ultramafite; 5. Diorite; 6. Schollen migmatite. After Häkli *et al.* (1979).

portions with or without sulphides. The major minerals in these rocks are pyroxenes, olivine, serpentine and amphibole.

Schollen migmatities, which mark tectonically complicated zones, are encountered in various parts of the Vammala area. They have a quartz dioritic or trondhjemitic matrix with fragments of mafic gneisses and plutonic rocks.

In the east of the area (Fig. 64) the schistosity trends east-northeast but in the centre the schistosity turns gradually towards east-southeast. In the west the schistosity strikes towards southeast. The dips vary from 70° to 90°. The tectonic pattern of the area is complicated by the fracture zone (Matisto 1971).

STORMI ULTRAMAFIC BODY

The Vammala nickel deposit occurs in an ultramafic body that is 1.5 km long, up to 600 m wide and extends to a depth of about 300 m. It is embedded in a high-grade metamorphic garnet and cordierite gneiss with graphite gneiss interlayers, concretions and iron sulphides. The ultramafic body shows subconformable contacts with the country rock gneisses (Fig. 65). In places the gneiss occurs as tongues in and between the ultramafic layers. The body is composed of three major superimposed ultramafic layers, some of which can be divided further into sublayers (Fig. 66).

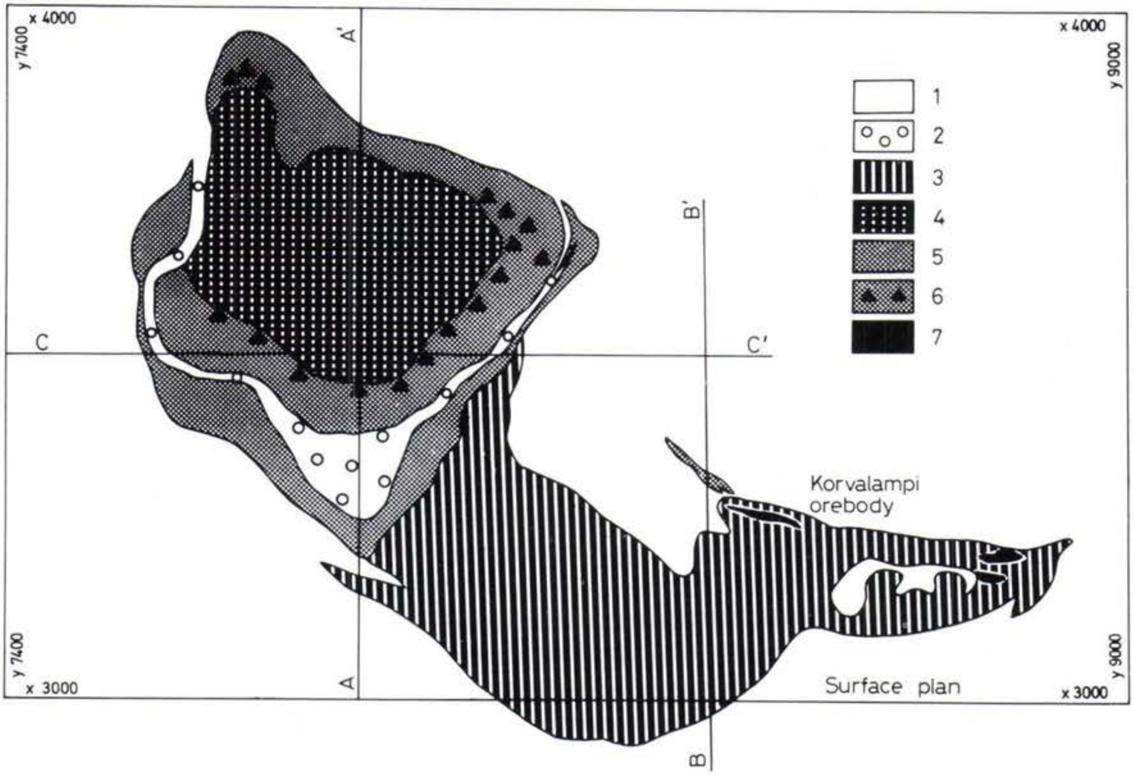
The lowest layer is peridotite and dunite in composition, with olivine, serpentine, orthorhombic and monoclinic pyroxenes as main minerals and phlogopite, amphibole and chlorite as accessories. At the basal contact, olivine is rather well preserved and shows a distinct cumulate texture. Orbicular peridotite, similar to that described from Kylmäkoski by Papunen (1980), occurs here and there at the base. The lowest layer is rich in sulphides and hosts the nickel ores of the Vammala deposit. Some of the sulphides are confined to the base of the layer but significant accumulations occur higher up, too.

The intermediate layer is hornblenditic in composition and contains amphibole, pyroxene, calcite, phlogopite and, occasionally, olivine as major minerals. In the uppermost portion of the hornblendite layer there is an agglomerate sublayer that can be traced throughout the ultramafic body. Narrow layers of hornblendite (from 10 to 100 cm in width) with orthopyroxene porphyroblasts are encountered in the hornblendite layer, suggesting that the major layer actually contains a succession of ultramafic flows.

The uppermost layer is composed of peridotite with serpentine, amphibole, olivine and pyroxene as major minerals. In places the primary minerals are almost wholly altered into serpentine. The acicular amphibole up to 1 cm long that occurs at certain horizons may or may not indicate boundaries between the magma flows. At the northern end of the ultramafic body a shallow layer of hornblendite rests on the upper peridotite layer.

The upper layer lacks primary sulphides, which were altered into magnetite. Together with chlorite, the magnetite forms a »hymn book texture» that outlines the shape of the primary sulphide blebs (Häkli *et al.* 1979).

A layer of phlogopite rock occurs in the contact between the lower ultramafic layer and the hornblendite layer. At the upper contact of the hornblendite with the upper peridotite layer there are narrow sublayers of diopside-bearing rocks with magnesian hercynite. These rocks are also encountered elsewhere in the hornblendite layer. They are metasediments that demark


x 4000
y 7400
A'
x 4000
y 9000
1
2
3
4
5
6
7
B'
C
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Korvalampi
orebody
y 7400
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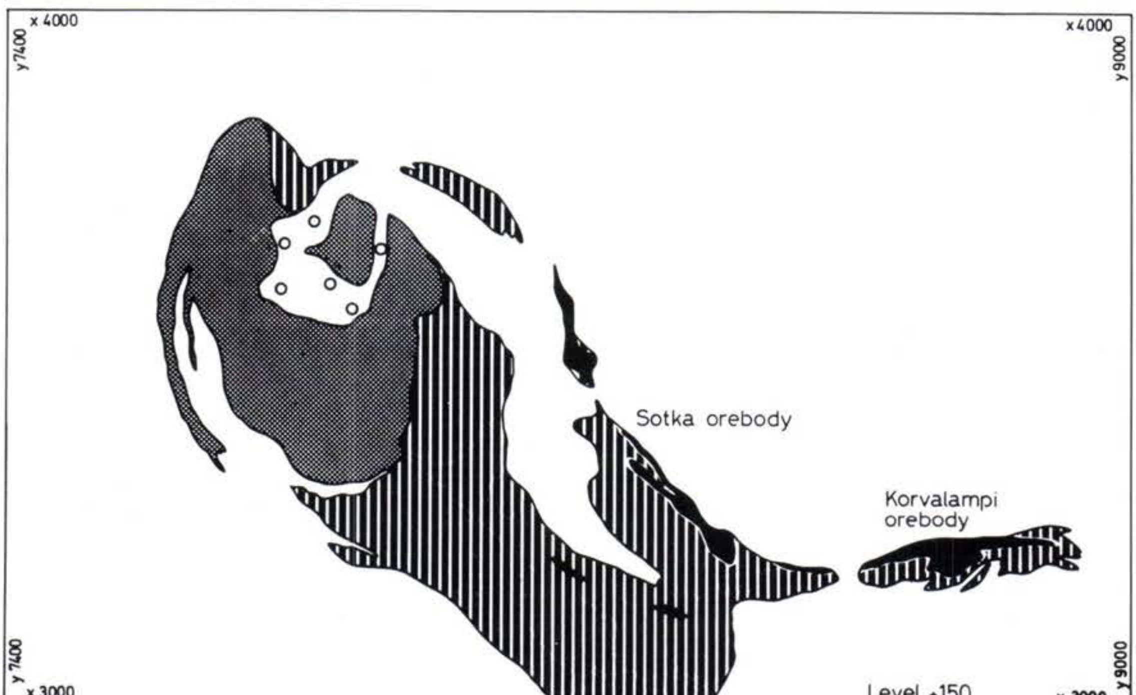
A
Surface plan
y 9000
x 3000
B


x 4000
y 7400
x 4000
y 9000
Sotka orebody
Korvalampi
orebody
y 7400
x 3000
Level +150
x 3000
y 9000

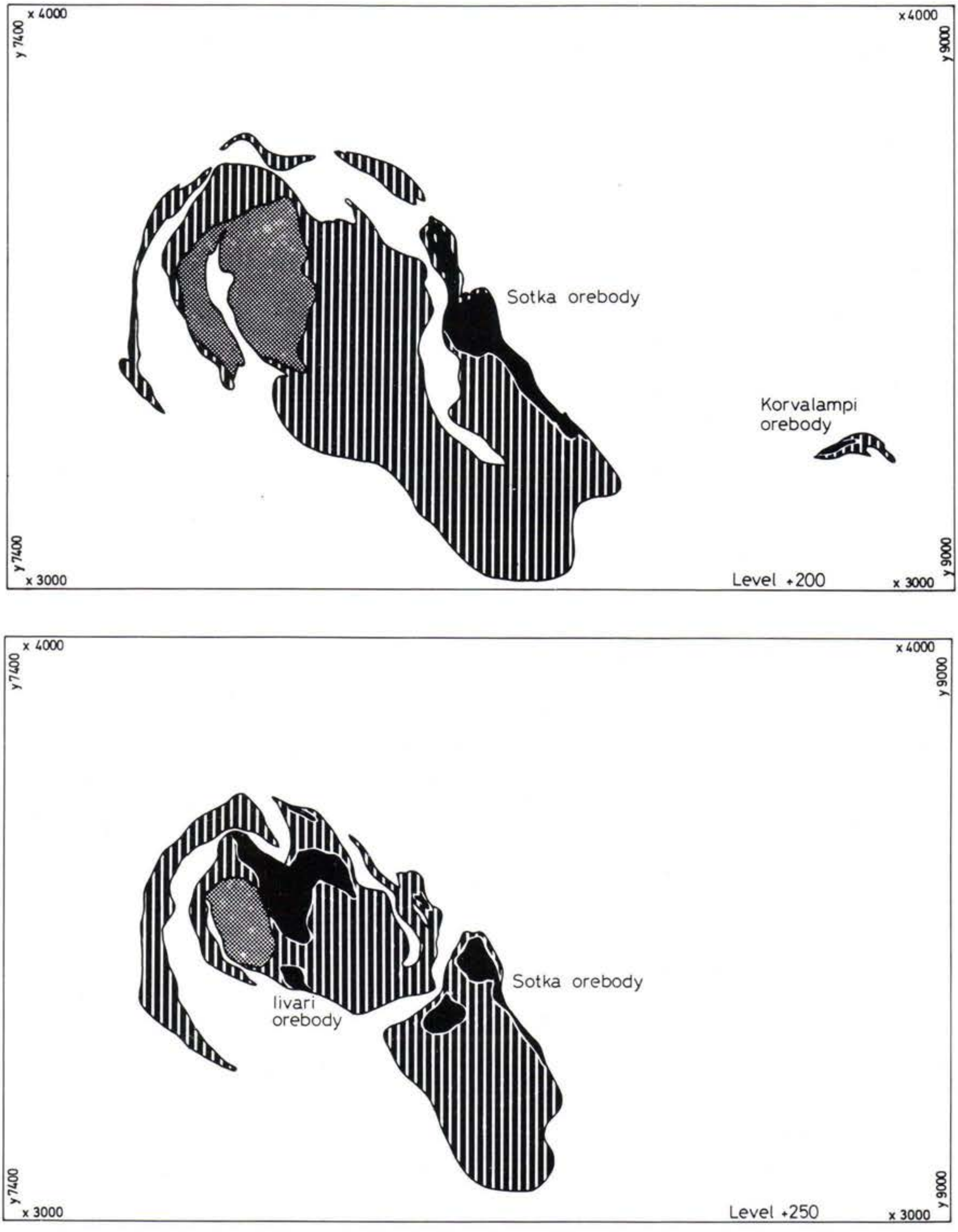
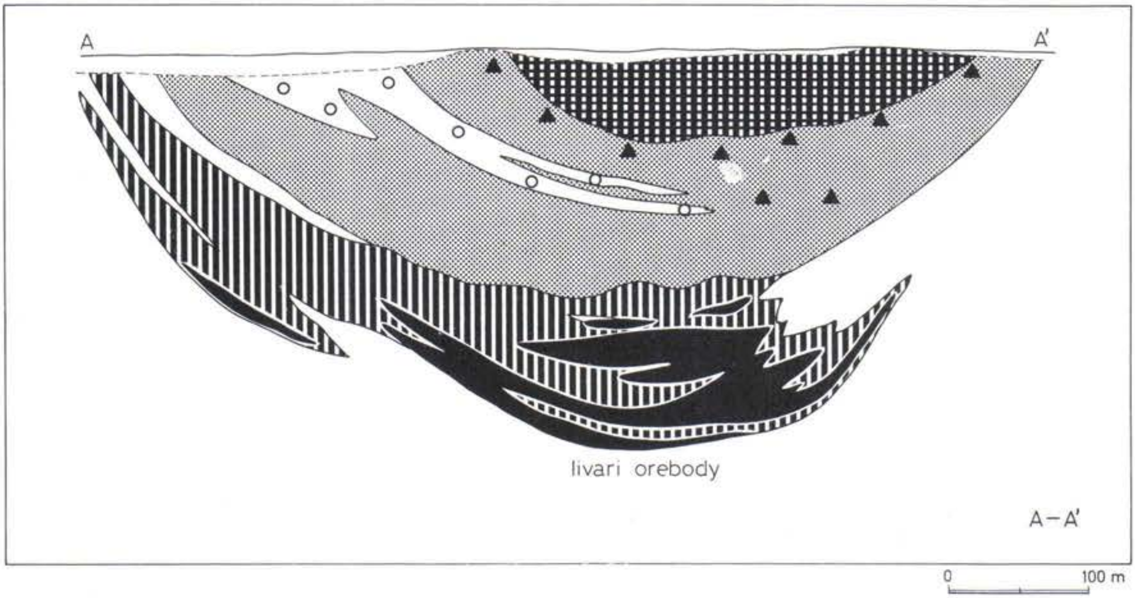
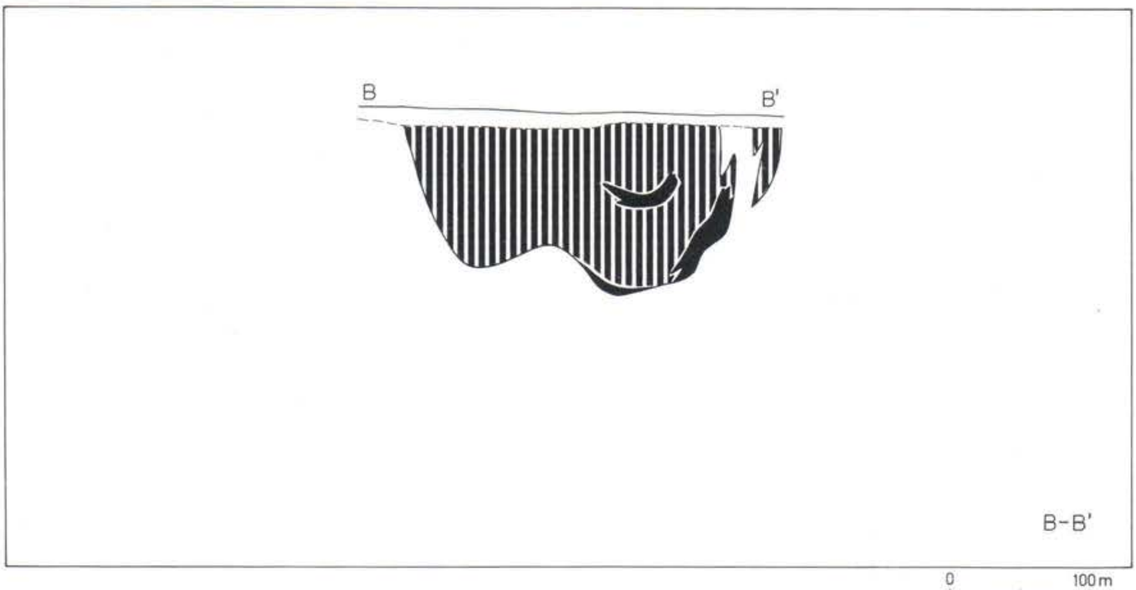


Fig. 65. The Vammala ultramafic body. 1. Mica gneiss; 2. Quartz diorite; 3. Lower ultramafic layer; 4. Upper ultramafic layer; 5. Hornblendite; 6. Agglomerate structure; 7. Ore.





the boundary layers between the ultramafic units and indicate that the discharges of magma alternated with tranquile periods.

The ultramafics are cut by dykes that vary from gabbro to granite in composition. The contacts of the dykes are rimmed by a reaction zone, 1 to 3 cm wide, composed of amphibole and talc.

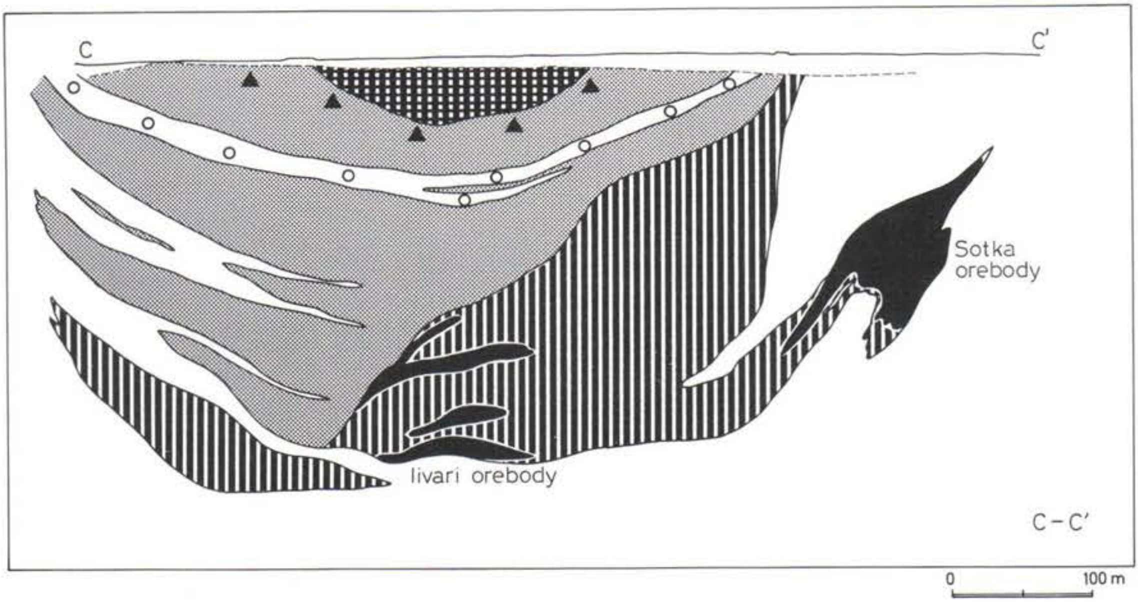


Fig. 66. Cross sections of the Vammala ultramafic body; symbols as in Figure 65.

OREBODIES

The orebodies are associated with the lowermost ultramafic layer. They occur mainly along the eastern and northern margins of the layer but are also met with in the interior and at the basal contact. Economically the most important of them are Sotka, Korvalampi and Iivari. The Sotka orebody is a subvertical slab, about 700 m long and up to 70 m wide. It is exposed in the east and plunges towards the northwest. The Iivari orebody at the base of the western part of the ultramafics is a pile of subhorizontal plates, 5 to 30 m thick, at a depth of 250 to 350 m.

At the contact with the mica gneiss but within the ultramafics the sulphides occur as matrix ore or massive veins that occasionally extend to the gneiss. From the contact inwards the matrix ore grades into a fine-grained sulphide dissemination.

At the northwestern end of the Sotka orebody the nickel sulphides extend into the mica gneiss for a distance of up to 10 m from the contact with the ultramafics.

Sulphide assemblages

The assemblage monoclinic pyrrhotite-pentlandite-chalcopyrite ± mackinawite predominates in the lower ultramafic layer. The sulphides are partly oxidized, and the borders of the pyrrhotite and pentlandite are often replaced by secondary magnetite. Narrow violarite seams are encountered between magnetite and pentlandite. Magnetite also fills the fissures in the chalcopyrite and pentlandite.

The assemblage monoclinic pyrrhotite-pentlandite-hexagonal pyrrhotite occurs at the contact between the lower ultramafic layer and the mica gneiss. Monoclinic pyrrhotite, pentlandite and chalcopyrite are the coexisting phases, and hexagonal pyrrhotite occurs as inclusions in the monoclinic pyrrhotite. In the Sotka orebody the assemblage pyrrhotite-pentlandite-chalcopyrite-mackinawate ± cubanite ± valleriite is also present.

Pentlandite exsolution bodies in pyrrhotite are rare, except in the Sotka orebody where they are more frequent.

At the basal contact of the intervening mica gneiss altered into garnet quartz diorite there is an assemblage of pyrrhotite ± arsenopyrite with a small amount of native gold. In places scheelite has also been encountered at the contact.

The exsolution textures of and the intergrowths between the sulphides suggest that the sulphides formed solid solutions at higher temperatures. According to Häkli *et al.* (1979), however, the sulphide phase segregated during crystallization into several subsystems in equilibrium with one other, which differentiated into metastable sulphide assemblages at lower temperatures.

Sulphide textures

The sulphide-silicate textures allow the ores to be subdivided into the following types:

1. Massive sulphides that occur as narrow veins, breccia matrix or accumulations at the contact of the ultramafics.
2. Matrix ore in the lower ultramafic layer. As the sulphides decrease, this type grades into disseminated ore. Pentlandite is often euhedral, whereas chalcopyrite shows sub- or anhedral grains.
3. Disseminated sulphides in the lower ultramafic layer, in mica gneiss and in the contact rocks. The sulphides occur as large blebs, fillings in fissures or inclusions in silicates.
4. A very weak and fine-grained sulphide dissemination in the hornblendite layer.

Table 40. Electron microprobe analyses of sulphides.

	1		2		3			4	5	6	7
	POT	PNT	POT	PNT	POT	MAC	PNT	POT	PNT	POT	PNT
S	39.83	32.86	39.98	33.42	38.60	35.61	33.55	39.10	32.11	39.98	33.50
Fe	59.64	34.72	59.74	32.85	60.92	57.32	29.27	59.48	28.44	59.01	29.77
Co	0.03	0.95	0.02	1.05	0.01	0.28	2.05	0.02	6.15	0.01	1.06
Ni	0.22	30.26	0.30	31.85	0.19	7.50	34.78	0.51	33.00	0.48	35.43
Total	99.72	98.79	100.04	99.17	99.72	100.71	99.65	99.11	99.71	99.48	99.76

POT = pyrrhotite; PNT = pentlandite; MAC = Mackinawite

1. Dissemination in peridotite; assemblage: monoclinic pyrrhotite-pentlandite-chalcopyrite-cubanite-mackinawite.
2. Low-grade dissemination in metaperidotite; assemblage: monoclinic pyrrhotite-pentlandite-mackinawite.
3. Intermediate dissemination in amphibole serpentinite; assemblage: monoclinic pyrrhotite-pentlandite-chalcopyrite-cubanite-mackinawite.
4. Low-grade dissemination in amphibole serpentinite; assemblage: pentlandite-chalcopyrite.
5. Low-grade dissemination in serpentinite; assemblage: monoclinic pyrrhotite-pentlandite-mackinawite.
6. Low-grade dissemination in serpentinite; assemblage: pentlandite-chalcopyrite.
7. Sulphide accumulation in garnetiferous mica gneiss: assemblage: monoclinic pyrrhotite-pentlandite-chalcopyrite.

Composition of sulphides

In chemical composition pyrrhotite is very close to the formula of monoclinic pyrrhotite. The nickel content of pyrrhotite varies between 0.19 and 0.51 % (Table 40). The pyrrhotite in the mica gneiss close to the ultramafics is rich in nickel assaying 0.48 % Ni.

The mean composition of pentlandite is very close to the stoichiometric, being $(Ni, Fe, Co)_{8.98}S_8$. The nickel, iron and cobalt contents of pentlandites seem to correlate with the type of sulphide assemblage and the locality. The pentlandite in the mica gneiss adjacent to the ultramafic is richest in nickel (Table 40).

Oxides

The ultramafics have primary and secondary oxides. The former include chromite, ilmenite and magnetite. Secondary magnetite is common in the serpentinized rocks and as an oxidation product of sulphides.

Ilmenite occurs either as individual or exsolution lamellae in magnetite. Chromite is encountered as a low-grade dissemination in the lower ultramafic layer but it does not form chromitite layers. The contact rocks are practically free from chromite.

Table 41. Mean chemical compositions of the rocks in the Vammala ultramafic intrusion.

Number of samples	1	2	3	4	5	6	7	8	9	10	11
	7	64	78	52	17	15	17	34	19	4	88
SiO_2	33.35	39.33	39.28	37.53	38.91	40.44	46.39	42.40	46.96	49.35	58.66
TiO_2	0.118	0.245	0.158	0.165	0.172	0.607	0.411	0.757	0.677	1.038	0.621
Al_2O_3	1.13	2.89	2.52	1.79	2.15	4.95	5.82	6.96	7.25	15.61	14.09
Cr_2O_3	0.727	0.791	0.940	1.086	1.144	0.609	0.567	0.423	0.410	0.029	0.110
FeO (tot)	17.65	14.39	13.61	13.84	12.96	13.80	11.88	12.33	12.20	9.82	8.77
FeO ($-Fe_{sulph}$)	12.37	12.24	11.43	11.97	10.39	12.59	7.69	11.62	10.55	9.38	6.23
MnO	0.147	0.149	0.149	0.173	0.169	0.152	0.166	0.154	0.131	0.242	0.076
MgO	28.26	25.71	28.28	30.82	30.57	20.47	17.42	16.77	15.19	4.88	6.32
CaO	2.05	4.83	3.18	1.15	1.51	7.13	8.65	9.29	7.58	4.64	2.32
Na_2O	0.045	0.225	0.137	0.070	0.082	0.589	0.368	0.866	0.814	3.129	2.227
K_2O	0.018	0.113	0.233	0.177	0.015	0.140	0.505	0.574	0.706	1.193	2.696
BaO	0.006	0.006	0.004	0.003	0.000	0.013	0.026	0.026	0.028	0.119	0.113
SrO	0.001	0.003	0.002	0.002	0.002	0.012	0.012	0.016	0.014	0.042	0.025
ZrO_2	0.000	0.001	0.001	0.001	0.000	0.004	0.003	0.006	0.006	0.023	0.017
P_2C_5	0.074	0.154	0.102	0.045	0.044	0.274	0.337	0.375	0.326	0.361	0.152
As	0.002	0.001	0.003	0.001	0.001	0.002	0.003	0.004	0.013	0.002	0.002
Ni (tot)	0.493	0.333	0.356	0.314	0.347	0.272	0.435	0.132	0.218	0.008	0.105
Ni (sulph)	0.450	0.238	0.246	0.223	0.283	0.166	0.407	0.040	0.152	0.005	0.077
Cu »	0.448	0.151	0.166	0.155	0.099	0.025	0.282	0.045	0.147	0.013	0.069
Co »	0.022	0.011	0.013	0.014	0.016	0.008	0.019	0.003	0.007	0.001	0.004
Zn »	0.010	0.005	0.006	0.006	0.005	0.005	0.005	0.004	0.006	0.004	0.019
Pb »	0.003	0.002	0.003	0.002	0.001	0.002	0.002	0.002	0.002	0.003	0.003
Fe »	4.11	1.68	1.70	1.55	2.18	0.94	3.25	0.55	1.28	0.34	1.97
S	3.11	1.31	1.33	1.17	1.52	0.76	2.35	0.33	1.31	0.20	1.47

1. Dunite, metadunite, 2. Peridotite, 3. Metaperidotite, 4. Serpentinite, 5. Amphibole serpentinite, 6. Cortlandite, metacortlandite, 7. Perknite, 8. Hornblendite, diopside hornblendite, 9. Amphibole-, pyroxene-, and mica-bearing rocks in the contact zone of ultramafic and acid rocks, 10. Diorite and quartz diorite, 11. Wall rocks (gneisses).

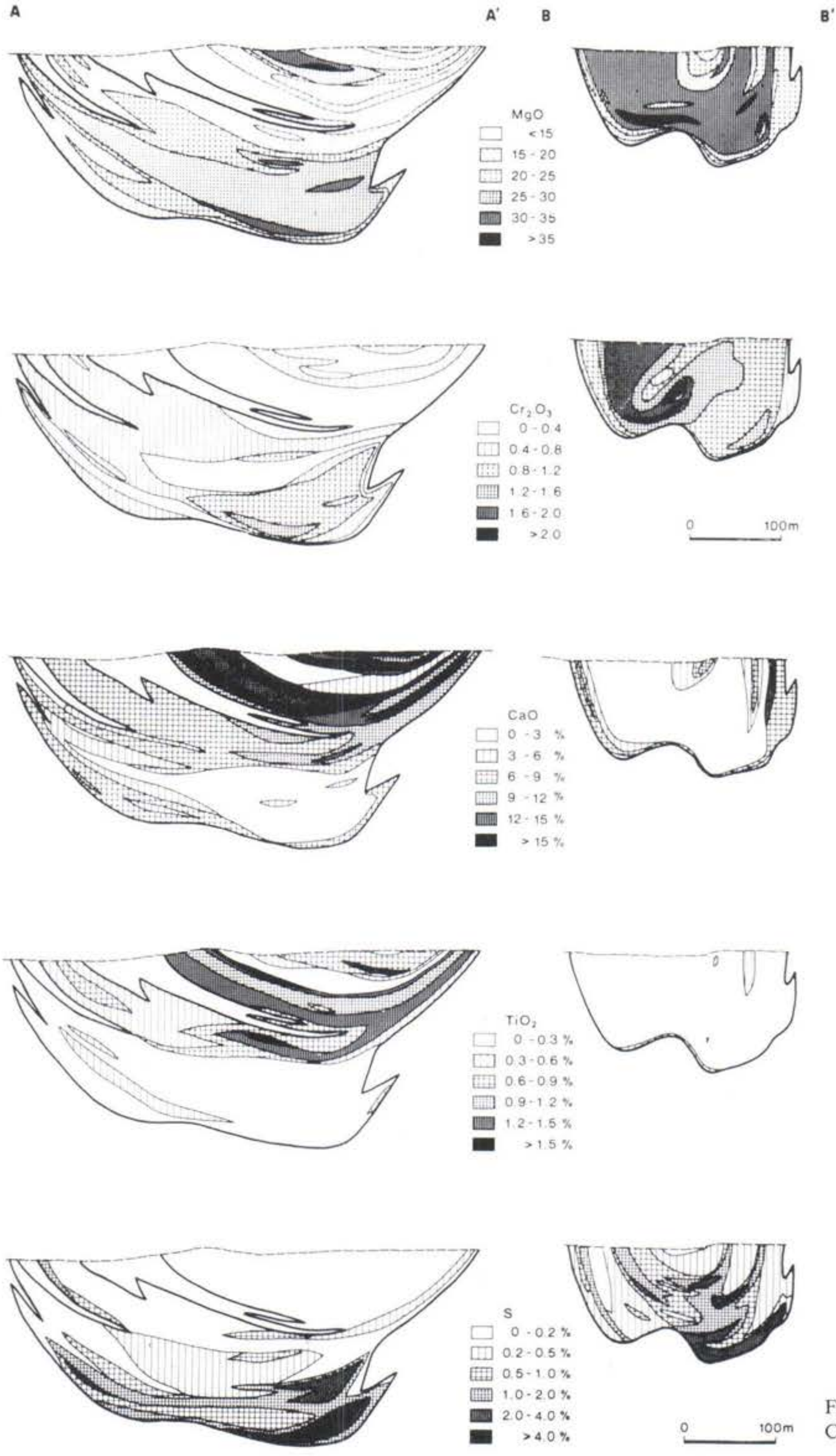


Fig. 67. Distribution of MgO, Cr_2O_3, CaO, TiO_2 and S in sections A and B.

CHEMISTRY

The ultramafics vary in composition from dunite to hornblendite. The mean compositions of the lithologic units of the Vammala ultramafic body are given in Table 41. The table also lists the compositions of some more silicic rocks that occur adjacent to the ultramafics and are presumably products of the reaction between the mafic magma and the argillaceous sediments.

The mean compositions of the ultramafic layers are listed in Table 42. The lowermost ultramafic layer has the highest magnesia values and is thus more ultramafic than the upper peridotite layer (Fig. 67). The values of Ni and Cr are also higher in the lower ultramafic layer than in the upper one, whereas the calcium values are markedly higher in the upper layer than in the lower one.

The variation in the main components is illustrated by the CaO-Al_2O_3-MgO and (Na_2 + K_2O)—Al_2O_3—MgO ternary diagrams (Figs. 68 and 69). The scatter in the plot towards the Al and alkali apexes can be largely attributed to the contamination of the margins of the ultramafics due to the migration of alkalies, calcium and aluminum from the country rock mica gneiss to the ultramafic body.

Table 42. Mean chemical compositions of the layers in the Vammala ultramafic intrusion.

	1	2	3
Number of samples	16	46	118
SiO_2	39.43	42.20	40.00
TiO_2	0.561	0.856	0.180
Al_2O_3	3.34	6.84	2.78
Cr_2O_3	0.492	0.401	0.97
FeO (tot)	13.75	12.09	13.58
MnO	0.173	0.153	0.158
MgO	23.50	16.67	27.25
CaO	7.18	10.20	2.93
Na_2O	0.194	0.920	0.153
K_2O	0.236	0.349	0.264
BaO	0.028	0.026	0.006
SrO	0.010	0.019	0.002
ZrO	0.004	0.007	0.001
P_2O_5	0.276	0.403	0.105
Ni	0.178	0.132	0.287
Cu	0.009	0.013	0.147
Zn	0.010	0.010	0.011
Pb	0.003	0.004	0.005
As	0.001	0.003	0.001
S	0.06	0.19	1.24
Cu (sulph)	0.009	0.013	0.142
Ni »	0.026	0.028	0.205
Co »	0.003	0.002	0.012
Zn »	0.004	0.004	0.006
Pb »	0.001	0.002	0.002
Fe »	0.15	0.36	1.64

1. Upper ultramafic layer, section A-A', 2. Hornblendite layer, section A-A', 3. Lower ultramafic layer, section A-A'.

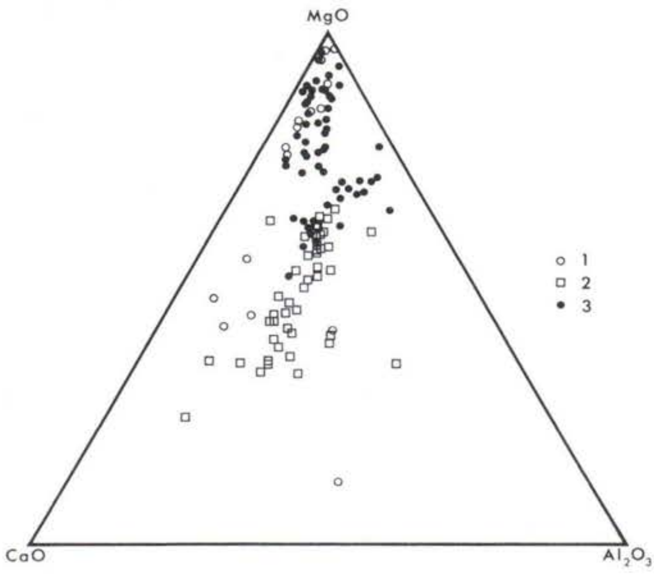


Fig. 68. MgO — CaO — Al_2O_3 diagram showing the composition of samples from the Vammala ultramafite. 1. Upper ultramafic layer; 2. Hornblendite layer; 3. Lower ultramafic layer.

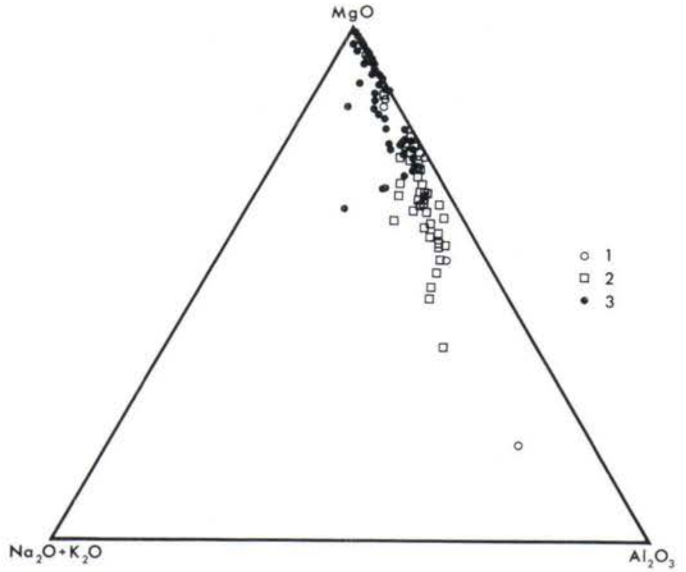


Fig. 69. MgO — (Na_2O + K_2O) — Al_2O_3 diagram. Symbols as in Figure 68.

Composition of olivine

The composition of olivine ranges from 85 per cent Fo to 49 per cent Fo and its nickel content from 600 ppm to 3,100 ppm, as shown in Fig. 70. The compositional variation in olivine is rather small in the lower ultramafic layer. The linear relationship between the Fo content and the Ni content of olivines in the hornblendite layer and the upper peridotite layer has been attributed by Häkli *et al.* (1979) to the oxidation of the sulphides immediately after the crystallization of the silicate magma, because this event did not allow nickel to redistribute between olivine and sulphide phase.

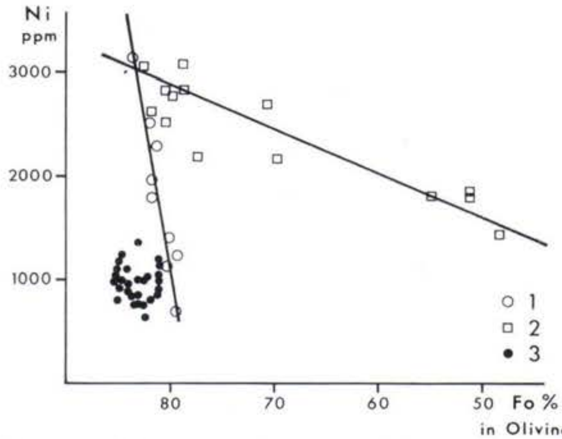


Fig. 70. Nickel versus Fo in olivine in the Vammala ultramafite. 1. Upper ultramafic layer; 2. Hornblendite layer; 3. Lower ultramafic layer.

Composition of the sulphide phase

The sulphide phase of the lower ultramafic layer averages 6.35 % Ni, 4.35 % Cu, 0.38 % Co, 50.57 % Fe and 38.35 % S. Only traces of platinum group elements are present. The nickel concentrate produced in 1980 averaged 0.34 ppm Pt, 0.25 ppm Pd and 0.02 ppm Rh.

The proportions of the three most important components of the sulphide phase, Ni, Cu and

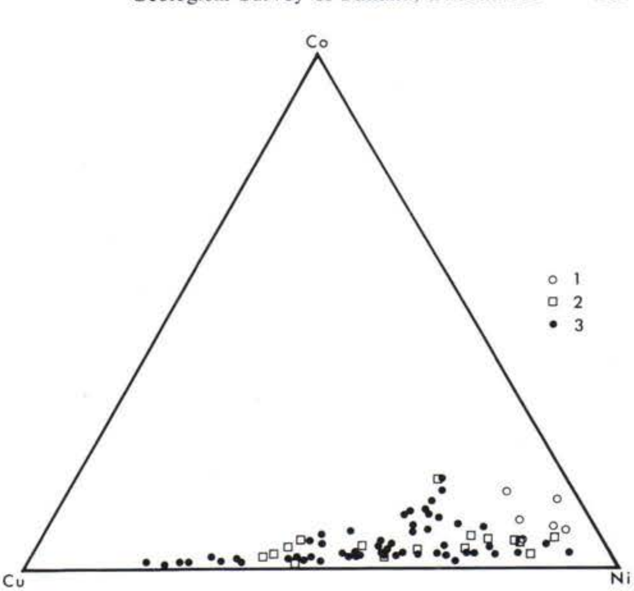


Fig. 71. Co — Cu — Ni diagram showing variation in composition of the sulphide phase in the Vammala deposit. 1. Upper ultramafic layer; 2. Hornblendite layer; 3. Lower ultramafic layer.

Co, vary considerably, as is shown by Fig. 71. At the base of the lower ultramafic layer, the Ni/Cu ratio is 4 but it decreases upward. In the lower portion of the hornblendite layer, the Ni/Cu ratio is 3, but over a distance of 30 m it decreases to 0.3, only to increase to 2 in the upper part of the layer. The Ni/Cu ratio is highest in the thickest part of the Sotka orebody.

Sulphur isotopes

The sulphide sulphur varies markedly in isotope composition. The $\delta^{34}S$ values of the lower ultramafic layer fluctuate around zero, averaging —0.79 per mil. In the hornblendite layer the average is +1.51 per mil (Table 43) and in the upper layer the $\delta^{34}S$ values are still higher, averaging +12.51 per mil. The corresponding values for the mica gneiss average —1.7 per mil.

The sulphur in the lower layer is very similar in composition to that in the other Finnish nickel deposits, which Papunen and Mäkelä (1980) hold as magmatic. The sulphur in the up-

Table 43. Sulphur isotope data of the Vammala ultramafic intrusion.

Layer	Number of samples	Average $\delta^{34}S$ (per mil)	Range $\delta^{34}S$ (per mil)
Upper ultramafic layer	7	+12.5	+5.37 — +19.48
Hornblendite layer	13	+ 1.51	—1.19 — + 2.65
Lower ultramafic layer	27	— 0.79	—2.19 — + 1.67
Wall rock mica gneiss and black schists	8	— 1.70	—4.2 — + 0.7

per layer is heavy and seems to derive from a different source, indicating that the upper layer consolidated under conditions that differed from those prevailing during the formation of the lower layer.

RADIOMETRIC DATING

Zircon and monazite fractions separated from a gabbroic pegmatite and a mafic pegmatite in the ultramafic body indicate an age of 1890 Ma for the ultramafics. The age is typical of synorogenic Svecokarelian plutonites and the same as that of the host rocks of the Kotalahti and Hitura nickel ores. It is also very close to the lead/lead age of 1 856 Ma measured from the Kylmäkoski chalcopyrite fraction.

GENESIS

Häkli *et al.* (1979) have suggested a genetic model for the Vammala nickel deposit. According to them emplacement of the ultramafic body started with the intrusion of the dunitic, sulphide-rich magma into water-bearing clay sediments, which resulted in the formation of peridotitic and hornblenditic variants at the margin of the flow.

The bulk of the magma consolidated as dunite. The sulphides carried as suspension sank to the base of the flow by gravitative differentiation. The sulphides that exsolved from the silicate magma as the temperature fell crystallized as higher horizons as low-grade dissemination. At subsolidus temperatures, nickel reequilibrated between the silicate and sulphide phases.

A succession of pyroxenitic flows discharged on top of the lower ultramafic layer. This magma was sulphide-saturated but did not contain sulphides in suspension. The pyroxenite flows obviously crystallized very close to or on top of the sediments, as is suggested by the agglomeratic structures and the intervening metasediments.

After the crystallization the pyroxenitic units were hydrometamorphosed into hornblendites.

The second set of ultramafic peridotitic flows, which was slightly less magnesium-rich than the first one, erupted on the hornblendite layer. Like the first peridotitic flow, the magma of the second flow was rich in sulphides. Meanwile, however, conditions has changed, and the sulphides were oxidized into magnetite.

ACKNOWLEDGEMENTS

We are indebted to the Outokumpu Company for permission to publish this study.

THE HYVELÄ NICKEL-COPPER OCCURRENCE

A. STENBERG and T. A. HÄKLI

The Hyvelä Ni-Cu sulphide occurrence is located in SW Finland in the WNW-trending Pori—Vammala—Kylmäkoski zone, some 6 km north of the town of Pori, close to the Vaasa highway. Apart from the Hyvelä deposit, several other Ni-Cu showings, such as Korkeakoski, Sahakoski, Harjunpää and Sääksjärvi, occur at the Pori end of the nickel zone. The Hyvelä deposit contains about 800,000 tonnes of drill-indicated ore averaging 0.26 % Cu and 0.52 % Ni.

GEOLOGICAL SET-UP

The Hyvelä area is part of the intensely metamorphosed Svecofennian migmatite belt. The supracrustal rocks of the area include mica gneisses, kinzigites, skarn rocks, graphite gneisses and amphibolites (Fig. 72). The mica gneisses, which are of the veined variety, often contain garnet. Rounded and elongated Ca silicate concretions are common. Amphibolite occurs as inclusions as do the somewhat less abundant gabbros and hornblendites.

In places the mica gneisses grade into kinzigites. Kinzigite, which is the wall rock of the Hyvelä norite, consists of two fairly strongly migmatised coarse layers and an intervening cordierite-predominant and more fine-grained layer. Sillimanite is occasionally encountered in the biotite-rich portions of the kinzigite.

The skarn rocks occur as thin interlayers in the kinzigite. They are diopside-predominant and usually contain pyrrhotite as a fine-grained dissemination.

The graphite gneisses are often met with as interlayers of varying thickness in the kinzigite. The carbon content of the graphite gneisses seldom exceeds 10 %. Pyrite and pyrrhotite are common constituents (the sulphur values often exceed 6 %).

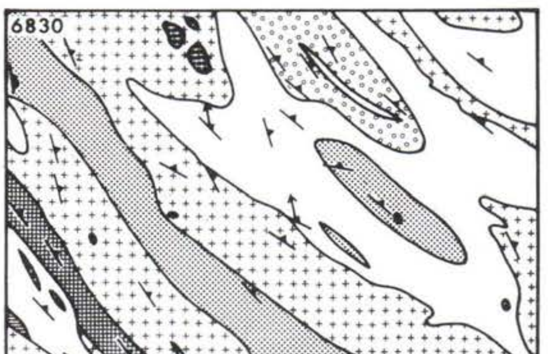


Fig. 72. Geology of the Hyvelä area. 1. Mica gneiss; 2. Kinzigite; 3. Quartz feldspar gneiss; 4. Amphibolite; 5. Trondhjemite gneiss; 6. Quartz diorite to granodiorite; 7. Gabbro; 8. Ore.

Around Hyvelä, the amphibolites occur as inclusions in mica gneiss. Larger amphibolite bodies are, however, also encountered both west of Hyvelä and farther east between Harjunpää and Harjunkangas. The majority of the amphibolites seem to be sedimentary in origin; the rare volcanic amphibolites occur east of the Hyvelä-Harjunpää zone.

The plutonites are mainly synorogenic quartz diorites that form parallel intrusion zones.

Extensive hornblende gabbro areas are encountered south of Hyvelä and north of it at Söörmarkku. Perknites, which occur north and east of Pori, are fairly coarse and intensely disintegrated rocks. The mafic rocks have a poor outcrop in the area; the small peridotite occurrence at Harjunpää is the only that has been studied in detail.

The rocks in the Hyvelä area trend WNW-ESE and dip 60°—80° NE. The fold axes trend predominantly NW with the plunge varying between 50° and 80°. The folding is usually isoclinical.

THE HYVELÄ NORITE INTRUSION

The Hyvelä norite intrusion, a slab-shaped body oriented parallel to the schistosity, has a length of about 400 m on the ground surface. The thickness of the slab varies from 20 to 100 m and its dip is 60° NE. In longitudinal section, the body shows a wavy footwall contact and a steep contact at the western end (Fig. 73). The slab extends to the +650 level at least. Its continuation at the western end has not been established.

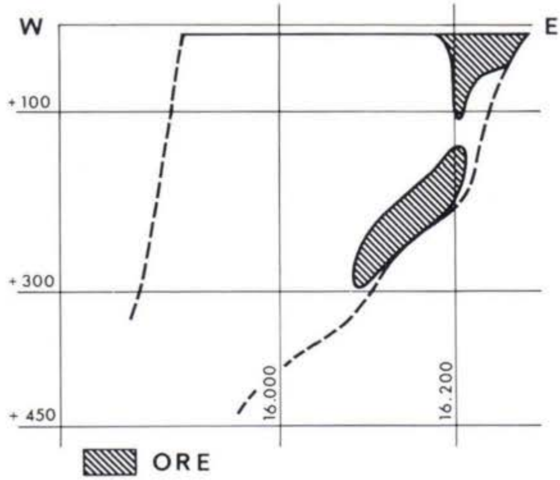


Fig. 73. Longitudinal section of the Hyvelä norite intrusion projected on a vertical plane.

The Hyvelä norite intrusion is tholeiitic in composition and mineralogy (Irvine and Baragar, 1971) (Fig. 74). It is composed mainly of norites and cummingtonite gabbros; olivine is absent. The main minerals are orthopyroxene (15—17 % Fe), poikilitic plagioclase (An 55—60 %), cummingtonite (13—14 % Fe) as an alteration product of orthopyroxene, pale brown hornblende and biotite.

In places, norite contains small perknite bodies with orthopyroxene, brownish hornblende and pale brown phlogopite as major minerals. The perknites are rare and usually occur as portions less than 2 m thick.

The norites grade through pyroxene-cummingtonite gabbros into cummingtonite gabbros with poikilitic plagioclase (An 45—50 %), cummingtonite and pale green hornblende as main minerals. The accessories are quartz, apatite, zircon and titanite. At the contacts the cummingtonite gabbros grade in places into cummingtonite gneisses.

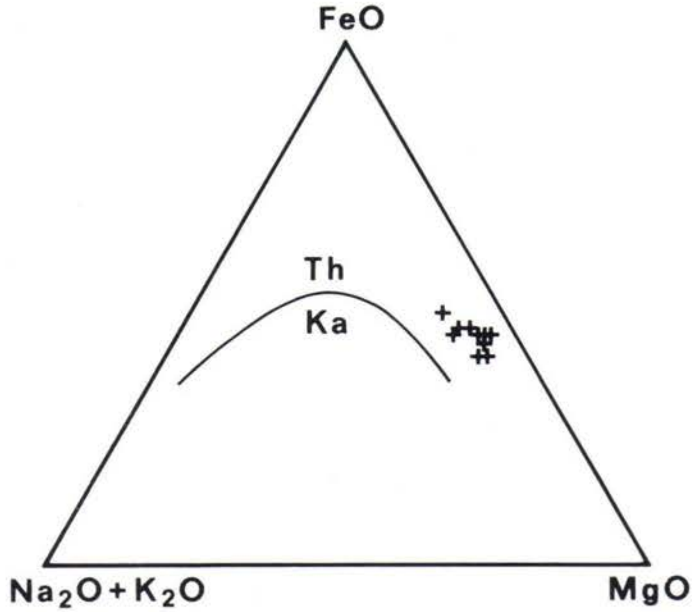


Fig. 74. Analytical data on drill hole P/Hy-14 plotted in an AFM ternary diagram. Th = tholeiitic, Ka = calc-alkaline.

Chemistry

The mean composition of the part of the Hyvelä intrusion intersected by drilling is given in Table 44 together with equivalent data on some other intrusions. In terms of its MgO and Al_2O_3 values, the Hyvelä intrusion lies between the Laukunkangas (Grundström, 1980) and Kotalahti (Papunen, 1970) intrusions, representing a rock between gabbro and pyroxenite in composition that crystallised from a tholeiitic magma. The high FeO values (total iron) at Hyvelä are attributed to the abundant sulphides; the sulphide iron is included in the FeO in Table 44. The similarity with the Laukunkangas intrusion is striking.

Table 44. Mean element values of some Finnish mafic intrusions.

	1	2	3	4	5
MnO	0.13	0.12	0.11	0.13	0.14
TiO_2	0.73	0.96	0.65	2.35	0.35
FeO	15.71	9.80	11.55	11.57	10.52
MgO	11.20	6.60	9.79	8.29	18.41
Al_2O_3	9.82	16.15	12.82	16.91	8.91
SiO_2	48.26	50.17	51.65	47.54	47.64
Na_2O	1.22	2.46	1.92	2.20	1.24
K_2O	1.08	0.73	0.85	0.27	0.65
CaO	4.19	8.18	5.93	9.39	5.57

1. Hyvelä, 2. Joutsenmäki-Tolvaniemi, 3. Laukunkangas, 4. Parikkala, 5. Kotalahti.

Differentiation

Shown in Figs. 75 and 76 are the mean compositions for some drill sections of the Hyvelä intrusion plotted in the ternary diagrams of Al_2O_3-MgO-CaO and Al_2O_3-MgO-(Na_2O + K_2O). The plots clearly demonstrate internal differentiation and that the proportion of mafic minerals increases from the outcrop up to section 15.950. The small deviations from the

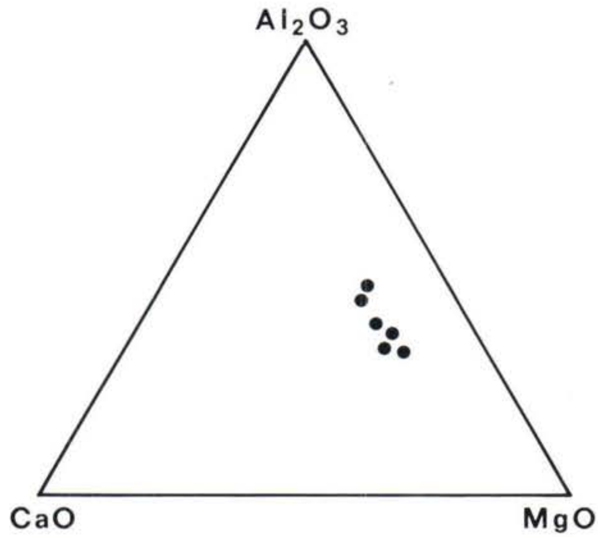


Fig. 75. The mean compositions of some drill sections plotted in a ternary CaO — Al_2O_3 — MgO diagram.

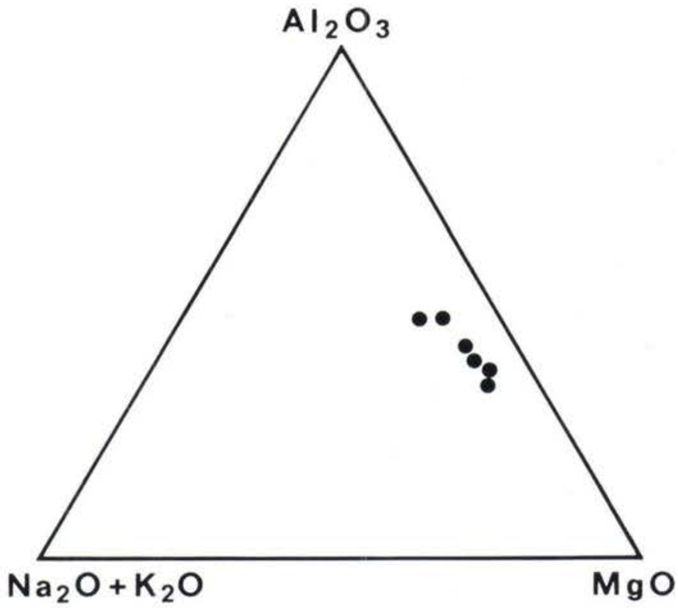


Fig. 76. The mean compositions of the same drill sections as in Fig. 75 plotted in a (Na_2O + K_2O) — Al_2O_3 — MgO diagram.

trend can largely be attributed to the variation in the sampling technique.

The Ni and Fe values of the mafic silicates seem to be fairly constant. The nickel content of the hornblende is 270 to 340 ppm and that of iron 6.9 to 7.9 %. The corresponding figures for the cummingtonite are 270 to 350 ppm Ni and 12.7 to 15.9 % Fe. The orthopyroxene assays 175 to 200 ppm Ni and 14 to 16.5 % Fe. These values are approximately equal to 3.5 % Ni in the sulphide phase. The pyroxenite is, however, an exception: its hornblende contains

Table 45. Au and PGE data on some drill intersections of the Hyvelä sulphide occurrence (ppm).

Drill hole	Intersection m	Au	Pt	Pd	Rh	Ir	Os	Ru
P/Hy-1	43.11— 44.75	0.40	< 0.025	0.13	0.020	< 0.025	< 0.025	< 0.025
P/Hy-1	63.70— 64.95	0.20	0.20	0.25	0.060	< 0.025	< 0.025	< 0.025
P/Hy-10	189.85—192.10	0.20	0.040	0.20	< 0.015	< 0.025	< 0.025	< 0.025
P/Hy-10	208.60—211.35	0.18	0.070	0.23	< 0.015	< 0.025	< 0.025	< 0.025

430 ppm Ni and 10.4 % Fe and its orthopyroxene 295 ppm Ni and 17.3 % Fe, indicating about 5 % Ni in sulphide phase.

The abundances of precious metals are low. The average Au and PGE values are shown in Table 45.

NICKEL-COPPER DEPOSIT

The Hyvelä Ni-Cu deposit is located at the eastern end of the intrusion and consists of a surface ore body and a deep-seated ore body. The surface ore body is truncated at the +100 level. The deep-seated ore body begins at the +150 level and extends to the +250 level. The sulphides are concentrated at the base of the intrusion. West of section 16.125 the sulphide accumulations are small and occur mainly at the contacts.

Composition of the sulphide phase

The sulphide phase averages 1.74 % Cu, 3.45 % Ni, 0.22 % Co and 57.6 % Fe. The nickel values are almost constant from one section to the other. In contrast, the Ni/Cu ratio changes in such a manner that it is 2.5 near the outcrop, but northwestwards it is reduced to 1.80 in section 15.950. The average ratio in the intrusion is 1.98.

Sulphide assemblages

The ore can be subdivided into disseminated ores and massive ores. The disseminated ores can be further subdivided into two subtypes: blebs in which the sulphides show well-developed boundaries against the silicates; and disseminations with breccia texture in which the sulphides are clearly younger than the enveloping silicates. As the sulphide abundance increases the dissemination grades into massive ores. Graphite is often encountered in association with the breccia ores.

The disseminated ores have pyrrhotite, pentlandite and chalcopyrite as their main minerals, and ilmenite, rutile, sphalerite, molybdenite and occasionally gersdorffite as accessories. The sulphide assemblages of the breccia and massive ores are very similar, the major minerals being pyrrhotite, pentlandite and chalcopyrite and the accessories sphalerite and gersdorffite. Adjacent to the pegmatite veins the sulphide assemblage has pyrrhotite and pentlandite as the main minerals and chalcopyrite as an accessory.

Composition of sulphides

Table 46. Electron microprobe data on pentlandites (in weight percents).

	1	2	3	4	5	6	7	8	9	10
Fe	30.51	29.47	29.93	30.45	30.72	29.33	32.65	29.27	31.22	35.2
Ni	34.19	34.65	34.14	34.07	33.90	34.71	32.91	34.78	35.51	30.9
Co	2.34	2.19	2.22	2.11	2.19	2.38	1.33	2.05	1.76	1.01
S	32.65	33.08	33.65	33.25	32.60	33.33	32.95	33.55	31.79	32.9
Total	99.68	99.39	99.94	99.87	99.41	99.75	99.84	99.65	100.28	100.1

1. Hy-1/44.70, 2. Hy-2/71.40, 3. Hy-10/197.15, 4. Hy-13/226.20, 5. Hy-26/311.80, 6. Ek/La-16/39.00 Laukunkangas, 7. Kylmäkoski, 8. Vammala, 9. Kotalahti, 10. Hitura.

The composition of pentlandite is fairly constant (Table 46). The mineral contains somewhat over 2 % Co and is rich in iron, the Fe/Ni ratio averaging 1.034, i.e. clearly higher than that of the pentlandites in Laukunkangas (Grundström, 1980), Vammala (Häkli *et al.*, 1979) and Kotalahti (Papunen, 1970). The difference is probably due to the rather high copper values in the sulphide phase at Hyvelä (Ni/Cu = 1.98). In places pyrite occurs as secondary accumulations. With its nickel content up to 1.7 % Ni and its low cobalt content, the mineral resembles the Ni-rich pyrites at Telkkälä (Häkli *et al.*, 1975) (Table 47).

Table 47. Electron microprobe data on pyrite from drill hole HY-2/68.45, Hyvelä (in weight percents).

S	52.53	53.05	52.57
Fe	44.98	45.26	45.92
Co	0.09	0.02	0.00
Ni	1.72	1.54	0.68
Sum	99.31	99.86	99.17

The nickel values of pyrrhotite vary considerably (0.15 to 0.67 % Ni) with an average of 0.4 % Ni (Table 48).

Table 48. Ni values of pyrrhotite from Hyvelä. Electron microprobe data.

Drill hole/Depth	%
P/Hy-1/44.70	0.36
P/Hy-1/58.05	0.49
P/Hy-2/71.40	0.45
P/Hy-10/190.30	0.52
P/Hy-10/197.15	0.38
P/Hy-10/199.35	0.40
P/Hy-13/202.10	0.43
P/Hy-13/226.30	0.53
P/Hy-17/88.70	0.39
P/Hy-17/149.80	0.16
P/Hy-17/240.05	0.67
P/Hy-26/311.80	0.54

GENESIS OF THE NICKEL ORE

The sulphur isotope determinations on the ore, ten in all, give an average of +0.3 per mil for $\delta^{34}S$, the range being from —0.6 to +1.0 per mil, suggesting that the sulphur in the Hyvelä deposit is magmatic in origin. Considering the gabbroic composition of the magma and the fairly high abundance of sulphides, it seems likely that a considerable proportion of the sulphides were transported as an immiscible liquid in the silicate magma during emplacement and that, when gravitatively settling, they produced heavy dissemination and massive ores. Some sulphides segregated during the crystallisation of the silicate melt, resulting in the formation of a fine-grained and weak sulphide dissemination. Later some portions of the ore were deformed and remobilised.

ACKNOWLEDGEMENTS

We thank the Outokumpu Company for permission to publish this study. We also thank Mrs. Kirsti Hämäläinen for microprobe analyses.

THE PETOLAHTI NICKEL-COPPER OCCURRENCE

P. SIPILÄ, P. ERVAMAA and H. PAPUNEN

The diabase-type of Ni-Cu occurrence at Petolahti is located in South Bothnia, some 35 km south of the town of Vaasa. The exhausted Korsnäs Pb mine is about 6 km west of it.

Impulse was given to the studies at Petolahti by a Ni-Cu-bearing sample sent by a local amateur prospector. In 1957—1959 the Geological Survey of Finland undertook systematic geological and geophysical mapping in the area. As a result, 17 holes were drilled at the target. The occurrence was found to contain slightly less than 100,000 tonnes of drill-indicated ore, averaging 0.70 % Cu, 0.65 % Ni and 0.02 % Co.

In 1969 Outokumpu Oy drilled five additional holes to delineate the richest portion of the ore. In 1972—1973 the company mined 85,700 tonnes of ore. The Petolahti occurrence was the subject of the study by P. Ervamaa (1962), and the following geological description is largely based on that work. For the present study fresh samples were taken for analysis from the occurrence, and the chapter on geochemistry is based on them.

GEOLOGY OF THE ENVIRONMENT

The bedrock of the area is part of the South Bothnia Svecokarelian schist zone that envelopes the Vaasa—Pietarsaari granite body west of the extensive Central Finland granite massif

(Nykänen 1960). The Petolahti Ni-Cu occurrence with its immediate environment is covered by heavy overburden. Drilling data, geophysical survey and the nearest exposures indicate that the regional bedrock is of uniform mica gneiss. In many places, Petolahti included, the mica gneiss is migmatitic. The granite and pegmatite veins are up to several metres wide. Graphite-rich interlayers are common in mica gneiss, although narrow interlayers of pyroxene gneiss and hornblende gneiss are encountered as well. The mica gneiss is intensely altered at the contact with the diabase. The predominant trend of schistosity of the mica gneiss at Petolahti is N O—35°W. The dip varies between 10° and 40°E or NE. The fold axes strike east-west over large areas and plunge 40°—70°E.

The diabase cuts the mica gneiss sharply and is thus the youngest rock. The Postjotnian olivine diabases in the Vaasa archipelago and Satakunta are about 1200 Ma old. The Petolahti diabase has not been dated but it is probably older than the Postjotnian diabases and related with the Häme diabase swarm. (Laitakari 1969).

DIABASE DYKE

Shape

The Petolahti Ni-Cu ore deposit is located in the ESE extremity of a lens -shaped diabase dyke (Fig. 77). The diabase dyke strikes N 56 W and dips 80° SSW; it is 600—700 m long and 5—70 m wide. At the ore the diabase is 5—10 m wide. The diabase lens narrows downwards, giving the whole intrusion of the shape of a cone. It may be a remnant of the basal part of a larger intrusion.

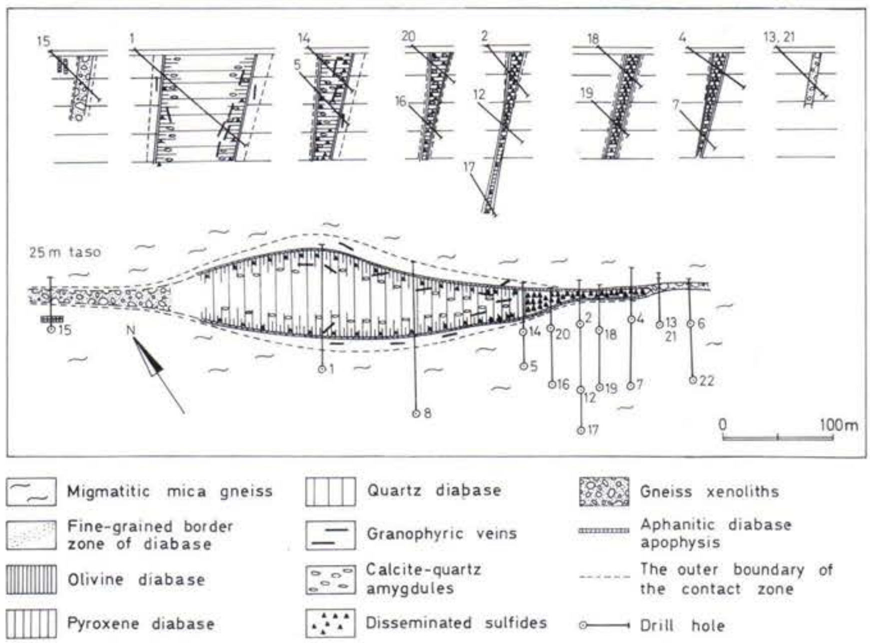


Fig. 77. The 25 m plan and sections of the Petolahti diabase.

Types of diabase

The Petolahti diabase is zonal in composition and lithological distribution, and heterogeneous in mineral composition and grain size. Apart from the fine-grained marginal zone, it exhibits a differentiation series from sulphide-bearing olivine diabase through pyroxene diabase to quartz diabase. Fine-grained and narrow diabase apophyses are encountered in the wall rock.

Quartz diabase

The core of the diabase lens is a medium-grained quartz diabase with a uniform abundance of a few percentages of quartz. The bulk of the diabase is of this type. The major minerals in the quartz diabase are plagioclase and diopsidic augite; quartz, potassium feldspar, albite, calcite, biotite, ilmenite and magnetite are less common. The accessories are apatite and titanite. The minerals seldom show secondary alteration.

The unoriented plagioclase laths, 1—5 mm long, give a distinctly ophitic texture to the rock. The grains are zonal in composition with An_{60-65} in the cores and An_{30-40} at the margins. Slight resorption is common. The augite is xenomorphic and distinctly smaller in grain size than is the plagioclase; the augite is also poor in iron.

Quartz, potassium feldspar and albite occur as a granophyric intergrowth between the plagioclase and the augite. The intergrowth represents the last event in the rock-forming process.

The quartz diabase contains very few sulphides. Ilmenite and ilmenomagnetite account for 4—8 % of the whole mineral composition of the rock. Oxides occur as a homogeneous dissemination.

The quartz diabase has only few carbonate-rich veins filling the fractures. In addition to the carbonate, which is pure calcite, the veins contain small amounts of quartz and chlorite.

The quartz diabase shows no signs of deformation other than the carbonate veins. Autometamorphic alterations of the minerals are also rare, and in this respect the quartz diabase clearly differs from the more mafic marginal and terminal portions of the dyke.

Pyroxene diabase

Towards its margins the core of the diabase lens grades into a more fine-grained variant, and serpentine spots appear that, as suggested by relict textures, are pseudomorphs after orthopyroxene and olivine. At the same time the abundance of the granophyric alkali feldspar-quartz intergrowth diminishes, and the diabase grades into a variant of more mafic composition. The abundance of oxides also decreases whereas that of sulphides increases; the composition and shape of the minerals change as well. The pyroxene diabase zone is 4—8 m wide.

The main minerals are plagioclase and diopsidic augite. The plagioclase occurs as sharp-edged laths, 1—2 mm in length, surrounded by poikilitic augite grains. The cores of the plagioclase grains are An_{60-65} and the margins An_{45-55} in composition. Hence the overall composition shows An values slightly above those of the quartz diabase. The augite is richer in Mg.

The mafic minerals of the pyroxene diabase are often intensely altered. The diopsidic augite is almost completely altered into pale green talc; olivine and orthopyroxene are altered into serpentine. Calcite, which occurs in ovoidal amygdules 1—20 mm in size, is a fairly common constituent, in places exceeding 15 % in abundance. In addition to calcite, the amygdules contain quartz and small amounts of serpentine, pyrrhotite, chalcopyrite, pentlandite and pyrite.

Sulphide-bearing olivine diabase

The olivine-rich zone with disseminated sulphides lies between the pyroxene diabase and the fine-grained marginal zone. The zone is at its narrowest, 0.5—1.0 m, at the spot where the diabase lens is at its widest. The olivine-rich zone widens towards the SE end of the lens, and the abundance of sulphides increases while the internal zones of the diabase lens pinch off. At the site of the highest grade ore the olivine diabase is 4—9 m wide.

The olivine diabase is a fine-grained rock, with plagioclase, diopsidic augite and olivine as major silicates. Intensely serpentinized orthopyroxene occurs in places. The abundance of sulphides reaches 40 %, whereas that of oxides is a mere 3 %. The accessories are biotite, calcite, alkali feldspars, quartz, spinel and apatite. Specks of serpentine, talc and chlorite are also met with.

Plagioclase occurs as distinctly zonal unoriented laths, 0.2—2 mm long, with a core of An_{60-70} and margins of An_{45-55}. The An value of the plagioclase is thus slightly higher than that of the diabase variants described above.

The predominant mafic mineral is either olivine or diopsidic augite. Olivine occurs as roundish grains measuring 1—4 mm in diameter and with a composition of Fa_{20-30}. The poikilitic augite grains have plagioclase laths as inclusions. The augite is poor in iron.

The abundance of Mg-rich orthopyroxene is invariably less than 10 % of the mineral composition of the whole rock.

Autohydration in the sulphide-bearing olivine diabase was clearly less intense than in the pyroxene diabase. The orthopyroxene and olivine are, however, almost completely altered into serpentine, whereas the diopsidic augite has remained intact.

Fine-grained marginal zone of the diabase, and aphanitic apophyses

The fine-grained marginal zone varies from a few centimetres to a metre in width. The thin extremites of the diabase lens are composed solely of this lithologic type.

Embedded in the fine-grained groundmass of plagioclase and diopside are scattered plagioclase laths 1—2 mm long (An_{60}) and orthopyroxene and olivine phenocrysts altered into serpentine. Biotite, quartz, potassium feldspar, albite, ilmenomagnetite and ilmenite are rare constituents; sulphides are almost completely lacking.

The drop-shaped quartz grains, resorbed plagioclase laths and locally abundant graphite at the tips of the diabase lens are relics on intensely assimilated wall rock inclusions. The abundance of quartz and plagioclase occasionally reaches 20—40 %.

Very fine-grained diabase porphyrites up to 15 cm wide have penetrated the mica gneiss. The apophyses barely reacted at all with the wall rock and do not show any differentiation. In chemical composition they probably correspond to the primary composition of the magma.

Granophyre veins

Close to the contact, the diabase exhibits scattered pale granophyre veins that are usually a few millimetres wide.

The major minerals are albite (An_5), quartz, chlorite and calcite. Albite and quartz, and in places chlorite, show granophyric intergrowth textures. The calcite grains are larger than the others. Pyrrhotite, chalcopyrite, pyrite and pentlandite are encountered occasionally. Apatite is an ubiquitous accessory. Diabase is intensely altered when close to these veins.

Granophyre veins are also encountered in the mica gneiss close to the contact with the diabase. The potassium feldspar in these veins is the predominant alkali feldspar; otherwise they are similar to the veins in the diabase.

The mode of occurrence and composition of the granophyre veins suggest that they crystallized from the last silicic residual melt, which, as far as the veins in mica gneiss are concerned, probably resulted from the partial melting of the wall rock.

Wall rock altered by contact metamorphism

Adjacent to the diabase dyke the wall rock was altered by the action of contact metamorphism. The alteration is most intense at the widest part of the diabase lens, where the alteration zone exceeds 10 metres in width. The zone narrows towards the end of the lens, being 3.5—2.5 m wide at the ore.

The structure of the mica gneiss is preserved in the outermost parts of the alteration zone, where plagioclase is altered into sericite, and biotite is partly chloritized. The alteration gradually increases in intensity towards the contact and is manifested by the intergrowth of alkali feldspars, quartz and chlorite, which occur as veins in the rock and rim quartz and sericited oligoclase grains. The alteration halo contains small amounts of sulphides in the contact with the diabase. The predominant sulphides are chalcopyrite, pyrrhotite, pyrite, pentlandite and violarite.

ORE IN DIABASE

Shape of the ore body

The Petolahti Ni-Cu ore body is located in the ultramafic portion of the south-east end of the diabase lens. At the 25 level the sulphide occurrence is 5—10 m wide and almost 100 m long. Downwards the orebody narrows in accordance with the shape of the diabase lens and entends no deeper than 70 m. Weak sulphide dissemination is also encountered in the olivine-bearing margins of the diabase and in a narrow zone in the wall rock close to the contact.

Ore minerals and ore types

The main sulphides are pyrrhotite, chalcopyrite and pentlandite. The accessories are spahalerite and galena, with violarite and primary pyrite only in the wall rock.

Ilmenomagnetite and ilmenite occur as uniform dissemination in the diabase. Magnetite is disseminated or then it occurs as a secondary mineral in associated with the sulphides.

There are three ore types in the Petolahti occurrence: 1) disseminated sulphides in olivine diabase, 2) sulphide veins in olivine diabase, 3) sulphide dissemination in wall rock.

Sulphide dissemination in olivine diabase

The most important ore type is the disseminated sulphides in olivine diabase. They occur between the silicates as interstitial blebs 0.2—4 mm in diameter. All three of the most common sulphides are encountered regularly in the blebs. Pyrrhotite is almost always enveloped by pentlandite and chalcopyrite. In places the sulphides occur as rounded nests, 4—10 mm in diameter, showing a zonal arrangement.

The disseminated sulphides in the olivine diabase are characterized by abundant exsolution textures. The pyrrhotite has chalcopyrite lamellae along the prismatic, pyramidal and basal planes, and pentlandite »flames» along the basal plane. Pentlandite also occurs in the extremities and along the borders of the pyrrhotite. Chalcopyrite contains cubanite and pentlandite exsolution bodies and a very fine-grained intergrowth of pyrrhotite-chalcopyrite-pentlandite-magnetite. Pentlandite contains exsolved pyrrhotite and chalcopyrite.

The exsolution textures suggest that the sulphides crystallized at high temperature, and pyrrhotite, chalcopyrite and pentlandite were primarily in solid solution. The exsolution bodies formed when the temperature dropped. Owing to the subsurficial conditions, the magma cooled rapidly and the volatiles did not reduce the crystallization temperature of the magma. The rapid cooling resulted in the formation of abundant exsolution textures (Ervamaa 1962).

Sulphide veins in olivine diabase

The olivine diabase is cut by sulphide veins 1—10 mm wide that crystallized from the residual portion of the sulphide melt enriched in copper, nickel and volatiles.

The sulphide veins contain relatively less pyrrhotite than do the disseminated sulphides. The pyrrhotite generally occurs as a fine-grained mosaic together with chalcopyrite and pentlandite, but it may form larger and slightly deformed grains. The pentlandite is often cataclastic.

The sulphides of the sulphide veins are almost totally free from exsolution textures. Only the largest chalcopyrite grains contain cubanite lamellae with associated pyrrhotite portions.

The veins have small amount of secondary pyrite, galena and native silver. The abundance of magnetite may reach 5 %. The microscopic textures suggest that magnetite crystallized before the sulphides.

Disseminated sulphides in wall rock

Close to the contact with diabase the mica gneiss exhibits a zone of weak sulphide dissemination a few tens of centimetres wide. Instead of the mineral assemblage of pyrrhotite-pentlandite-chalcopyrite encountered in the diabase, the mica gneiss has the assemblage of pyrite-violarite-chalcopyrite. Other minerals are pyrrhotite, pentlandite and small amounts of sphalerite. The sulphides occur partly as a fine dissemination in a granophyric intergrowth of feldspars, quartz and chlorite, and partly as larger blebs. The grains do not show zonality.

Chalcopyrite is the predominant ore mineral in the wall rock sulphide dissemination. Chalcopyrite occurs as large grains and as microveins at and along the margins of pyrrhotite, pyrite, pentlandite and violarite. The sulphides have very few exsolution bodies; oxides are lacking in the wall rock with disseminated sulphides.

The sulphides in the mica gneiss were obviously formed by volatiles escaping from the diabase magma simultaneously with the alteration of the gneiss. The scarcity of exsolution textures suggests that the sulphides crystallized at a relatively low temperature.

GEOCHEMISTRY OF THE DIABASE

Table 49 lists some mean chemical compositions of the Petolahti rocks. The rocks were analyzed by XRF and AAS methods at the Geological Laboratory of Outokumpu Oy. The samples were taken systemically from drill cores. The sampling interval in the middle of the diabase dyke was 10 m and in the heterogeneous margin and sulphide-bearing portion 1—3 m.

It is typical of the Petolahti diabase that the MgO content decreases rapidly as differentiation progresses. The Si, Ti, Ca, Na, K and P values increase steadily at the same time. In composition, the fine-grained marginal zone corresponds to the pyroxene diabase.

The ternary diagrams in Fig. 78 demonstrate that, except for a gap between the pyroxene diabase and quartz diabase, the differentiation series is continuous. The quartz diabase is presumably a hybrid that was formed when the diabase magma assimilated the mica gneiss fragments caught up with it. In the wide middle portion of the diabase lens, the assimilation continued until it was completed. At the narrow ends, where the magma cooled rapidly, there are still relics of mica gneiss fragments. In the ternary diagram, the fine-grained marginal zone and the pyroxene diabase plot within the same area. The fine-grained marginal zone represents the primary composition of the magma, according to which the magma was tholeiitic.

The mica gneiss does not exhibit a clear systematic change in composition outwards from its contact with the diabase. Adjacent to the diabase there is a sulphide bearing black schist that differs from the mica gneiss in composition. The mica gneiss is intensely migmatized; hence, the samples cannot be compared with one another.

The quartz diabase does not exhibit variation in composition. Towards the margins of the diabase, SiO_2, CaO and the alkalies decrease and MgO, S, Mg/Si, Mg/(Na + K) and K/Na increase. The maxima and minima are at the sulphide-bearing olivine diabase.

Table 49. Mean chemical compositions of the Petolahti rocks.

Number of analyses	1.	2.	3.	4.	5.
	14	10	7	12	5
SiO_2	41.42	45.81	50.00	46.19	62.88
TiO_2	0.55	0.64	0.85	0.76	0.45
Al_2O_3	11.93	14.98	15.53	15.60	16.54
Cr_2O_3	0.23	0.15	0.04	0.13	0.05
FeO*	16.08	11.05	11.16	9.91	5.15
MnO	0.19	0.16	0.20	0.17	0.07
MgO	18.80	12.95	6.76	12.14	3.92
CaO	5.82	7.84	9.24	8.71	1.88
SrO	0.01	0.03	0.02	0.03	0.02
BaO	0.02	0.03	0.04	0.02	0.08
Na_2O	1.23	1.73	2.35	1.83	3.54
K_2O	0.39	0.64	0.83	0.50	4.51
P_2O_5	0.06	0.08	0.12	0.10	0.12
ZrO_2	0.01	0.01	0.01	0.01	0.02
S	2.29	0.62	0.09	0.22	0.24
	98.63	97.72	97.24	96.32	99.47
Cu	4290	1329	116	474	24
Ni	4702	1231	16	404	27
Zn	67	70	51	78	121
Pb	14	7	7	5	18
Co	141	45	5	27	3
As	17	20	18	17	45

* Total Fe calculated to FeO; Cu, Ni, Zn, Pb, Co and As in ppm, other elements in weight percents.

1. Sulphide-bearing olivine diabase, 2. Pyroxene diabase, 3. Quartz diabase, 4. Fine-grained marginal zone, 5. Mica gneiss (not the mineralized portion at contact).

Fig. 79 shows a histogram illustrating the variation in the values of the above elements at the narrow sulphide-bearing SE end of the diabase lens (drill hole 12) where the diabase body is about 6 m wide. The silicic differentiates are lacking and the diabase is composed of fine-grained marginal zones interrupted by a sulphide-bearing olivine diabase. Owing to the narrowness of the dyke, the marginal zones are rather wide.

The Postjotnian olivine diabases in Satakunta and in the Vaasa archipelago differ from the Petolahti diabase mainly in their lower MgO

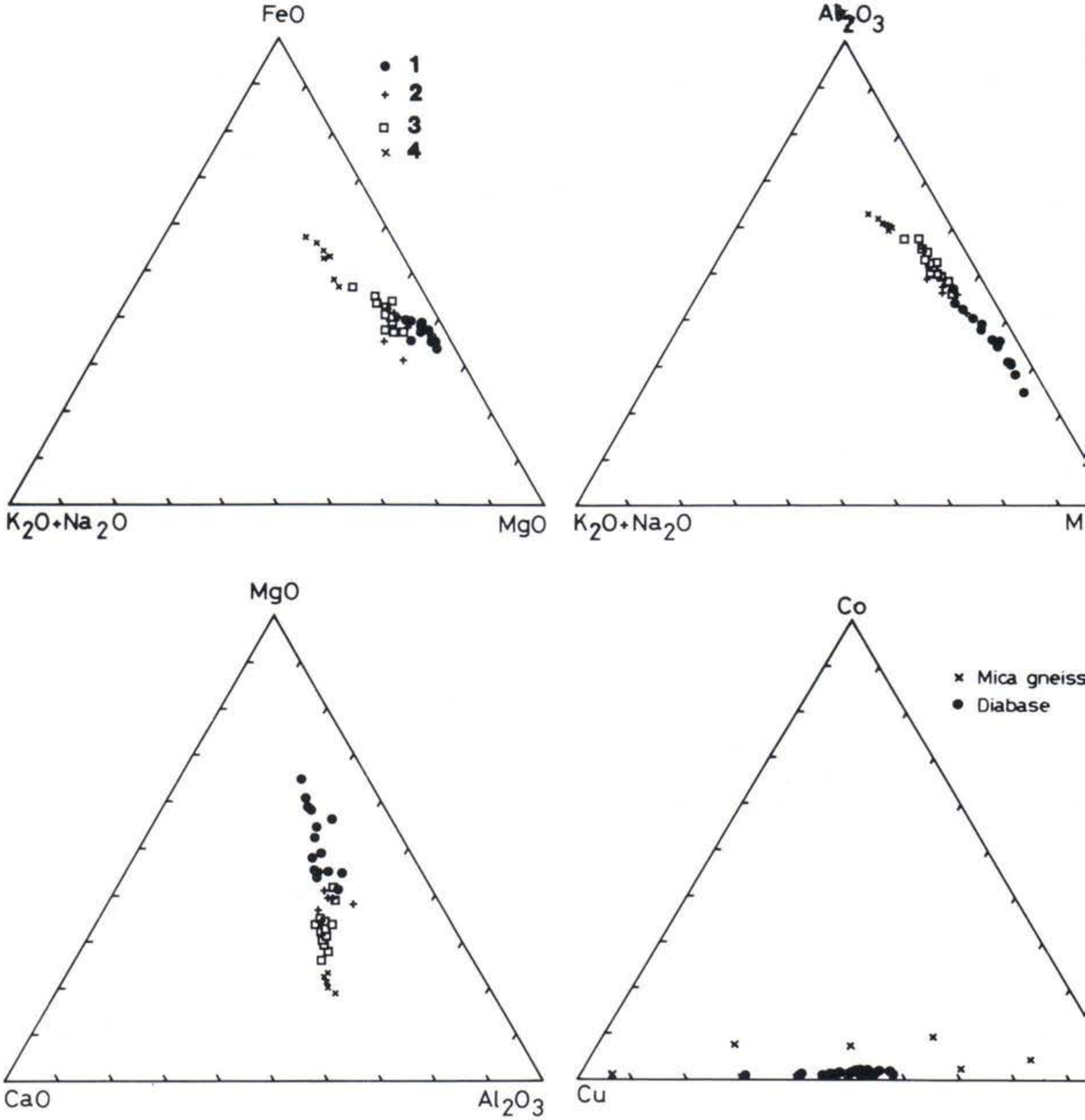


Fig. 78. Ternary diagrams of the Petolahti rocks: 1. Sulphide-bearing olivine diabase; 2. Pyroxene diabase; 3. Fine-grained border zone of diabase; 4. Quartz diabase.

values and higher alkali values. According to Ervamaa (1962), an olivine diabase in the Vaasa archipelago (Kobberget, Korsnäs) assays 7.59 % MgO, and 3.37 % $Na_2O + K_2O$. According to Kahma (1951), the Satakunta olivine diabase has 5.90 % MgO and 3.76 % $Na_2O + K_2O$

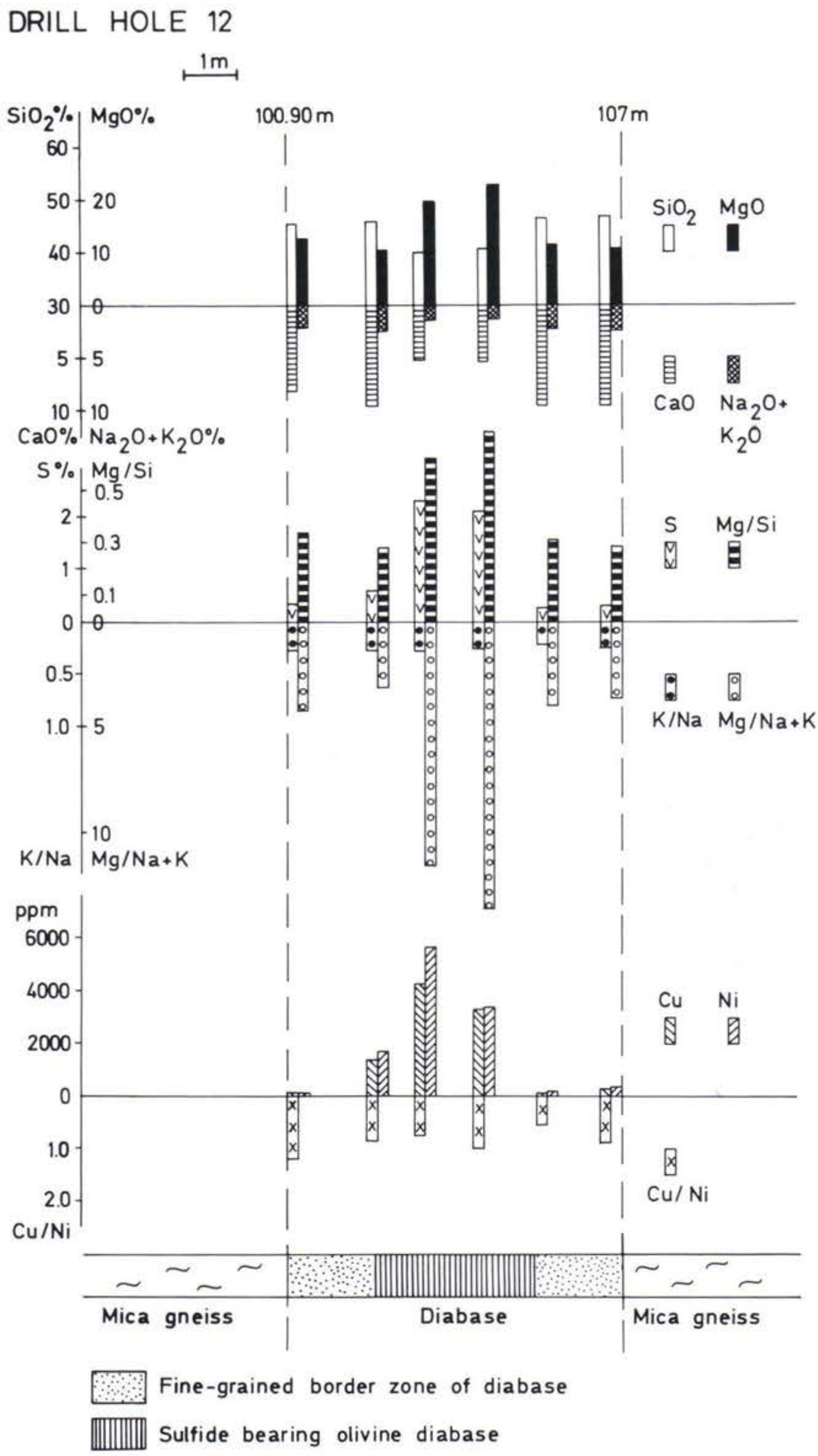


Fig. 79 Variation in chemical composition in a profile across the Petolahti diabase dyke.

(average of five analysis). The corresponding values for the marginal zone of the Petolahti diabase are 12.14 % MgO and 2.33 % Na_2O + K_2O, and for the sulphide-bearing olivine diabase 18.80 % MgO and 1.62 % Na_2O + K_2O.

GEOCHEMISTRY OF THE SULPHIDE OCCURRENCE

Incorporated in sulphides, the Petolahti olivine diabase averages 0.47 % Ni, 0.43 % Cu, 0.01 % Co and 2.29 % S. According to Ervamaa (1962), the most heavily mineralized sulphide portion assays 0.65 % Ni, 0.70 % Cu, 0.02 % Co and 3.27 % S (drill hole 4). On the basis of the latter values, the sulphide phase contains 47.4 % Fe, 7.4 % Ni, 8.0 % Cu, 0.2 % Co and 37 % S (Ervamaa, 1962). Table 50 lists the mean Ni, Cu, Co, Zn and Pb values of the sulphide phases of the Petolahti rocks.

Table 50. The mean Ni, Cu, Co, Zn and Pb values of the sulphide phases of the Petolahti rocks recalculated to 100 % sulphides (37.5 % S).

Rock type	Ni	Cu	Co	Zn	Pb
Sulphide-bearing olivine diabase	7.70	7.03	0.23	0.01	0.02
Pyroxene diabase	7.45	8.04	0.27	0.42	0.04
Quartz diabase	0.66	4.83	0.21	2.13	0.29
Vein of massive sulphides	27.41	5.21	0.78	0.06	0.04
Fine-grained marginal zone	6.89	8.08	0.46	1.33	0.09
Mica gneiss with disseminated sulphides at the contact with the diabase	4.61	4.02	0.13	1.07	0.02

The Ni/Cu ratio for the sulphide-bearing olivine diabase is nearly constant, i.e. 1.1. The Ni/Cu ratio is 0.9 for the pyroxene diabase and 0.1 for the quartz diabase. The fine-grained marginal zone has the same ratio as the pyroxene diabase. The Ni/Co ratio is high for the olivine diabase, i.e. 33. For the pyroxene diabase it is 27, for the quartz diabase 3 and for the fine-grained marginal zone 15. Compared with the other Ni-Cu occurrences in the Finnish ultramafic and mafic rocks (Papunen *et al.,* 1979), the Ni/Co ratio for the Petolahti occurrence is anomalously high and the Ni/Cu ratio below average. The Ni/Cu and Ni/Co ratios vary considerably in the sulphide-bearing contact zone of the mica gneiss, the Ni/Cu ratio averaging 1.1 and Ni/Co 35.

CONCLUSIONS

The Petolahti diabase dyke cuts the enveloping mica gneiss sharply. The diabase does not show any deformation structures. It was emplaced in its present position after the Svecokarelidic orogeny, but it has not been dated. It is chemically different from the Postjotnian olivine diabases in Satakunta and the Vaasa archipelago mainly in that it has higher magnesium and lower alkali values. It evidently belongs to the set of Subjotnian Häme diabases described by Laitakari (1969).

During the emplacement, wall rock fragments were caught up by the diabase magma. The magma cooled rapidly at the narrow ends and along the margins of the diabase lens and so the wall rock relics survived. In contrast, assimilation continued until completed in the middle of the diabase lens. The assimilation is shown in the differentiation diagram as a gap between the quartz diabase and pyroxene diabase. After the crystallization of the margins and the narrow extremites of the dyke, the crystallization of the magma in the middle of the dyke began with the formation of the olivine diabase.

The sulphides, which now occur as dissemination in the olivine diabase, segregated at the same time. The progress in differentiation resulted in the formation of the pyroxene diabase zone, and finally, of the quartz diabase. The sulphide veins in the olivine diabase crystallized from the residual sulphide melt. The last volatiles of the magma gave rise to intense autohydration, which was restricted mainly to the pyroxene diabase zone.

The disseminated sulphides in the olivine diabase have abundant exsolution textures. These indicate that the sulphides crystallized as solid solutions at high temperature and a fairly low water vapour pressure, and that they were exsolved when the temperature dropped.

Amygdules filled with carbonate and quartz suggest that the diabase crystallized near the surface under conditions not so different from those of the volcanic rocks. Lindquist and Laitakari (1980) have described similar amygdules from diabase in the Orivesi area.

The magma gave rise to contact metamorphic alterations in the wall rock. The alteration zone is up to 10 m wide. Metasomatic alterations are minimal and are restricted to the very contact itself. Thermometamorphic alterations, however, are most distinct. The source of the quartz-alkali feldspar granophyre between the quartz and plagioclase grains was probably in the molten mica gneiss.

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NICKEL-COPPER DEPOSITS IN SWEDEN

G. NILSSON

INTRODUCTION

Sweden is per capita a very great nickel consumer through its steel industry, accounting for about 4 % of the nickel consumption of the whole world. According to the Swedish Minerals Policy Committee gross consumption in 1975 was 28,500 tonnes of nickel. The total nickel production from Swedish mines is insignificant. In 1845—1945 only about 4,000 tonnes of metallic nickel were produced. Nearly half of this came from Kleva, Kuså, Slättberg and some other very small deposits in southern Sweden. The bulk of the rest being from Lainijaur mine in the northern part of the country. The Lainijaur deposit has been described by Grip (1961) in a publication that includes short descriptions of the other deposits as well. Most of the older nickel deposits have been described in Swedish by Tegengren (1924). Recently a nickel sulphide bearing, layered mafic intrusion at Notträsk in northern Sweden has been documented by Arvanitidis (1982).

NICKEL SULPHIDE DEPOSITS OF MAFIC ASSOCIATION

Nickel-copper deposits of Proterozoic age and of mafic association are known from about 30 places in different parts of Sweden (Fig. 1, Table 1). Most of them are situated in small gabbroid bodies or dolerite dykes intruded in the Svecokarelian orogenic belt (1800—c. 2000 Ma); only a few have ultramafics among the host rocks. Their nickel tonnage tends to be small or very small. The median value of Cu/(Ni + Cu) is 0.44 for deposits in southern and northern Sweden. The corresponding value for the nickel content in 100 % sulphides is 2.5 % Ni for both parts of the country.

The youngest of the Swedish nickel sulphide occurrences of mafic association is probably the very small dolerite dyke with a contact ore at Lun(n)dörren (Vogt 1887) within the Middle Allochthon of the Caledonides (Gee 1978). It is one in a suite of dykes dominated by tholeiites exhibiting pronounced ocean-floor affinities. The geochemistry and tectonic setting, however, indicate that the intrusions are connected with a period of moderately deep mantle melting, probably during the initial stages of the opening of the pre-Caledonian Iapetus Ocean (Solyom *et al.* 1978). Age determinations of these dykes have given a Rb/Sr isochron of 735 ± 260 Ma (Claesson 1976). The Cu/(Ni + Cu) ratio is about 0.54 in analysed hand specimens from the Lundörren deposit.

Table 1. Data on Swedish nickel deposits. Deposit numbers refer to the appended map.

No.	Deposit name	Type of intrusion	Metric tons		Grade		
			Nickel	Copper	% Ni	% Co	% Cu
201	Furuberget	Differentiated sill	170	90	0.3	0.03	0.16
202	Kukasjärvi	Ultramafic sill	10,400	9,800	0.4	0.02	0.4
203	Fiskelträsk	Gabbroid border zone of granodiorite pluton	11,000	11,000	0.2	0.02	0.2
205	Östra Skogträsk	Gabbroid border zone of granodiorite pluton	300	240	0.44	(0.03)	0.34
207	Notträsk	Layered intrusion, funnel-shaped			0.2—0.5 1.0	0.02—0.08 0.11	0.13/ /0.4
209	Storbodsund	Horizontal, tabular, mafic pluton	1,400	1,000	2.3	0.09	0.6
210	Lainijaur	Mafic dyke	4,100	2,800	2.2	0.13	1.0
211	Älgliden	Differentiated multiple dyke	26,000	90,000	0.20	0.03	0.69
213	Bastutjärn	Layered intrusion	4,800	3,600	0.16		0.12
214	Risliden A	Ultramafic sill	700	200	0.69	0.05	0.17
	C	»	1,300	200	0.70	0.05	0.11
	D	»	1,900	1,100	0.73	0.03	0.41
216	Lappvattnet	Ultramafic lenses and fragmental ore in paragneiss	11,000	2,300	1.0	0.02	0.21
217	Mjövattnet	Ultramafic lenses and fragmental ore in paragneiss	3,000	450	1.4	0.015	0.21
219	Vallen A	Ultramafic sill			0.4	0.015	0.09
	B	Ultramafic sill (?)			0.55	0.02	0.18
220	Brännorna A	Ultramafic sill	1,900	150	0.63	<0.01	0.05
	B	»	300	55	0.62	0.03	0.11
224	Rörmyrberget	Differentiated multiple sill	26,000	2,500	0.4— 1.0	0.01— 0.03	0.03— 0.09
225	Gårkälen	Ultramafic sill	140	60	0.40	0.04	0.18
227	Kälen	Ultramafic sill	290	190	0.41	0.04	0.27
231	Förnätra	Mafic dyke	125	225	0.5	0.06	0.9
232	Lun(n)dörren	Dolerite dyke			0.44	0.02	0.51
233	Slättberg	Dolerite dyke	4,000	3,500	0.6— 0.7	0.07	0.5— 0.6
234	Kuså	Differentiated mafic stock	(85)	(90)	0.93	(0.08)	1.02
235	Ekedal	Mafic stock			0.70	0.10	0.12
238	Gaddbo	Mafic stock			0.66	0.03	0.26
239	Frustuna	Dolerite dyke	(300)	(400)	0.3	0.04	0.4
240	Ruda	Mafic stock (?)	(600)	(400)	0.36	0.014	0.26
241	Lillsjön	Dolerite dyke			1.43	0.11	0.63
245	Risebo	Dolerite dyke			1.1	0.04	0.38
246	Kleva	Elongate, mafic pluton	1200	500	1.9	0.2	0.8
247	Virserum	Layered intrusion			0.75	0.10	0.55

% S	Cu / Ni + Cu	Co / Ni + Co	Pt / Pt + Pd	% Ni_S	References
5.8	0.35	0.08		c. 2	Boliden Mineral
8.0	0.49	0.055		c. 2	— » —
3.2	0.50	0.11		2.4	Frietsch 1980, p. 11
9.3	0.44	(0.08)		1.8	Grip 1961, p. 67
3.2—3.8	0.21—0.34	0.07—0.14	0.45—0.5	2.9—5.1	Arvanitidis 1982
30	0.3	0.1	c. 0.44	1.2	
21.0	0.42	0.04		c. 4.2	Grip 1961, p. 68; Grip and Frietsch 1973, p. 177
23.0	0.30—0.40	0.055—0.105		c. 3.6	Grip 1961
6.15	0.78	0.13		1.2	Grip and Frietsch 1973, p. 258; Statens Industriverk 1979:9, p. 97
7.2	0.43			0.8	Boliden Mineral
7.9	0.20	0.60		3.3	
6.6	0.14	0.06		4.0	
4.9	0.36	0.60	0.60	5.7	
4.4	0.17	0.02	c. 0.75	8.9	
5.1	0.13	0.01		10.2	
2.1	0.18	0.036		7.2	
2.5	0.25	0.03		8.2	Boulders
1.05	0.08	—		21.2	
3.8	0.15	0.04		6.2	
0.7—4.8	0.05—0.14	0.02—0.04	(0.33—0.46)	7.8—33.0	
3.9	0.31	0.09		3.9	
3.6	0.40	0.09		4.3	
18.0	0.64	0.12		1.1	Lundbohm 1899, pp. 43—44; Tegengren m fl 1924, p. 119; Grip 1961, p. 69
4.6	0.54	0.04		3.6	Blomberg and Lindström 1879, pp. 15—17; Vogt 1887, pp. 16—17; Tegengren m fl 1924, pp. 132—133
18.0—27.5	0.47	c. 0.09		1.0—1.3	Löfstrand 1903, pp. 107—115, Tegengren m fl 1924, pp. 203—204; Magnusson 1973, pp. 164—166; Åhman 1974, pp. 77—84
13.0	0.52	0.08		2.6	Löfstrand 1903, pp. 115—118; Geijer 1917, pp. 58—69 Tegengren m fl 1924, pp. 201—202; Hjelmqvist 1948, pp. 55—58; Grip 1961, p. 71
11.7	0.15	0.12		2.3	Löfstrand 1903, pp. 119—121; Tegengren m fl 1924, p. 295; Grip 1961, p. 73
15.2	0.28	0.04		1.7	Löfstrand 1903, pp. 121—122; Tegengren m fl 1924, p. 295; Grip 1961, p. 73
6.6	0.57	0.12		1.8	Tegengren m fl 1924, p. 310; Grip 1961, p. 73; Stålhös 1975, pp. 95—96
3.0	0.42	0.04		4.5	Landström 1887; Sorg 1919; Tegengren m fl 1924, pp. 326—327; Grip 1961, p. 73; Wikström 1983, pp. 53—54, 83
22.5	0.31	0.07		2.4	Wikström 1983, pp. 75, 83
7.1	0.26	0.04		5.9	Asklund 1928, pp. 37—38
26.2	0.30	0.09		2.8	Brögger and Vogt 1887; Santesson 1887; von Post 1887; Tegengren m fl 1924, pp. 349—353; Grip 1961, pp. 71—73
18.8	0.42	0.12		1.5	Tegengren m fl 1924, p. 344

Kleva

Kleva Mine had the largest mined nickel tonnage of the deposits in southern Sweden (Brögger and Vogt 1887; Santesson 1887, von Post 1887). It was discovered back in 1691 and was periodically mined for copper until nickel was proven in 1838. Twenty-five years later the mine started to produce nickel and according to official statistics 54,380 tonnes of ore containing 1,027 tonnes of nickel were mined.

The mine is located in the east and centre of an E-W striking elongate massif of gabbronorite, quartz gabbro and quartz diorite. The intrusion is about 6.5 km long and up to 2.5 km wide. Rocks in the environment consist of synorogenic granites, metasediments, felsic and mafic metavolcanic rocks, and paragneisses. The MgO content of the gabbroid massif varies from 5 % to 13 % (anhydrous); near the ores it is about 6 %.

The age of the gabbroid intrusion has not been established. Wilson and Sundin (1979) report a K-Ar age of 1585 Ma based on a single determination by Polkanov and Gerling in the 1950s, but they point out that the value must be regarded with extreme caution. Geological observations indicate that the intrusion may be somewhat older than the synorogenic Svecokarelian granites in that part of Sweden, i.e. older than 1800 Ma, possibly about 1850 Ma.

Massive sulphides and breccia ore constituted at least two zones of faulted, irregular pipe and stocklike bodies surrounded by disseminated sulphides in the gabbronorite. The mined ore averaged about 1.9 % Ni. According to J.H.L. Vogt (1923), the metal contents recalculated to 100 % sulphide phase were about 2.6 % Ni and 1.5 % Cu, which gives a Cu/(Ni + Cu) ratio of 0.35. Recent analyses on samples from outcrops and dumps give 2.8 % Ni, 1.2 % Cu and 0.3 % Co in the sulphide phase and a Cu/(Ni + Cu) ratio of 0.30. Disseminated sulphides usually have higher Cu/(Ni + Cu) ratios than do the massive sulphides.

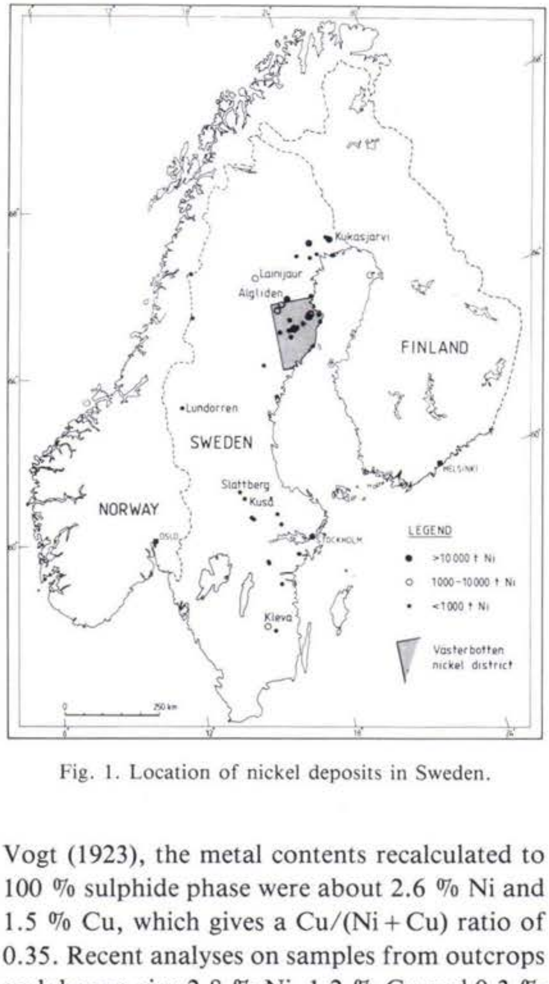


Fig. 1. Location of nickel deposits in Sweden.

Kuså

This deposit is situated in central Sweden and, like Kleva, was originally mined for copper. Ore production started in 1805 and the existence of nickel was probably proven in about 1817. The production for nickel smelting started in 1850, after which mining operations were carried out periodically until the small mine was exhausted in 1941. The total output has been about 9,000 tonnes of ore containing 1—2 % Ni. According to Grip (1961), 3,500 tonnes of ore containing 0.93 % Ni, 1.02 % Cu and 13.0 % S were mined by Boliden Mineral during 1940—41.

The mined ore was located in the margin of a small, differentiated intrusive composed of gabbroid and hornblenditic rocks intruded into a Svecokarelian synkinematic granite massif (Löfstrand 1903, Geijer 1917, Grip 1961). The MgO content in the host rocks is about 14—19 %. The age of the intrusive is still uncertain, but it is probably somewhat lower than that of the Kleva gabbro. Nickel and copper sulphides constitute disseminations in rock that is mainly mela-pyroxene-hornblende gabbronorite and also contains some olivine-pyroxene hornblendite. Cracks filled with sulphide occur in the granite along the contact against the hornblendites. Disseminated sulphides are usually uniformly distributed in the ore and may constitute up to 50 vol-%. The nickel content in 100 % sulphides has been calculated to be about 2.6 % and the Cu/(Ni + Cu) ratio is 0.52. The ore has been reported to contain traces of platinum.

Lainijaur

Ni-Cu deposits associated with Proterozoic gabbroid intrusions and of about the same age as Kleva are also known in several places in northern Sweden. Although the Lainijaur deposit no longer has the largest proven Ni tonnage among them, it is still the best known because of mining operations carried out by Boliden Mineral in 1941—45. According to Grip (1961), production during that period was 100,526 tonnes of ore averaging 2.20 % Ni, 0.93 % Cu and 0.1 % Co. The deposit is located in about the same stratigraphical position as most of the base metal deposit in the Skellefte field (Fig. 3), i.e. in a transition zone between folded metasediments and metavolcanic rocks. The host rock is a NE-SW striking dyke of gabbronorite which cuts the base of a syncline and extends upwards as several »wing-shaped» sills, forming a phacolith-shaped body on the top. In the latter, quartz gabbro and quartz diorite overlie the gabbronorite without any sharp contacts. A few analyses of gabbroid boulders from dumps show 5—17 % MgO (anhydrous). The gabbronorite contains some olivine, and Grip reports an optically determined composition of Fo_{76} for the olivine from the phacolith.

The ore types are: low-grade Ni-Cu dissemination in gabbronorite, massive contact ore and nickel arsenide veins. The contact ore is at the base of the phacolith, on both sides of the dyke. The nickel arsenide veins have been found mainly in metasediments immediately below the contact ore. Disseminated sulphides in the gabbronorite commonly contain 0.1—0.4 % Ni, or recalculated to 100 % sulphides, about 3 % Ni. The ratios Cu/(Ni + Cu) and Co/(Ni + Co) are about 0.5 and 0.09, respectively. Massive sulphides have the same nickel content in the sulphide phase but are poorer in copper and cobalt in relation to nickel. The Cu/(Ni + Cu) ratio is about 0.1 whereas Co/(Ni + Co) is 0.01. According to the analyses reported by Grip, the corresponding ratios for the mined ore were about 0.3 and 0.06. A recalculation of the ore tonnage of the deposit taking into consideration diamond drilling carried out by Boliden Mineral during the 1970s has given a somewhat higher ratio of 0.4 for Cu/(Ni + Cu) and 0.1 for Co/(Ni + Co). In any case the ratios are similar to those of the Kleva deposit.

Slättberg

Another type of Ni-Cu deposit is Slättberg in central Sweden (Löfstrand 1903). Nickel was proven there in 1817 and mining operations were carried out periodically from 1851 to 1943.

The total output to date has been at least 20,000 tonnes of Ni-Cu ore, but the mine is still far from exhausted.

The host rock of this deposit is a WSW-ENE striking gabbroid dyke, at least 1,600 m long and 3—6 m thick, in a Svecokarelian synkinematic granite massif. The MgO content in the metamorphosed gabbroid rocks analysed is 5—10 % MgO (anhydrous). The age of the dyke is not known. Aeromagnetic measurements suggest a relationship with a massif of Svecokarelian late-kinematic gabbroid rocks situated farther northeast, but this has not yet been verified by geological observations.

Massive sulphides occur mainly in a 1.2—4.5 m thick zone in the central part of the dyke, but locally also at the contacts. Disseminated sulphides are common in the host rock. Fine-grained pyrite is very common in addition to pyrrhotite, chalcopyrite and pentlandite, especially near the contacts of the massive sulphides. According to official reports, the mined ore assayed 1—2 % Ni. Recent analyses of samples from outcrops and dumps give an average of 0.7 % Ni, 0.6 % Cu, 0.07 % Co and 27.5 % S. Recalculated to 100 % sulphides, the nickel content is very low, being only 1.0 %. The Cu/(Ni + Cu) and Co/(Ni + Co) ratios are 0.47 and 0.09, respectively.

Älgliden

Älgliden, a prospect in northern Sweden belonging to Boliden Mineral has the largest nickel tonnage of mafic-associated deposits (Grip and Frietsch 1973). It is a dyke at least 3500 m long and up to 100 m wide within a massif of synkinematic granodiorite. The dyke is composed of gabbroid and subordinate ultramafic rocks, which have been interpreted as formed by several magmatic injections. Disseminated sulphides are fairly uniformly distributed in the rocks. Together with some massive sulphides in the central part of the dyke they form a low-grade copper-nickel ore containing about 90,000 tonnes of copper and 26,000 tonnes of nickel. The average percentage of nickel is only about 0.2 %. Recalculated to 100 % sulphides, it is 1.2 %. The Cu/(Ni + Cu) ratio for the whole deposit is 0.78, one of the highest values for Swedish nickel sulphide deposits.

NICKEL DEPOSITS OF ULTRAMAFIC ASSOCIATION

Nickel sulphide deposits with economic potential and of types previously unknown in Sweden have been located in recent years in the Proterozoic bedrock of Västerbotten county, northern Sweden. The great majority of them belong to a homogeneous group of deposits associated with ultramafic rocks in a metasedimentary environment. They are similar in character to the Svecokarelian nickel-copper deposits of central and southern Finland (Papunen *et al.* 1979) and evidently belong to the same metallogenic province.

In other parts of Sweden, nickel deposits of Proterozoic age associated with ultramafics are known in only a few places. The largest and northernmost of them is a sill-like, metamorphosed ultramafic intrusive in partly graphite and sulphide-bearing Karelian metasediments at Kukasjärvi (Frietsch 1980). It was discovered by Boliden Mineral during the 1970s.

The host rock of this deposit is similar to those of some deposits in the Västerbotten nickel district, but the composition of the sulphides differs. The ore is of a low-grade, disseminated type and has at least 10,000 tonnes contained nickel. The average nickel content is about 0.4 %. Recalculated to 100 % sulphides, the nickel content is much lower than in the Västerbotten deposits, being only about 2 % as against an average of 10 % in the latter. On the other hand, the Cu/(Ni + Cu) ratio is higher, i.e. 0.49 as against 0.21. Thus the composition of the sulphides indicates a similarity to gabbroid deposits in the environment. Therefore the Kukasjärvi deposit is believed to be a cumulate from a gabbroid melt.

Potential sources of nickel together with cobalt, gold, silver, and PGE (platinum group elements) are some bodies of low-alumina peridotite and detrital serpentinite (mainly conglomerates) in the Upper Allochthon of the Caledonides (Du Rietz 1935, 1956; Stigh 1979, 1981; Gee and Zachrisson 1979). These rocks usually contain 0.2—0.3 % Ni (total) and during serpentinization, mineral assemblages containing heazlewoodite and awaruite, for example, have been formed (Filippidis and Annesten 1980). Concentration experiments have given good results and concentrates containing about 45 % Ni have been obtained. At present the deposits known are subeconomic. However, their reserves of nickel and other metals is very large, and it is presumed that they will be of economic interest in the future.

The aim of this paper is to give a general survey of the nickel district of Västerbotten county, with an outline of the ultramafic rocks and descriptions of two recently discovered small nickel-copper deposits, Lappvattnet and Brännorna.

Regional geology of Västerbotten county (B. Lundberg)

The bedrock of the area, which comprises most of the Precambrian rocks of Sweden and Finland, is commonly attributed to the Svecokarelidic orogeny, from 2500 to 1800 Ma. The nickel-copper deposits occur in the northern part of a large sedimentary basin that comprises central Norrland and continues in central Finland (Fig. 2). This basin is dominated by greywackes and pelitic sediments that are generally strongly metamorphosed, migmatized and intruded by granitoid rocks. Basaltic volcanics (pillow lavas, tuffs etc.) occur infrequently, mainly along the border zone of the basin. The well-defined northern boundary of the basin extends in a northwesterly direction through the Skellefte district. The southern boundary is less well defined, partly because metamorphism has obliterated the primary features of the rocks. The main trend of the boundary, however, seems to be northwesterly, i.e. parallel to the northern boundary. In the west, the basin is restricted by the unconformably overlying sedimentary rocks of the Caledonian Front and the nappes of the Caledonian orogeny.

Intense folding and migmatization preclude the establishment of any stratigraphy within the basin. Along the northern boundary, however, in the rather well-preserved Skellefte district, there are some important features that aid interpretation of the geology farther south. The Skellefte field represents a transition zone between a continental domain in the north and a marine domain in the south (Lundberg, 1980). Volcanism of predominantly rhyolitic to dacitic composition has thus given rise to extensive pyroclastic deposits and lava domes in the

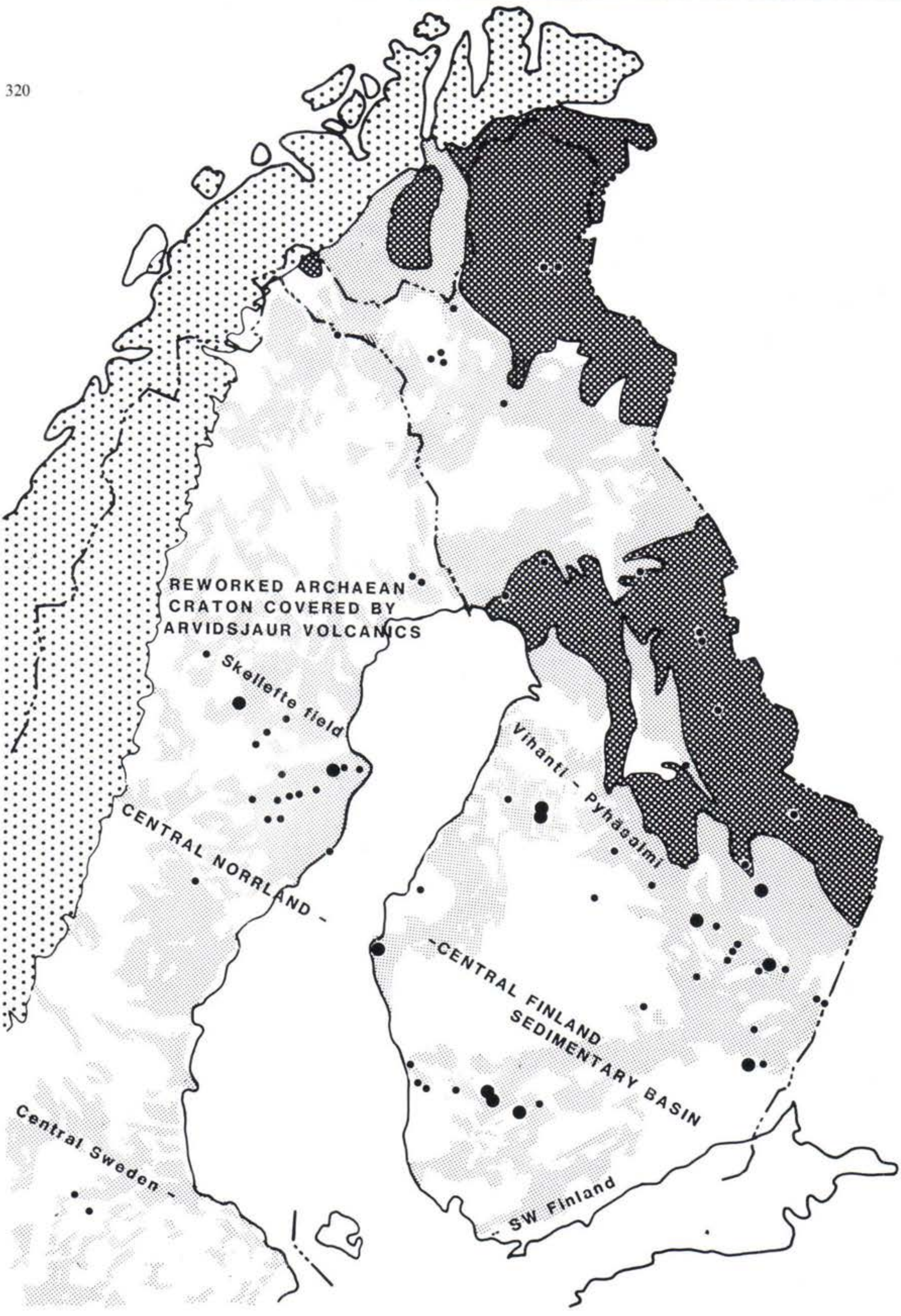


Fig. 2. Nickel-copper occurrences in central part of the Baltic Shield; 1. Caledonides; 2. Svecokarelian plutonic rocks; 3. Svecokarelian supracrustal rocks; 4. Archaean terrain.

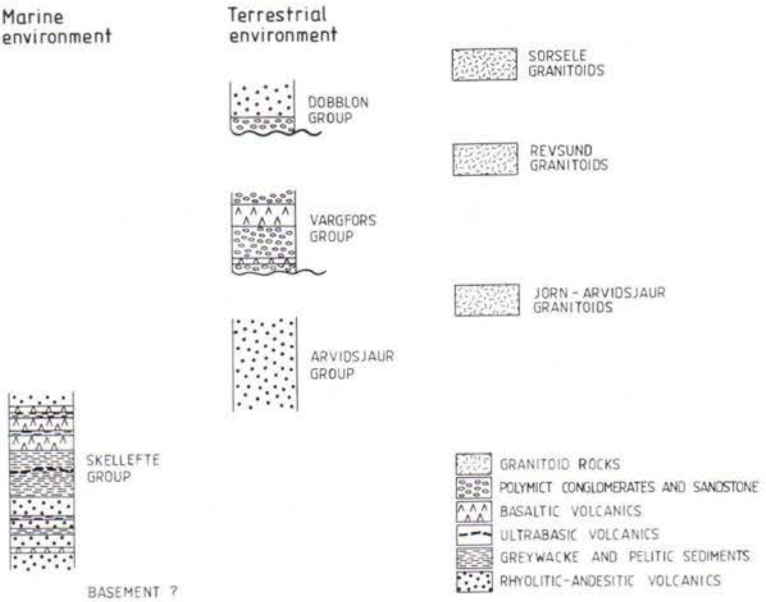


Fig. 3. Synoptic stratigraphic scheme of the Skellefte field.

marine environment and terrestrial lava flows and tuffs on the continental side. Massive sulphide deposits containing mainly pyrite, chalcopyrite and sphalerite occur within the marine volcanics and in the associated volcanoclastic sediments. Greywackes and pelitic sediments are intercalated in the marine acid volcanics to some extent. Mainly, however, they constitute an overlying formation in which basaltic volcanics (lava flows, pillow lavas, tuffs) are often present and sometimes even dominate the epiclastic sediments.

The terrestrial volcanics (Arvidsjaur Group), which are partly contemporaneous with the marine deposits (Skellefte Group) tend to overlie the marine deposits conformably whenever the relationship be established. The stratrigraphy of the area after Lundberg (1980) is presented in Figure 3.

According to Lars-Åke Claesson (pers. comm.), the acid intermediate volcanics and associated intercalations of basalts belong chemically to the calc-alkalic magma series. The basaltic volcanics occurring stratigraphically higher up and being associated with greywacke sed-

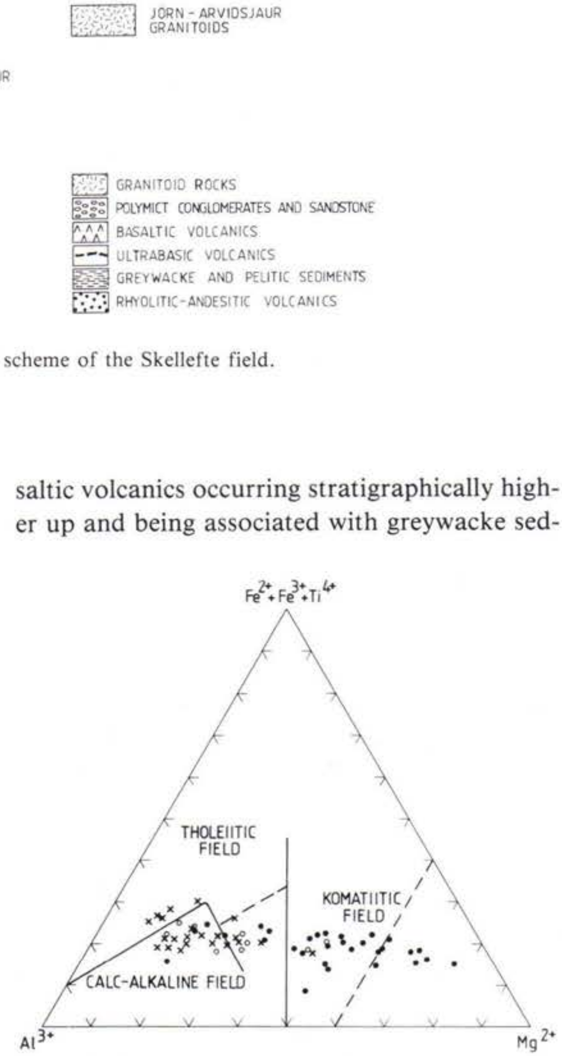


Fig. 4. Major marine and terrestrial volcanic rocks of the Skellefte field showing an apparently comagmatic trend in a Jensen cation diagram (prepared by L.-Å. Claesson 1980). *Skellefte Group:* ● Marine basalts associated with greywacke sediments. ○ Marine basalts associated with felsic volcanic rocks. *Arvidsjaur Group:* X Terrestrial basalts and andesites.

iments have a chemical composition which, when plotted on a Jensen cation diagram, reveal a marked komatiitic trend (Fig. 4).

Various authors have attempted a plate tectonic interpretation for the area, involving the subduction of a southern plate beneath a northern continental plate, accompanied by calc-alkalic volcanism and intrusive activity at the continental margin (Hietanen 1975). The character of the basement for the volcanic rocks is unknown, although certain outcrops of gneissose granitoids are suspected of being part of the underlying continental crust.

The greywackes of central Västerbotten can be correlated indisputably with the sedimentary units of the Skellefte Group (Fig. 3). They are probably also more or less contemporaneous with the acid-intermediate volcanics that, according to the model given above, were restricted to a zone at the continental margin.

Owing to the scarcity of radiometric datings, the ages of the rocks under consideration are somewhat uncertain. The only relevant figure is a zircon dating of the Jörn granitoids by Aftalion *et al.* (1982) giving an age of 1891^{+7}_{-6} Ma; these granitoids intrude the calc-alkalic volcanics but are thought to be close in age to and even comagmatic with the latter.

Conglomerates and basaltic volcanics of the Vargfors Group overlie the above rocks (with a marked erosional unconformity). A minimum age for the Vargfors Group is given by the intruding Revsund granitoids dated at 1747 ± 40 Ma (Welin *et al.* 1971). The granitoids commonly included in this heterogeneous group are widespread, intruding the greywacke complex in central Norrland. They should thus be attributed to a process distinctly later than the original folding of the basin but related to migmatization and flow folding.

As can be seen from Figure 2, the sedimentary basin of central Norrland has its continuation in central Finland, where it is bounded in the north by an Archean craton (Kahma 1978; Simonen 1960) with acid-intermediate volcanics at the boundary; the volcanics, with their associated massive sulphide deposits and syntectonic granitoids, exhibit radiometric ages close to 1900 Ma (Helovuori 1979). In the south, the sedimentary basin is bounded by similar volcanics that contain deposits of banded iron ores and massive sulphides (Latvalahti 1979) and thus resemble the bedrock of central Sweden. This volcanic activity took place about 1880—1920 Ma ago (Latvalahti 1979, quoting Kouvo & Tilton 1966 and Simonen *et al.* 1978). A considerable number of nickel-copper deposits in Finland are associated with ultramafic bodies in the central sedimentary basin (Fig. 2, Papunen *et al.* 1979). The Vammala deposit in the southwest has been dated to 1890 Ma (Häkli *et al.* 1979). The main geological features of southern and central Norrland in Sweden agree very well with those of central Finland, and radiometric datings, although few in Sweden, are consistent with the model for geological evolution given above.

Geology of the nickel district

The bedrock of central Västerbotten, which contains the known nickel-copper deposits, is dominated by veined gneisses and migmatites derived from marine sediments, greywackes and, to a lesser extent, pelitic sediments (Fig. 5). Certain horizons are clearly indicated on magnetic and electromagnetic maps owing to their appreciable graphite content and finely dispersed pyrrhotite. The aeromagnetic maps in particular, which are available for most of the area, often illustrate the stratigraphy and fold patterns well in spite of intermittent strong flow

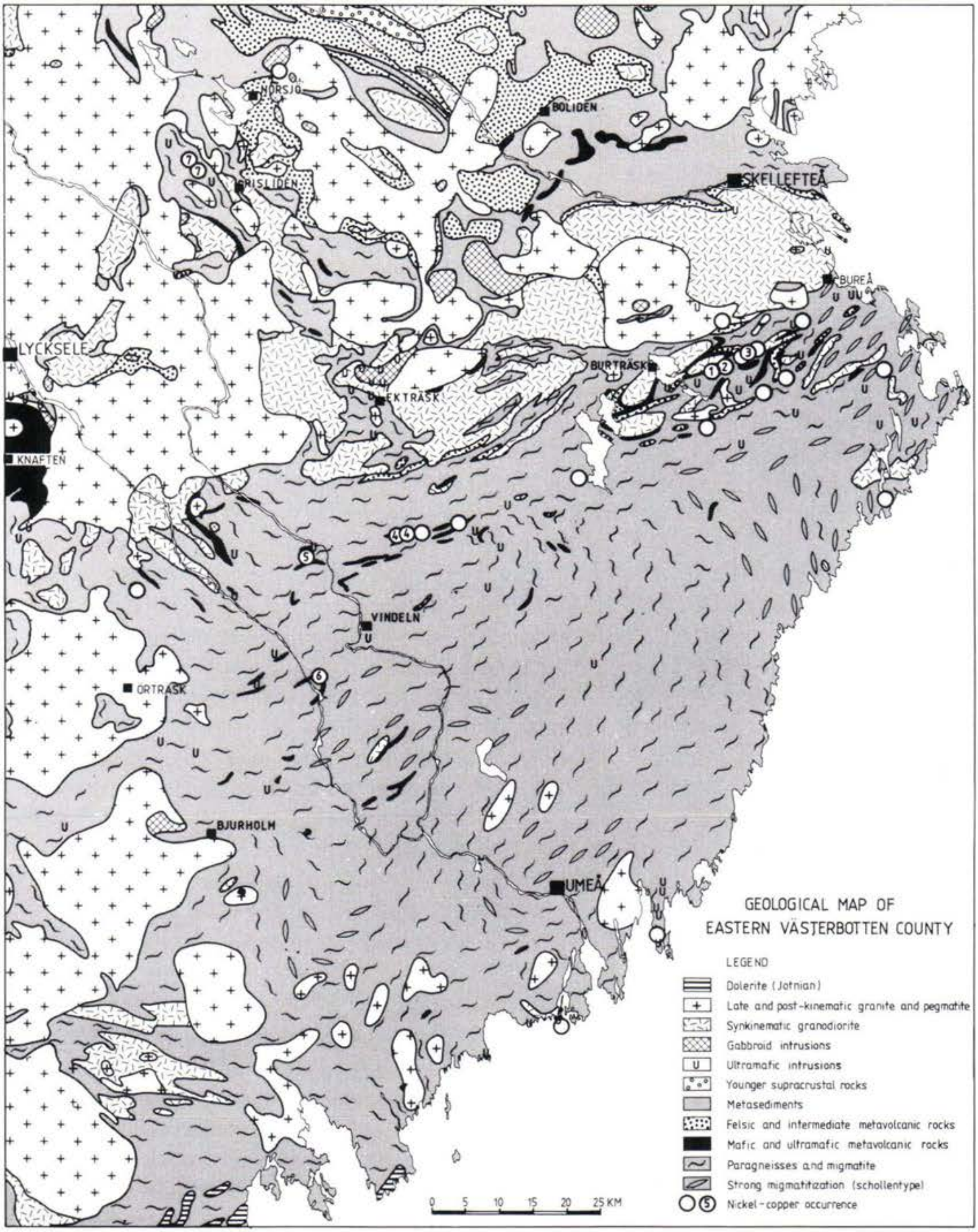


Fig. 5. Nickel occurrences of the eastern Västerbotten county: 1. Lappvattnet; 2. Brännorna; 3. Mjövattnet; 4. Rörmyrberget; 5. Gårkälen; 6. Kälen; 7. Risliden. »Permission for distribution» approved by the security officer, The National Land Survey of Sweden, 2. 11. 1983.

folding, gneissification and migmatization. Carbonate rocks and skarn horizons occur in very restricted numbers, mainly in the area south and southwest of Burträsk. Intercalations of basaltic volcanics, mostly transformed into amphibolites, often occur within the sediments. Metabasaltic pillow lavas occur to the north in the Skellefte field, in outcrops southwest of Umeå and in a larger area south of Lycksele.

Two main groups of intrusive granitoid rocks, one older and one younger, can be distinguished in the area. The older group consists of plutons of dioritic to granitic, often tonalitic, composition. They have been termed synkinematic and should probably be correlated with the Jörn granitoid (Fig. 3). These granitoids are often foliated and are affected by later migmatization. It has been suggested that at least some of these plutons, e.g. the one close to Burträsk, represent doming of the granitic basement; no evidence for such an interpretation has been found during recent geological mapping.

Members of the younger group of granitoids are widespread in central Norrland and are commonly referred to as »Revsund granites». Several different types occur, but the most typical is a weakly differentiated coarse porhyritic, relatively quartz-rich granitoid. In the coastal region it is closely associated with pegmatites and migmatization whereas farther west a very similar variety lacking or with scarce pegmatites is frequent. The latter type has been dated to 1747 $\pm$ 40 Ma (Welin *et al.* 1977) by the Rb-Sr method, which makes it definitely younger than the geological events described above. It is thought to be separated from the supracrustals of the Skellefte Group by erosion and deposition of the Vargfors Group (Fig. 3).

Metamorphosed ultramafic rocks occur frequently as small bodies within the sedimentary complex. Ultramafic pyroclastites have been indicated in an area south of Lycksele, where they form an apparent stratigraphic horizon. The majority of the ultramafic rocks, however, have an intrusive character, probably being sills or, in some cases, pipes. They are generally tabular or lensoid bodies up to a few hundred metres long and a few tens of metres wide, although some are almost equidimensional. Compositionally they are peridotites (serpentinites), pyroxenites, hornblendites and picrites. Many are mineralized with varying amounts and proportions of pyrrhotite, pentlandite and chalcopyrite.

The factors affecting the distribution of the ultramafic bodies are still uncertain, and there are arguments for both a stratigraphic and a tectonic control. Most of the bodies known to date occur in a zone about 100 km long and 15 km wide, extending from Bureå on the coast in a west-southwesterly direction towards Örträsk (Fig. 5). This zone is characterized by a marked tectonic lineament as seen from aeromagnetic maps, but it also roughly follows the regional strike of the steep to moderately dipping sediments. Outside this zone, ultramafic bodies appear either in several short parallel zones and in zones trending in other directions or as separate occurrences.

Gabbroid rocks are sparse in the area, those present occurring mainly north of the Bureå-Örträsk ultramafic zone. The intrusives are seldom more than a few kilometres in size, and in the southern part of the area they are mostly very small. At Ekträsk there is a layered intrusive body with an ultramafic base and, according to boulders in the drift cover, probably with anorthositic parts at a higher level. A number of intrusives within the area have similar characteristics whereas others seem to be more homogeneous. Small nickel deposits are sometimes associated with these rocks. Most of the gabbroid rocks seem to be associated in time and space with the Jörn granitoids (Gavelin, 1955), although a few e.g. the small gabbroic body associated with the Lainijaur nickel deposit (Grip 1961), appear to be associated rather with the synsedimentary volcanism of the Skellefte Group.

Geochemistry of the ultramafic rocks

Some geochemical characteristics and trends of the ultramafic and mafic rocks are illustrated in Figures 6—8. The analyses were made by the Geological Survey of Sweden for prospecting purposes, using an optical emission spectrograph equipped with a tape machine (Si, Ti,

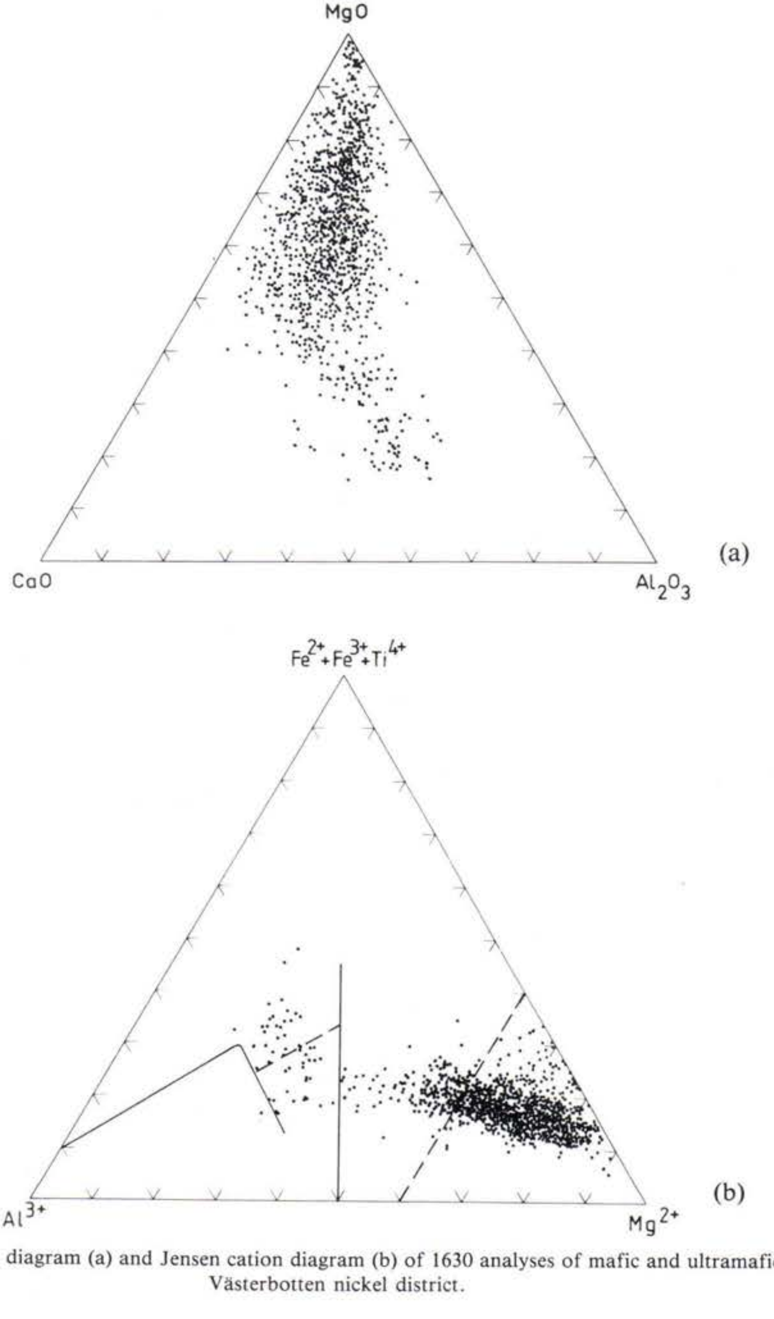


Fig. 6. CaO-MgO-Al_2O_3 diagram (a) and Jensen cation diagram (b) of 1630 analyses of mafic and ultramafic rocks in the Västerbotten nickel district.

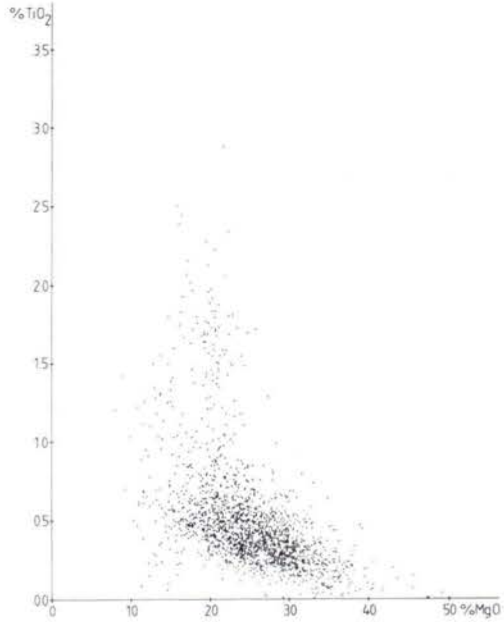


Fig. 7. Plot of wt % TiO_2 versus wt % MgO (anhydrous) of 1630 analyses of mafic and ultramafic rocks in the Västerbotten nickel district.

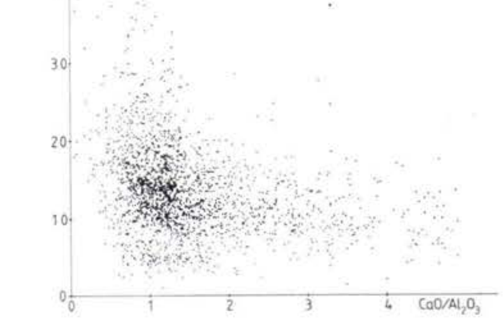


Fig. 8. Plot of CaO/Al_2O_3 versus Al_2O_3/TiO_2 of 1630 analyses of mafic and ultramafic rocks in the Västerbotten nickel district.

Fe_{tot}, Mn, Mg, Ca and Cr) and atomic absorption (Na and K). Details of the techniques used and data on precision have been reported by Danielsson (1967). Most of the samples analysed derive from glacial boulders, but some are from outcrops and drill holes. Ultramafic rocks were strongly favoured for analyses, which explains the low density of points in the gabbroid part of the diagrams. Gabbroid intrusions, on the other hand, are not as common as ultramafic intrusions inside the nickel district. All the rocks analysed are metamorphosed and commonly lack primary mineral phases and textures. The dispersion on the diagrams may, therefore, at least in part, be a result of various chemical alteration processes associated with metamorphism.

The CaO-MgO-Al_2O_3 plot shows a gapless trend on the CaO side of the diagram (Fig. 6a). In reality, however, the trends of individual intrusions vary. Most of them are more or less depleted in aluminium, but there are many with a normal to undepleted trend. Consequently the CaO/Al_2O_3 ratio ranges from 0.7 to 2.1 for most of the rocks.

In the Jensen cation plot (Fig. 6b) most of the analyses fall into the field of ultramafic komatiites, with a continuous trend to the tholeiitic field.

The TiO_2-MgO plot (Fig. 7) shows a large dispersion, but a trend of increasing TiO_2 content with decreasing MgO can be seen for samples containing more than 20 % MgO. At about this MgO content and towards lower values in the gabbroid rocks the trend is more scattered. TiO_2 seems to rise more rapidly with decreasing MgO content. Some of the high TiO_2 values in the interval at about 20 % MgO represent magnetite-richer samples from gabbroid intrusions. Other high values in the same interval cannot yet be explained. They represent rocks of picritic and hornblenditic compositions.

The Al_2O_3/TiO_2 ratios show a very large dispersion in Figure 8, but most of the samples have ratios that cluster between 10 and 17.

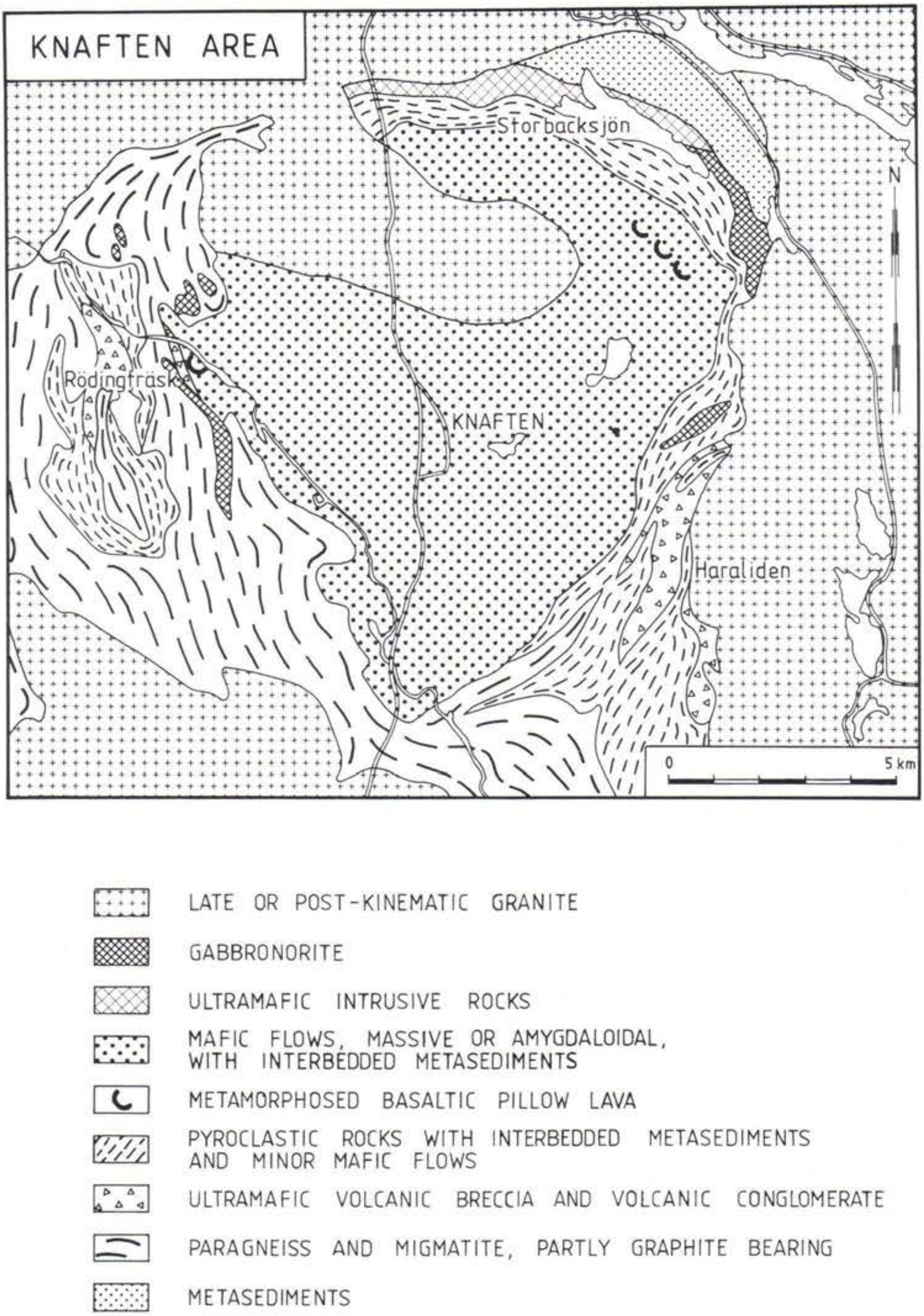


Fig. 9. Geology of the Knaften area. »Permission for distribution» approved by the security officer, The National Land Survey of Sweden, 2. 11. 1983.

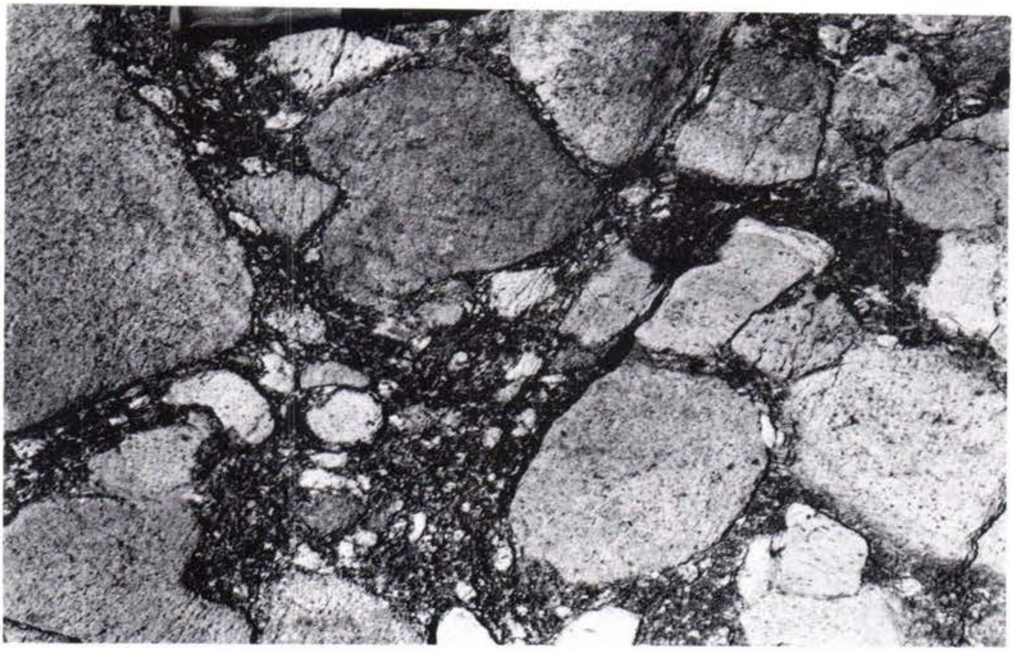


Fig. 10. Presumed volcanic breccia of komatiitic composition from Haraliden, Knaften area.

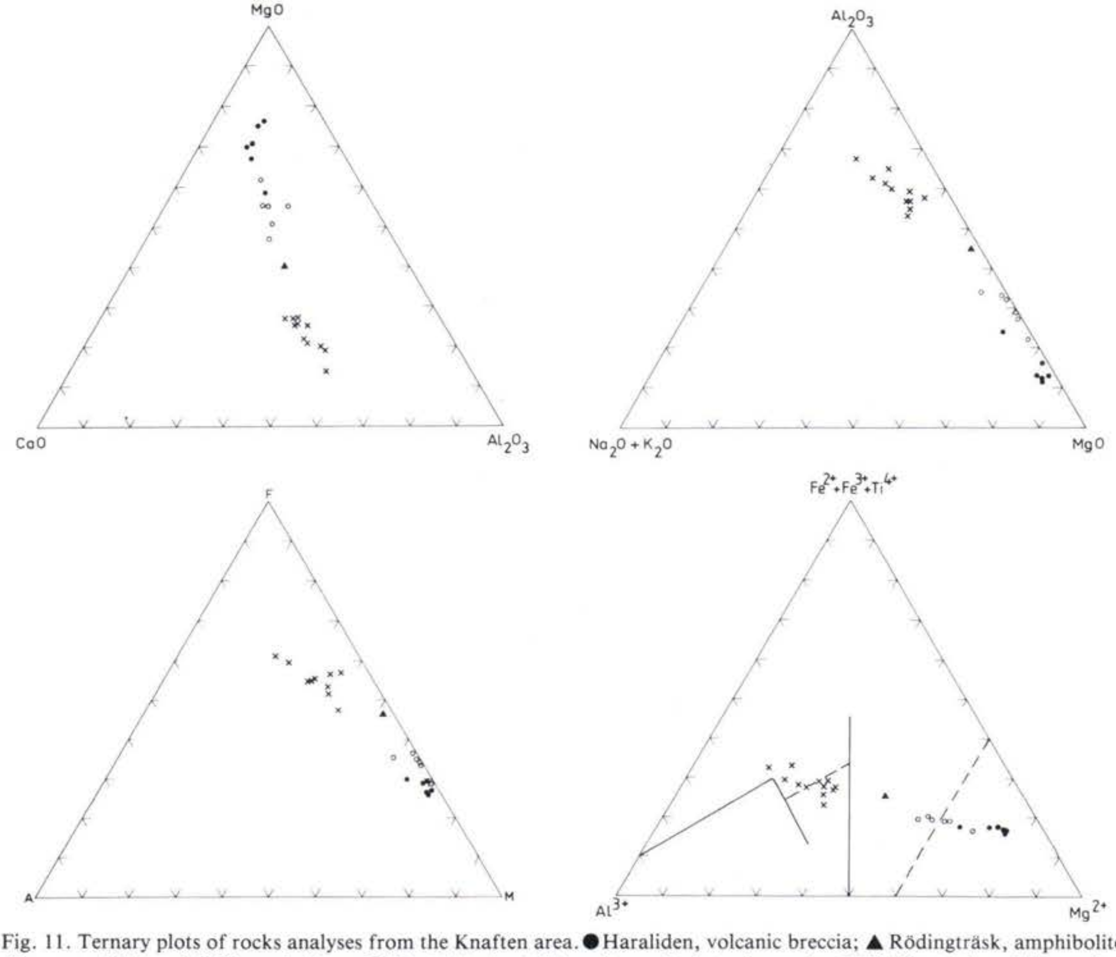


Fig. 11. Ternary plots of rocks analyses from the Knaften area. ● Haraliden, volcanic breccia; ▲ Rödingträsk, amphibolite (Svensson 1970 and 1980, analysis no. 244); ○ Storbacksjön, ultramafic intrusive rocks; X Rödingträsk, gabbronorite.

Table 2. Chemical compositions of rock fragments from the Haraliden volcanic breccia recalculated free of volatile components.

	1	2
SiO_2	45.4	48.2
TiO_2	0.92	0.66
Al_2O_3	9.1	9.7
FeO*	11.4	10.4
MnO	0.19	0.18
MgO	22.4	17.3
CaO	8.8	9.8
Na_2O	0.1	1.1
K_2O	0.1	0.5
P_2O_5	0.08	0.13
Cr_2O_3	0.43	N.D.
Total	99.05	98.82
CaO/Al_2O_3	0.97	1.01
Al_2O_3/TiO_2	9.9	14.8
$\frac{Mg^{2+}}{Fe_{tot}+Mg^{2+}}$	0.78	0.75

1. Presumed komatiite, average of 5 analyses
2. Presumed pyroxenitic komatiite

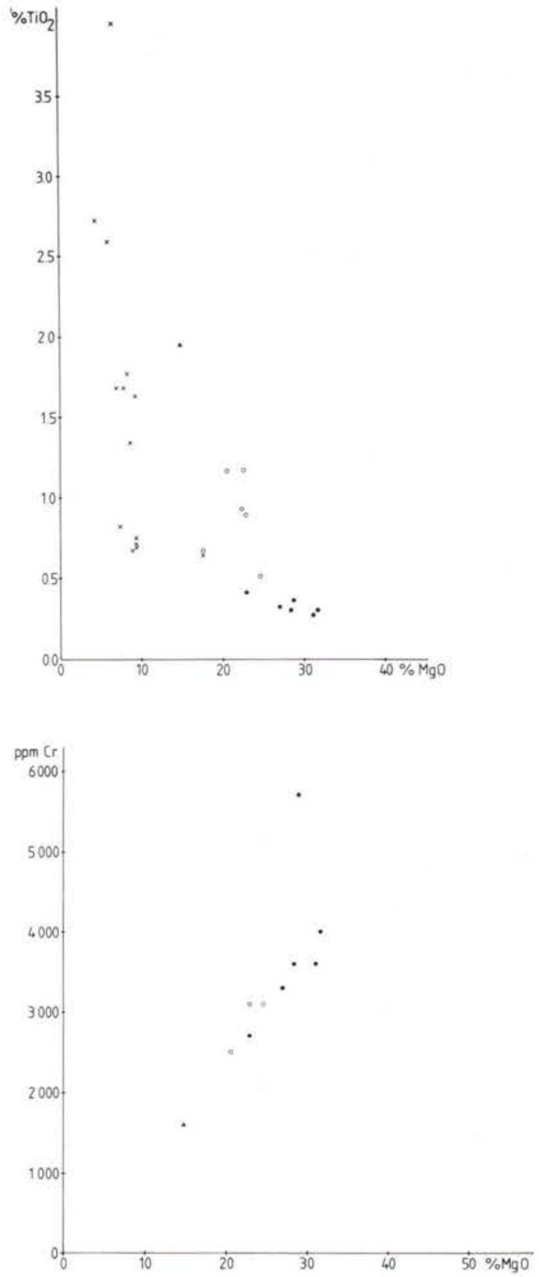


Fig. 12. Plots of wt % MgO versus wt % TiO_2 and wt % MgO versus ppm Cr for rocks from the Knaften area (anhydrous basis). Symbols as in Fig. 11.

As illustrated by the diagrams, the mafic and ultramafic intrusions in the nickel district are similar in geochemistry to komatiitic rocks in other parts of the world. The CaO-MgO-Al_2O_3 and TiO_2-MgO plots are, for example, similar to the plots of komatiites and allied rocks from Barberton and other South African Archean greenstone belts (Viljoen *et al.* 1982), whereas the Jensen cation diagram resembles plots from the Archean Abitibi greenstone belt in Canada (Jensen and Pyke 1982). The mafic and ultramafic intrusions of the Västerbotten nickel district appear to have crystallized from magmas with compositions similar to those represented by some komatiitic volcanic sequences.

The Knaften area south of Lycksele is of special interest in this respect because of the occurrences of ultramafic rocks with fragmental structures interpreted as volcanic breccias (Figs. 9—10). These rocks are subordinate in a sequence consisting mainly of metavolcanic rocks of basaltic composition. In addition, several horizons of intermediate volcanic rocks and intercalations of graphite schists and other metasediments are interlayered in the sequences. Pillow flows, amygdaloidal horizons and pyroclastic rocks are within the mainly nonfoliated basaltic metavolcanic rocks. Thin dykes of felsic porphyries have also been observed cutting the layered sequence. In the northeastern part of the Knaften area a mafic-ultramafic intrusion that is probably layered occurs along the contact between the metavolcanic rocks and the metasediments.

Five of six analysed fragments from the volcanic breccias at Haraliden in the eastern part of the area contain 18—25 % MgO (anhydrous). In the proposed terminology of Arndt and Nisbet (1982), the rocks, if of volcanic origin, are komatiitic breccias. The chemistry of the rocks also shows a good resemblance to komatiites from other parts of the world except that they contain rather high TiO_2 (Figs. 11—12, Table 2). The CaO/Al_2O_3 ratios range from 0.7 to 1.2, with an average close to unity. For comparison, some analyses of mafic and ultramafic, mainly intrusive rocks from the Knaften area have been plotted in the diagrams. The suggested gap in the diagrams is caused by a lack of analyses for all the igneous rock types, for example, the metabasalts from the central part of the area. The volcanic breccias seem to be comagmatic with the intrusive rocks.

The nickel-copper deposits and their host rocks

The nickel-copper deposits in this part of Sweden exist in two different environments. The group of deposits associated with ultramafics in a marine sedimentary environment is at present of greatest interest. The other, somewhat less homogeneous group includes deposits associated with gabbroid dykes and massifs, for example, the closed Lainijaur mine (Grip 1961), the Storbodsund and Bastutjärn occurrences and a deposit associated with the gabbroid dyke of Älgliden. The following account concerns the ultramafics in a marine sedimentary environment.

Nickel mineralization associated with ultramafic rocks were first found in central Västerbotten in 1971 during prospecting carried out by SGU. A description of the initial work in the area and the prospecting methods employed has been given by Nilsson (1973). To date, about 40 prospects have been indicated, some as occurrences in the bedrock and some as mineralized boulders in the overburden. About half of the prospects have been investigated by diamond drilling. In a few of them ore reserves of 0.5—1.5 million tonnes containing over 0.8 % Ni have been proved but the district definitely has a greater ore potential.

The majority of the known nickel-copper deposits are situated within an area extending from Bureå in the northeast to Örträsk in the southwest (Fig. 5). Within this area two narrow almost parallel zones may be distinguished; the Lappvattnet-Mjövattnet zone in the east and the Backviken-Gårkälen zone in the west.

The two largest known deposits in the district, Lappvattnet and Rörmyrberget, are situated within these two zones respectively. Several smaller nickel-copper prospects occur in the vicinity of these two deposits, some within and some outside the zones mentioned. Five nickel-copper deposits have been located at Risliden, in the northwestern part of the district. These deposits are situated in the central part of a five-km-long zone trending in a NW-SE direction and containing ultramafic rocks. Several small nickel-copper-mineralized ultramafic bodies occur as isolated remnants in the migmatitic bedrock on the coast, in the region of Umeå. East of Umeå, however, a couple of small deposits exhibit a more regular linear trend.

All the known nickel deposits in the district are associated with ultramafic bodies that are differentiated only slightly or not at all. Gabbroid rock types only occur in the Rörmyrberget

Fig. 13. »Jackstraw-texture» in metaperidotite from the Lappvattnet deposit. Polished surface.

deposit and in very subordinate amounts in some other intrusions. In the terminology of Marston *et al.* (1981, Table 1), the ultramafic rocks consist of metamorphosed dunites, peridotites and picrites (pyroxenites), with hornblendites subordinate in some deposits. Olivine is largely, altered into serpentine, and pyroxenes into anthophyllite, cummingtonite and actinolite. In the hornblendites, which generally contain some biotite, even the hornblende is altered into secondary amphiboles.

Primary igneous textures are seldom well preserved. Pseudomorphs after cumulus olivine have been observed in serpentinites and olivine peridotites in a few deposits. Idiomorphic crystals of zoned pyroxenes have also been seen in pyroxenites but they are very scarce. In some the ultramafic rocks exhibit the characteristic »jackstraw-texture» (Evans and Trommsdorff 1974) caused by the pseudomorphing of metamorphic olivine by elongate serpentinite replacements. (Fig. 13).

Relict olivines are colourless and unzoned. Olivines with a light brown colour have only been observed in the Risliden area. Electron microprobe analyses performed on olivine cores in samples of host rocks from some Ni-Cu deposits show olivine compositions from maximum Fo_{81} to Fo_{91} with 0.06 % NiO and 0.40 % NiO, respectively (Table 3). Manganese varies from 0.09 % MnO to 0.24 % MnO and the contents of calcium and chromium are very low.

The nickel-bearing ultramafic bodies usually occur as sills that only very locally cut the banding or other structures of the gneiss host rock. The Backviken deposit is tentatively interpreted as being emplaced along a pipe structure.

Table 3. Compositions of olivines from some Ni-Cu-deposits (wt %).

	1	2	3	4	5	6	7	8	9	10
SiO_2	39.6	40.4	40.2	40.7	39.7	39.3	40.0	40.4	39.5	39.3
Al_2O_3	0.06	0.04	0.05	0.06	0.02	0.04	0.03	0.03	0.02	0.02
FeO*	15.5	12.4	12.7	11.0	15.8	17.9	11.9	8.4	14.7	15.8
MnO	0.19	0.09	0.14	0.10	0.23	0.24	0.14	0.10	0.19	0.23
MgO	44.7	47.0	46.7	47.9	44.5	42.7	47.3	50.2	45.3	44.7
CaO	<0.02	ND	<0.02	0.01	ND	ND	<0.01	<0.01	ND	ND
Cr_2O_3	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NiO	0.20	0.17	0.22	0.21	0.07	0.06	0.17	0.40	0.06	0.07
mol % Fo	83.6	87.0	86.6	88.4	83.2	80.7	87.3	91.3	84.4	83.3

1. Lappvattnet, 70E—150E sections, 40—80 m level, average of 5 olivines, 2. Lappvattnet 260E section, 120 m level, most magnesian olivine, 3. Brännorna, A-body, average of 7 olivines, 4. Brännorna, A-body most magnesian olivine, 5. Gårkälen, average of 2 olivines, 6. Kälen, average of 4 olivines, 7. Römyrberget, average of 41 olivines, 8. Römyrberget, most magnesian olivine, 9. Risliden, A-body, average of 2 olivines, 10. Risliden, C-body, average of 4 olivines. ND = not determined.

The majority of the ultramafic bodies are very small. The largest is the Rörmyrberget intrusion, which is at least 1.7 km long and 320 m wide.

The gneisses and migmatites housing the ultramafic bodies often contain appreciable amounts of graphite and pyrrhotite. The graphite has been interpreted as of sapropelic origin, partly because of the high content of vanadium and molybdenum in the graphite-rich rock sections. The graphite gneisses from Lappvattnet contain 300—550 ppm V and 10—20 ppm Mo, which is appreciably higher than in nongraphite gneisses. Graphite also occurs as small isolated grains or aggregates within the ultramafic rock itself. This can be explained as assimilation of the host rock by the intruding ultramafic magma, for which there are other indications, too. If this is true, the intrusion might also have incorporated sulphur from the sulphides of the gneiss.

The ore sulphides occur as dissemination and veinlets, the latter sometimes brecciating the host rock. Massive sulphide mineralizations are less common but occur in subordinate amounts in Lappvattnet and Mjövattnet. Pentlandite, pyrrhotite and chalcopyrite are the most common sulphide minerals. Pyrite may also occur, for example, in breccia ore. Gersdorffite is a common accessory nickel mineral.

The nickel content of the sulphide phase calculated to 100 % sulphides varies from 3 to 23 wt. % Ni_s between the different deposits. The average for all the deposits investigated is about 8 % Ni_s, the median being 7 % Ni_s. In the Brännorna deposit and a couple of similar intrusions within the Lappvattnet-Mjövattnet zone the sulphide phase is particularly rich in nickel, being as high as 20 % Ni_s. Apart from this, however, there seems to be no clear difference between the various parts of the district. The Cu/(Ni + Cu) ratio of the deposits varies between 0.07 and 0.53, with an average of 0.21; in most deposits it is between 0.1 and 0.3, being somewhat lower in the Lappvattnet-Mjövattnet zone than in other parts of the district. The latter applies to the Co/(Ni + Co) ratio as well.

To date 50 analyses of platinum group metals from ten deposits have been carried out. These show contents from very low up to 1.5 g/t Pt and 1.8 g/t Pd, the values being lower in the Lappvattnet-Mjövattnet zone than in other parts of the district. The Pt/(Pt + Pd) ratio varies between 0.45 and 0.75, with an average of 0.57 in samples from seven deposits.

Deposits of the Lappvattnet-Mjövattnet zone

Geology

The bedrock around the nickel-copper deposits of this zone consists mainly of quartz-plagioclase gneiss with minor amounts of biotite gneiss. The rocks, which have the character of veined gneisses, are sedimentary rocks of greywacke type. Massive gneisses and amphibo-

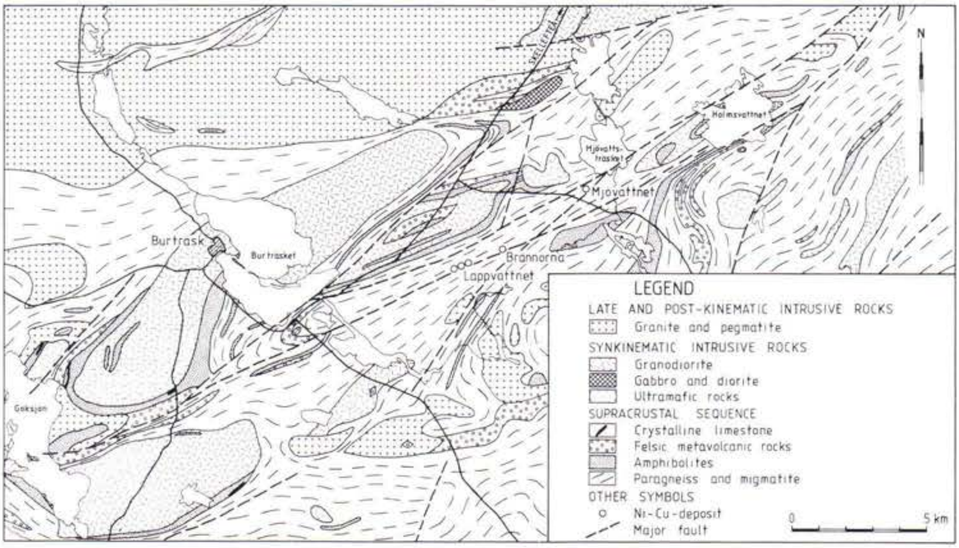


Fig. 14. Geology of the Lappvattnet area. »Permission for distribution» approved by the security officer, The National Land Survey of Sweden, 2. 11. 1983.

Table 4. Chemical compositions of metamorphosed ultramafic host rocks from the Lappvattnet and Brännorna deposits recalculated free of volatile components.

	1	2	3	4	5	6	7	8	9
SiO_2	50.2	52.6	44.4	55.3	52.1	42.8	49.2	46.8	49.7
TiO_2	0.18	0.29	0.12	0.15	0.28	0.06	0.05	0.22	0.43
Al_2O_3	3.2	4.6	1.8	2.7	5.4	0.98	1.16	3.6	7.1
FeO*	9.8	9.5	8.7	5.5	8.3	10.2	9.2	10.1	7.9
MnO	0.15	0.16	0.17	0.15	0.22	0.12	0.13	0.17	0.15
MgO	32.0	27.4	39.2	30.0	24.8	43.8	38.2	33.7	25.4
CaO	3.4	3.8	4.4	4.7	5.7	0.6	0.8	4.2	7.5
Na_2O	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1
K_2O	0.2	0.1	0.1	0.5	1.2	0.1	0.1	0.1	0.1
P_2O_5	0.02	0.16	0.03	0.06	0.06	0.01	0.02	0.03	0.21
Cr_2O_3	0.46	0.47	0.61	0.47	0.48	0.17	0.17	0.37	0.41
Total	99.64	99.23	99.44	99.72	98.71	99.16	99.17	99.37	98.96
CaO/Al_2O_3	1.07	0.83	2.44	1.74	1.05	0.66	0.70	1.16	1.05
Al_2O_3/TiO_2	17.8	15.8	15.0	18.0	19.6	16.5	23.4	16.5	16.7
$\frac{Mg^{2+}}{Fe_{tot}+Mg^{2+}}$	0.85	0.84	0.89	0.91	0.84	0.88	0.88	0.86	0.85

1. Peridotite, Lappvattnet 110E and 150E sections, average of 7 analyses, 2. Picrite, Lappvattnet 150E section, 3. Olivine peridotite, Lappvattnet 590E section, 240 m level, 4. Peridotite, Lappvattnet 590E section, 240 m level, 5. Picrite, Lappvattnet 590E section, 240 m level, 6. Dunite, Brännorna, A-body, average of 7 analyses, 7. Olivine peridotite, Brännorna, A-body, average of 14 analyses, 8. Peridotite, Brännorna, B-body, average of 5 analyses, 9. Picrite, Brännorna, B-body.

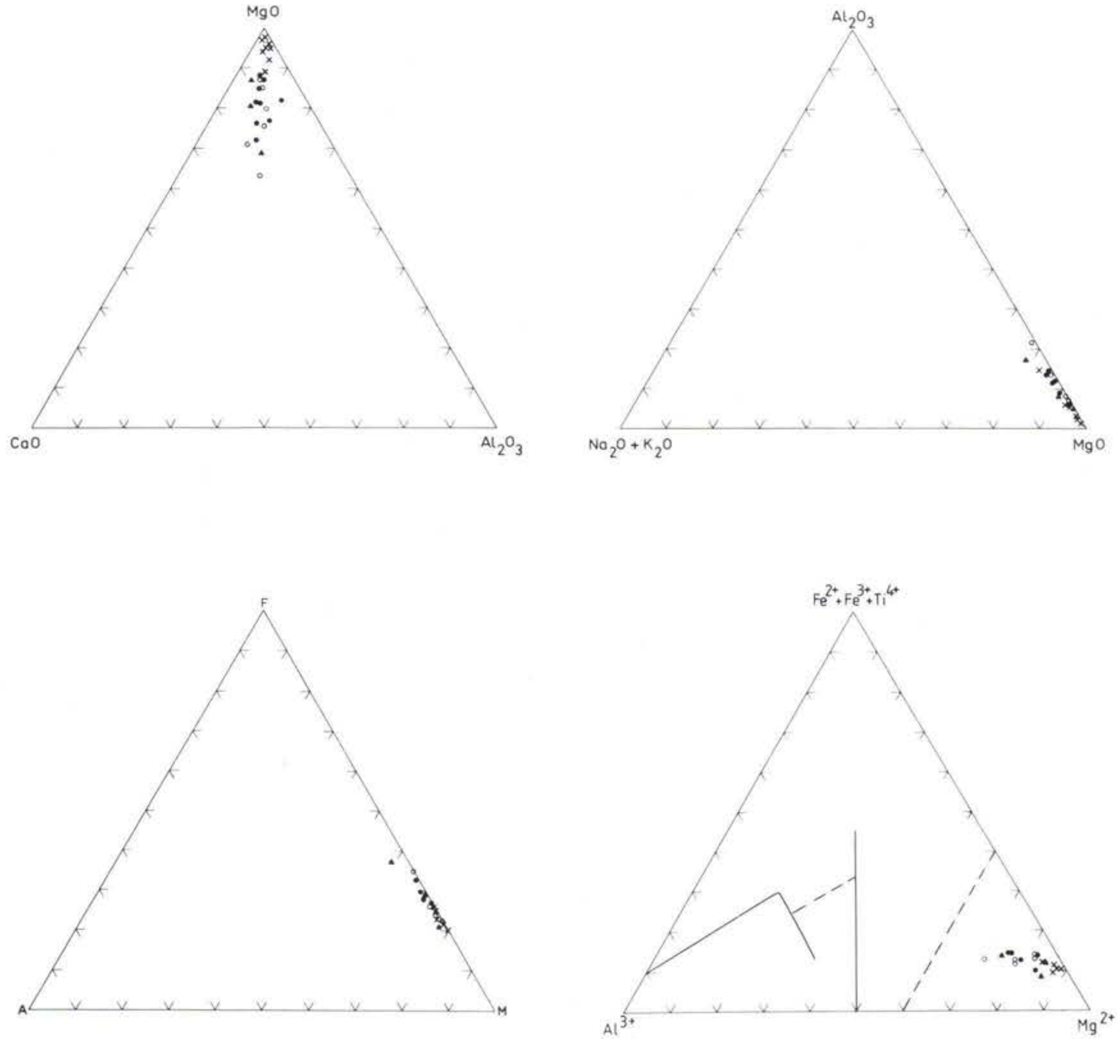


Fig. 15. Ternary plots of host rock analyses from the Lappvattnet and Brännorna deposit. ● Lappvattnet, 110 E and 150 E sections; ▲ Lappvattnet, 590 E section, 240 m level; X Brännorna, »upper body»; ○ Brännorna, »lower body».

lites are less abundant. The grade of metamorphism near the Ni-Cu ores is of mid-amphibolite facies. Garnet and cordierite have only been observed together in areas of strong migmatization (Fig. 4). Graphite occurs in the gneisses in a zone, 100—200 m wide, around the deposits, but also in parallel zones farther off. Granite dykes and, particularly, pegmatite dykes cutting the gneisses are common in the area.

The ultramafic bodies in this zone are seldom longer than 150 m and vary from less than a metre to 40 m in width. Some of the bodies are Ni-Cu sulphide-bearing; others only contain pyrrhotite. Geochemical data on the ultramafic rocks at Lappvattnet and Brännorna are given in Table 4 and Figures 15—16. According to the Jensen diagram (Fig. 15d), all the plotted ultramafic rocks are komatiitic in composition.

Geophysical ground surveys and core drilling have shown that the gneisses form rather reg-

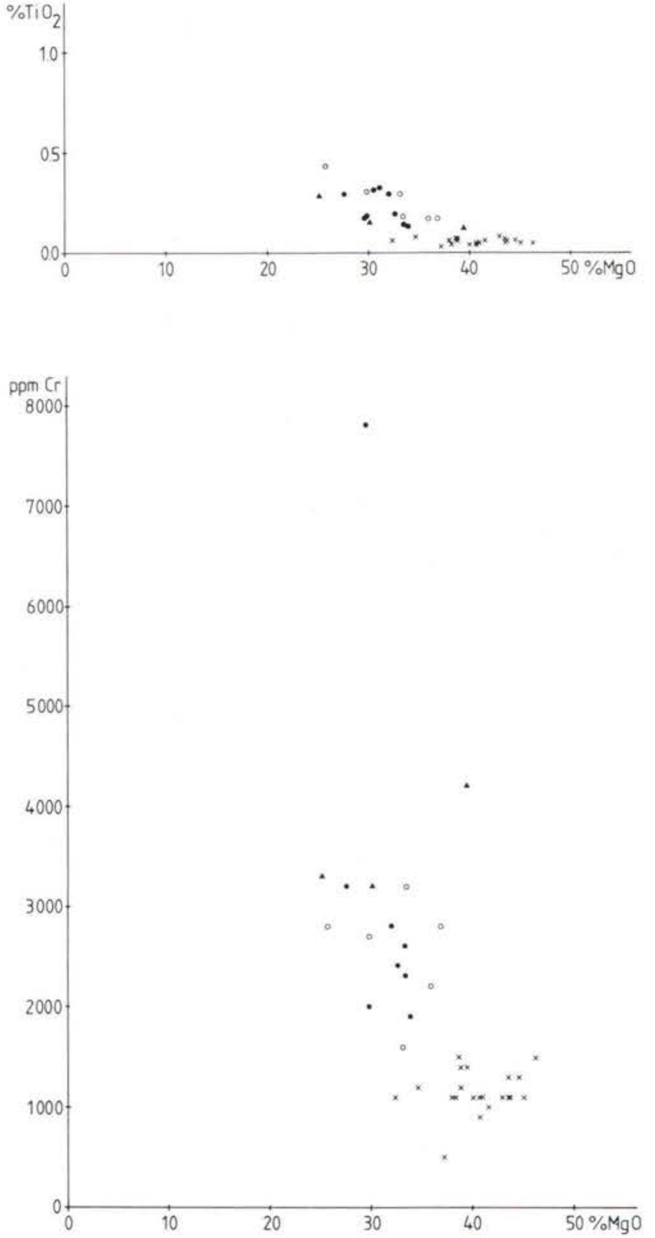


Fig. 16. Plots of wt % MgO versus wt % TiO_2 and wt % MgO versus ppm Cr for host rocks from the Lappvattnet and Brännorna deposits (anhydrous basis). Symbols as in Fig. 15.

ular horizons trending NE or ENE and dipping 70°—90° towards SE. In outcrop, the gneisses exhibit strong isoclinal folding with the axes of the small folds plunging about 50° towards NE. This direction is prominent all along the zone and can probably be correlated with the form and structure of the granodioritic intrusions immediately to the north (Figs. 5 and 14).

The area is transected by several faults, e.g. those trending northeast about 2.5 km to the NW and 1 km to the SE of the Lappvattnet deposit (Fig. 14). Even in the intervening area, faulted and crushed rocks are present in places. One zone of strongly crushed bedrock is 5—15 m wide and runs 30—50 m to the south of the Lappvattnet, Brännorna and Mjövattnet deposits. As they now appear, the faults are young features but with indications that they follow older zones of weakness. It is thought that early tectonic movements may have affected the ultramafic bodies and the mineralizations associated with them and caused local remobilization of sulphide material into fragmental ore or redeposition of sulphides in the gneisses, thereby producing mineralizations outside the ultramafic bodies.

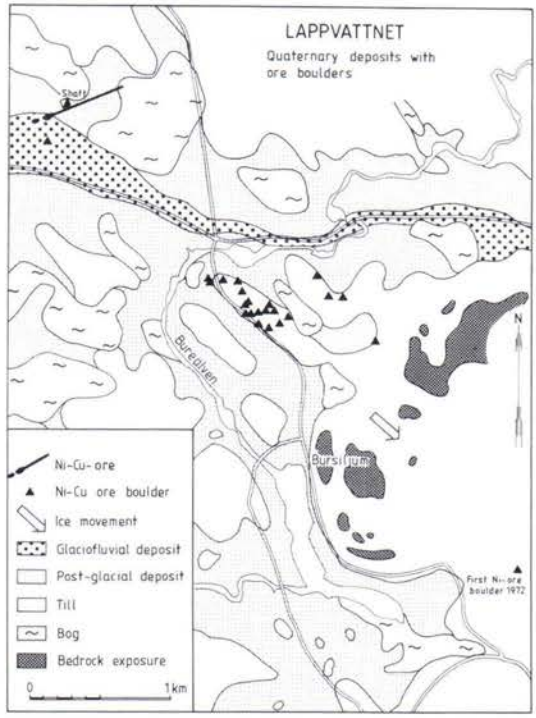


Fig. 17. Quaternary deposits of the Lappvattnet area; geology by L. Rodhe 1982.

Lappvattnet deposit

The first indications of the Lappvattnet deposit were discovered by SGU in summer 1972 through systematic examination of glacial till for boulders of Ni-Cu ore and ultramafic rocks. They discovered that boulders could not be traced farther inland against the direction of ice movement than to the edge of a large area dominated by glaciofluvial sediments (Fig. 17). Geophysical investigations were continued the following winter by slingram, magnetometric and gravimetric techniques. The results helped in the interpretation of the bedrock structures, but there were no anomalies that could have been caused by Ni-Cu ores.

The investigations were extended in summer 1973 by using dogs to localize the most promising boulders. So many new findings were made that the source of the glacial boulders could be interpreted. The boulders constituted two fans, the westernmost one pointing towards a gravel pit within the area of glacifluvial sediments. Interpretation of the geophysical survey at Mjövattnet to the northern edge of the gravel pit indicated a structure that could have been caused by the Ni-Cu occurrence. Follow-up exploration was therefore concentrated on the environment of the gravel pit. Part of a projecting ore-rich ultramafic rock was discovered in the gravel pit. Ice striations on the rock surface indicated that it could not be an outcrop. The boulder, which has been estimated to weigh at least 500 tonnes, is composed of metaperidotite, a rock type found earlier in the ore-bearing boulders. Pyrrhotite, pentlandite and chalcopyrite were present throughout the boulder as an even dissemination, and the samples analysed showed an average content of 1.0 % Ni, 0.22 % Cu and 3.3 % S. Ten more boulders of the same type and two mineralized gneiss boulders were found close to the large boulder.

The accumulation of so many large ore boulders within such a small area suggested that the

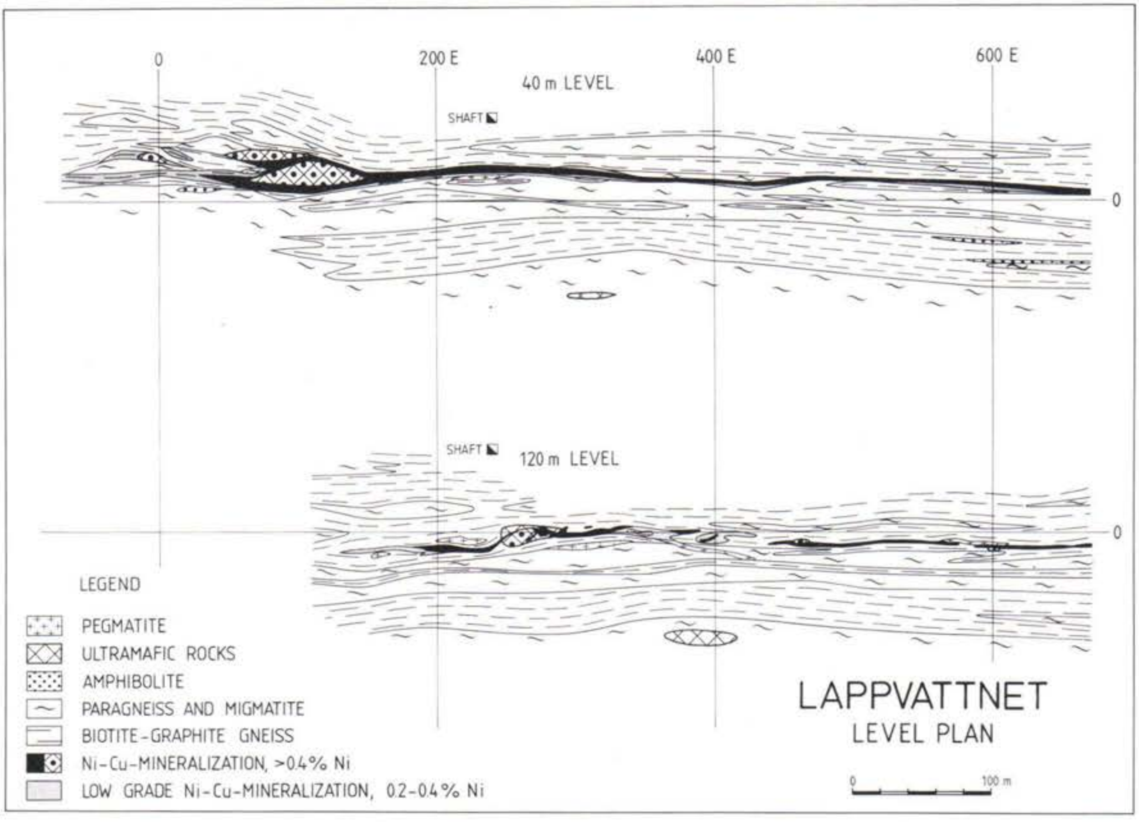


Fig. 18. Lappvattnet, 40 m and 120 m level plans.

Ni-Cu occurrence must be located near the gravel pit. Diamond drilling was started autumn 1973. The third drill hole revealed Ni-Cu sulphides in the gneiss and the fifth hole intersected an ultramafic body about 100 m from the large ore boulder and 4.6 km from the first boulder found in 1972.

At the request of NSG (The State Mining Property Commission), the drilling of the Ni-Cu occurrence continued periodically until spring 1978. From 1978 to 1982, NSG investigated the feasibility of mining the ore. A prospecting shaft was sunk, and ore was extracted from the 120-m level for concentration experiments. Deeper levels were explored through diamond drilling. NSG was not able to undertake detailed geological survey during the underground work and so the shaft was closed in 1982 without satisfactory knowledge of the geology of the tunnel and the appearance of different types of sulphide mineralizations.

The result of the underground investigations was negative. The ore bodies are too thin and too poor in nickel, and the country rocks too tectonized and too waterbearing for mining to be economically viable.

The Lappvattnet deposit is situated in an area of low topography, where the bedrock is covered by 12 to 14 m of quarternary deposits (till and glaciofluvial sediments). Our knowledge of the ore and surrounding rocks is thus based entirely on the study of drill cores, short visits underground at the 120-m level and the interpretation of geophysical data.

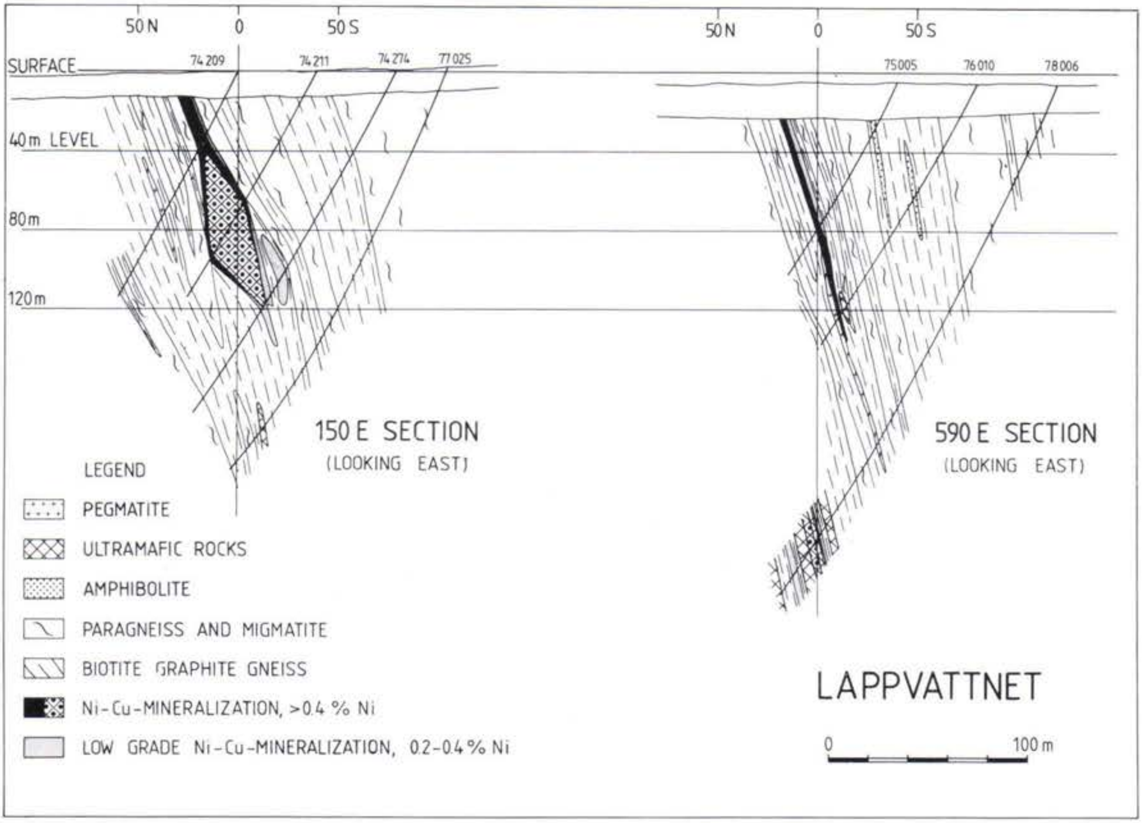


Fig. 19. Lappvattnet, cross-sections 150 E and 590 E.

In contrast to most of the nickel-copper occurrences in the district, the Lappvattnet deposit is associated with both the ultramafic rocks and the surrounding gneisses. Tectonometamorphic processes probably redistributed nickel and copper and redeposited them in a zone of tectonic weakness, partly within the ultramafic bodies themselves and partly within the gneiss. The Mjövattnet deposit seems to have the same characteristics.

The nickel deposit of Lappvattnet can be described as a thin mineralized slab of gneiss which is thickened (in its western part) by two small rounded ultramafic bodies (Figs. 18—19). The slab, which is concordant with the structure of the gneiss, strikes WSW, dips about 70° towards SSE and plunges approximately 20° towards the east. With a cut-off of 0.4 % Ni, the mineralized slab is 620 m long and 1—10 m wide (average 3.5 m) in the gneiss. In depth it ranges from 40 m in the west to 210 m in the east. The largest ultramafic body in the western part of the slab is lensoid in cross section: about 90 m long, at least 120 m deep and a maximum of 20 m wide. It plunges about 30° to the east. A weak nickel-copper mineralization continues for a farther 130 m to the WSW along the strike, and weak mineralizations continue downwards in several of the drill sections. The cut-off value used defines the ore body sharply against the hanging wall, whereas in the foot wall a narrow zone of weak nickel mineralization often occurs adjacent to the ore. A central ore zone is defined through both the gneiss and the ultramafic body using a cut-off of 0.8 % Ni. This latter zone includes a fine-grained fragmental ore that is 0.1—1.1 m thick.

Metaperidotite with or without »jackstraw-texture» is the most common rock type in the largest ultramafic bodies. Metapicrite, which constitutes mainly a thin zone along their contacts with the surrounding gneiss, is also the most common rock type in small ultramafic bodies. Metaolivine peridotite has been found in only one drill hole in a less well examined ultramafic body at the 240-m level in section 590E. Pegmatites brecciate the ultramafic rocks in several places.

The MgO content of the ultramafic host rocks in the western part of the deposit is 25—33 % MgO (anhydrous); the CaO/Al_2O_3 ratio is close to unity. Olivine compositions (Table 3) range from Fo_{81} to Fo_{87}. The average composition in the upper part of the largest body is $Fo_{83.6}$ with a very small variation. At the 120-m level, the olivine compositions in the same body have a much greater variation, and the olivine richest in magnesia has a composition of $Fo_{87.0}$. The nickel content of the olivines ranges from 0.12 % NiO to 0.19 % NiO.

The Ni-Cu mineralization at Lappvattnet is composed of three main ore types:

1. Disseminated ore in ultramafic rocks
2. Disseminated ore in gneiss
3. Fragmental ore in gneiss and subordinate in ultramafic rocks

In addition, subordinate coarse-grained massive ore occurs in association with pegmatites brecciating the ultramafic host rocks (Fig. 20).

The disseminated ore in ultramafic rocks is commonly characterized by a fairly uniform distribution of sulphide grains and aggregates, but it may also contain veinlets and stringers of massive sulphides. Near the contacts with the surrounding gneiss the ultramafic bodies may be brecciated with sulphides as cement. In the gneisses, on the other hand, the disseminated ore type is very heterogeneous. Ore breccias, veins, veinlets and stringers are very common, and the term »disseminated» is often misleading.

The fragmental ore contains about 4 % Ni and is the major ore type in view of the total nickel tonnage of the deposit. It is commonly sharply defined against the host rocks and the disseminated ore types (Figs. 20—21). Fragmental ore occurs as tabular bodies, lenses, veins and veinlets. The ore type is characterized by numerous more or less well rounded inclusions of quartz, plagioclase, mica and country rock material in a fine-grained sulphide matrix.

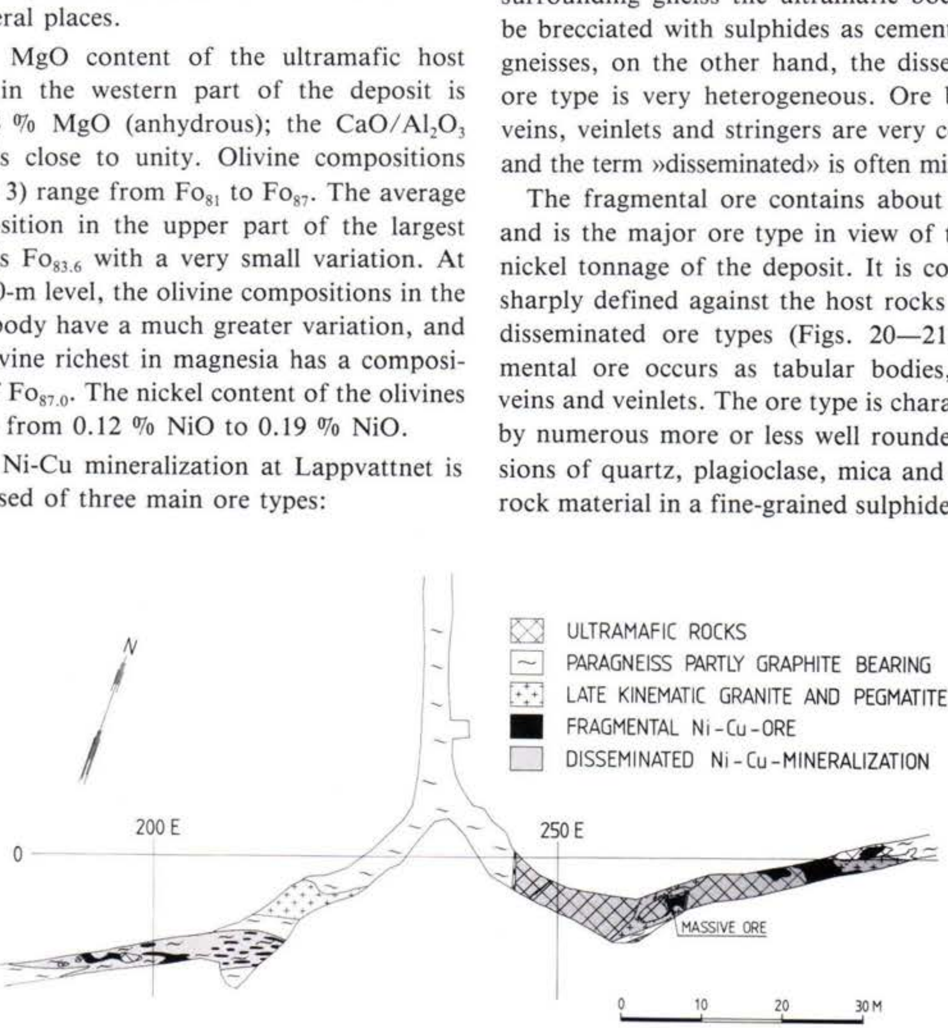


Fig. 20. Geological plan of Lappvattnet 120 m level illustrating the occurrence of different types of Ni-Cu ores.

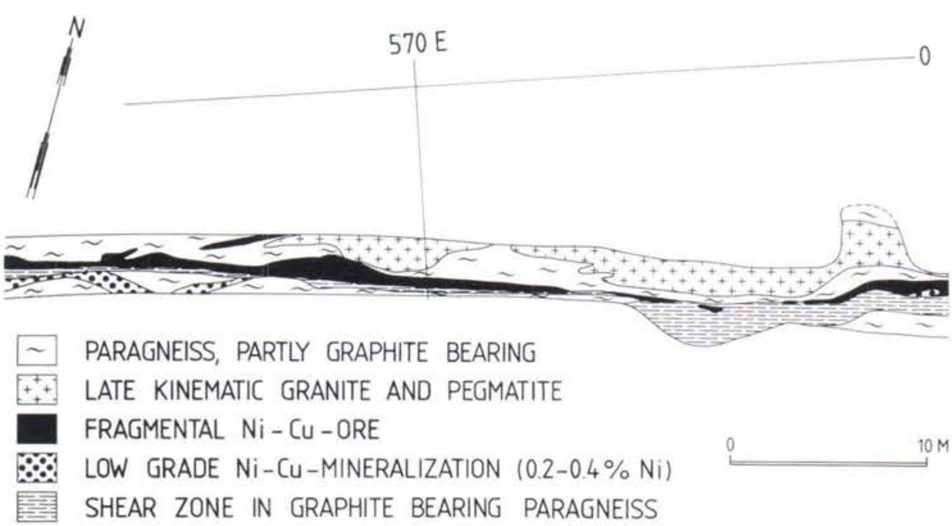


Fig. 21. Geological plan of Lappvattnet 120 m level illustrating the occurrence of fragmental ore in paragneiss.

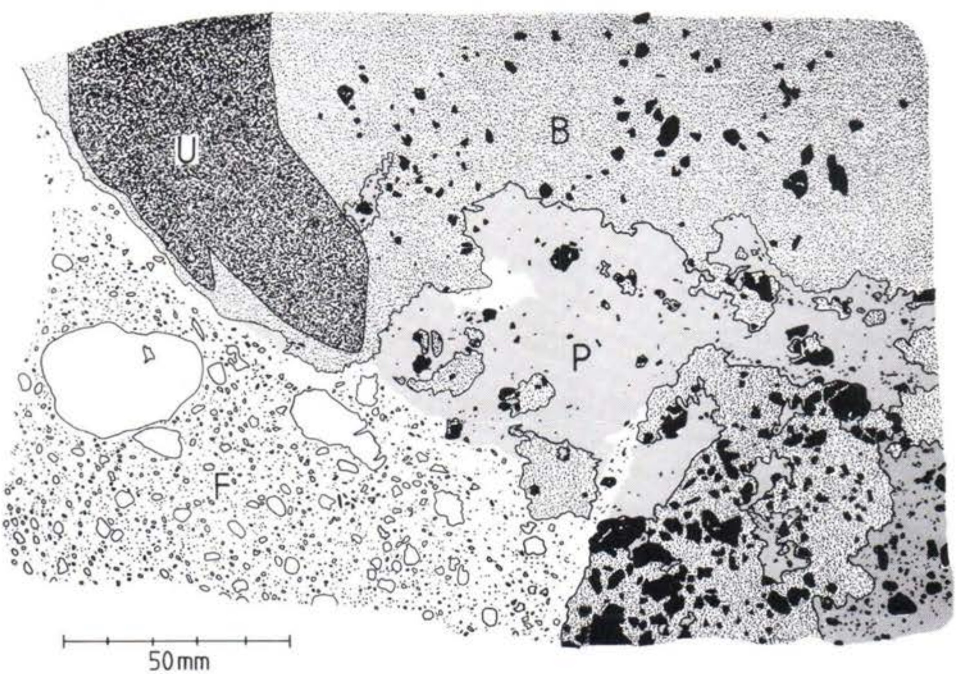


Fig. 22. Sketch of a polished specimen from a contact between fragmental ore (F), coarse-grained pyrrhotite ore (P) and ultramafic microbreccia (B) with a preserved portion of an ultramafic rock with disseminated sulphides (U). Coarser ultramafic fragments in the microbreccia are traced in block.

The size of the inclusions ranges commonly from less than 1 mm to 50 mm, but fragments up to 0.5 m have been observed. Many of the fragments of quartz and gneiss material are rimmed by graphite.

Contacts between fragmental ore and gneiss are commonly sharp. The ore is usually concordant with the gneiss structure, but on a small scale it may cut the structure as thin »dykes» (Fig. 21). At contacts with the more competent ultramafic rocks, the fragmental ore often passes sharply over to a very thin zone of fine or coarse-grained sulphides poor in inclusions, followed by a fine-grained breccia of mainly ultramafic rock in a sulphide matrix (Fig. 22). The coarse-grained sulphides in particular often penetrate the ultramafic rocks as irregular veins. Pentlandite is more common in the fine-grained sulphides than in the coarse-grained varieties, in which pentlandite occurs mainly as exsolution »flames» in pyrrhotite.

Rich concentrations of an almost identical type of fragmental pyrrhotite mineralization are known in many horizons of graphite and sulphide-bearing schists and gneisses in this part of Sweden. The pyrrhotite in them is not accompanied by nickel minerals but often by pyrite and very small amounts of chalcopyrite.

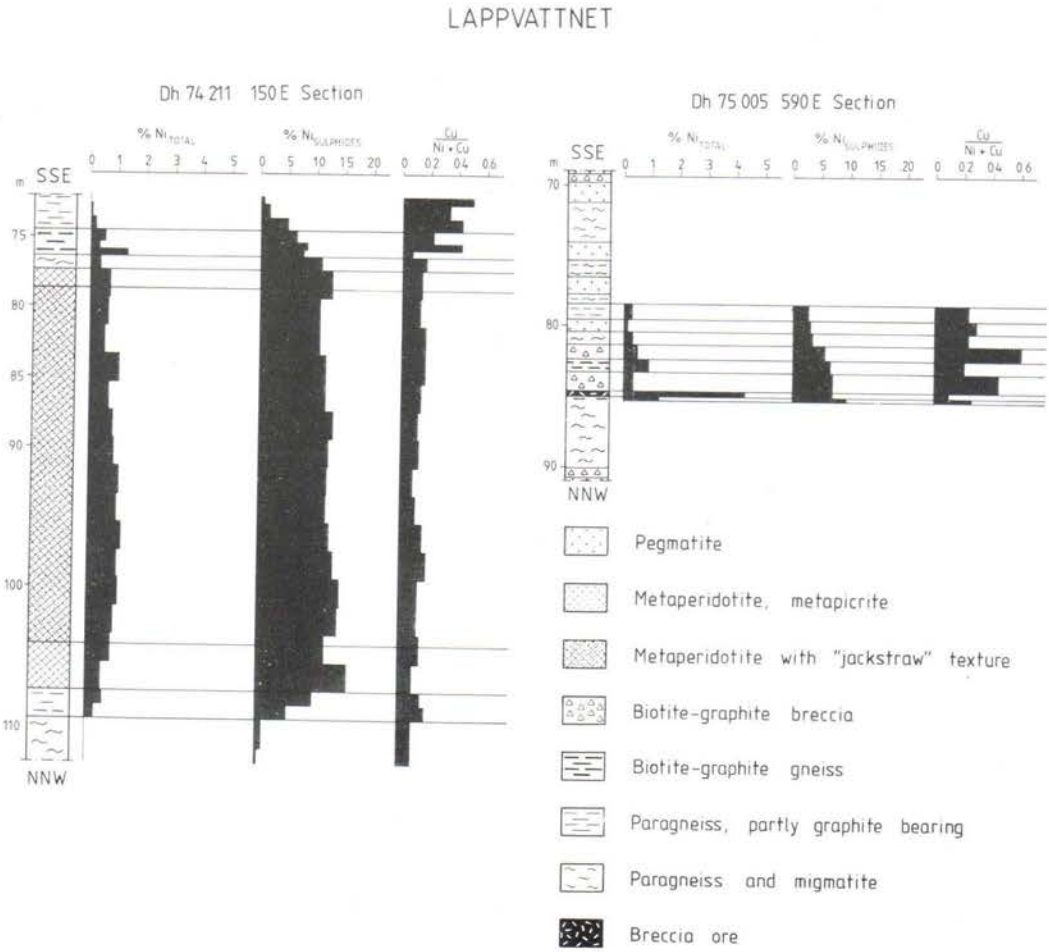


Fig. 23. Variation of sulphide geochemistry in two drill holes from the Lappvattnet deposit.

No mafic or ultramafic rocks are known in the surroundings. Fragmental ore textures of the same type have been described from several Norwegian and Swedish base metal deposits (Vokes 1968, Geijer 1971). These textures probably also occur in some Ni-Cu deposits. Zurbrigg (1963), for example, has shown pictures of a similar ore type in a description of Thompson Mine in Manitoba Nickel Belt, Canada. The origin of the ore type is obscure. Ni-Cu sulphides may have been separated originally as a sulphide melt from an ultramafic magma and intruded into a fault zone or between sedimentary layers, but later tectonic movements after the formation of the gneisses must have mobilized and strongly reworked the sulphides together with the country rocks to produce the present fragmental texture of the ore. Vokes (1968, 1969) refers to the German term »Durchbewegung» for this process and points out the difficulty of finding a satisfactory equivalent in English. Metamorphic processes also seem to have changed the original composition of the sulphide phase. Nickel from silicates probably did not upgrade the ore very much, but some of the original copper content must have been remobilized to sulphide veinlets in the surroundings, especially to shear zones in graphite-bearing gneiss in the hanging wall. The massive Ni-Cu sulphides associated with pegmatites are also products of metamorphic remobilization.

The composition of the sulphide phase (100 % sulphides) varies as a function of rock and mineralization type. This is illustrated in Fig. 23, where Ni_{total}, $Ni_{sulphides}$ and the Cu/(Ni + Cu) ratio are plotted along bore holes. Assuming a sulphur content of 38 %, the average metal content of the sulphide phase for the whole deposit is 8.9 % Ni, 1.8 % Cu and 0.17 % Co; the average Cu/(Ni + Cu) ratio is 0.17. The disseminated ore in ultramafic bodies averages higher nickel values in the sulphides than do the disseminated ore and fragmental ore in gneiss (Table 5). The fragmental and massive ore types are chemically very well defined by their comparatively low content of copper in relation to nickel (Table 6).

The current proven ore reserves of Lappvattnet are 1 million tonnes of ore with an average of 1.0 % Ni, 0.2 % Cu and 4.4 % S. About 67 %

Table 5. Composition of different ore types in the Lappvattnet deposit calculated from analyses of drillcores.

	Disseminated ore in ultramafic rocks		Disseminated ore in gneiss		Fragmental ore	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Wt % Ni	0.68	0.32	0.73	0.33	4.16	1.19
Wt % Co	0.015	0.006	0.015	0.10	0.07	0.03
Wt % Cu	0.16	0.07	0.24	0.22	0.17	0.16
Wt % S	2.9	1.4	3.6	1.2	18.8	4.1
% Ni_s	9.0	3.2	7.6	1.9	8.4	1.5
% Cu_S	2.4	1.1	2.5	1.8	0.4	0.4
% Co_S	0.2	0.05	0.16	0.1	0.15	0.05
$\frac{Cu}{Ni+Cu}$	0.19	0.12	0.25	0.11	0.04	0.04
$\frac{Co}{Ni+Co}$	0.02	—	0.02	—	0.017	0.007
Number of drillholes	10		34		18	

Ni, Cu and Co analyses by atomic absorption. S analyses by gravimetric method. Arithmetic mean ($\bar{x}$) and standard deviation (s) refer to the composition of different drillholes. Calculation of the nickel content in 100 % sulphides. (% Ni_S) assumes an average content of 38 % S.

Table 6. Chemical analyses of hand specimens from the Lappvattnet deposit, 220 m level.

	ppm					wt. %		% Ni_S	$\frac{Cu}{Ni+Cu}$	$\frac{Co}{Ni+Co}$
	Ni	Co	Cu	Zn	Pb	S	As			
Disseminated ore in jackstraw textured metaperidotite (250E/5S)	7490	168	1736	57	11	3.33	0.01	8.5	0.188	0.022
Fragmental ore (500E/10S)	50860	540	540	220	50	23.90	0.01	8.1	0.005	0.011
Massive ore (270E/5S)	72800	1360	930	100	40	38.60	0.01	7.3	0.013	0.018

Analysed by atomic absorption after leaching with bromine methanol at Outokumpu Oy Exploration, Geological Laboratory, Finland.
Calculation of the nickel content in 100 % sulphides (% Ni_S) assumes 38 % S in disseminated and fragmental ores.

of the tonnage, that is within 76 % and 78 % of the nickel and copper contents, respectively, is located within the gneiss. Corresponding figures for the Mjövattnet deposit are 74 % of the tonnage, and 55 % and 64 % of the nickel and copper contents respectively. The figures for Mjövattnet are only tentative owing to the existence of massive ore in the ultramafic body, the size of which has not yet been accurately established.

Opaque mineralogy (H. Papunen)

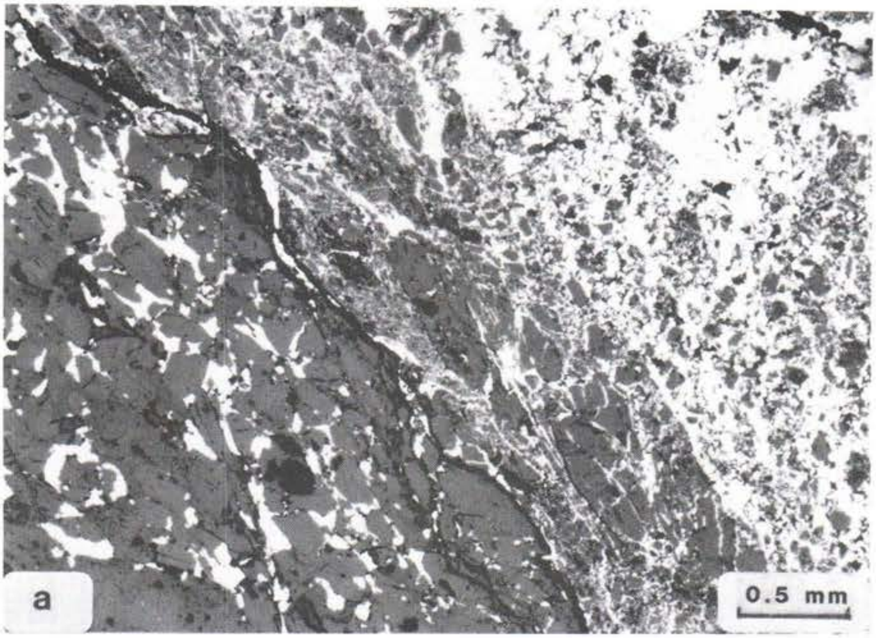
Pyrrhotite, pentlandite and chalcopyrite are the most common opaque minerals in the deposit. Pyrite, graphite, ilmenite and magnetite exist locally in appreciable amounts together with the main ore minerals.

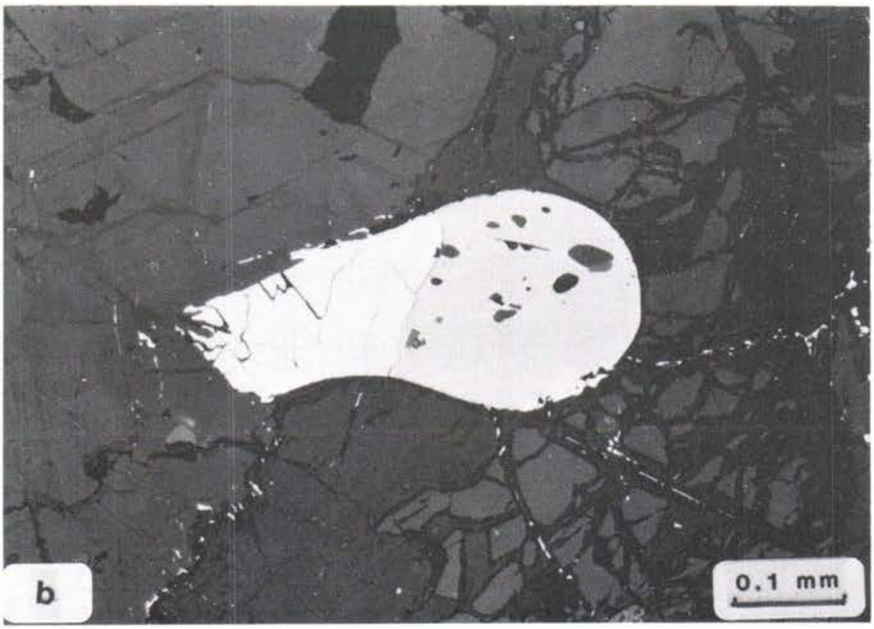
The disseminated ore in metaperidotite is characterized by interstitial sulphide grains with the crystal forms of the enclosing silicates (Fig. 24a). Some grains, however, have typical forms of rounded droplets and constitute inclusions in hornblende (Fig. 24b). The hexagonal variety of pyrrhotite always predominates but pentlandite, too, is locally very abundant.

Monoclinic pyrrhotite exists as minor flakes in hexagonal pyrrhotite together with feathers of exsolved pentlandite. In serpentinized metaperidotites the sulphide grains have been slightly replaced locally by silicate veins (serpentine); pyrrhotite has been attacked more easily than pentlandite, which still occurs as exsolution flames in serpentine. Magnetite is also a common replacing mineral in sulphide blebs, and the cracked pentlandite seems to be the host best favoured by the magnetite veins. Alteration of pyrrhotite into pyrite and marcasite has been observed locally (Fig. 24c).

Massive ore is composed of medium to coarse-grained pyrrhotite with interstitial rods of pentlandite. In places chalcopyrite exists as thin veinlets, but generally the abundance of chalcopyrite is very low. Magnetite and ilmenite exist as rounded inclusions in pyrrhotite. Although common, euhedral inclusions of silicate minerals and graphite flakes are not so abundant as in fragmental ore.

The fragmental ore with sharp contacts occurs in disseminated ore or in gneisses. The form of the breccia fragments varies from euhedral silicate grains to round silicate »balls» and further into finely ground crystal mush. The mica flakes of the fragments locally display distorted, bent forms indicating deformation during brecciation. Pyrite, a common mineral in the sulphide matrix, locally forms fine-grained micrographic intergrowths with pentlandite and chalcopyrite (Fig. 24d); usually,


a
0.5 mm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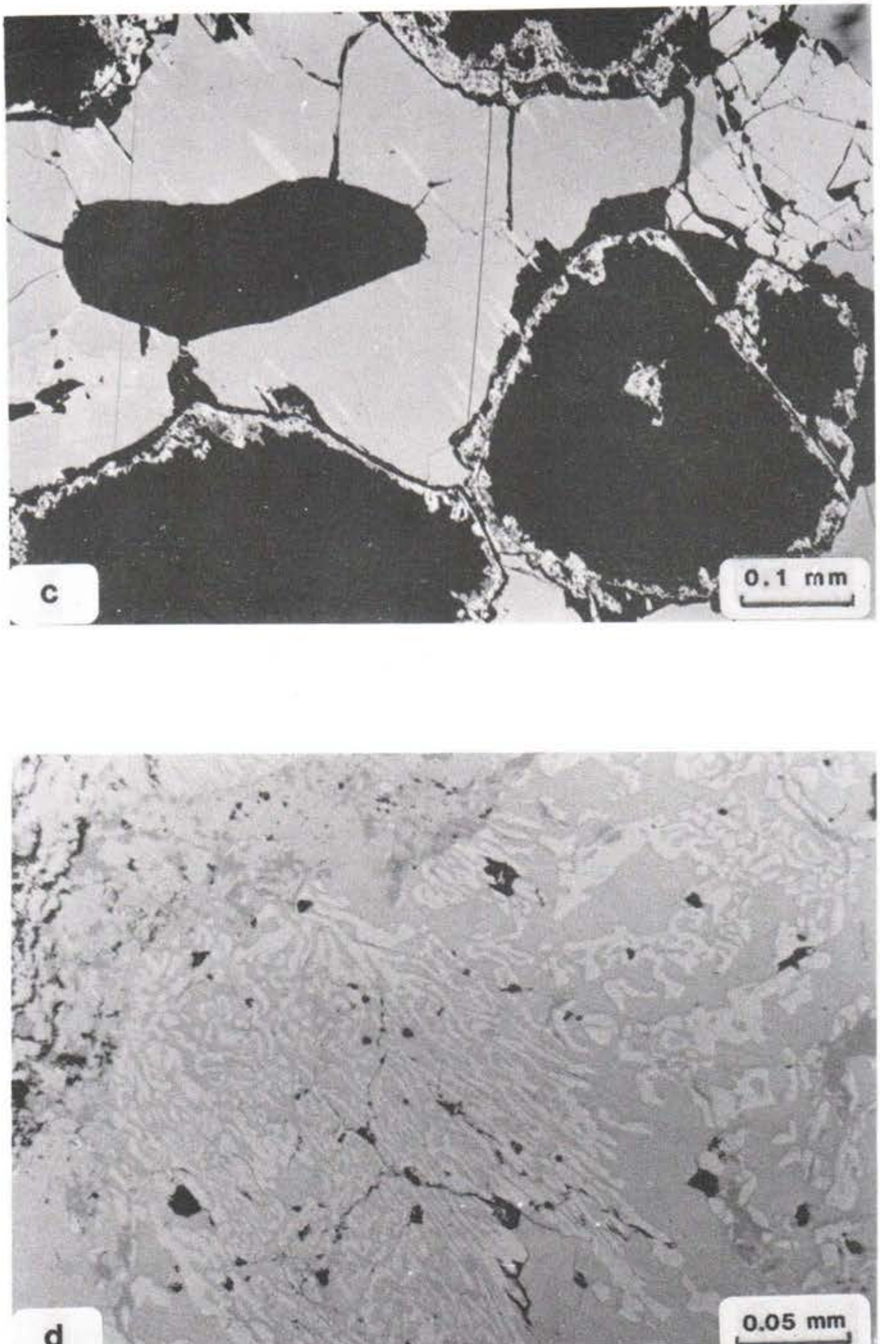

Fig. 24. Photomicrographs of the Lappvattnet ore types a) sulphide microbreccia (right) and interstitial disseminates sulphides in metaperidotite (left); sharp contact between the ore types diagonal in the photograph; b) sulphide drop (pyrrhotite and pentlandite) in metaperidotite; c) secondary fine-grained pyrite (white) rim around altered pyrrhotite-pentlandite grains; d) micrographic intergrowth of chalcopyrite (gray) and pyrite (white); minute pyrrhotite grains are medium gray.

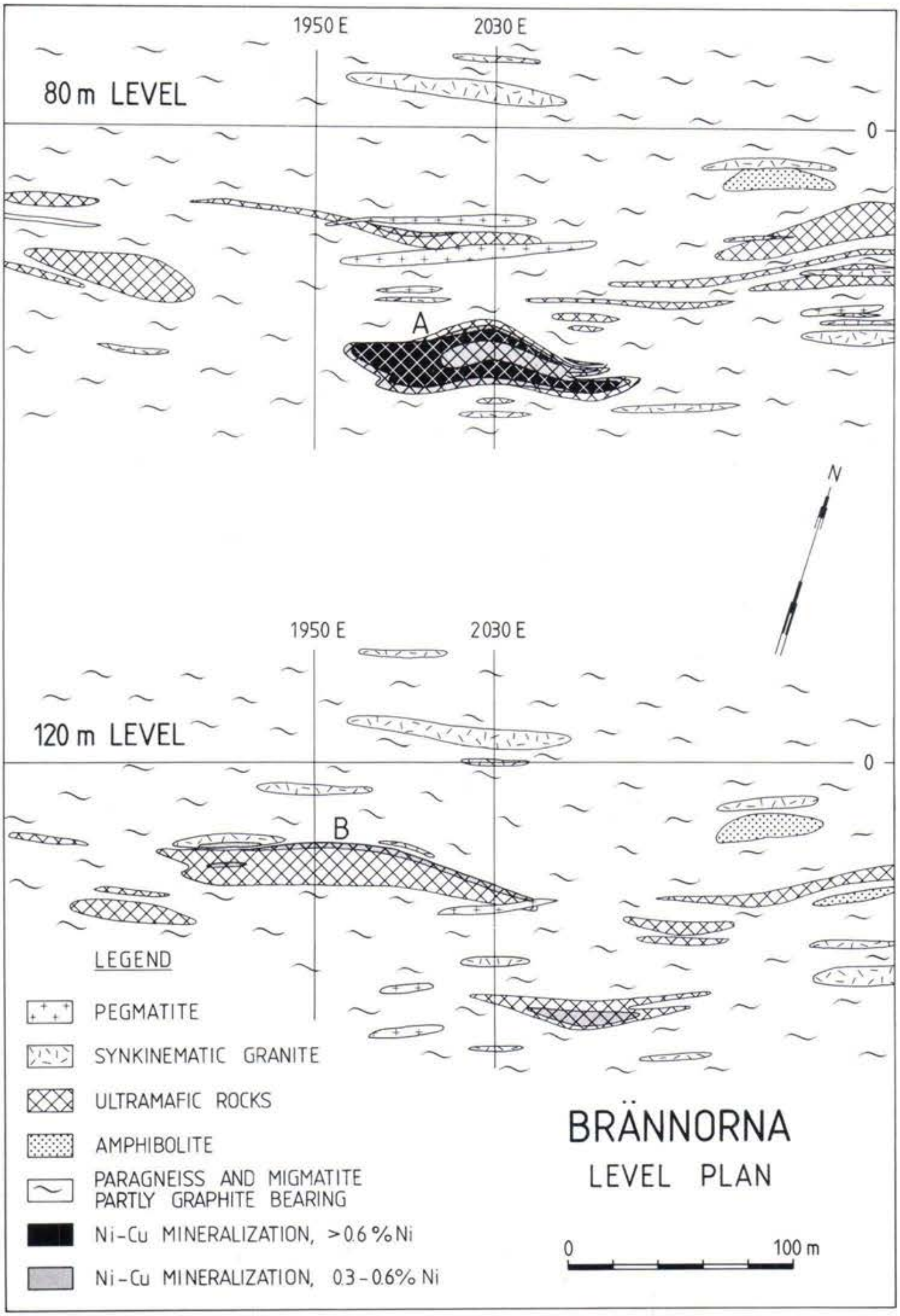

Fig. 25. Brännorna, 80 m and 120 m level plans.

however, it occurs as idiomorphic crystals in pyrrhotite. The magnetic monoclinic variety of pyrrhotite is most common in breccia ore. Pentlandite forms individual grains, and the fine exsolution lamellae are rather rare. Graphite, which is a common mineral in all ore types but is most abundant in the fragmental ore, seems to be a constituent of the host gneissic wall rock. In sections graphite exists as a mass of flakes around breccia sulphides or as inclusions in sulphides. A network of brecciating pyrrhotite intersects the graphite aggregates. In gneissic wall rock graphite occurs as large flakes oriented parallel to the mica minerals.

Accessory opaque minerals include mackinawite and sphalerite that exist together with chalcopyrite. Gersdorffite is rather common and locally contains tiny inclusions of PGM, mainly sperrylite. Molybdenite, nickeline, argentian pentlandite and chromite are rare accessory minerals.

Brännorna deposits

The nickel deposit of Brännorna lies 1.3 km ENE of Lappvattnet (Fig. 14) and is part of the same ultramafic zone. The area is almost entirely covered by Quaternary deposits. The overburden above the mineralization is about 9 m thick.

The nickel and copper mineralizations at Brännorna occur within two parallel ultramafic bodies (Figs. 25 and 26) at different depths. Subordinate mineralizations occur north of these bodies in a narrow zone within gneiss. The mineralizations associated with the ultramafic bodies are of magmatic origin, and almost the entire nickel content occurs within the confines of these bodies.

The tonnage of nickel is larger within the upper A-body, which is 120 m long and up to 40 m wide. It extends from the bedrock surface down to a depth of about 100 m. The rocks in

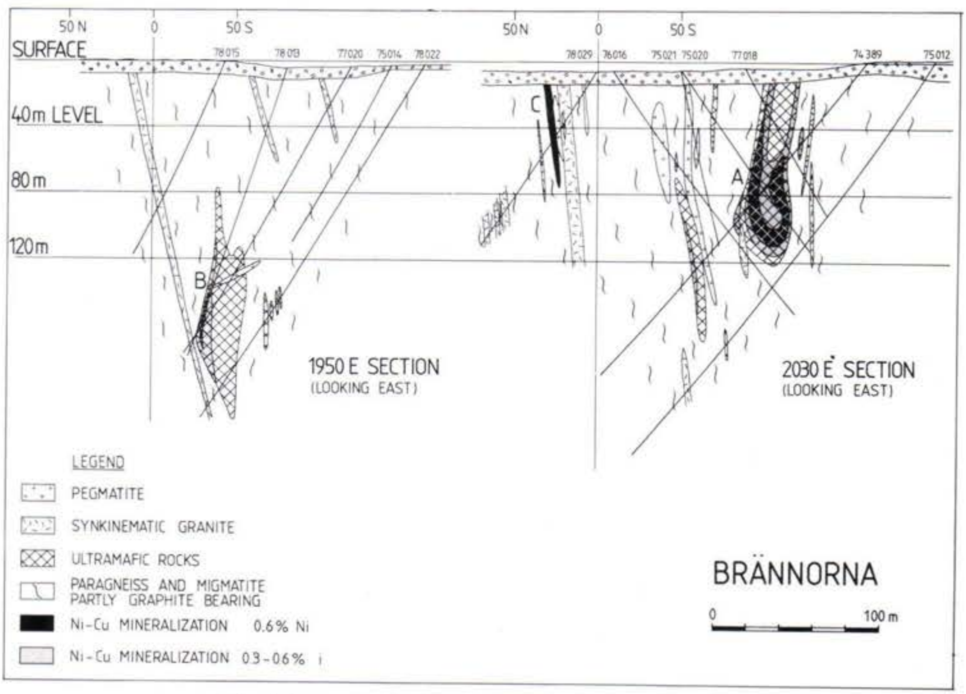

Fig. 26. Brännorna, cross-sections 1950 E and 2030 E.

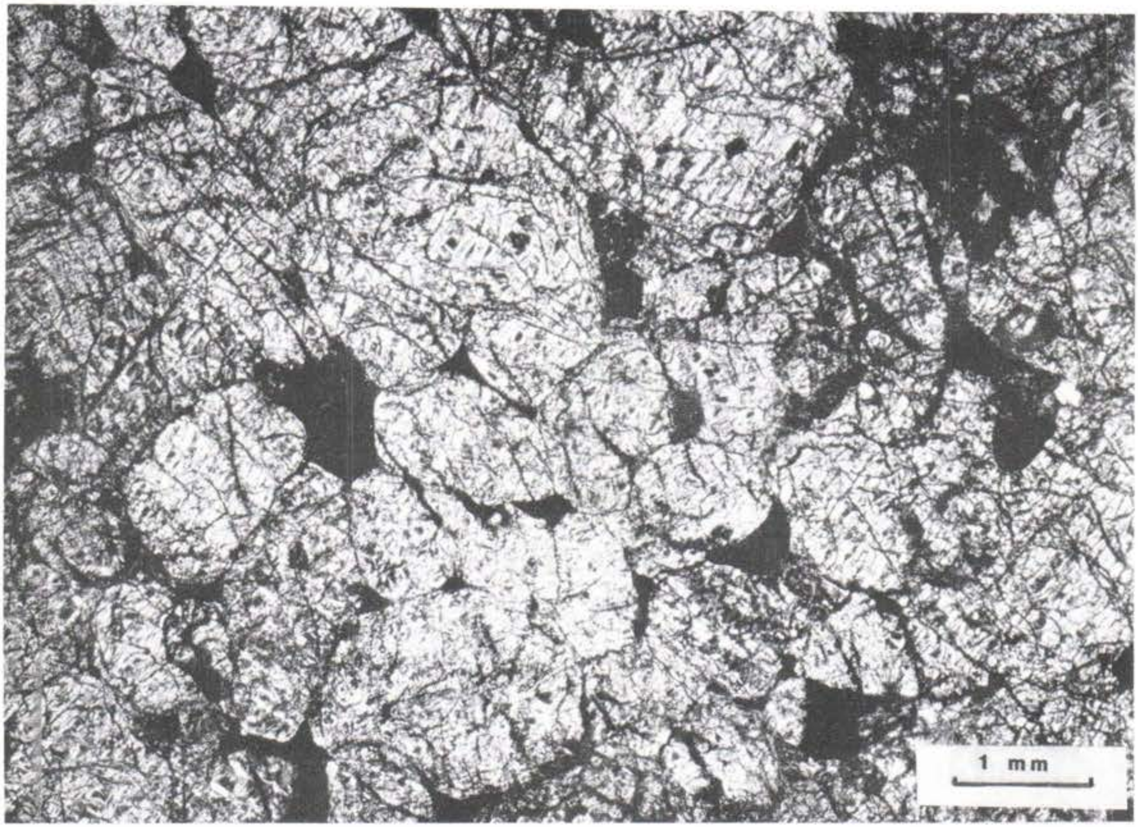

Fig. 27. Photomicrograph of serpentine pseudomorphs after olivine and intercumulus sulphides (black) in serpentinite from the A body at Brännorna. Crossed nicols. Bar scale = 1 mm.

this body contain 32—46 % MgO (calculated volatile free) and consist of serpentinite (metadunite) and metaperidotites. The former rock type is most common in the central and deeper parts of the body and constitutes a serpentinized olivine cumulate. Pseudomorphs after closely packed olivine with interstitial sulphides have been observed in thin sections (Fig. 27). Olivine compositions are uniform about Fo_{87} with 0.2 % NiO.

Disseminated nickel and copper sulphides occur throughout all the rocks, and almost every part of the body contains over 0.3 % Ni (Fig. 28). A narrow zone poorer in nickel is often found close to the contact with the surrounding gneiss. The nickel contents are highest immediately inside this zone, especially where the rock consists of serpentinite. A 2-m wide zone of mineralizated gneiss occurs only at the eastern end of the body, along its northern contact. The body is estimated to contain at least 300,000 tonnes of ore with 0.63 % Ni, 0.04 % Cu, 0.02 % Co and 1.1 % S.

The lower B-body is about 160 m long, up to 25 m wide, and has a vertical extent of about 90 m. The central part of the body consists mainly of metaperidotite, the remainder of metapicrite. The magnesium content, which is generally lower than in the upper body, varies from 26 to 36 wt. % MgO (calculated volatile

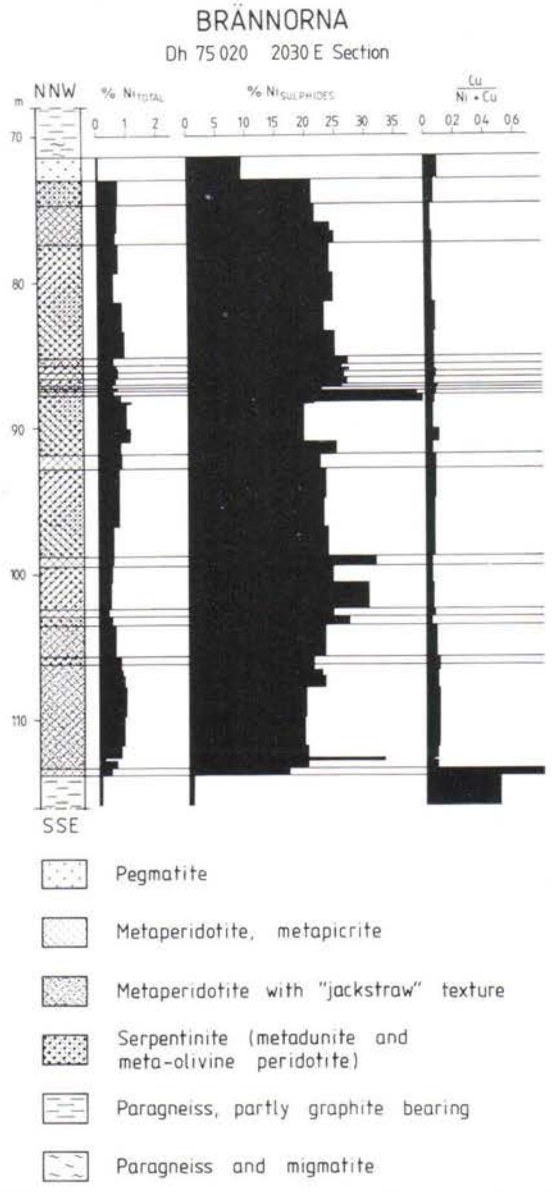

Fig. 28. Variation of sulphide geochemistry in a drill hole intersecting the A body at Brännorna.

free). This body also has disseminated sulphides although continuous disseminations with more than 0.3 % Ni consitute only a small part of the total volume. The highest Ni and Cu-contents are found in a 6-m wide zone near the northern contact. In the gneiss there is a 2-m wide mineralizated zone of restricted extent with dissemination, veinlets, fracture fillings and, in the gneiss, sulphide breccias. This ore body is much smaller than the upper one and has about 50,000 tonnes of ore with 0.62 % Ni, 0.11 % Cu 0.03 % Co and 3.79 % S.

The magnesium content of the upper ultramafic A-body has been estimated to be about 40 % MgO, and that of the lower B-body about 32 % MgO. The difference in MgO content is reflected in the composition of the sulphide phases recalculated to 100 %. The A-body contains more than twice as much nickel as the B-body (Table 7), and so the Cu/(Ni + Cu) ratio is correspondingly lower for the A-body. The great differences in sulphide compositions depend in part on upgrading of sulphides with silicate nickel in the A-body (Fig. 29).

The sulphide breccias of the contact mineralization in the B-body are as poor in copper in relation to nickel as is the fragmental ore in Lappvattnet. The nickel content in 100 % sulphides, however, is only about 3 % Ni. The breccias are thought to be metamorphic ore formations in shear zones.

The separate nickel-copper mineralization in the gneiss, i.e. the C-body, is similar in type to the disseminated ore of the Lappvattnet deposit and probably lies within the same zone of tectonic weakness. The mineralization, which is known only from three drill holes, assays 0.48 % Ni,

Table 7. Calculated compositions of disseminated sulphides in ultramafic rocks of the Brännorna deposit.

Ultramafic body	% Ni_S	% Cu_S	% Co_S	$\frac{Cu}{Ni+Cu}$	$\frac{Co}{Ni+Co}$
A	22.4	1.6	0.6	0.07	0.03
B	8.1	1.4	0.3	0.14	0.04

Calculation of % Ni_S, % Cu_S and % Co_S in 100 % sulphides assumes an average content of 38 % S.

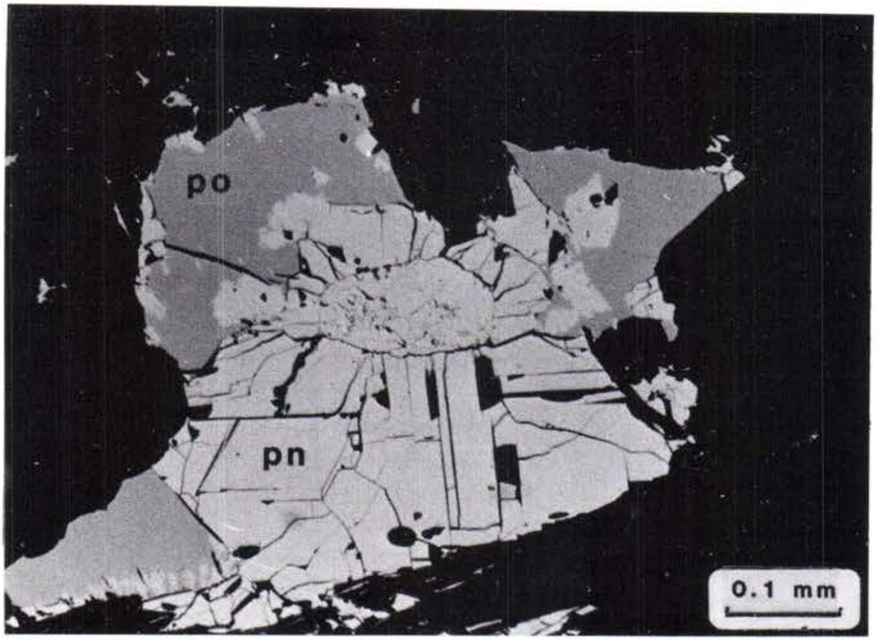

Fig. 29. Photomicrograph of the Brännorna A-orebody depicting pentlandite-rich sulphide grains (pn = pentlandite, po = pyrrhotite).

0.26 % Cu, 0.01 % Co and 3.06 % S. The nickel content in 100 % sulphides is about 6 % Ni_S and the Cu/(Ni+Cu) ratio is 0.15.

Mjövattnet deposit

The deposit is beneath a small lake immediately west of Mjövattnet, a village 25 km south of the town of Skellefteå (Fig. 5).

Small sills of ultramafic rocks occur in two parallel zones along the northwestern side of a fault east of the deposit (Fig. 14). Most of these ultramafic bodies lack or are poor in sulphides but they are all composed of similar rock types, i.e. metaperidotites and metapicrites. The sulphide mineralization, which closely resembles the Lappvattnet deposit, forms a NE-SW-striking slab of gneiss, the southwestern end of which contains a metaperidotite body.

The mineralization differs from the Lappvattnet deposit in that a thin slab of massive ore occurs in the central part of the ultramafic body. Only one drill hole has penetrated this part of the deposit. The position of the slab indicates a certain relationship between the massive ore and the narrow zone of fragmental ore that is present in the mineralized gneiss. The fragmental ore is, however, much finer grained than the massive ore. The ultramafic rock in the drill hole (to the southeast of the massive ore) is twice as rich in nickel as that to the northwest (Fig. 30). The nickel content recalculated to 100 % sulphides, however, is somewhat higher in the northwestern part.

The deposit is estimated to contain 200,000 tonnes of ore with 1.4 % Ni, 0.2 % Cu, 0.01 % Co and 5.1 % S. The compositions of the sulphide phases in the different ore types are shown in Table 8. Comparison with Tables 5—6 shows a similarity with the values given for Lappvattnet.

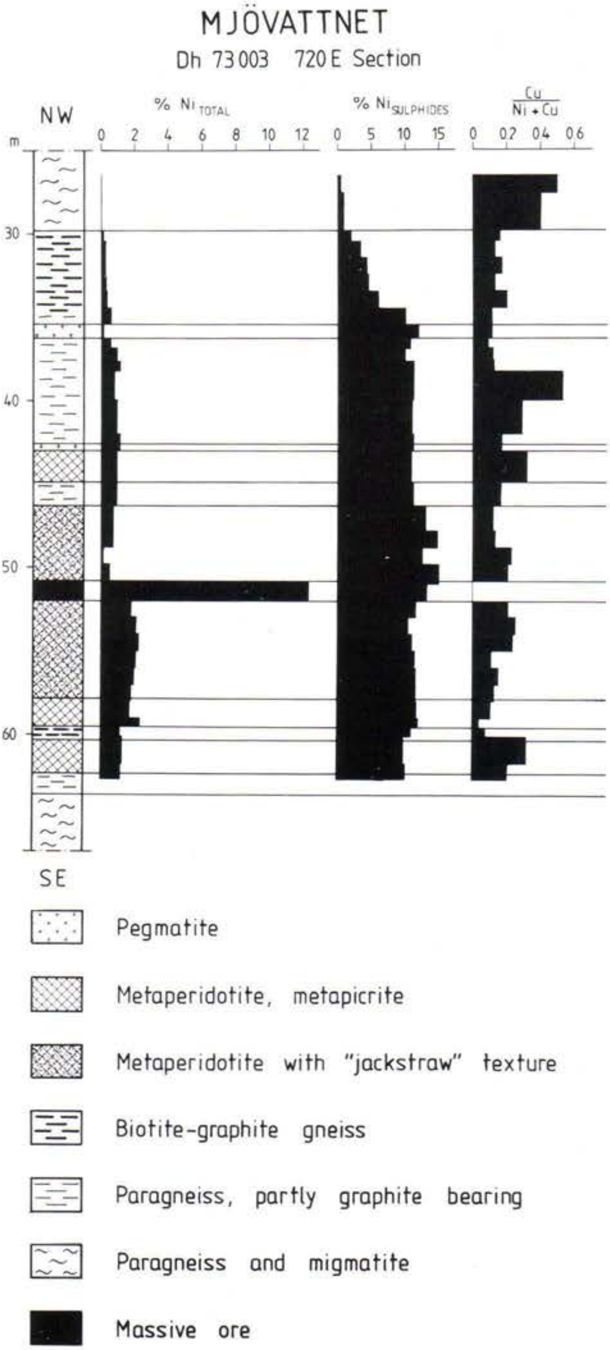

Fig. 30. Variation of sulphide geochemistry in a drill core intersecting the ultramafic body in the southwestern part of the Mjövattnet deposit.

Table 8. Calculated composition of the sulphide phases in the Mjövattnet deposit.

	% Ni_S	% Cu_S	% Co_S	$\frac{Cu}{Ni+Co}$	$\frac{Co}{Ni+Co}$
Disseminated ore in ultramafic rocks	11.6	2.8	0.2	0.19	0.02
Massive ore	13.6	0.07	0.18	0.01	0.01
Disseminated ore in gneiss	7.6	1.6	0.1	0.18	0.02
Fragmental ore	8.2	0.1	0.1	0.01	0.01

Calculation of % Ni_S, % Cu_S and % Co_S in 100 % sulphides assumes an average content of 38 % S.

Deposits of the Vindeln area

Geology

The Vindeln area encompasses the western part of the ultramafic zone Bureå-Örträsk. The area includes the Rörmyrberget deposit and some other very small nickel-copper occurrences (Fig. 5).

The predominant rock types in the area are paragneisses and migmatites of the same type as in the Lappvattnet area. Most of the nickel deposits are surrounded by graphite and sulphide-bearing gneisses. The Rörmyrberget deposit is an exception. The host rocks of this ultramafic body consist mainly of garnet-bearing veined gneisses.

Quartz-feldspar gneisses of volcanic origin are rare. Massive or layered amphibolites occur subordinately in many places, particularly near Rörmyrberget. A larger area of amphibolites is situated about 25 km WNW of Vindeln. Slightly schistose volcanic conglomerates and breccias, presumably of volcanic origin, have been found in this area in a layered succession of pyroclastic rocks and metasediments. Rocks of basaltic and picritic compositions occur as fragments in the conglomerates (Fig. 31). The area is best correlated with the Knaften area farther to the WNW.

A large number of ultramafic bodies are known within the Vindeln area. They vary considerably in size, the largest intrusion being at Rörmyrberget. Many of the bodies, however, are small and of approximately the same dimensions as those in the Lappvattnet area, that is, seldom more than 150 m long and 40 m wide.

The composition of the ultramafic bodies, both in rock type and mineralogy, is also very similar to that of the ultramafic bodies in the Lappvattnet area. The amount of serpentinite is probably somewhat higher and the »jackstraw» texture is less common in the metaperidotites. Another difference is that many of the ultramafic bodies exhibit a regular structure of serpentinite bands in a matrix consisting of pyroxene and amphibole. The rocks commonly grade into amphibolites, and some of them give the impression of being strongly compressed volcanic breccias or conglomerates. They often contain finely disseminated pyrrhotite, which is always low in nickel.

The majority of the ultramafic bodies are distributed along two parallel zones following the structure of the gneisses in an E-W to ENE-WSW direction (Fig. 5). Rörmyrberget and the small Gårkälen deposit are in the northern zone. Several ultramafic bodies are found out-

Fig. 31. Volcanic conglomerate containing rock fragments of basaltic and picritic composition; 25 km WNW of Vindeln.

side these zones but their internal relationship is not yet known; some of them may belong to the other parallel zones mentioned above, whereas others are isolated deposits. The very low-grade nickel-copper deposit at Kälen belongs to the latter category.

In contrast to the Lappvattnet area, the zones of ultramafic bodies do not follow distinct faults; rather their appearance seems to have been affected by folding. The supracrustal rocks in the area have been subjected to two phases of deformation at least. Isoclinal folds of an older deformation phase seem to have strongly affected the distribution of rocks. Their axial planes are slightly overturned to the south, and the strikes of the fold axes are often parallel to the observed ultramafic zones. A later deformation phase with open folds and fold axes striking about N-S has further complicated the rock distribution. There was probably also a still later deformation phase with fold axes about NW-SE or possibly NNW-SSE, but its influence is still not clear.

Rörmyrberget deposit

Rörmyrberget probably has the largest tonnage of low-grade nickel ore of all the deposits in the nickel district. The deposit is situated 14 km NNE of the village of Vindeln in an area covered largely by bogs. Diamond drilling investigations were performed in 1979—82, but knowledge of the ultramafic body is still very limited.

The ultramafic intrusion can best be described as a multiple sill. The sill is 1700 m long and up to 320 m thick. It strikes E-W and dips from subvertical to about 60° to the south. The plunge has not been established.

The intrusion is older than the isoclinal folding and has been affected by later faults. Cross-cutting pegmatite dykes are very common, and a few narrow synkinematic granite dykes have also been observed.

Drill holes through the larger sills show that the ultramafic rocks are layered. Two or more differentiated layers have been observed in several drill holes. Identified layers consist largely of metapicrites and to a lesser extent of gabbroid rocks. Metaperidotites and serpentinites are common in the basal parts. The serpentinites are cumulates. Pseudomorphs after cumulus olivine are fairly common, especially in the serpentinites. Layers with pyroxene cumulates probably also occur, but they are too strongly altered for identification. In places »jackstraw» texture has developed in the metaperidotites.

The MgO content of the rocks commonly varies between 12 % and 30 % but there are cumulates with more than 40 %. The CaO/Al_2O_3 ratio tends to be close to unity. Parts of the intrusion, however, show an alumina-depleted trend.

In over 90 % of the samples analysed, olivine composition range from Fo_{82} to Fo_{91} with a maximum of about Fo_{88-89}. The content of nickel in the olivine is 0.02—0.41 % NiO.

Nickel and copper sulphides occur as disseminations in several layers of the sills and in cross-cutting shear zones as well. Interstitial sulphides have been observed in serpentinized olivine cumulates, and sulphide droplets occur in some of the disseminated layers. Ore breccias are less common.

About ten ore bodies can be distinguished with a cutoff of 0.6 % Ni. They contain 140—4,100 tonnes of nickel and they grade from 0.6 % Ni to 1.5 % Ni. Lowering of the cutoff to 0.4 % Ni gives 7,000 tonnes of nickel for the largest body. The average Cu/(Ni + Cu) ratio is 0.09 with a variation of 0.06—0.16. The nickel content in 100 % sulphides is commonly 7—10 % Ni or 18—23 % Ni, depending on the MgO content of the host rocks, the highest values being in serpentinites. One of the ore bodies

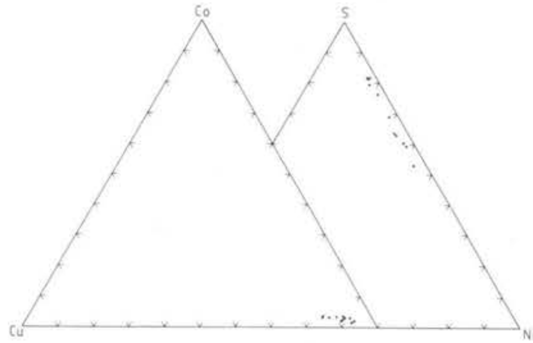

Fig. 32. Ni-Cu-Co and Ni-Cu-S diagrams depicting compositions of different orebodies in the Rörmyrberget deposit.

is conspicuously rich in fine-grained pentlandite in relation to other sulphide minerals. Consequently the nickel content of sulphides is 32 % Ni. In that ore body, some of the pentlandite at least was formed during serpentinization of the olivines. Upgrading with silicate nickel seems to have influenced the nickel content of sulphides in other serpentine-rich layers of the intrusion, too (Figs. 33a and b).

Only a few analyses of platinum and palladium are available from Rörmyrberget. A sample of disseminated sulphides from an outcrop of metaperidotite contains recalculated in 100 % sulphides 33 g/t Pt and 39 g/t Pd, which gives a Pt/(Pt + Pd) ratio of 0.46. Samples from drill cores have given much lower contents. The above ore body rich in pentlandite contains 3.6 g/t Pt and 7.3 g/t Pd in sulphides, thus having a Pt/(Pt + Pd) ratio of 0.33.

The sulphide geochemistry of the ore bodies of the Rörmyrberget deposit is illustrated in figure 32.

Selecting the cutoff of 0.4 % Ni, the current proven ore reserves of Rörmyrberget are about 4 mill. tonnes with an average of 0.6 % Ni and 0.06 % Cu. Raising the cutoff to 0.8 % Ni, gives 660,000 tonnes of ore with 1.1 % Ni and 0.08 % Cu. However the ore bodies are too scattered, thin and poor in nickel to have economic interest.

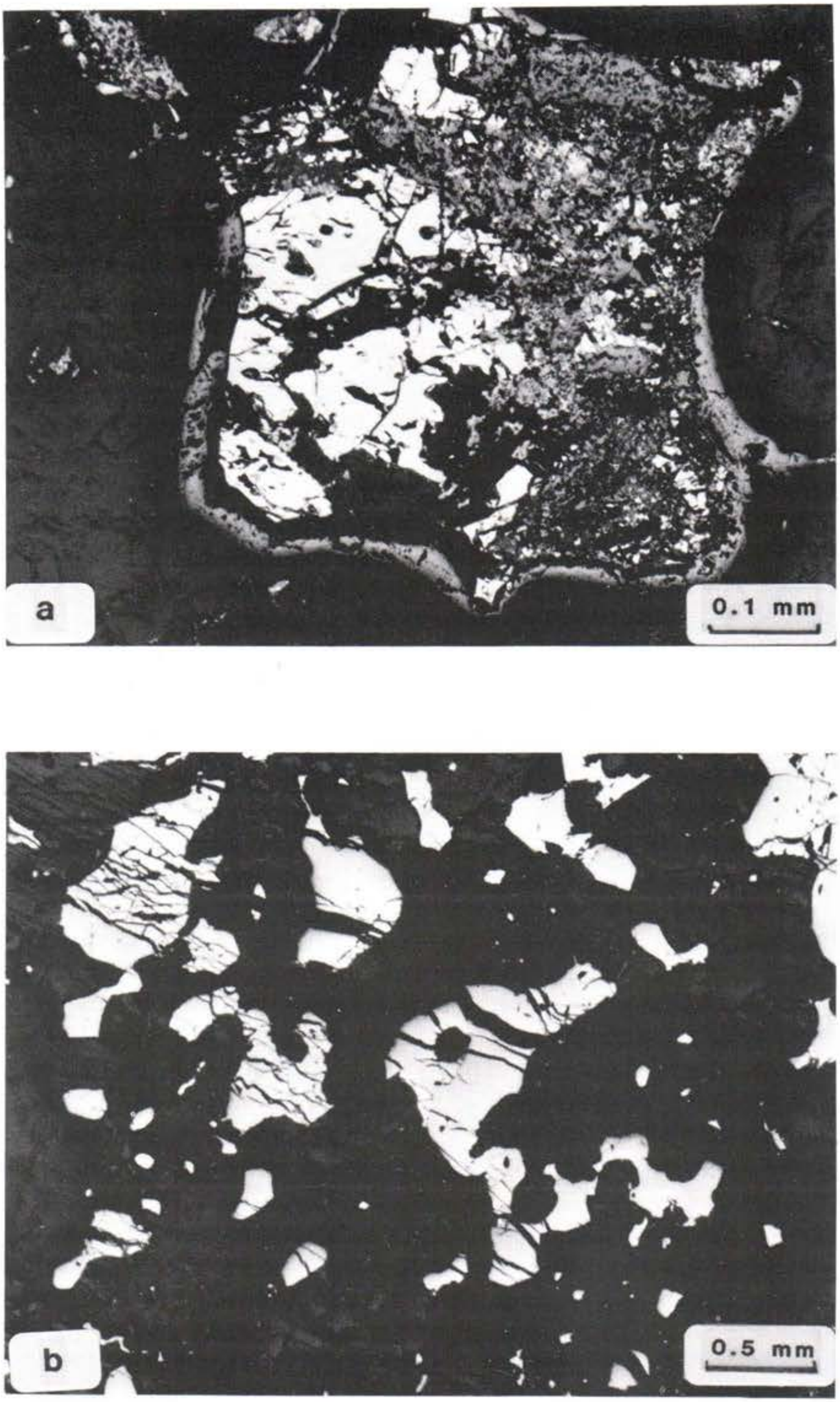

Fig. 33. Photomicrographs of the Rörmyrberget disseminated sulphides: a) pentlandite grain capsulated by magnetite, b) intersitial sulphides.

Deposits of the Risliden area

This area is situated in the northwestern part of the nickel district and differs geologically from the Lappvattnet and Vindeln areas in that the main structures of the bedrock trend NW-SE. Known mainly from the diamond drill investigations carried out during 1979—1982 ultramafic sills are located in a zone at least 10 km long and a few hundred metres wide extending in the same direction as the main geological structures. The bedrock along this zone is composed mainly of strongly isoclinal folded, largely graphite and sulphide-bearing paragneisses. Amphibolites occur as intercalations in especially graphite-poor layers of the paragneisses. The amphibolites are considered to be of pyroclastic origin. All these older rocks are intensely intruded by pegmatites and to a lesser degree by late kinematic granites.

Subeconomic low-grade nickel-copper sulphide mineralizations have been found in association with five small ultramafic bodies. The largest two are about 300 m long, from less than one metre up to 10 m wide and at least 200 m deep. They are composed mainly of metapicrites, but metaperidotites and serpentinites (metadunites) are also very common, especially in the central parts of the bodies. In places the metaperidotites exhibit »jackstraw» texture. Subordinate massive amphibolites have been observed together with metapicrite in the largest ultramafic body. They probably represent a gabbroid part of the intrusive body.

Only a few host rock analyses are available from the deposits. Their MgO content varies 20—42 % (anhydrous), and the CaO/Al_2O_3 ratio is 0.7—1.4. Olivine compositions determined for two of the deposits are $Fo_{83.3}$ respectively $Fo_{84.4}$ and 0.06—0.07 % NiO.

Nickel and copper sulphides occur as disseminations, veinlets and sulphide breccias in all types of ultramafic rocks as well as in the gneisses in the immediate vicinity and in the pegmatites. Most of the contained nickel, however, is situated within the limits of the ultramafic bodies. A striking feature in the mineralogy of the Risliden deposit is that accessory arsenides are more common in them than in other deposits of the nickel district. The arsenides have been observed in sulphide veinlets in particular. The largest Risliden ore body contains a small »jackstraw»-textured sulphide ore in serpentinite. It is characterized by elongate serpentines in matrix of massive sulphides containing 5—6 % Ni recalculated in 100 % sulphides. A similar texture has been described as »interstitial spinifexoid» from Birchtree mine in Thopmson Belt, Canada, by Peredery (1982, p. 196 and Figure 20).

The nickel percentage in the various ore bodies is consistently about 0.7 % whereas the copper and cobalt contents vary within the ranges of 0.1—0.4 % and 0.02—0.05 % respectively. Recalculated to 100 % sulphides, the largest ore body contains 5.7 % Ni, 3.2 % Cu and 0.2 % Co. Corresponding values for the next two largest are 3.3—4.0 % Ni, 0.6—0.8 % Cu and about 0.2—0.3 % Co. The Cu/(Ni+Cu) ratio is 0.36 for the largest ore body and 0.14—0.20 for the others.

The ore breccias of the Risliden deposit contain 0.9—2.3 % Ni and have a Cu/(Ni + Cu) ratio of 0.02—0.31 or an average of about 0.1. Their nickel content in 100 % sulphides is commonly somewhat lower than the average for the ore bodies.

PGE have been proven in two ultramafic bodies. Analysed sections of a drill core from the largest nickel ore body contains an average of 14.4 g/t Pt, 9.4 g/t Pd and 0.3 g/t Ir in 100 % sulphides. Corresponding values for one of the smaller ore bodies are 1.90 g/t Pt, 1.25 g/t Pd and 0.36 g/t Ir. The Pt/(Pt + Pd) ratios are 0.60 in both cases, whereas the Pd/Ir ratios are different, i.e. 2.6 and 35, respectively.

THE CLASSIFICATION OF SWEDISH NICKEL DEPOSITS

In this paper the nickel sulphide deposits of Sweden are grouped for descriptional purposes into those of mafic and ultramafic association. Available information on the mafic deposits in particular is too scarce for a more detailed division. There are, however, distinct differences in the MgO contents of the host rocks and the compositions of sulphide concentrations between the ultramafic deposits of the Västerbotten district and almost all the other nickel sulphide deposits elsewhere in the country. The low-alumina peridotites and detrital serpentinites of the Caledonides also constitute well defined groups of deposits, but they are beyond the scope of this paper, because the nickel concentrations in them are of metamorphic origin.

The ultramafic-associated nickel deposits in the Västerbotten district commonly have most rocks containing more than 18 % MgO, although lower contents may occur subordinate in some of them. The mafic deposits on the other hand have only a few cumulates with this much MgO.

The differences in MgO content between the two groups of host rocks are reflected in the Ni-Cu-S diagram (Fig. 34) and in the calculated nickel content in 100 % sulphides (Fig. 35). Especially the latter plot shows a clear difference between the nickel-richer ultramafic deposits and the nickel-poorer mafic deposits. The same plot also shows the diverging high contents of the nickel in the sulphides of the Brännorna A body and some of the ore bodies comprising the Rörmyrberget deposit. The divergence has been attributed to upgrading of the nickel sulphide content by silicate nickel during serpentinization in accordance with the model presented by Eckstrand (1975).

Differences between the mafic and ultramafic deposits are also prominent in the Ni-Cu-Co diagrams (Fig. 34), even if the proportions of

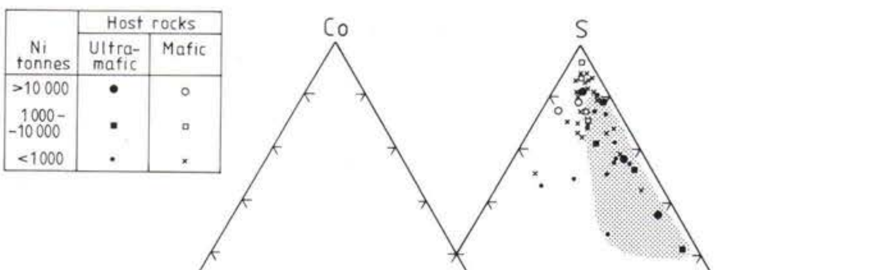

Fig. 34. Ni-Cu-Co and Ni-Cu-S diagrams depicting the sulphide compositions of Swedish nickel sulphide deposits. The deposits associated with ultramafics of the Västerbotten district fall inside ruled areas.

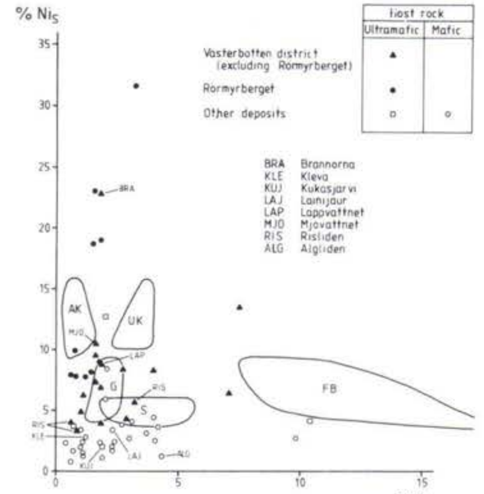

Fig. 35. Plot of the contents of Ni_S and Cu_S calculated in 100 % sulphides for Swedish nickel sulphide deposits (assuming 38 % S in sulphides). Comparison is made with Naldrett (1982) for deposits of different associations (AK = Archaean komatiites, UK = Ungava komatiites, S = Sudbury, G = other gabbros, FB = flood basalts).

nickel and copper have been only roughly estimated for many of the ore bodies. The ratio Cu/(Ni + Cu) is on an average lowest in the Västerbotten group of deposits in accordance with the MgO-richer nature of their host rocks in relation to the bulk of the mafic deposits (Wilson and Anderson 1959, Naldrett and Cabri 1976).

Applying the classification of Naldrett and Cabri (1976) in the revised form proposed by Naldrett (1981), all the deposits of the Västerbotten district and the majority of the other Swedish deposits are connected with synorogenic intrusions in the Svecokarelian fold belt; they should therefore be included in the main class of »bodies emplaced during orogenesis» (class Cl). The low-alumina peridotites and detrital serpentinites belong to the same main class, in which they best correspond to »possible mantle diapirs» in the subclass of »tectonically emplaced bodies» (class C2a). A few deposits associated with dolerite dykes, for example the Lundörren deposit, have to be grouped as »other medium and small intrusions» in the main class of »intrusions in cratonic areas» (class B3).

The relevance of the proposed classification to the ultramafic deposits of the Västerbotten district is questionable. Many of the ultramafic bodies there appear to be connected with some volcanic activity, possibly rift volcanism, and therefore the main class of »synvolcanic bodies» (class A) would seem to be more valid. Volcanic activity produced mainly thin successions of basaltic lavas and pyroclastic rocks, although subordinate ultramafic volcanic rocks also occur in several areas. If the inferred volcanic breccias of the Knaften area are accepted as originating from a komatiitic melt, the ultramafic intrusives of the district may also have komatiitic parental magmas; in any case their main element geochemistry is similar to that of komatiites. On the other hand, most of the nickel deposits in the district have nickel contents, recalculated to 100 % sulphides, which are low in

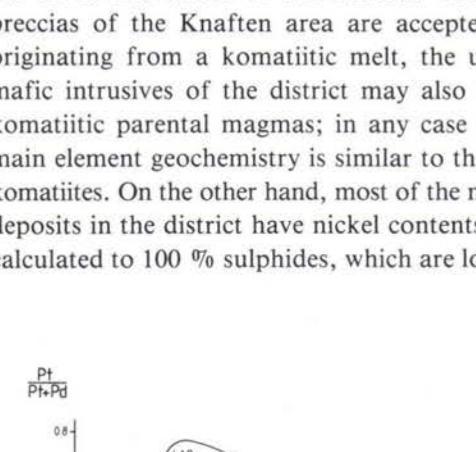

Fig. 36. Plot of Pt/(Pt + Pd) versus Cu/(Cu + Ni) for some nickel occurrences in the Västerbotten district in comparison with the deposits reported by Naldrett (1982). BAS = Bastuviken, LAP = Lappvattnet, MUN = Munkviken, RIS = Risliden, RÖR = Rörmyrberget and SÄV = Sävar.

relation to the values reported by Naldrett (1981). The comparison made in Fig. 35 indicates a similarity to gabbro related deposits. The available analyses of platinum and palladium in Fig. 36 do not represent all of the deposits and must therefore be used with some caution. The plot compares the ratios Cu/(Ni + Cu) and Pt/(Pt + Pd) of analysed samples from some of the Västerbotten deposits with the corresponding ratios of different deposits reported by Naldrett (1981). Again the similarity to the gabbro related deposits is obvious. The only sample that plots inside the field of Archean komatiites is from one of the Rörmyrberget ore bodies.

Ecxept for the main element geochemistry, it seems very likely that the deposits of the Västerbotten district are related to tholeiitic magmas. Further studies are, however, necessary before that can be confirmed. If they are to be classified as »synvolcanic bodies», then currently the most appropriate subclass is that of »uncertain type in tectonically reworked terranes» (class A3b).

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NORWEGIAN NICKEL DEPOSITS: A REVIEW

R. BOYD and F. NIXON

INTRODUCTION

Historical background

Nickel mining in Norway began shortly after the first description of iron-nickel sulphide, later called pentlandite, by T. Scheerer, professor of metallurgy at the University of Kristiania (Oslo) in 1845 (Scheerer 1845). Scheerer's samples came from the Espedalen deposit in central S. Norway (Fig. 1), at which copper had previously been mined, and from which nickel was mined from 1848. This was rapidly followed by mining at Ertelien (1849) and in the period 1859—1883 by operations in the Bamble area on the S. coast (Meinkjær, Nystein), at Romsås, Sigdal, Senja, Evje, Skjækerdalen and at Hosanger (Fig. 1) (Vogt 1901). Production peaked at 283t Ni metal/year in the period 1874—76 at which time Norway was the world's leading producer of the metal (Vogt 1892). Subsequently production in Norway declined and the bulk of the world's nickel in the 1880s came from the then recently discovered lateritic deposits in New Caledonia. With short breaks nickel mining at several of the larger deposits in S. Norway continued until 1945 when mining at Hosanger and Flåt ceased because of lack of reserves.

Active exploration for new nickel deposits has continued however, at a particularly high level in the early 1970s, and has led to the discovery of one new deposit of significance, the Vakkerlien deposit SSW of Trondheim (Thompson *et al.* 1980), and to an increase of several 100 % in the reserves of the previously known Bruvann deposit in the Råna layered intrusion in N. Norway (Boyd & Mathiesen 1979), the latter being by far the largest deposit known in Norway.

Geological background

Orogenic belts spanning the time period from the Upper Archean to the Lower Palaeozoic are found in Norway. Nickel mineralizations are known from the continuations of Lower and Middle Proterozoic and Archean rocks in N. Norway into Finland and the Soviet Union (Gorbunov 1968; Papunen *et al.* 1979) (Plate 1), but prospecting to date in Norway has failed to reveal other than modest showings in rocks of these periods (see below). The deposits to be reviewed in this paper fall almost without exception into:

a) the Upper Proterozoic (= Sveconorwegian = Grenville) orogenic belt of S. Norway, or
b) the Caledonian orogenic belt.

In a) almost all the host complexes are relatively small intrusions, of a dominantly mafic, as opposed to ultramafic, character while b) includes mineralizations in mafic and ultramafic cumulates in layered intrusions and mineralizations in obducted ophiolites as well as in other bodies less easily characterized. The deposits will be treated in the order outlined above with, in addition, a summary of prospecting results in other areas regarded as having a potential for nickel mineralization.

ARCHEAN

In Norway Archean rocks are confined to the extreme north of the country, in the Lofoten islands and in Finnmark on the Finnish and Russian borders. The Archean is composed mainly of granitic and gneissic rocks, but it also contains members of a typical greenstone-belt association as in the Karasjok area of the Finnmark mountain plateau, which extends to the south into Finland (Gaál *et al.* 1978; Papunen *et al.* 1979).

To date no nickel deposits of any importance have been found in the Norwegian Archean, but several areas have been regarded as having nickel potential and have been the object of exploration. The two most important areas are the granitoid/gneiss area in southern Pasvik near the Russian border and the Karasjok greenstone belt.

South Pasvik

The south Pasvik area became of interest for nickel exploration with the discovery in 1977 of several erratic boulders of mineralized ultramafic rock. Since that time a concerted effort has been made to locate bedrock sources of this mineralization (Nixon 1982).

The area is a high grade metamorphic terrain dominated by granitic and biotite hornblende gneisses. Mica schists, amphibolites and pyrrhotite-rich garnet amphibolites have also been recognized. Zones of ultramafic rock and olivine gabbro intrusives have subsequently been discovered during exploration. This geological environment extends to the east into the USSR and to the west into northern Finland. In both Finland and in the USSR ultramafic rocks occur with some associated nickel sulphide mineralization, e.g. Allarechka (Likhachev 1978).

The mineralized boulders in Pasvik are all essentially harzburgitic in mineralogy. The best boulder grades 3.47 % Ni, 0.53 % Cu and 10.8 % S. The average grade of 17 discovered boulders is 1.837 % Ni, 0.71 % Cu and 6.6 % S. In the subsequent search for a bedrock source for these boulders several highly altered peridotites were discovered in the area. These ultramafic bodies display features indicative of recrystallization under conditions of moderately high metamorphic grade. No nickel sulphides were found associated with them. Olivine, serpentine, amphibole (after pyroxene) and phlogopite are the dominant silicates with magnetite being the dominant opaque mineral.

Several of the boulders contain significant amounts of colourless amphibole (tremolite). This is the case for the discovery boulder in the area. This rock is a medium-grained, granoblastic ultramafic rock consisting of 40 % olivine and 25 % colourless amphibole and has a high sulphide content. Sulphides (25 % Po, 4 % Pn) appear to form a net texture around the silicate grains and, although partially recrystallized, the texture is probably magmatic in origin. Boulder tracing has led to the discovery of two outcrops of olivine gabbro in the area close to the Soviet and Finnish borders in the most southerly part of the Pasvik area. Sulphide contents of the rocks are generally less than 3 %. The highest assay values obtained were 0.27 % Ni and 0.33 % Cu from a sample which had a visually estimated sulphide content of 3—5 percent. The arithmetic mean Cu/Cu + Ni ratio of 18 assayed samples is 0.39 indicating a slight enrichment of nickel relative to copper.

Karasjok Greenstone Belt

Henriksen (in press) has described a komatiite-bearing sequence of greenstones in the Karasjok area of Finnmark. Although metamorphosed to lower amphibolite facies these rocks locally show primary volcanic features and chemical data indicate the presence of both a komatiitic and a tholeiitic series. The sequence was thought to be of uppermost Archean age, based on dating of a cross-cutting dyke (Meriläinen 1976) and a correlation with more closely studied units in Finland. To date only a limited part of the Karasjok Greenstone Belt has been the object of detailed prospecting, this without the discovery of significant mineralization. Recent Sm-Nd work (Mearns & Krill, pers. comm. 1985) indicates a L. Proterozoic age for this belt.

PROTEROZOIC

The boundary between the Archean and the Proterozoic in northern Norway is poorly defined, but available evidence suggests that Lower Proterozoic rocks are dominant in the Proterozoic of the northern part of the Baltic Shield in Norway while Middle Proterozoic rocks are dominant in the southern part. For many of the Proterozoic deposits our knowledge, both on the local and regional scales, is so limited as to prohibit their ready assignment within any of the published classifications of nickel deposits (e.g. Naldrett 1981a); they will be treated in an approximate geographical order, from north to south.

Pasvik

In the eastern part of Finnmark in the Pasvik valley, the Petsamo Group of rocks which in the USSR hosts several nickel sulphide deposits (Gorbunov 1968) crosses into Norway. The Petsamo Group in Pasvik is much thinner than in the USSR. It extends in the form of an arc-like synclinorium from Skogfoss on the Russian border to Spurvtjønn on the Finnish border, a distance of some 34 km. In the central parts of the area it has a maximum thickness of some 8 km, thinning down to 2 km in the west. No formal stratigraphy has yet been established for the Petsamo Group in the Pasvik region. From the available data however the preliminary stratigraphic sequence shown in Table 1 can be established.

Table 1. Preliminary stratigraphy of the Petsamo group in the Pasvik Region (after Bugge 1977, and Nixon 1981).

UPPER GREENSTONE UNIT
- dominantly greenstone with zones of quartz sericite phyllite, graphite phyllite, tuffs, limestones, quartzites. Gabbros.

PHYLLITE UNIT
- phyllite, graphitic phyllite, minor greenstone, limestone and quartzite. Gabbro and serpentinite.

LOWER GREENSTONE UNIT
- dominantly greestone with minor limestone and tuffitic horizons. Gabbro.

QUARTZ KERATOPHYRE UNIT

AMYGDALOIDAL LAVA UNIT
- andesitic lavas with minor limestone, quartzite and tuff units in the upper levels.

BASAL CONGLOMERATES
- polymict conglomerate with a wide range of pebble materials.

PRIMARY UNCONFORMITY

ARCHEAN BJØRNEVANN FORMATION

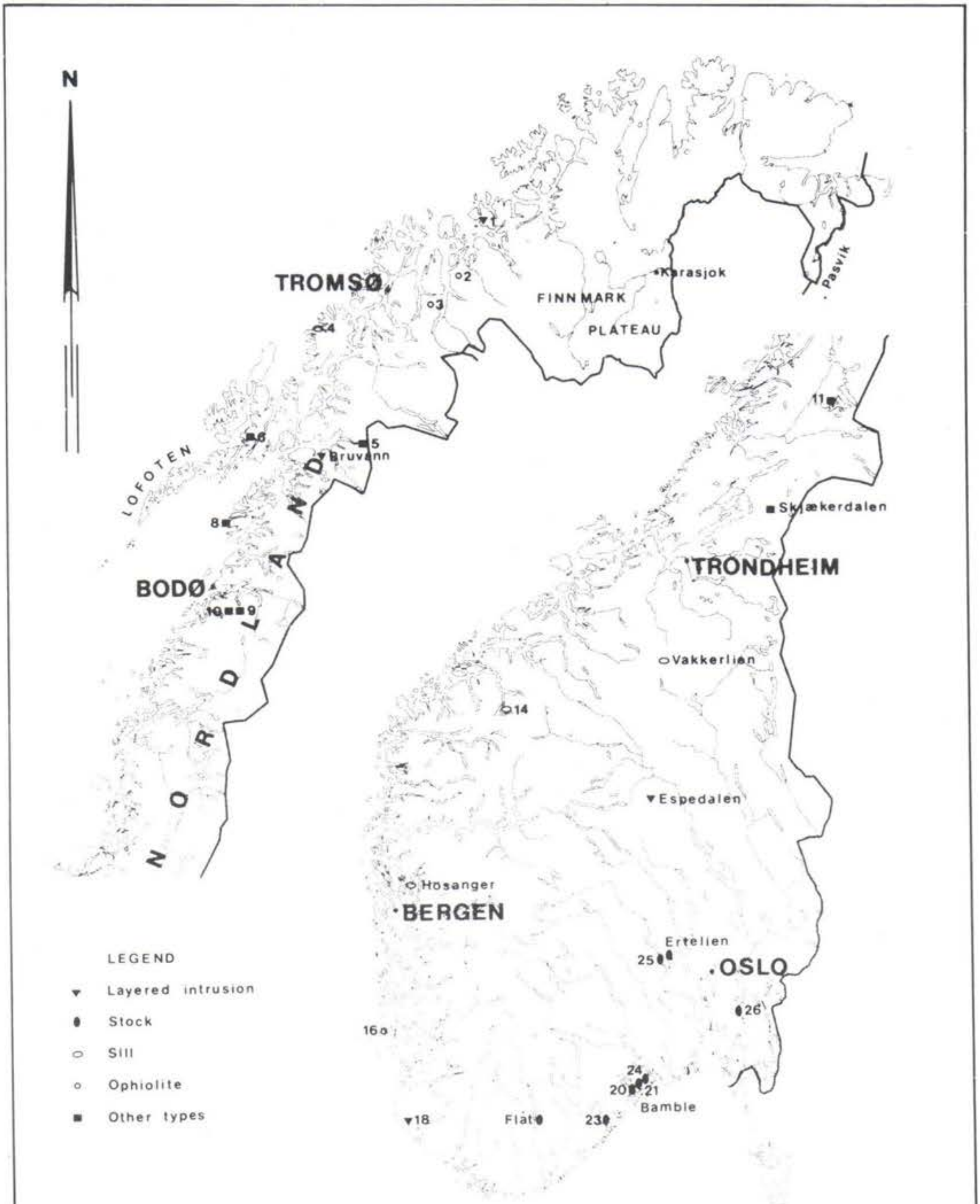


Fig. 1. Map of Norway showing the location of the most significant nickel deposits and of other localities and areas mentioned in the text. Other deposits can be located on appended map. The deposits are numbered as on map and in Table 2 minus 300.

The Petsamo Group was deposited at a continental margin. The lowest part of the sequence is continental and the sediments of the basal conglomerate were deposited in a fluviatile environment. The amygdaloidal lava group is partly subaerial and partly submarine. The greenstone units show evidence of deposition in progressively deepening seawater and have indications of active synsedimentary faulting. The overall structure of the Petsamo Group in Norway is apparently fairly simple and is right way up in spite of being affected by polyphasal deformation. The quartz keratophyre is probably L. Proterozoic in age (Råheim, pers. comm.). The metamorphic grade of the Group is upper greenschist facies, the grade decreasing eastwards into the USSR.

Most of the ultramafic bodies in the Petsamo Group are situated in, or adjacent to the Phyllite Unit. Some 14 individual bodies have been discovered, the majority being highly serpentinized. The ultramafic bodies are of limited size, with the largest body having a strike length of the order of 1000 m and a thickness of 80—100 m. Their form is controlled by a predominant extensional mode of deformation with development of rodding and boudinage. The ultramafics are practically sulphide free although pyrrhotite with pentlandite flames has been observed. The best nickel values from the area have been obtained from a talc-chlorite schist with 0.3 % Ni over 1.7 m of drill core. Exploration in the area which has been carried on sporadically over a number of years has now been abandoned. Both the Petsamo Group and its contained ultramafics are of considerably smaller dimensions than their equivalents in the USSR.

Senja

A small nickel deposit in Proterozoic gneisses on the island of Senja in Troms county (Fig. 1) was worked during the period 1872—1886. Approximately 950 tonnes of nickel and 500 tonnes of copper were produced from ore with an average grade of 0.9 % Ni (Table 2). The deposit occurs within a multiple intrusive of leucogabbros and anorthosites, which show very complex relationships. Locally the rocks show a primary banding, but this is commonly disrupted by later intrusive phases.

The main ore lens at Hamn is some 80 m long and 15 m wide at the surface wedging out downwards. Ore was reported on the bottom level (62 m) prior to the flooding of the mine by seawater. The sulphides are pyrrhotite, pentlandite and chalcopyrite as breccia mineralization and as disseminations in gabbro and pyroxenite layers near the margins of the massif. Pentlandite occurs mainly as net-texture grains varying up to a maximum diameter of 1 mm and with an average diameter of 0.15 mm. Flame pentlandite is minor (ca. 1 % by volume). A typical assay of rich mineralization gives:

Ni %	Co %	Cu %	Fe %	S %
2.5	0.13	0.33	42.3	26.8

Rombaksbotn

Nickel-copper occurrences have been recorded associated with small mafic lenses in the Precambrian Rombak window near Rombaksbotn some 15 km east of Narvik in Nordland county. At the Rombaksbotn showing mineralization consists of a small pod of massive nickeliferous pyrrhotite in an amphibolite lens in gneissose granite. Assays of massive sulphide average 1.6 % Ni, 0.14 % Cu and 0.11 % Co.

Lonkanfjord

Nickel sulphides are located in association with metasupracrustal inclusions in mangerites near Lonkanfjord on Hinnøy, the easternmost of the Lofoten islands. The sulphides, mainly pyrrhotite with minor pyrite and chalcopyrite, occur as a fine-grained dissemination concentrated in cm wide bands. Best samples give:

Ni %	Co %	Cu %	S %
0.7	0.01	0.25	13

Table 2. Geochemical data on Norwegian nickel deposits for which data representative of the whole deposit is available. The deposit numbers refer to appended map.

NORWAY

No.	Depost name	Age of host complex	Nature of host complex	Status of deposit	Type of data	Metric tons		Grade			Cu	Co	Pt	% Ni_S
						Nickel	Copper	% Ni	% Cu	% Co	Ni + Cu	Ni + Co	Pt + Pd	
304	Senja	Pr.	Synorogenic polymagmatic intrusive	Producer, abandoned	c.p.	950	500	0.87	0.46	—	0.35			3
307	Bruvann, Råna	L.P.	Synorogenic polymagmatic layered m/um intrusive	Developed prospect.	r.	141 900	34 400	0.32	0.08	0.015	0.20	0.04	0.259	10—15
312	Skjækerdalen	L.P.	Synorogenic polymagmatic m/um breccia	Producer, abandoned	c.p. + r.	2 240	1 120	0.22	0.11	0.015	0.33	0.06		5
313	Vakkerlien	L.P.	Synorogenic m/um sill	Developed prospect	r.	4 000	1 600	1.0	0.4	0.021	0.29	0.02	0.692	9—12
315	Hosanger	Pr.	Synorogenic m sill	Producer, abandoned	c.p.	4 200	1 600	1.05	0.35	0.045	0.28	0.04	0.238	7
316	Fæøy	L.P.	Allochthonous ophiolite, base of sheeted dyke complex	Producer, abandoned	c.p.	800	1 000	2.1	2.63	0.131	0.56	0.06	0.275	2.5—5
317	Espedalen	Pr.	Synorogenic layered m/um intrusive	Producer, abandoned	c.p. + r.	1 000	400	1.0	0.4	0.557	0.18—0.44	0.36		6.5
319	Flåt	Pr.	Synorogenic polymagmatic m stock	Producer, abandoned	c.p.	19 500	12 200	0.75	0.47	0.058	0.39	0.08	0.326	6
320	Meinkjær	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p.	520	230	1.21	0.53	—	0.31			3.5—4
321	Nystein	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p.	360	150	1.16	0.48	—	0.29			3.5—4
322	Ertelien	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p. + r.	4 200	2 800	1.04	0.69	0.173	0.40	0.14	0.258	2—4
323	Høgås	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p.	30		1.5		0.057		0.04	0.341	5
324	Vissestad	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p.	77	32	1.28	0.53	—	0.29			3.4—4
325	Sigdal	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p.	50	35	0.62	0.44	0.090	0.41	0.13		1—2.5
326	Romsås	Pr.	? Preorogenic mafic stock	Producer, abandoned	c.p.	150	55	0.91	0.33	—	0.27			3.6

Pr. = Proterozoic, L.P. = Lower Palaeozoic; m. = mafic, um. = ultramafic; c.p. = cumulative production, r. = reserve

Geiranger

Nickel mineralization is found associated with folded metagabbroic lenses in gneisses north of Geirangerfjord in the Basal Gneiss area of Western Norway (Lieungh 1976). A gabbroic sill has been multiply deformed and now forms separate lineated bodies. The gabbro has been thoroughly altered with all original textures being obscured by metamorphism. In thin section the rock consists of rounded garnet porphyroblasts scattered throughout a groundmass of hornblende, biotite, quartz and apatite. The main sulphides are pyrrhotite and chalcopyrite with minor pentlandite and millerite. The deposit was investigated by drilling in 1976 with only minor mineralization being discovered. The best grades were of the order of 0.85 % Ni, 0.35 % Cu and 8.7 % S with low gold and platinum values.

Espedalen

The Espedalen area (Fig. 1), 180 km NNW of Oslo, was a copper mining district from as early as 1666 and thereafter intermittently until 1750. Nickel mining commenced in 1848 and continued until 1856, to be taken up again from 1874 to 1878 and 1917 to 1918. The deposits lie within an allochthonous unit consisting mainly of several intrusive suites of basic to ultrabasic character: the unit is probably related to the Jotun Nappe though geographically isolated from it.

The regional geology of the Espedalen area has been described by Heim (1981). The mineralization is related to the second of three intrusive suites which is dominated by small layered intrusions consisting of peridotite, pyroxenite and norite. Bodies of this type, 10 to 1000 m along their long axes are found emplaced near the contact between anorthosite and gabbro in an older complex. The latter is antiformal with an anorthosite core overlain by gabbro.

Mineralizations of breccia type occur near the floors of several of the host intrusives and though the overlying peridotites are generally sterile both pyroxenite and norite commonly contain disseminated sulphides. Most of the observed ore textures are of primary or late magmatic character. The main sulphides are pyrrhotite, chalcopyrite and pentlandite in decreasing order, pentlandite usually forming free grains. Locally pyrite is an important phase. Several of the richer mineralizations are partly controlled by tectonic features. The nickel potential of the area was re-assessed in the mid 1970's. Several mineralizations were discovered in the drill holes but their continuity is sporadic and the remaining mineralization is thought to be of limited tonnage. Geochemical data from the Espedalen mineralizations including platinum group element (PGE) analyses from Naldrett *et al.* (1979) are given in Table 2 and are discussed in a later section.

Hosanger

The Hosanger deposit (Fig. 2) has been described by Bjørlykke (1949). It is located in a phacolith or large sill of norite which forms part of the Anorthosite Complex within the Bergen Arc System. Rb/Sr isochron studies indicate that the Anorthosite Complex was subjected to granulite facies metamorphism at 1064 ± 24 Ma (Pringle & Sturt 1972; Sturt *et al.* 1976): it is possible that the Complex is related to the rocks of the Jotun Nappe (Kvale, 1960), but this has not yet been proved and the precise relationship of the Hosanger norite to the Anorthosite Complex is also unclear. The norite body has slightly sheared contacts against the country rock which is a heterogeneous quartzofeldspathic gneiss. The norite contains xenoliths of the gneiss near its outer contact and there are sills of norite in the country rock. According to Bjørlykke (1949) the peripheral and northerly parts of the norite are enriched in mafic minerals, both orthopyroxene and hornblende, locally to the extent of being ultramafic. The norite, in-

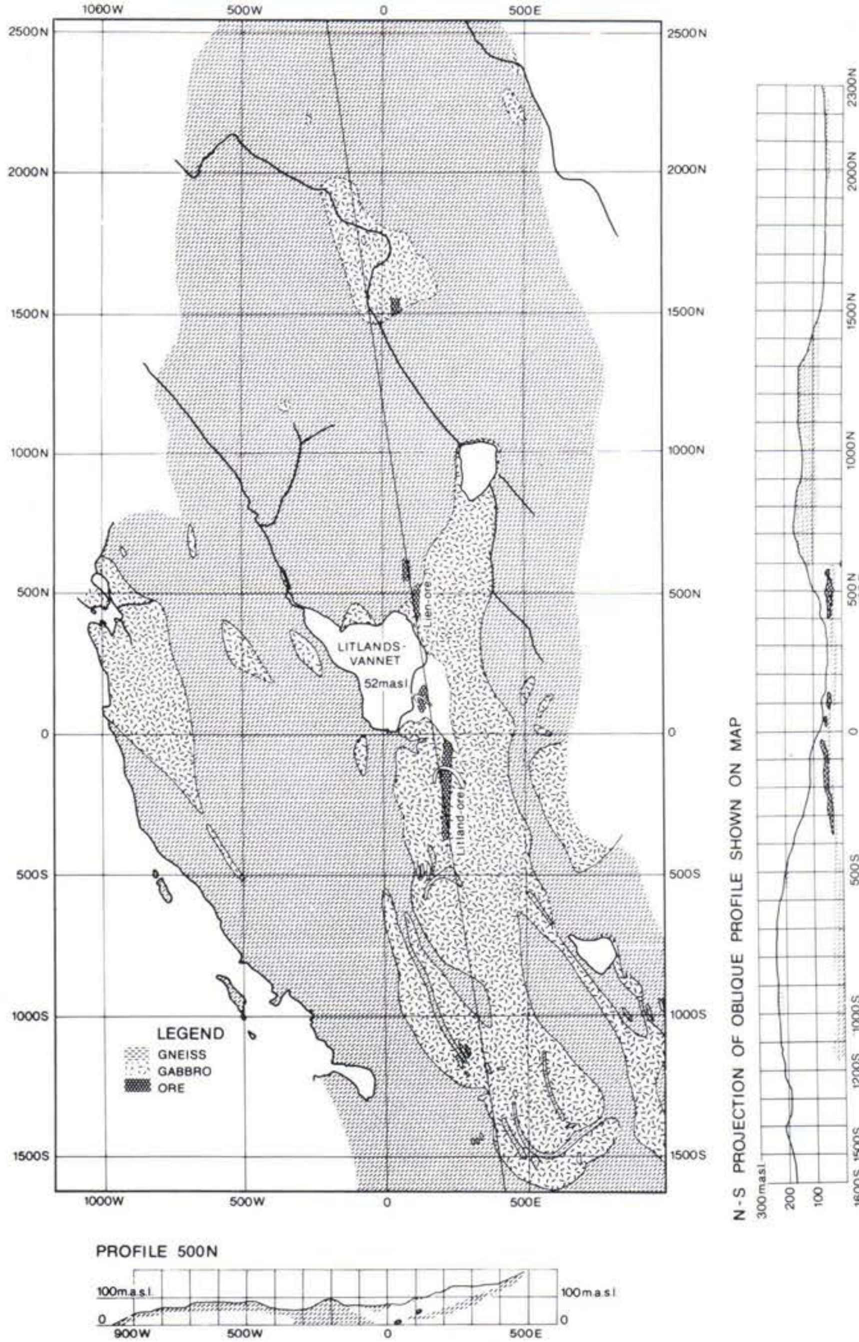


Fig. 2. Geological map and profiles of the Hosanger area (after Bjørlykke 1949).

cluding its mineralized portions, is cut by veins of pegmatite and aplite, many of which, but not all, are parallel to the outer contacts of the phacolith. The intrusion which is partly overlain by country rock, has been affected by upright folds and faults.

The Hosanger mineralization was discovered in 1875 and mining began in 1883. The first production period lasted until 1894 and subsequently the mine was in production from 1899—1901, 1915—1926 and 1933—1945. Mining ceased because of exhaustion of the reserves: subsequent exploration has confirmed that remaining reserves are insignificant. The mineralization is of two main types:

1) Disseminated to matrix sulphide, occurring irregularly and with diffuse margins in zones up to 30 m thick near the base of the intrusion (Lien and Litland bodies).
2) Veins of massive Ni-rich sulphide cutting both norite and country rock xenoliths (Nonås mineralization).

There are also veins of Cu-rich sulphide which cut across bodies of pegmatite within the norite. The primary sulphides present are: pyrrhotite, pentlandite, chalcopyrite and pyrite. Bjørlykke (1949) reported no significant difference in the assemblages in the two main types of mineralization, but indicated that the veins have relatively pyrite-rich margins and that they are finer grained than the disseminated mineralization. Pentlandite is present as a filling in minute cracks and cleavages in pyrrhotite grains and as small grains marginal to pyrrhotite. Data on the geochemistry of the Hosanger mineralization are given in Table 2: these figures are based on production statistics and reflect the fact that of the total tonnage produced (c. 460,000 tonnes) only 11,000 tonnes came from the Nonås orebody; this mineralization had an average grade of ca. 2.5 % Ni and maximum grades of c. 4 % Ni. Bjørlykke (1949) demonstrated a negative correlation between Cu/(Cu + Ni) and % Ni in the mineralizations at Hosanger.

Ertelien

The Ertelien deposit (Fig. 1) is located in the Ringerike district about 40 km NW of Oslo. The deposit and its host complex lie within the Kongsberg Series, most recently described by Starmer (1981), which consists of gneiss and migmatite, several granitic plutons and at least two structurally distinct types of mafic body — concordant lenses and discordant plugs — all of which, except certain of the granites and the crosscutting dykes, predate the main Sveconorwegian orogeny.

Several of these mafic bodies contain sulphide mineralization and copper was mined from a number of showings in the early part of the 18th century. Only one of these deposits has had a significant tonnage of Ni-bearing sulphides, the Ertelien deposit, which was discovered in the late 1840s and was a producing deposit intermittently from 1849 until 1920.

The Ertelien deposit (Vogt 1893) forms part of a norite plug with maximum dimensions 600 m E-W and 450 m N-S, round which the foliation of the country rock has in general been deformed, though locally wedges of gneiss extend into the norite. Major rock types in the body include olivine norite, norite and various types of gabbro (Johannesen 1974): hornblende peridotite is found close to the northern margin of the intrusion. Though several parts of the periphery of the intrusion are mineralized, the only significant accumulation is on the northeastern margin of the body. Mining in this area extracted the bulk of a rich massive and breccia mineralization consisting of pyrrhotite, chalcopyrite and pyrite, almost all the pentlandite present being in the form of lamellae or flames in pyrrhotite. The Ni content in pure sulphide of this mineralization has been variously estimated at between 2 and 4 %. Locally zones of massive pyrite are present. Relatively extensive weak sulphide mineralization is also present in the northeastern part of the intrusion, but this has both low absolute grade (ca. 0.1 %—0.2 % Ni, 0.08 %—0.18 % Cu) and a low grade of Ni in sulphides.

Sigdal

The Sigdal area lies just over 20 km west of Ertelien. Several small mineralizations are known, of which the largest, Grågalten, was mined from 1874—77 (Vogt, 1901). Paulsen (1942) states that the mineralizations are in the form of veins and lenses of massive/rich sulphide in bodies of norite. A copper-rich breccia mineralization and disseminated sulphides are also present (Sund 1969). The sulphide assemblage is pyrrhotite, pentlandite, chalcopyrite and pyrite but the content of nickel in sulphides is very low (Table 2). The Grågalten mineralization had a strike length of 68 m and a thickness of 4 m.

Bamble

The gneisses of the Kongsberg-Bamble Formation of S. Norway (Bugge 1943) have probably been subjected to both Svecofennian (= Hudsonian) and Sveconorwegian orogenies with upper amphibolite facies, locally granulite facies metamorphism in both cases (Starmer 1976). They contain a large number of concordant pods or lenses of metanorite, some of them mineralized (e.g. Meinkjær, Nystein), thought to be of pre-Sveconorwegian age, as well as certain plug-like bodies which may be post-Sveconorwegian. These bodies contain numerous prospect pits and small mines, mainly dating from the nineteenth century, but only two deposits have produced in excess of 100 t Ni metal (Meinkjær, Nystein) and prospecting in the 1960s and 1970s gave little reason to suggest that significant tonnages at any grade remain in any of these bodies.

The Meinkjær deposit has been described by Vogt (1893) and by Jerpseth (1979). The host is a hornblendic metanorite with surface dimensions 105 m × 55 m. Mineralized zones possibly up to 10 m wide and 30 m long occur at several areas along the outer contact of the body. There is no apparent systematic change in silicate mineralogy from the core to the rim of the body. The mineralization shows all gradations from massive to disseminated, but because the deposits have been worked out it is not possible to give an accurate picture of the distribution of the various types.

The Nystein deposit (Vogt 1893, Petersen 1979) is located in a body of hornblendic metanorite (200 m × 100 m) which itself lies almost in contact with a larger body of metanorite (1200 m × 700 m), both lying within a zone of amphibolite which is thought to be an older intrusive. The location of the workings indicates that the mineralization occupied the core of the smaller metanorite body which may be an outlier of the larger one. The mineralization ranges from massive to disseminated. The sulphide assemblage in both these deposits is pyrrhotite, pentlandite, chalcopyrite and pyrite.

The Vissestad mine, in common with Meinkjær and Nystein, was in production in the 1860s and 1870s and during and just after World War I, but on an even smaller scale than the other two deposits. The tip from the workings covers the whole of the host norite so that more recent work (Petersen 1979) is based purely on grab samples.

The Vissestad norite is a quartz-hornblende norite, probably an outlier of a larger body. Data on the production are given in Table 2. The sulphide paragenesis would appear to be similar to that in Meinkær and Nystein.

Høgås

The Høgås deposit lies 3 km E of Tvedestrand, 170 km SW of Oslo. The main period of production at this mine was at the end of World War I.

The deposit has been described by Sæther (1949) and Lindahl (1981). The host norite has maximum dimensions 500 m × 130 m, but may be a composite body consisting of two intrusive generations. The sulphides are associated with the smaller and younger of the two bodies, which appears to have been emplaced along the margin of the larger mass. The mineralization had a strike length of 100 m and a maximum thickness of 2 m. The deposit contained both massive and disseminated sulphides but their relationships are unclear as the deposit has been worked out. Samples of disseminated sulphide from the tip grade up to 0.6 % Ni.

Romsås

The Romsås deposit lies approximately 40 km SE of Oslo (Fig. 1). The regional geology of the area which consists mainly of Middle Proterozoic granites and gneisses has been described by Berthelsen (1980) and Skjernaa & Pedersen (1981), but the mafic intrusives in the area have yet to be described in any detail: Berthelsen (1980) suggests that they are pre-Sveconorwegian in age (ca. 1200 Ma). The Romsås deposit lies at the presumed base of a norite body (375 m × 245 m) which has a long axis striking NW-SE and which dips eastwards (Grønlie 1975). The mineralization forms lenses up to 40 m long and 10 m thick. Grab samples grading up to 1.4 % Ni, 0.17 % Cu, 0.061 % Co and 4.6 % S have been found. Production lasted from 1866 to 1876. Several similar but smaller bodies in the area have been exploited in the past. A notable feature of the Romsås norite is the presence of a wedge of orbicular norite ('orbicules' of hypersthene, rimmed by biotite, in a matrix mainly of feldspar and quartz) along part of the base of the body, and locally separated from the mineralized norite by a thin band of country rock (Vogt 1893).

Flåt (Evje-Iveland)

Several small nickel deposits and one of medium size are situated in the Evje-Iveland area some 30—60 km north of Kristiansand in southern Norway (Fig. 3). This area has played a central role in the Norwegian nickel industry. The exploitation of the largest deposit in the area — the Flåt mine near Evje — resulted in the establishment of a nickel refinery in Kristiansand in 1910. Flåt and other deposits in southern Norway continued to supply this refinery until 1929 when it was bought by the Canadian company, Falconbridge Nickel Mines Ltd. The refinery is still in operation, treating nickel matte from Canada.

The geology of the area is dominated by the Proterozoic Evje-Iveland Amphibolite Complex, an elongate body measuring 35 km in a N-S direction and some 10—15 km in width (Barth 1947; Pedersen 1975 and 1973) (Fig. 3). Within the amphibolite complex there are several bodies of mafic and ultramafic rocks with which the nickel showings are usually associated. The area has undergone several phases of deformation and of magmatism over a prolonged period. Gabbros have undergone amphibolite facies metamorphism and show various stages of conversion to amphibolite. Ultramafic rocks are concentrated in the central portions of the Amphibolite Complex and in general they seem to fall into two groups with a broad transition between them. Dunitic peridotites and harzburgites form one group and monomineralic hornblendite the other. Between the two groups anthophyllite-cummingtonite- and tremolite-hornblende-bearing types are common.

The nickel showings in the area can broadly be classified into two main groups (Nixon 1977):

1. Disseminated mineralizations with up to 15 % sulphides.
2. Massive mineralizations with pyrrhotite as the dominant sulphide, in which the sulphides occur mainly as veins or fracture fillings. These massive bodies are dominantly associated with hornblende-rich rocks.

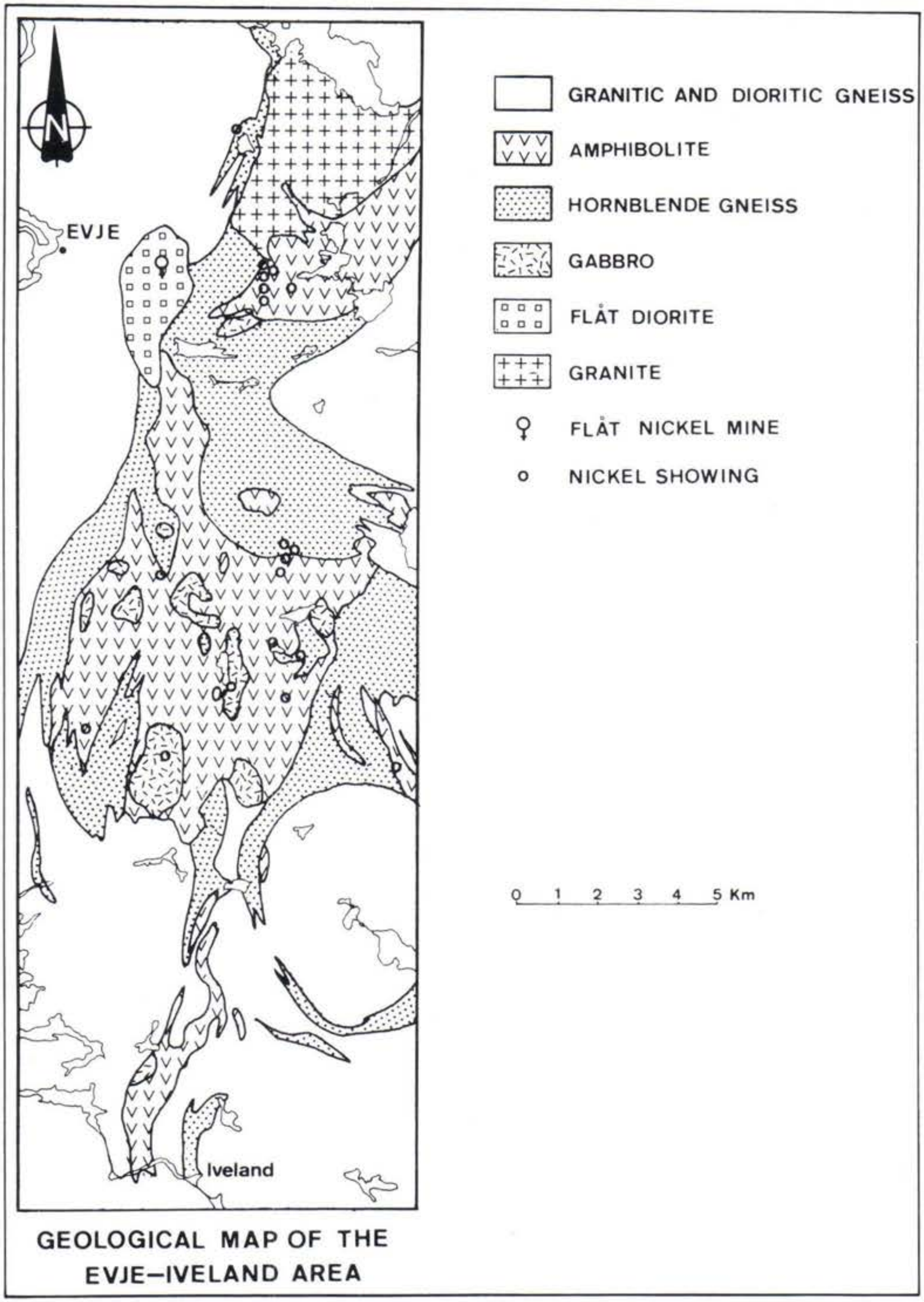


Fig. 3. Regional geological map of the Evje area.

The disseminated mineralizations have a lower Ni/S ratio than the massive types which without exception are very small. A number of disseminated showings occurring both in gabbro and ultramafic bodies were investigated in the late 1960s and early 1970s but all proved to be of limited size.

The largest deposit to have been in production in the area is the Flåt mine near Evje (Fig. 3). This was Norway's largest nickel mine and between 1872 and 1944 2.6 million tonnes of ore with 0.75 % Ni and 0.47 % Cu on average were mined. The deposit has been described by Bjørlykke (1947).

The deposit occurs in the so-called »ore diorite», an intrusive body some 4 × 2 km in size occurring in the northwestern part of the Amphibolite Complex. The »ore diorite» is petrographically a quartz diorite, with hornblende and opaques occurring in minor amounts. The diorite exhibits several subfacies, the most important being fine grained equigranular to porphyritic varieties and coarse grained porphyritic types. Barth (1947) regarded the diorite as a massive facies of the Evje-Iveland Amphibolite. However, recent investigations by mining companies in the area (Nixon 1977) indicate that the body is a separate intrusion.

The ore body at Flåt is associated with a fine grained diorite and has the form of an elongated pencil as shown in Fig. 4. In its upper parts the body has a regular form with the axis dipping 45° to the south. At depth the ore body gradually flattens out and the vertical thickness increases to a maximum of almost 100 m. The total length along the ore axis is approximately 900 m and the deepest workings are some 400 m below surface. The ore is a typical dissemination type with the average composition being 75 % silicate gangue, 12—13 % sulphides, 8 % magnetite and 4 % apatite. Primary sulphide minerals are pyrite, pyrrhotite, pentlandite and chalcopyrite. Secondary millerite and violarite are found in some parts of the deposit. Pentlandite is seen to form granular stringers around pyrrhotite grain boundaries and also along frac-

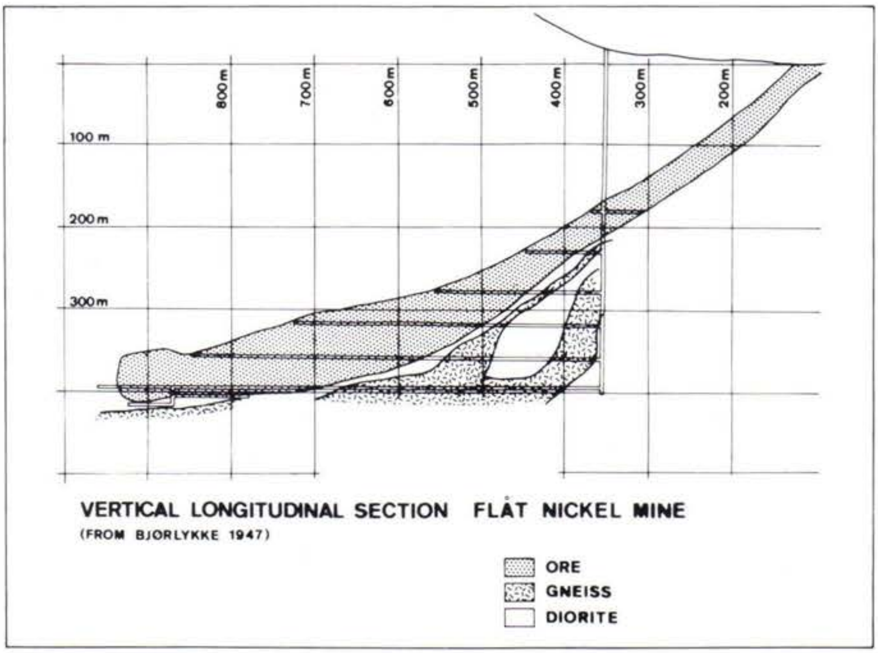


Fig. 4. Approximately N-S profile through Flåt mine (after Bjørlykke 1947).

tures within it. Bjørlykke (1974) regarded the ore as being formed from a magma enriched in sulphides which intruded the older amphibolites. During cooling sulphides segregated along a large gneiss xenolith within the diorite.

Homse

The Homse deposit is situated within the Egersund Anorthosite, approximately 50 km S of Stavanger.

The rocks in the area are dominantly fine to medium grained anorthosites. Surface showings occur along a strike length of 50 m associated with a very coarse grained anorthosite and also seem to be closely associated with fault zones. The main sulphides are pyrrhotite, chalcopyrite, pentlandite and pyrite with minor bravoite and marcasite. Sulphides occur as disseminations, fracture fillings and as breccias. Assays from surface showings average:

Ni %	Cu %	Co %	Fe %	S %
0.95	1.30	0.12	57.3	37.2

Pentlandite occurs dominantly as relatively large grains in aggregates partly altered to bravoite along or near joints and fractures in pyrrhotite.

The deposit was drilled in 1973 (Hovland, 1973), and three zones of mineralization were outlined with an average grade of 0.5 % Ni, 0.3 % Cu, 9 % S. No further work has been done on the property.

The ilmenite mine of A/S Titania situated in the same Anorthosite Province with reserves of some 300,000,000 tonnes of ore averaging 18 % TiO_2 produces a sulphide concentrate of some 13,000 tonnes per year containing 4.5 % Ni and 1.6 % Cu and 0.8 % Co.

CALEDONIAN OROGEN

Nickel mineralizations in layered intrusions

Reinfjord

Low grade nickel sulphide mineralization has been found in the Reinfjord layered intrusion (Søyland-Hansen 1971; Vrålstad 1975) which forms part of the Seiland intrusive province in N. Norway. The province includes suites of layered intrusions and dykes of the following magmatic parentage: sub-alkaline basalt, calc-alkaline basalt, alkali-olivine basalt, as well as an alkaline suite including carbonatites. The magmatic evolution of the area has been related to a mantle diapir situated above a steepening subduction zone (Robins & Gardner 1975). The age of the bodies ranges from ca. 550 to ca. 500 Ma (Sturt & Roberts 1978). The Reinfjord ultramafic complex has been studied by Bennett (1974) who concluded that the body had an ultramafic parent magma and that it has similarities to the Alaskan type of concentric layered intrusion. The mineralization, which grades 0.2 % Ni, occurs at the outer margin of the body at a contact between pyroxenite and garnet hornfels within a zone up to 100 m thick. Primary sulphides present are: pyrrhotite, pentlandite, chalcopyrite and pyrite. About 50 % of the pentlandite present forms flames or lamellae in pyrrhotite. The Cu/(Cu + Ni) ratio is ca. 0.5 with about 4 % of each in pure sulphide; locally the Cu/(Cu + Ni) ratio is less than 0.1. The topography of the area is extremely rugged and no mineral inventory was made during the prospecting in the early 1970s.

Bruvann (Råna)

The Bruvann deposit is located in the northwestern part of the Råna layered mafic-ultramafic intrusion near Narvik in the northernmost part of the county of Nordland (Fig. 1). Though mineralization in this area was registered late in the nineteenth century, its nickel content was first recognized by Foslie in the years immediately preceding WW I though his first publication on the area came several years later (Foslie 1921).

The intrusion was emplaced during the Caledonian orogeny and has been dated at ≧ 409 ± 40 Ma. (A. Andresen, pers.comm.). The body has a roughly oval shape and a surface area of approximately 70 km² (Fig. 5). Surface structural data and interpretation of gravity measurements suggest that the intrusion has the approximate form of an inverted cone, the axis of which plunges northwestwards and which has a maximum depth extent of about 2.5 km (Sindre *et al.* 1981). The structure of the intrusion has been affected by at least the last two phases of Caledonian deformation, first E-W to NE-SW trending, and second, N-S trending upright, open to gentle folds. The first of these is associated with local thrusting of which one expression was the upthrusting of the northwesternmost part of the intrusion.

The major rock types show a roughly concentric distribution with the following, some-

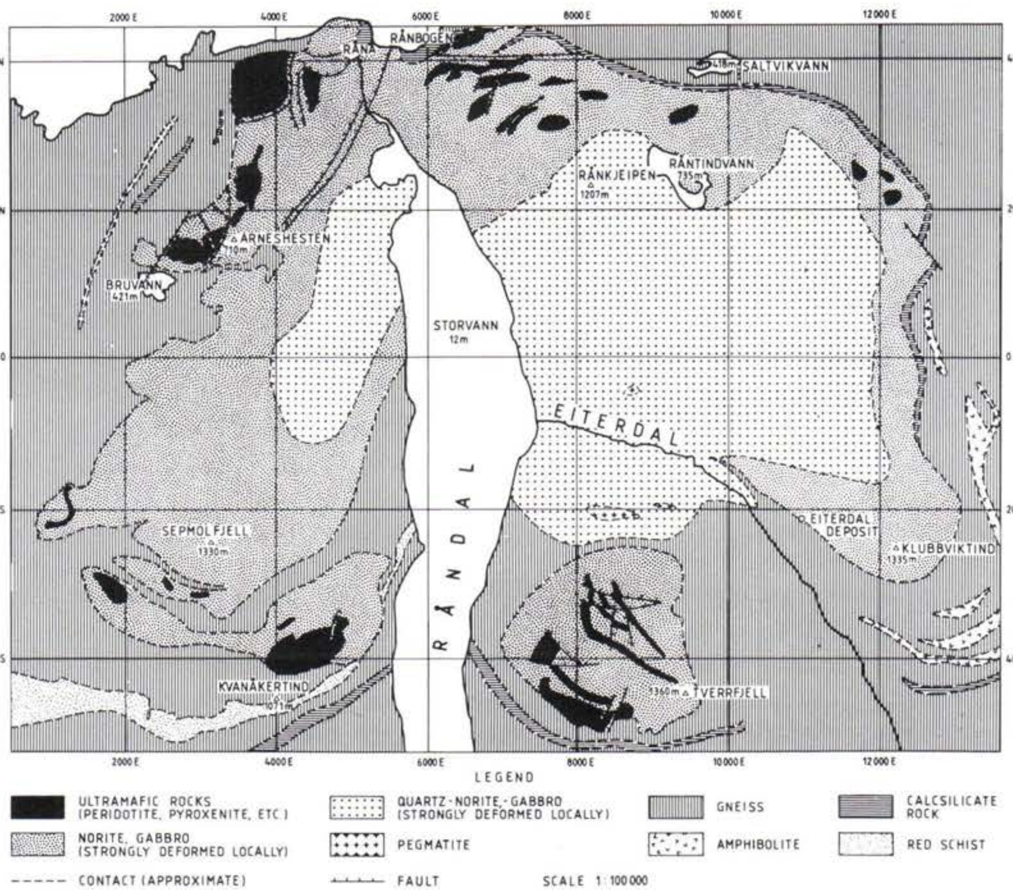


Fig. 5. Geological map of the Råna intrusion (from Boyd & Mathiesen 1979).

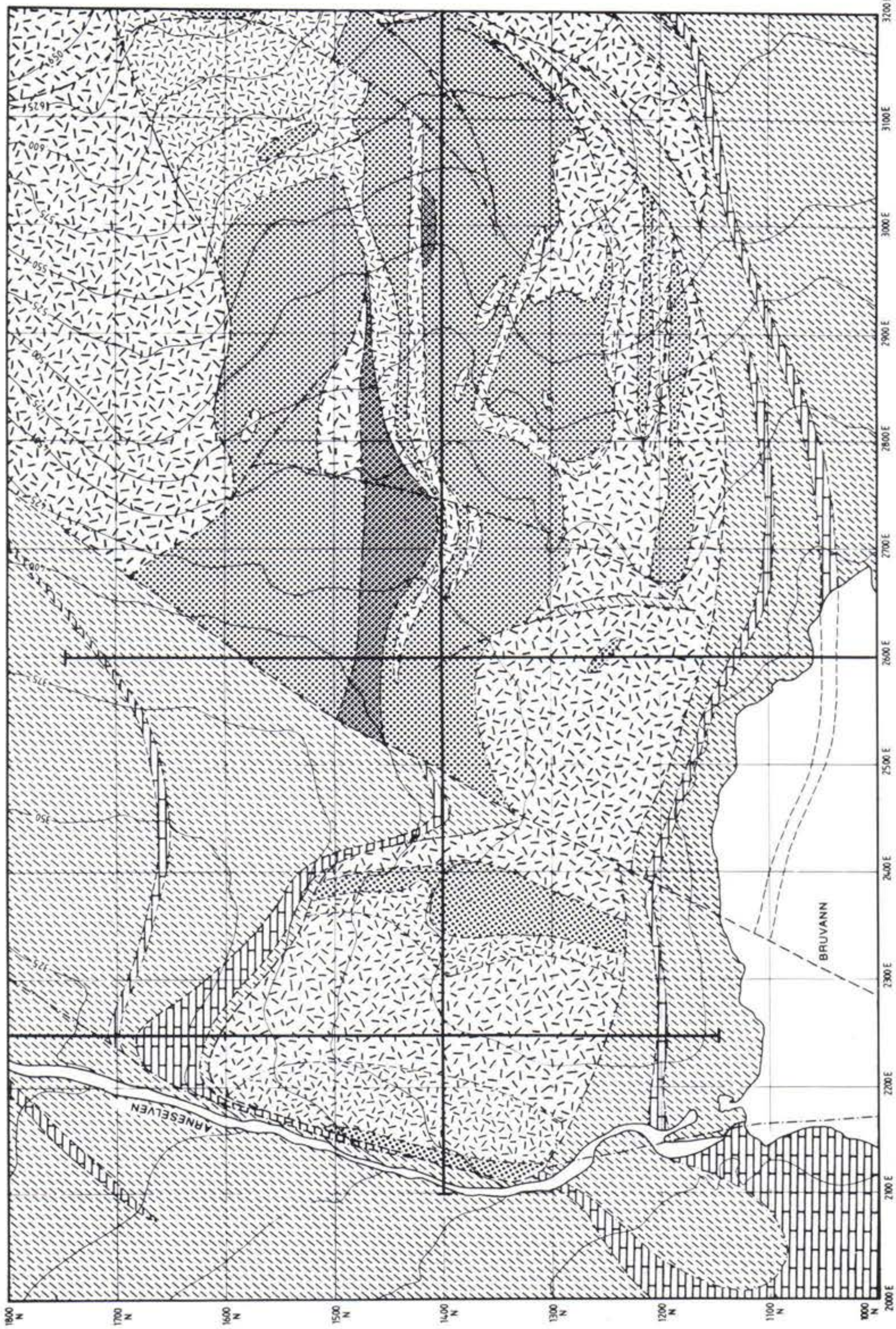


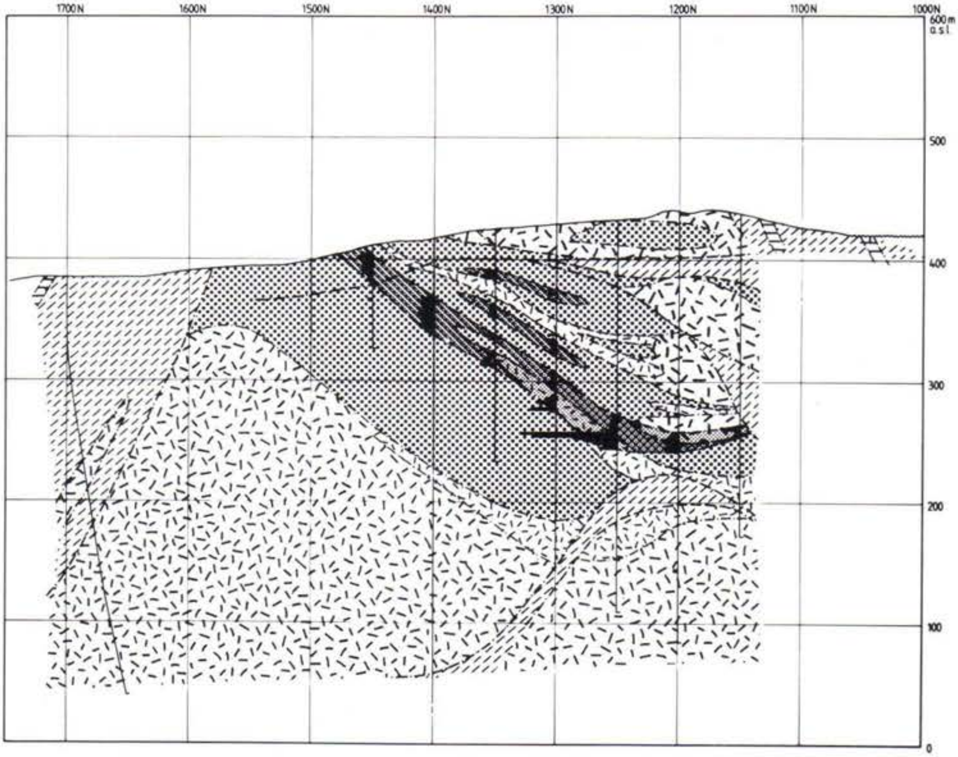
Fig. 6. Geological map of the Bruvann area, Råna. The legend is given in Fig. 9. The heavy lines give the location the profiles shown in Figs. 7, 8 and 9.

what idealized sequence in the most complete sections:

— quartz norite core: ultramafics absent, gabbroic varieties common
— norite zone (300—2000 m): ultramafics subordinate
— ultramafic zone (0—800 m): norite subordinate
— contact norite (< 50 m)

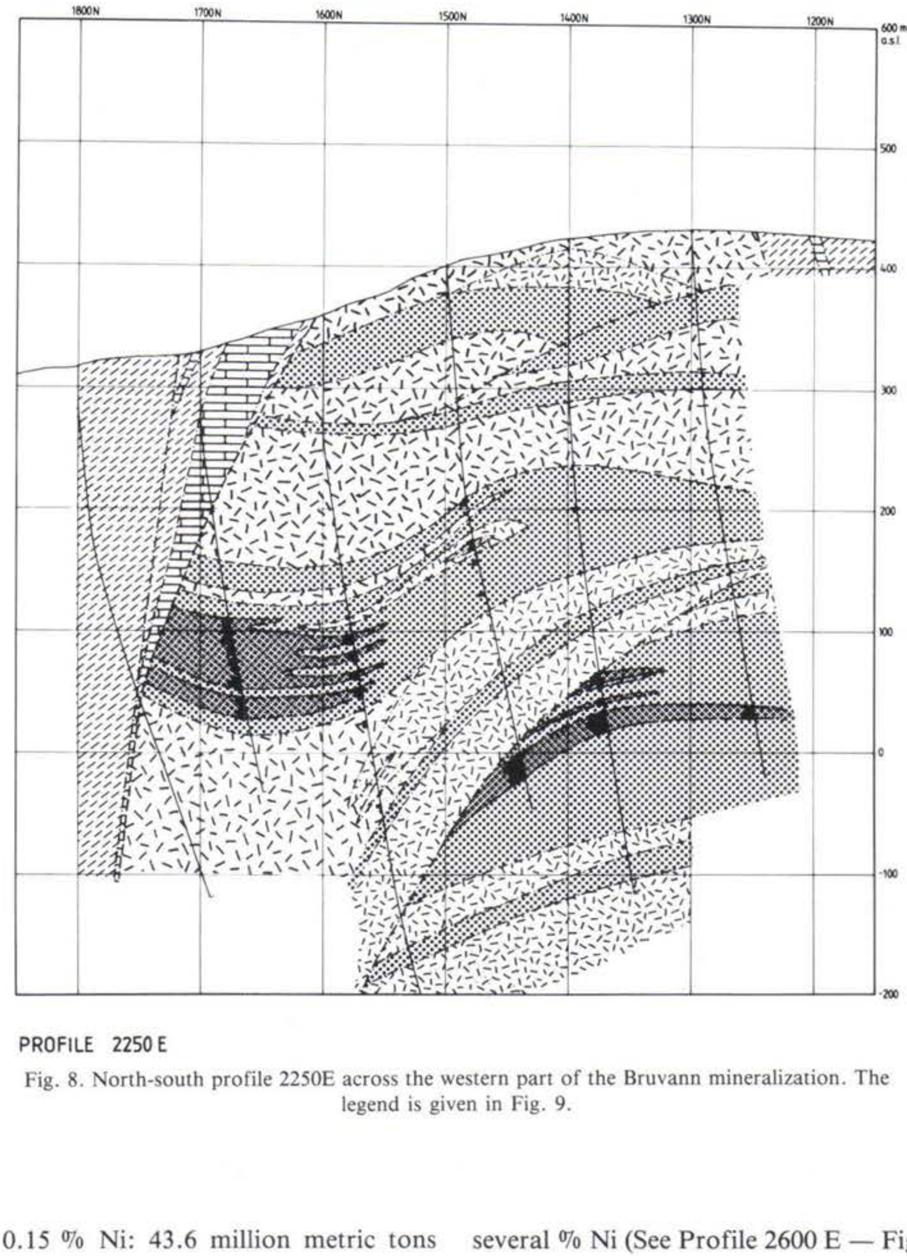
Most of the intrusion can be explained in terms of cyclic repetitions of the whole, or part of the crystallization order: olivine — orthopyroxene — plagioclase — clinopyroxene with the following ranges in composition in the intrusion as a whole: Fo_{90-69}, En_{85-54}, An_{84-37} and $En_{53}Ofs_5Wo_{42}$ to $En_{38}Ofs_{18}Wo_{44}$ respectively (Boyd 1982). The presence of assemblages inconsistent with the above crystallization order, local reversals in cryptic variation trends and cross-cutting relationships seen in the field indicate that the intrusion formed from multiple influxes of fresh magma originating in a deeper-lying chamber which itself was undergoing fractional crystallization.

Though Ni-Cu bearing sulphides are known from several parts of the intrusion, only one sizeable accumulation, the Bruvann deposit (Fig. 6) has been found. In the course of the 1970s approximately 28,500 m of diamond drilling was carried out in this deposit. The mineralized tonnage present can be described as follows:



PROFILE 2600 E

Fig. 7. North-south profile 2600E across the eastern part of the Bruvann mineralization. The legend is given in Fig. 9.



PROFILE 2250 E

Fig. 8. North-south profile 2250E across the western part of the Bruvann mineralization. The legend is given in Fig. 9.

Cut-off, 0.15 % Ni: 43.6 million metric tons with 0.33 % Ni, 0.08 % Cu and 0.015 % Co, alternatively

Cut-off, 0.3 % Ni: 26.4 million metric tons with 0.42 % Ni, 0.1 % Cu and 0.02 % Co.

Significant portions of the mineralization have grades in excess of 0.6 % Ni and several holes intersect massive sulphides with grades of several % Ni (See Profile 2600 E — Fig. 7). The deposit has maximum dimensions of 900 m E-W and 500 m N-S: it outcrops at 500 m a.s.l. at its eastern extremity and extends to at least 100 m below sea level at its western extremity. It is divided in two by a NE-SW trending hinge fault, the throw of which (downwards to the W) increases northwards from about 200 m close to the lake, Bruvann (Figs. 6 and 9).

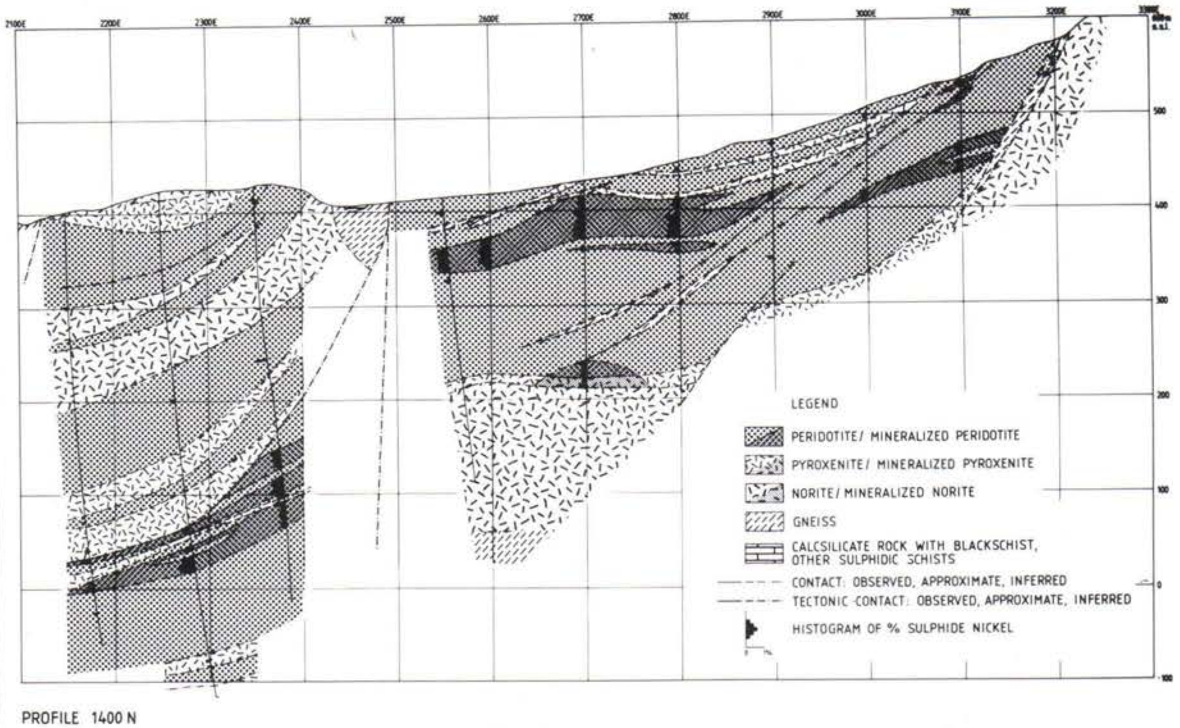


Fig. 9. East-west profile 1400N across the Bruvann mineralization.

West of this fault the sequence within the intrusion from top to bottom is as follows:

	Country rock
50—250 m:	interbanded norite, pyroxenite and peridotite
50—100 m:	upper mineralized peridotite with thin pyroxenite bands
40—100 m:	interbanded peridotite and pyroxenite with subordinate norite
20—100 m:	lower mineralized peridotite
60—120 m:	sterile peridotite
0—50 m:	pyroxenite
>300 m:	norite

The lowermost six units do not reach the surface. Based on drillhole evidence the units dip at moderate angles to the NW and are affected by gentle upright folds with axes trending approximately E-W; they meet the country rock at high angles (Figs. 8 and 9) which, taken with the nature of the contacts observed in drillholes, strongly indicates that the contacts are not primary. The relationship between the upper and the lower mineralized zones, if any, is not known; it is possible that the upper zone is an overthrust continuation of the lower.

East of the hinge fault only the five lowermost of the units indicated above are present. Here the units dip southwards with dips of approximately 45° near the surface and decreasing with depth (Fig. 7); the structure may be the northern half of an open synform the axis of which dips gently westwards. It is probable that the intrusion solidified under tectonically unstable conditions. The norite ridge NE of the deposit continues in depth west of the hinge fault and cuts the pseudostratigraphy shown above; it also seems probable that the norite in the southern part of the Bruvann area has an intrusive relationship with the mineralized sequence. A further complication is the presence within the intrusion of numerous tectonic slices of country rock, of various types, whose geometry is rarely amenable to simple interpretation on the basis of drillhole intersections.

The typical sulphide assemblage falls within the following: pyrrhotite (50—80 %), pentlandite (10—35 %), chalcopyrite (5—15 %) and minor amounts of pyrite. Traces of arsenopyrite, gersdorffite, niccolite, molybdenite and sphalerite are present locally as well as variable amounts of graphite and oxides. The vast bulk of the mineralization occurs interstitially to olivine, with or without orthopyroxene, in peridotite, though locally olivine norite and pyroxenite are also mineralized. Richer mineralization has the net texture described by Naldrett (1973). Massive sulphide, with silicate inclusions, has been found in four N-S profiles where they intersect grid line 1250N, and though profile 2600E (Fig. 7) shows massive mineralization in apparent continuity with disseminated sulphides, this is not the case at several of the other localities and the factors governing the location of the massive sulphides in general are unclear. This is partly because present evidence is not sufficient to permit mapping of the size and shape of the masssive sulphide bodies. Point count analysis of a number of thin sections (Malvik 1977) indicates that only 1 % of the pentlandite is present as flames or lamellae in pyrrhotite, the remainder occurring as free grains marginal to pyrrhotite. Sulphur isotope analyses indicate that the sulphur in the Bruvann mineralization is of magmatic origin (Boyd & Mathiesen 1979). Small accumulations of sulphide are present in other parts of the Råna intrusion, generally on or close to the outer contact of the body: several of the mineralizations have a sulphur isotope composition which suggests the presence of a component of sulphur from the country rock.

The Bruvann deposit is currently the subject of a study to assess the economic feasibility of combined production of sulphide concentrate, industrial mineral grade olivine and crushed pyroxenite as road material.

Nickel mineralization in ophiolites and ophiolite fragments

Lyngen

Unpublished mapping (Boyd & Minsaas, in preparation) suggests that the Lyngen mafic complex 40 km E of Tromsø in N. Norway is a disrupted, inverted ophiolite complex containing the following units: folded layered gabbro with tectonically emplaced ultramafic bodies, tectonized sheeted dyke/gabbro zone, greenstone. Prospecting in the early 1970s revealed the presence of nickel mineralization associated with small serpentinite bodies in the complex. Individual samples returned over 1 % nickel but the mineralizations proved to be of very limited extent.

Ste

The Ste gabbro is located in Reisadalen 80 km E of Tromsø in N. Norway. Regional mapping (Zwaan 1977) indicates that the Ste rocks are a western continuation of the Vaddas gabbro, recently studied by Stephens (1982) who suggests that the Vaddas complex may be ophiolitic in origin. Most of the Ste gabbro consists of feldspathic hornblende gabbro, but pyroxene bearing varieties are present locally. The body contains irregular zones up to 50 m thick and 600 m long of weak sulphide dissemination in gabbro. Values up to 0.45 % Ni_{total} and 0.26 % Cu have been found, but grades are in general under 50 % of these values. The Ni:Cu ratio is highly variable.

Fæøy

Nickel deposits are situated on the island of Fæøy in south west Norway. Fæøy represents part of the Karmøy ophiolite with sheeted dykes in gabbro being the main host rock type (Sturt *et al.,* 1980). The mineralization which is no longer accessible for observation occurs in lenses plunging parallel to linear structures in country rocks. Thickness varies from a few cms to 7 m. Down to 140 m three separate ore lenses were worked. The Fæøy mine was in sporadic production from 1896 to 1922 with some 37,000 tonnes of the ore being produced with an average grade of 2.6 % Cu and 2.1 % Ni. The mineralization is dominantly massive and fine to medium grained. Main sulphides are granular pyrrhotite with blocky pentlandite and chalcopyrite. Pyrite may be present in small amounts. The host rock for the sulphides is a partly chloritized amphibolite. The deposit is interesting partly because of its high content of Pt and Pd with average grades being quoted (Foslie & Høst, 1932) as 1.12 g/t Pt and 2.97 g/t Pd. Recent sampling has given up to 11 g/t Pt in certain samples. In polished section composite grains of kotulskite Pd (Te, Bi) and an unusual Pd Hg-Te mineral probably temagamite ($Pd_3Hg\ Te_3$), have been recognized (R. Buchan, pers. comm.).

Isolated ultramafic bodies

Isolated ultramafic bodies, mainly of peridotite or dunite, are a common feature at certain tectonostratigraphic levels in the Caledonides of Norway and Sweden (Stigh 1979; Qvale & Stigh, in press), and it is widely accepted that many of these bodies had their origin in ophiolitic sequences, either as ultramafic cumulates or in the depleted mantle zone. Studies in Sweden have shown that certain of these bodies contain heazlewoodite and awaruite formed during serpentinization (Filippidis & Annersten 1980); other Swedish sources have considered these bodies as a potential source of nickel despite their low grade (ave. approximately 0.2 %) (SOU 1979). Their grade of Ni in sulphides may be very high. Ultramafic bodies of this type are common in Norway, but have not, to date been assessed as potential sources of nickel.

Mineralizations in other types of mafic intrusive

Lillefjellklumpen

This mineralization is located in the Grong mining district about 200 km northeast of Trondheim, an area most recently described by Kollung (1979). It is only 5 km from the Skorovass copper deposit which has been described by Halls *et al.* (1977) and by Reinsbakken (1980). Halls *et al.* (1977) interpret the geology of the area in terms of an ensimatic island arc of L. to M. Ordovician age which was uplifted and eroded before emplacement in its present position in the Scandinavian phase of the Caledonian orogeny. They indicate that small bodies of Cu-Ni bearing sulphides are present at several localities within the plutonic infrastructure of the island arc. Only one of these bodies was known from ealier times and it is so far the only one to have been described in any detail — the Lillefjellklumpen mineralization (Foslie & Høst

1932). The mineralization is associated with a small body of hornblende metagabbro and has the form of a massive vein with a maximum length of ca. 20 m, a maximum thickness of just over 2 m and a depth along the vein of up to 3 m. Most of the mineralization has been mined out. Foslie & Høst (1932) give the following estimate of the average mineralogical composition of the sulphide body: pyrrhotite (64 %), pyrite (15 %), pentlandite (12 %), chalcopyrite (3 %), magnetite (4 %) and silicates (2 %), corresponding to an average Ni content of ca. 4 % and a Cu/(Cu + Ni) ratio of 0.2. Attention was given to this mineralization because of its relatively high content of platinum metals, an average for the whole mineralization of 4 g/metric ton.

Skjækerdalen

Nickel mineralization at Skjækerdalen (Fig. 1) is associated with a diorite-gabbro intrusive in quartz-feldspar schists of the Gula group. This deposit has been described by Løvaas (1970) and Lieungh (1977). Mining at Skjækerdalen commenced in 1876 and during the working period 1876—1891 approximately 18,750 tonnes of ore were mined with an average grade of 1.26 % Ni and 0.63 % Cu. A small nickel smelter was built in 1881.

The Skjækerdalen intrusive is situated in weakly banded mica- and quartz-feldspar schists locally with graphitic zones. The intrusive is a lenticular gabbroic body of some 3—4 km length and 1—1.5 km width surrounded by a 10—15 m wide zone of dioritic composition. The gabbro is not a uniform rock, but has the form of an intrusive breccia containing comagmatic fragments of diorite, leucogabbro, melagabbro and ultramafic rock. Fragments of local wall rock schists are also common. The fragments range in size from less than 10 cm up to 20 m. Most of the fragments are angular, but several show narrow reaction rims, this especially around ultramafic fragments. Layering can be seen in some of the gabbro fragments. The matrix of the »breccia» varies from melagabbroic to leucodioritic. The magmatic fragments are always more mafic than the local matrix in which they are situated.

There are seven main nickel showings in the gabbro, all located in brecciated areas. Throughout the breccia the mineralization is connected to melagabbroic and ultramafic fragments mainly as a sulphide dissemination. Rich dissemination and locally massive ore have also been observed in more leucocratic gabbros. Nickel mineralization occurs over a 1700 m long and 300 m wide zone following the inner portions of the gabbro breccia parallel to the general schistosity. Several lines of evidence point to formation of the ore during a magmatic crystallization process either as sulphide layers or as heavily impregnated mafic-ultramafic rocks, which at a later stage have been broken up into separate fragments with some subsequent mobilization and redistribution of sulphides.

The sulphides present are pyrrhotite, pentlandite and chalcopyrite. Pyrrhotite is the main ore mineral with a grain size of 1—5 mm. Pentlandite occurs as 0.1—1 mm grains in pyrrhotite and rarely as exsolution flames. Bravoite is often observed as an alteration product of pentlandite. Chalcopyrite occurs mainly in pyrrhotite as grains of 0.1 mm size or as lamellae. Linnaeite is also observed in some sections. Recent assays indicate a grade of 0.87 % Ni, 0.33 % Cu and 6.71 % S with gold values in the 0.1 ppm range and trace contents of Pd and Pt.

Vakkerlien

The Vakkerlien nickel deposit is situated near Kvikne in Central Norway (Fig. 10). It has recently been described by Thompson, Nixon and Sivertsen (1980). The Kvikne area lies in the Gula unit of the central Norwegian Caledonides. The Gula is considered to include the oldest parts of the Trondheim nappe and is at least

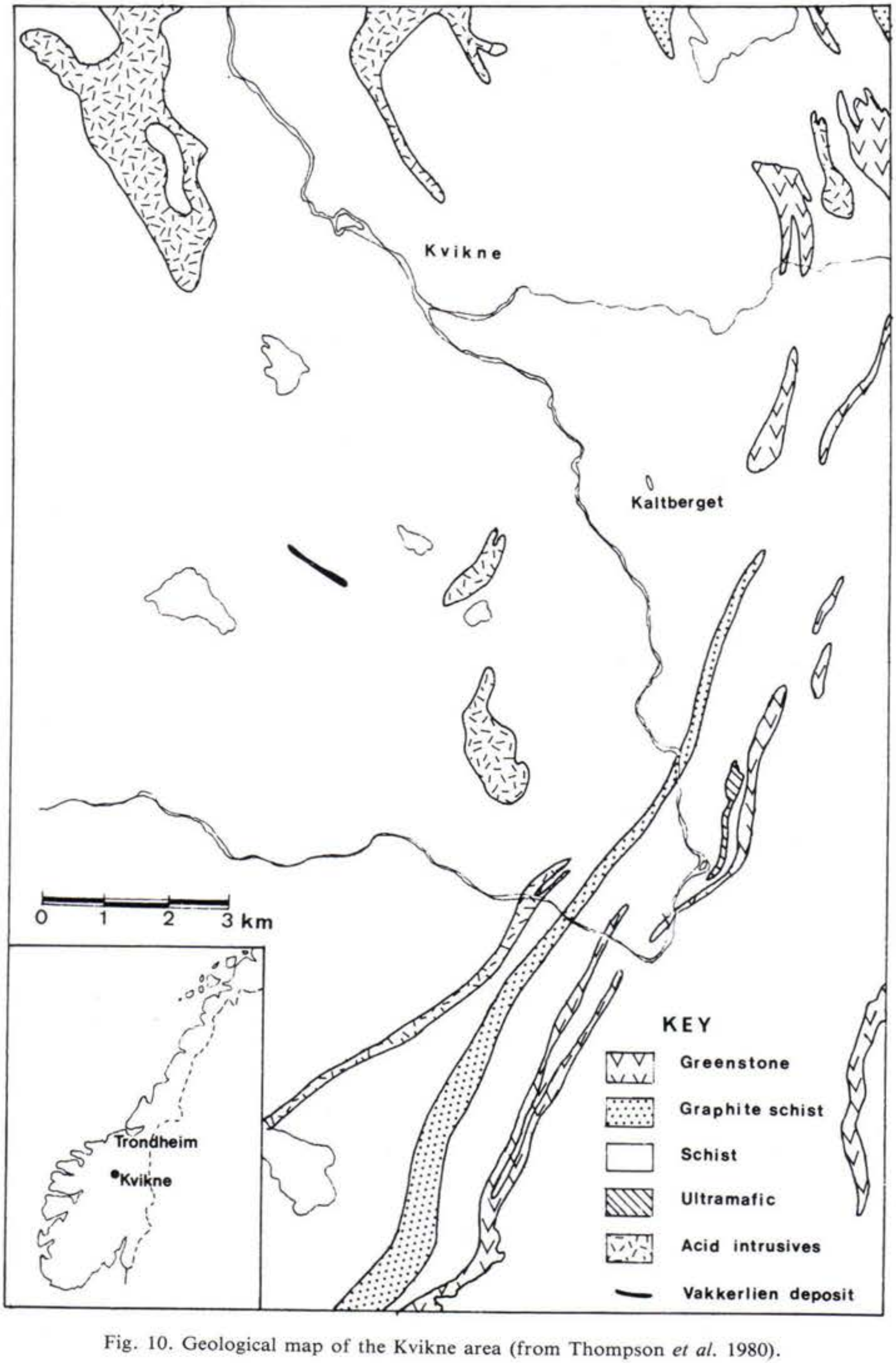


Fig. 10. Geological map of the Kvikne area (from Thompson *et al.* 1980).

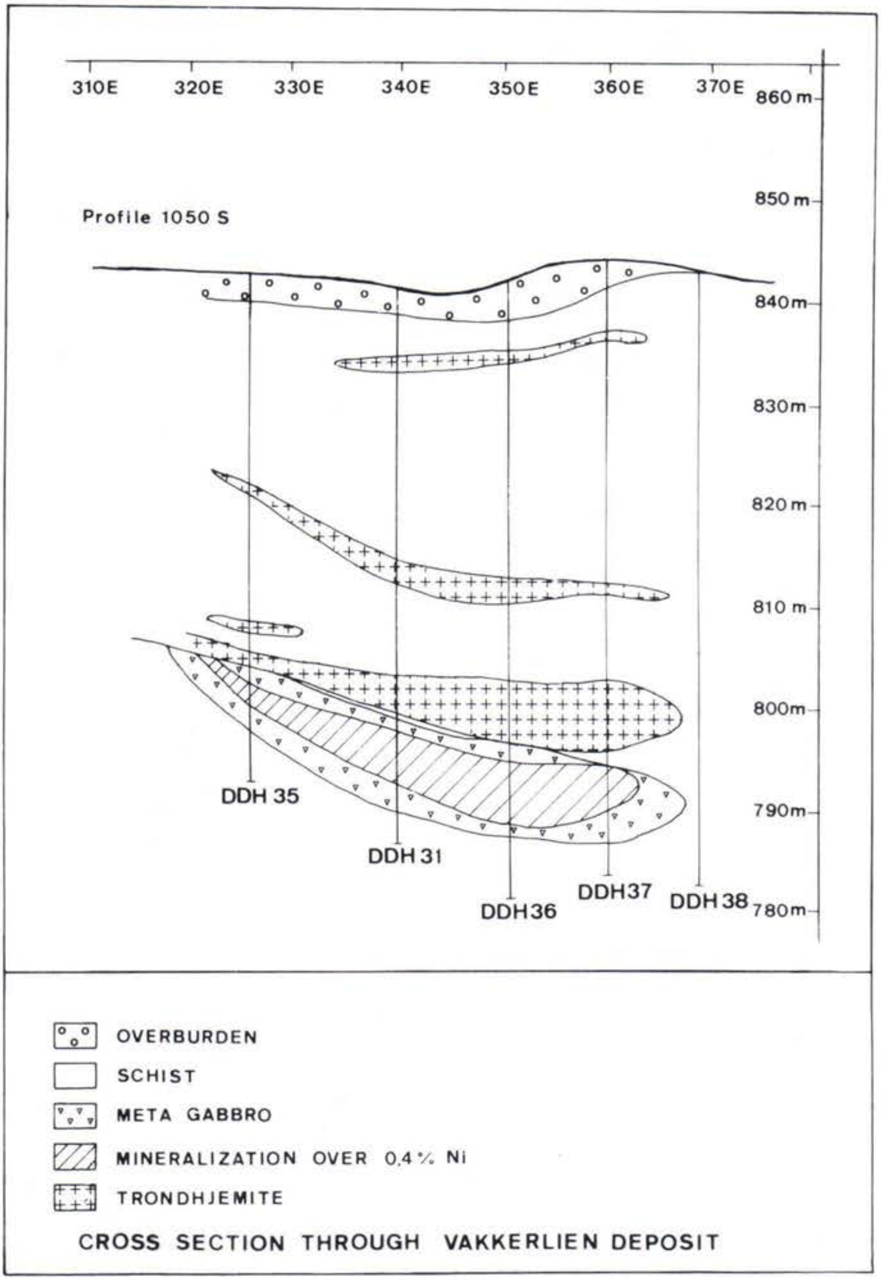


Fig. 11. Geological profile through the Vakkerlien deposit (from Thompson *et al.* 1980).

mainly probably Proterozoic in age (Roberts 1978). The Gula consists of a series of psammitic, calcareous, graphitic and pelitic schists with subordinate amphibolites (Gula volcanics) and occasional bodies of ultramafic and gabbroic rock. The metamorphic grade is medium to upper amphibolite facies, and structural investigations in the region have defined four phases of deformation with the major deformation being two early isoclinal fold phases.

The Vakkerlien body (Fig. 11) was investigated in the period 1975—79. Geophysical investigation and subsequent diamond drilling delineated a mineralized metagabbroic body over 1250 m long with an elliptical cross-section containing approximately 400,000 metric tons grading 1 % Ni and 0.4 % Cu. The mineralized zone is located in the central portions of the metagabbroic body which plunges gently southeastwards parallel to the regional lineation. At its southern end the metagabbroic body is cut off by a later trondhjemitic intrusion and no major extension has been located further to the south.

Considerable lithological variations are present within the Vakkerlien metagabbro, but the rocks can be divided into two main types, metagabbroic and ultramafic, with alteration and deformation producing further variation. The metagabbro types make up c. 50 % of the body and vary in texture from coarse to highly sheared and altered varieties. The main minerals are plagioclase and amphibole in varying but mainly equal amounts. Accessory minerals include quartz, calcite, biotite, chlorite, clinozoisite, sphene, rutile, sericite and sulphides.

The ultramafic rock types vary from undeformed to highly sheared and altered. Coarse ultramafic rock consists of amphibole and chlorite in variable proportions. Accessory minerals include talc, carbonate, quartz, plagioclase, sphene and rutile. Shearing results in a marked amphibole and chlorite foliation and a dramatic increase in the biotite content. Although in detail the distribution of rock types is exceedingly complex, a simple broad zonation can be seen across the body with ultramafics clearly dominating on the southwestern side of the body and metagabbro types on the northeastern side.

Numerous schist inclusions are found indicating that the body was intruded as a liquid and probably differentiated in place. Nilsen (1974) suggests that this and other mafic and ultramafic bodies in the Gula group represent intracrustal cumulates related to the Gula metavolcanics. Whole rock chemistry however fails to support this genetic connection, and the actual relationship of the Vakkerlien metagabbro to the Gula volcanics, if any, remains uncertain.

The Vakkerlien sulphide body occupies an approximately central position along the axis of the metagabbro body (Fig. 11) and compares in shape to the main body, pinching and swelling along its length. A variety of sulphide types is found, hosted both by metagabbroic and ultramafic rock types. The first type, designated massive vein sulphide which makes up to 50 % of the mineralization occurs as discrete veins varying from 2 cm to 30 cm in width. The veins commonly cut through the host rocks. The second sulphide type, stringer sulphide, is essentially a variant of the above type. Stringer sulphide constitutes less than 20 % of the mineralization and is restricted to highly sheared rock types. Sulphides occur as stringers and shears less than 1 cm in width both concordant with, and discordant to foliations. Massive vein sulphide can grade into stringer sulphide with increasing host rock deformation. The final sulphide type is characterized by disseminated sulphides interstitial to metagabbro or ultramafic silicates and varying in proportions from 5—40 % sulphide. The host rock type for disseminated sulphides is consistently non-foliated and apparently undeformed.

All the major sulphide phases are ubiquitous in all three sulphide types, although the modal proportions are highly variable both between and within these types. Disseminated sulphides are the most compositionally uniform type. The most common phases are pyrrhotite and pentlandite in modal proportions varying from 10:1 to 3:1. Chalcopyrite is the other common sulphide and shows a highly variable distribution. Pyrite is present in most samples and is estimated to constitute a maximum of 5 % of the sulphides. Accessory gersdorffite and violarite are present. Pyrrhotite generally forms large uniform grains with rare pentlandite exsolution flames abutting on fractures, grain boundaries and twin planes. Monoclinic pyrrhotites contain more than 1 wt % Ni, ranging up to 3.05 wt % Ni, anomalously high when compared to the nickel contents of pyrrhotites reported from other nickel sulphide localities. Hexagonal pyrrhotites, however, contain a more typical value, less than 0.31 wt % Ni. Pentlandite occurs predominantly as coarse blocky grains. Pentlandite analyses indicate a high nickel content, 37—38 wt %, but with cobalt being generally low. Pyrite appears to be largely secondary, replacing pyrrhotite and inheriting the high nickel content. Chalcopyrite was found to be essentially stoichiometric.

The Vakkerlien metagabbroic body has clearly suffered severe deformation and it is suggested that the present form of the body is the result of isoclinal folding of a differentiated gabbro sheet. It can be assumed that the Vakkerlien sulphides were potentially relatively mobile under these deformational conditions. No deformation model, however, can adequately explain the present distribution of sulphides if an original basal position is envisaged. Massive vein sulphide and stringer sulphide show clear evidence of remobilization, the sulphide chemical data suggesting that metamorphic fluids may have been active in the process. Local plastic remobilization may also have occurred, particularly in highly discordant sulphide stringers. Disseminated sulphides have clearly been recrystallized in that they now occupy a position interstitial to metamorphic silicates presumably originating as sulphide interstitial to igneous silicates. Their position, however, in essentially undeformed metagabbro and ultramafic rock suggests that large scale remobilization has not affected these sulphides and that the deformation style within the metagabbro — the absorption of strain largely on discrete shear zones — has preserved the disseminated sulphide roughly is its primary position. Thus it is suggested that the unusual position of the sulphides reflects an original igneous concentration with additional remobilization of some sulphide in deformed metagabbro and ultramafic.

Several other smaller nickel occurrences are known in association with mafic and ultramafic intrusions in the Kvikne area. The most notable of these is the Kaltberget showing (some 8 km from Vakkerlien) where small pockets of pentlandite-rich ore are associated with a large sheet-like ultramafic body.

Small deposits in Nordland

Tverrbrennfjell: This mineralization occurs in a small gabbroic body with maximum dimensions 1 km × 2 km which forms a part of a complex of granitic and dioritic rocks about 40 km SE of Bodø. The host complex is of uncertain age but was probably emplaced during the Caledonian orogeny. The mineralization forms several thin (1 m) zones of indeterminate length. Analyses show 1 % Ni and 0.5 % Cu with between 2.75 and 4.5 % Ni in pure sulphides.

Lilleåleiden: This deposit lies about 40 km SSE of Bodø in a small gabbroic body (40 × 15 m^2) in garnet mica gneiss. The mineralization (Vogt 1892) forms a zone of dissemination up to 1 m wide along the southern contact of the gabbro over a distance of 30 m; locally zones of massive sulphide up to 20 cm wide are present. Analyses of the two types of mineralization show:

Disseminated:	0.9 % Ni,	0.3 % Cu,	4.25 % S
Massive:	5.5 % Ni,	0.8 % Cu,	30.25 % S

Måløy: Måløy is a small island situated some 60 km NNE of Bodø. Nickel mineralization was found in 1883 on the south side of the island near sea level. The deposit was worked underground until 1886 when the workings were flooded by sea water in the lowest drifts. Approx. 200 tonnes of hand sorted ore are reported to have been mined.

The two main rock types on Måløy are mica schists and marbles. Concordantly intercalated in the schists are dark grey amphibolitic bands, usually less than 0.5 m wide and commonly garnet bearing. The rocks are folded with dominant rodding plunging 30°—60° SW.

Mineralization occurs as:

1) veins and fracture fillings in marble and
2) rich impregnation in amphibolitic rocks

The compact veins in the marble vary between 1 and 3 m in width, and are seen to occur in one definite horizon. An assay of such a vein gives:

Ni %	Cu %	Co %	S %
5.5	0.28	0.11	36.6

Rich impregnation of sulphides in amphibolitic rocks was only observed on the mine dumps. Assays gave:

Ni %	Cu %	Co %	S %
3.0	0.4	0.08	15.7

In thin section large subhedral hornblendes occur throughout. Quartz and feldspar occur as interstitial material. Rounded, inclusion-bearing (i.e quartz) garnets partially altered to a fine grained carbonate are present. Massive pyrrhotite, containing highly violaritized blocky pentlandite, »flame» pentlandite and chalcopyrite occur enclosing rounded patches of hornblende, quartz and felspar. The supposed down plunge extension of the deposit was drilled in 1973 with negative results.

DEPOSIT CLASSIFICATION

A number of classifications of mafic and ultramafic rocks and associated nickel deposits have been published, the most recent being that of Naldrett (1981a). This classification is given in Table 3 together with an attempt at assigment of the Norwegian deposits within it.

Most of the Norwegian mineralizations fall into category C, bodies emplaced during orogenesis, though within this category a number of the mineralizations are of uncertain magmatic association. The Homse and Reinfjord mineralizations are of interest in that they would appear to be associated with an anorthositic complex and an Alaskan type complex respectively, two magmatic associations from which there are very few recorded examples of Ni sulphide mineralization.

Table 3. Classification of mafic and ultramafic bodies and associated nickel mineralizations, modified after Naldrett (1981a) with assignment of Norwegian Ni mineralizations within the classification, where possible.

Magmatic association	Associated mineralization
A. Synvolcanic bodies	
1. Komatiitic suites	
2. Tholeiitic suites	
a) Synvolcanic layered intrusions	Pasvik (Petsamo Group)
b) Anorthositic bodies	Homse
3. Uncertain types	
B. Intrusions in cratonic areas	
C. Bodies emplaced during orogenesis	
1. Synorogenic intrusions	Espedalen, Hosanger, Råna, Vakkerlien
2. Tectonically emplaced bodies	
a) Ophiolite complexes	Fæøy, Lyngen, Ste
b) Mantle diapirs	
c) Uncertain types	Ertelien, Flåt
3. Alaskan-type complexes	Reinfjord
4. Uncertain types	

ORE GEOCHEMISTRY

Average geochemical data for the deposits described in this paper are given in Table 2 — for certain of the smaller deposits no reliable data is available and some of the data in Table 2 are not modern and may be less than accurate.

Fig. 12 shows a plot of % Ni and % Cu in sulphides with fields related to specific deposit-types as shown by Naldrett (1981b). The majority of Norwegian deposits plot, as would be expected, in the field described as »other gabbro» with three (Espedalen, Flåt and Fæøy) plotting in the overlapping »Sudbury field» characterized by a higher Cu content. The relatively high Cu/(Cu + Ni) ratio of the Fæøy mineralization is similar to that found in Ni mineralizations in the upper levels of ophiolites elsewhere, as in showings in the Bay of Islands ophiolite described by Smith (1958).

Two deposits, Bruvann and Vakkerlien, have % Ni in sulphide contents which place them in, or close to the field shown for Ungava komatiites by Naldrett (1981b). Several lines of evidence point to multiple magma pulses as having been important in the development of the Råna intrusion (see above) and it is possible that the earliest magmatic pulses with which the Bruvann mineralization is associated were akin to high Mg basalt. Thompson *et al.* (1980) indicate that the Vakkerlien mafic body was a sheet, differentiated in place to give similar volumes of mafic and ultramafic rock: a prerequisite for this is a relatively magnesian primary magma.

PGE analyses lend further credence to the suggestion that both the Bruvann and Vakkerlien mineralizations were associated with relatively magnesian primary magmas. Naldrett (1981b) demonstrates that the ratio (Pt + Pd)/(Ru + Ir + Os) appears to have values under 8 for sulphide bodies related to komatiites in general and under 2 for Archean komatiites whereas the same ratio has values in excess of 10 for mineralizations (twelve deposits) associated with other magma types; two exceptions to the latter generalization are cited, one of them being Espedalen (5.74). The PGE data on disseminated sulphides at Vakkerlien given by Thompsom *et al.* (1980) yield an average (Pt + Pd)/(Ru + Ir + Os) ratio of 3.705 which lies between the ratios for Archean komatiites and those for Katiniq and Donaldson West (Naldrett 1981b). Preliminary data (Page & Boyd, work in progess) suggests that also the Bruvann

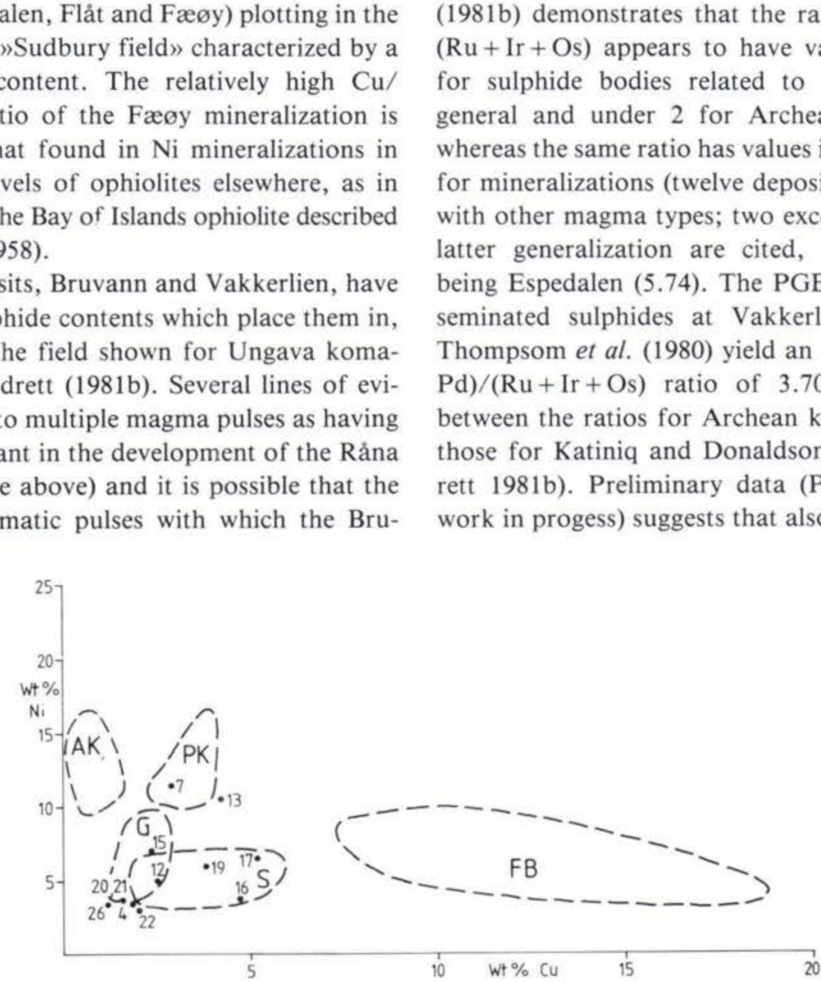


Fig. 12. Plot of Ni against Cu (% in sulphides) for Norwegian nickel deposits. The fields AK (Archaean komatiite), PK (Proterozoic komatiite), G (gabbro), S (Sudbury) and FB (flood basalt) are for Ni deposits in these environments as given by Naldrett (1981 a). The numbering is as on Table 2 and map minus 300.

mineralization probably has a relatively flat chondrite-normalized PGE distribution pattern (=low (Pt+Pd)/(Ru+Ir+Os) ratio) with a negative Pt anomaly and some similarity to the pattern for the Pipe deposit (Naldrett 1981b), but with even lower concentrations.

CONCLUSIONS

This paper presents a collation of data of varying age and quality from many sources. It is possible to draw some conclusions on genetic aspects of specific deposits, but the inhomogeneity of the data on the deposits and locally the lack of various forms of geological background information restrict the possibilities for more general conclusions on the metallogenic province level.

The one clear concentration of deposits is related to the Kongsberg-Bamble Formation in S. Norway at least part of which has been interpreted by Falkum (1980) as a deep-seated right-lateral shear zone which was active throughout the Sveconorwegian orogeny. Torske (1976, 1977) related the Kongsberg-Bamble Formation to a broader zonation within an orogenic belt thought to be parallel to the south coast of Norway. Berthelsen (1980) related the mafic magmatism with which the nickel mineralizations are associated to a tensional stage immediately prior to the Sveconorwegian orogeny: he proposed that the Kongsberg-Bamble Formation represents the margin of an eastern plate and interprets its western margin as the locus of an eastward-dipping suture zone of Sveconorwegian age, a model which may be reconcilable with that of Falkum (1980), but which is at variance with Torske's interpretation as regards the polarity of subduction locally and the main strike direction of the orogeny as a whole.

The Hosanger and Espedalen deposits would both seem to be related to late magmatism within rocks of the Jotun Nappe or its probable equivalents.

As indicated above, a number of the deposits within the Caledonian orogen are related to ophiolite complexes or fragments thereof. Several of the other deposits — Vakkerlien, Skjækerdalen and Bruvann (Råna) are located within a specific tectonostratigraphic unit, the middle unit of the Upper Allochthon (Gula and equivalents) (IGCP Project 27, in preparation). Lesser deposits occur at a higher tectonic level in Nordland in the Uppermost Allochthon, but in rocks which may be a tectonic repetition of those which host nickel deposits in the Upper Allochton. A proper evaluation of these speculations requires considerably greater knowledge both of the nickel deposits and their host complexes and of the structural environment in which they are located.

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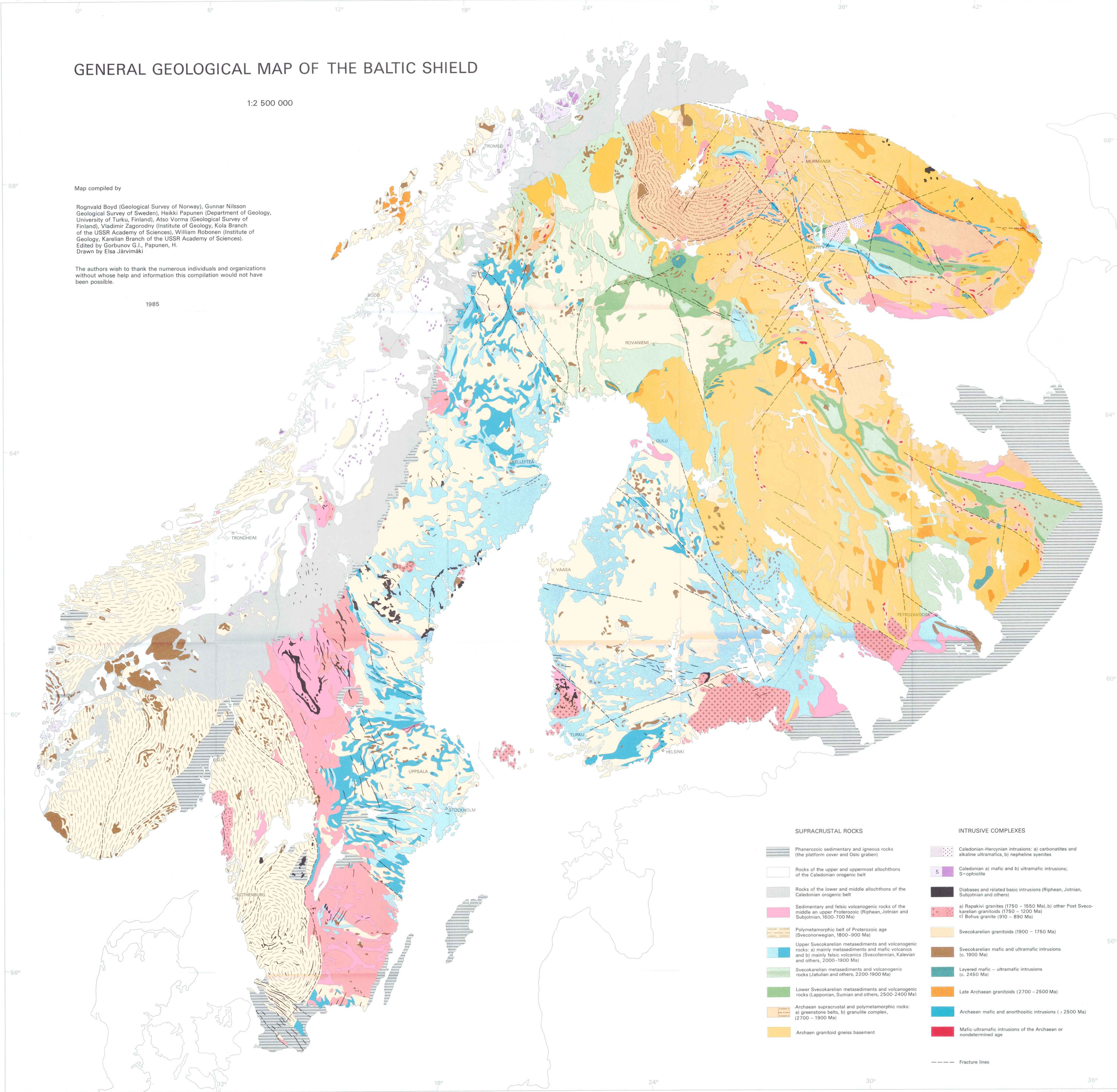
GENERAL GEOLOGICAL MAP OF THE BALTIC SHIELD
1:2 500 000
Map compiled by
Rognvald Boyd (Geological Survey of Norway), Gunnar Nilsson Geological Survey of Sweden), Heikki Papunen (Department of Geology, University of Turku, Finland), Atso Vorma (Geological Survey of Finland), Vladimir Zagorodny (Institute of Geology, Kola Branch of the USSR Academy of Sciences), William Robonen (Institute of Geology, Karelian Branch of the USSR Academy of Sciences).
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1985
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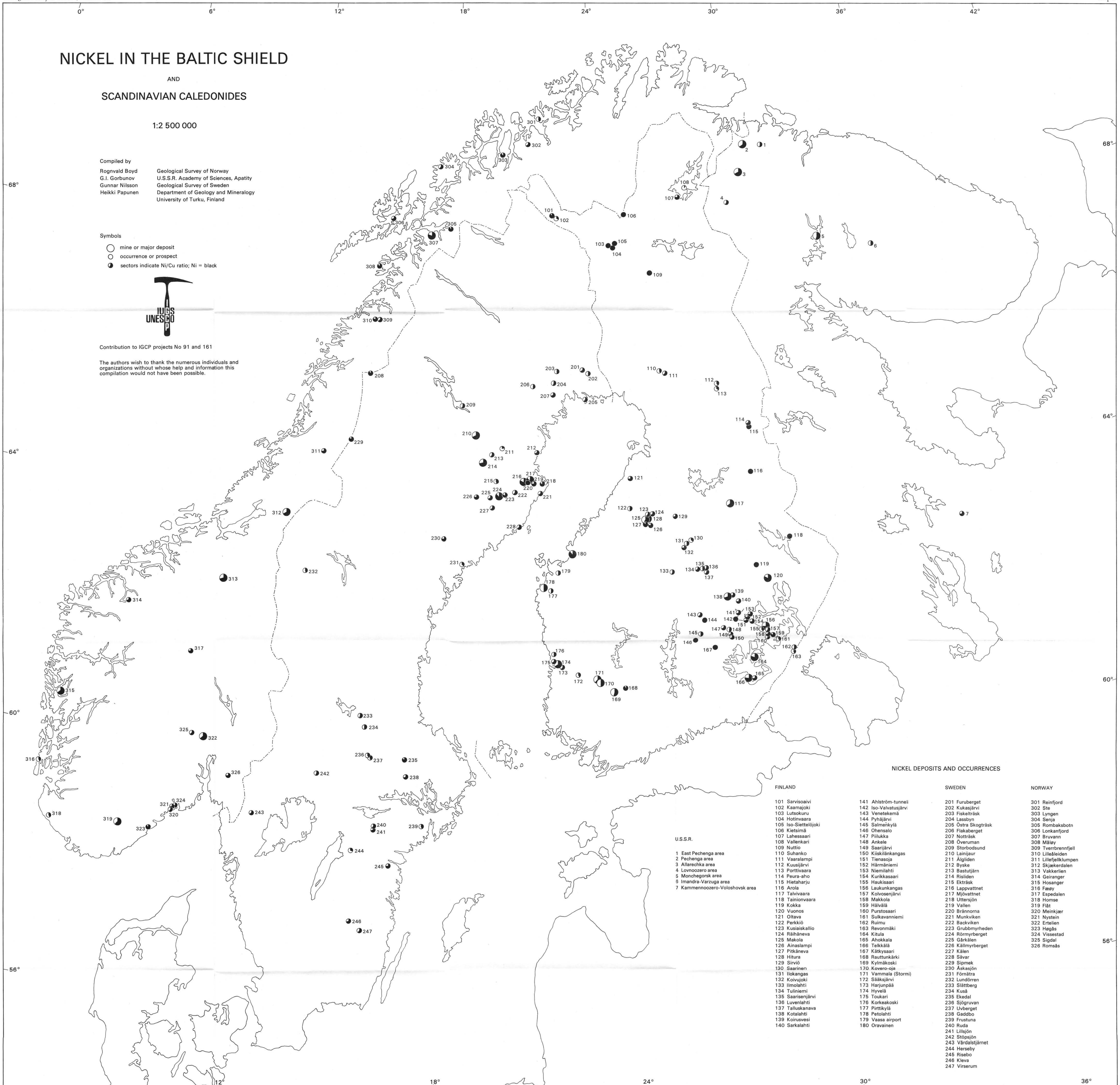
BERGEN
TURKU
HELSINKI
OSLO
UPPSALA
STOCKHOLM
GOTHENBURG
SUPRACRUSTAL ROCKS
Phanerozoic sedimentary and igneous rocks (the platform cover and Oslo graben)
Rocks of the upper and uppermost allochthons of the Caledonian orogenic belt
Rocks of the lower and middle allochthons of the Caledonian orogenic belt
Sedimentary and felsic volcanogenic rocks of the middle an upper Proterozoic (Riphean, Jotnian and Subjotnian, 1600-700 Ma)
Polymetamorphic belt of Proterozoic age (Sveconorwegian, 1800–900 Ma)
Upper Svecokarelian metasediments and volcanogenic rocks: a) mainly metasediments and mafic volcanics and b) mainly felsic volcanics (Svecofennian, Kalevian and others, 2000–1900 Ma)
Svecokarelian metasediments and volcanogenic rocks (Jatulian and others, 2200-1900 Ma)
Lower Svecokarelian metasediments and volcanogenic rocks (Lapponian, Sumian and others, 2500-2400 Ma)
Archaean supracrustal and polymetamorphic rocks: a) greenstone belts, b) granulite complex, (2700 – 1900 Ma)
Archaen granitoid gneiss basement
INTRUSIVE COMPLEXES
Caledonian-Hercynian intrusions: a) carbonatites and alkaline ultramafics, b) nepheline syenites
Caledonian a) mafic and b) ultramafic intrusions; S=ophiolite
Diabases and rélated basic intrusions (Riphean, Jotnian, Subjotnian and others)
a) Rapakivi granites (1750 – 1550 Ma), b) other Post Sveco-karelian granitoids (1750 – 1200 Ma) c) Bohus granite (910 – 890 Ma)
Svecokarelian granitoids (1900 – 1750 Ma)
Svecokarelian mafic and ultramafic intrusions (c. 1900 Ma)
Layered mafic – ultramafic intrusions (c. 2450 Ma)
Late Archaean granitoids (2700 – 2500 Ma)
Archaean mafic and anorthositic intrusions (› 2500 Ma)
Mafic-ultramafic intrusions of the Archaean or nondetermined age
Fracture lines



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